Post-Sandy Flood Resiliency in NYC:
How to Prevent Subway Systems from Increasing Storm Surges

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Introduction

Millions of people in New York City rely on public transportation daily to commute across the city. On average, 5.5 million people ride the subway on any given weekday across the 472 stations and 665 miles of track.[1] When there are disruptions in service within the system, they affect everyone who relies on the subway. Extreme weather events are likely to disturb subway service and flood tunnels and with climate change increasing the frequency in storms and flood events, subway service will be disrupted more frequently. As a result, flood resiliency plans should be created so that flooding is less likely to occur inland and disrupt subway service as little as possible should it occur. In 2012, Superstorm Sandy showed us how unprepared the city actually is in tackling flood issues. The aftermath of Sandy resulted in new plans and initiatives for flood resilience in the event that a similar or more severe storm would occur in the future. Several government reports, such as the PlaNYC and A Stronger, More Resilient New York reports, attempted to tackle flood prevention across different sectors. However, careful planning and proposed initiatives haven't been enough. The aftermath of Hurricane Ida in the summer of 2021 revealed that the planning done after Sandy was not enough. Though the concern of Ida was heavy and intense rainfall that caused a lot of inland flooding and led to the death of 16 people in the city,[2] it was clear that the government did not respond to the emergency as well as they could have. What happened to all of the preparedness and resiliency that the city promised after Sandy? Only as little as half of the initiatives proposed after Sandy were implemented. Flooding does not seem like a pressing issue for the government, though it is for New York City. Taking into account the sea level rise and storm vulnerability that the city will

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[1] "Subway and Bus Ridership for 2020," MTA, accessed December 15, 2021, https://new.mta.info/agency/new-york-city-transit/subway-bus-ridership-2020.

[2] Jesse McKinley, Dana Rubinstein, and Jeffery C. Mays, "The Storm Warnings Were Dire. Why Couldn't New York Be Protected?," *The New York Times*, September 3, 2021, sec. New York, https://www.nytimes.com/2021/09/03/nyregion/nyc-ida.html.

face in the coming years, New York City's own failed initiatives after Superstorm Sandy, as well as case studies of how cities and countries with a history of flooding and storms tackle resiliency efforts, we can examine which flood protection plans will work in New York City and what will not.

Sea Level Rise and Storm Vulnerability

Climate Change in NYC

As a coastal city, New York City is especially vulnerable to flooding from storm surges and other extreme weather events. Hurricanes, tropical storms, nor'easters, rain storms, high tide, and increase in sea level are currently the primary causes for flooding in NYC.[3] Around 400,000 residents and at least 14 subway stations are contained within the 100-year floodplain, the area that has a one percent chance of flooding in any given year, and that number is only expected to increase due to climate change and rising sea level.[4] According to the New York City Panel on Climate Change in 2016, sea levels are expected to rise between 8 to 30 inches (20.3 to 76.2 cm) by 2050, and 15 to 75 inches (38.1 to 190.5 cm) by 2100.[5] Sea level rise and a warmer climate will drive up the intensity of the storms seen in the Northeast, and if the trajectory of these storms reaches New York City, the impact of storms and flooding will be higher than what was previously predicted.[6] Storms have also been hitting NYC more frequently than before, as the trajectory of tropical storms is changing.[7] More frequent storms and higher storm intensity will

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[3] "Flood Risk in NYC" (Department of City Planning (DCP), November 2016).
[4] Ibid; Douglas Hill, "Vulnerability and Potential Losses in New York City from Coastal Flooding," in *Storm Surge Barriers to Protect New York City Against The Deluge* (Against the Deluge: Storm Surge Barriers to Protect New York City, Brooklyn, New York, United States: American Society of Civil Engineers, 2012), 58–70, https://doi.org/10.1061/9780784412527.005.
[5] "Flood Risk in NYC."
[6] Andra J. Garner et al., "Impact of Climate Change on New York City's Coastal Flood Hazard: Increasing Flood Heights from the Preindustrial to 2300 CE," *Proceedings of the National Academy of Sciences* 114, no. 45 (November 7, 2017): 11861–66, https://doi.org/10.1073/pnas.1703568114.
[7] Ibid.

increase flooding and other negative ramifications whenever a storm hits the city. Over the past decade, there have already been many anomalous extreme weather events that have caused flooding across the city. On October 29, 2012, Superstorm Sandy was one of the first devastating storms that hit the city that resulted in unprecedented flooding. Even with preparations, the city could not predict the severity of the storm and many sectors were closed for several days as the city recovered and restored service to damaged areas. For several months and even years after, the city continued to repair the damages from Sandy and implement better flood prevention systems. Since then, there have been several more storms that have impacted the city. Most recently, Hurricane Ida hit the Northeast on September 1 and 2, 2021 and led to unexpected flooding across the city and the suspension of the entire subway system.[8] The likelihood of a Sandy-like storm hitting New York City has increased from a one-in-500-year event to a one-in-25-year event in the past 200 years, and with climate change, an extreme storm event may even become a one-in-five year event by 2030.[9]

Superstorm Sandy

In preparation for Superstorm Sandy, all public transportation across New York City was preemptively shut down on October 28, 2012 at 7 PM, almost 24 hours before the predicted arrival of Sandy.[10] Sandbags were piled in front of various subway entrances and along tunnels to prevent as much water from entering underground, and station entrances were boarded up for the

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[8] John Bacon Hauck Ryan W. Miller and Grace, "'We're Not out of This yet': At Least 46 Dead after Flooding Overwhelms NYC, Northeast," USA TODAY, accessed December 15, 2021, https://www.usatoday.com/story/news/nation/2021/09/02/deadly-flooding-new-york-new-jersey-hurricane-ida-louisiana/5692877001/.

[9] "Safeguarding Our Shores: Protecting New York City's Coastal Communities from Climate Change" (New York City Comptroller, May 9, 2019), https://comptroller.nyc.gov/reports/safeguarding-our-shores-protecting-new-york-citys-coastal-communities-from-climate-change/.

[10] "Fixing NYC's Subway after Sandy," accessed November 10, 2021, https://www.cbsnews.com/pictures/fixing-nycs-subway-after-sandy/.

same reasons.[11] Residents of certain areas, particularly those in downtown Manhattan and along the shore, were told to evacuate.[12] Despite all of the precautions that the city took, no one anticipated the damage that occurred as a result of the storm. Stormwater flooded many subway stations, tunnel entrances, and ventilation structures, and all of the subway tunnels connecting outer boroughs to Manhattan were inundated.[13] One notable example was South Ferry Station, which flooded with 15 million gallons (18.9 million liters) of saltwater and was closed for five years and cost $350 million in damages.[14] Several subway lines remained inoperable for days after Sandy and caused water and corrosive damage to much of the equipment.[15] Immediate relief included pumping as much water out of subway stations as possible and arranging for shuttle and other alternative services to the subway as they were being repaired.[16] The aftermath of Sandy prompted local and federal governments to implement efforts to combat flooding within public transportation systems, and in particular, how to prevent flooding within underground tunnels and subway systems.

[11] "A Stronger, More Resilient New York" (City of New York, June 11, 2013), 177.
[12] "Fixing NYC's Subway after Sandy."
[13] "A Stronger, More Resilient New York," 178.
[14] "Fixing NYC's Subway after Sandy."
[15] "A Stronger, More Resilient New York," 178.
[16] "Fixing NYC's Subway after Sandy."

Proposed Flood Responses in NYC

PlaNYC: A Stronger, More Resilient New York

Mayor Michael Bloomberg launched PlaNYC in 2007 to address the issues of the ever growing city—how to accommodate for one million residents and how to "adapt to and mitigate the growing risks of climate change."[17] The report published one year after Sandy in 2013 not only addressed more general issues of climate change, but also was a direct response to the damage that Superstorm Sandy left on the city. This report served as a general response to the storm and efforts that the government would undertake to repair and rebuild the city. A more specific report, titled "A Stronger, More Resilient New York," was also released and outlined specific projects that each sector would take on to repair issues and to work on greater resiliency efforts for the future. Nearly a decade later, only around half of the initiatives put forward in the plans have been executed, and most of those initiatives have only focused on repairs. Despite the increasing rate that major storms have hit New York City after Superstorm Sandy, the government has not begun to prioritize flood resiliency when it comes to urban planning.

2013 Progress Report

The 2013 PlaNYC progress report, published approximately one year after Hurricane Sandy, continued to address these issues but also attempted to address a somewhat newer impediment to NYC—floods and storm surges. The progress report introduces several general approaches that could combat storm surges, such as creating coastal wetlands and dunes along shorelines, and others that could combat inland flooding, such as the creation of green infrastructure.[18] As opposed to grey infrastructure, which is defined as human-engineered wastewater management systems, green infrastructure includes open spaces, natural areas, street

[17] "A Greener, Greater New York," Progress Report, PlaNYC (City of New York, 2013), 4.
[18] Ibid, 17.

gardens, and other innovations that are able to process stormwater from streets and sidewalks and reduce stress on wastewater treatment systems.[19] The green infrastructure also has the ability to prevent streets from flooding and water from entering underground tunnels and subway systems through vents or station entrances. In the report, Mayor Bloomberg also created the Special Initiative for Rebuilding and Resiliency (SIRR) to help rebuild communities that were most affected by Sandy and to "increase the resilience of the built environment and critical infrastructure to the effects of climate change."[20] In theory, the SIRR would have worked on resiliency initiatives that prioritize vulnerable populations—for example, those in areas with a direct risk of flooding, or those who rely on public transportation. Instead, the most comprehensive action that the SIRR took was to generate a report.

A Stronger, More Resilient New York

In addition to the annual PlaNYC progress report, a special report generated by the SIRR titled "A Stronger, More Resilient New York" was published on June 11, 2013 that specifically addressed resiliency efforts in the aftermath of Hurricane Sandy and how to equip the city for future events of a similar capacity. Through ambitious but achievable strategies, the report outlined initiatives in several different sectors across the city, including coastal protection, utilities, transportation, and wastewater management, and initiatives in community rebuilding. The three main strategies that the SIRR focused on in the transportation sector include: 1) protecting assets to maintain system operations, 2) preparing the transportation system to restore service after extreme climate events, and 3) implementing new and expanded services to increase system flexibility and redundancy.[21] Though these strategies were extremely crucial to rebuilding the transportation sector after Sandy, many of these strategies were only reactive methods. These

[19] Ibid, 19.
[20] Ibid, 49.
[21] "A Stronger, More Resilient New York."

reactive efforts focused only on reacting to the aftermath of a storm—how to clean up after a storm has hit the city, how to return service as quickly as possible to damaged sectors, and what to do after a flood has already occurred within the tunnels underground. Although some flood protection efforts are outlined, it is important to note that they are largely mitigating efforts, or those that try to reduce damage as much as possible rather than preventing floods from occurring in the first place.

The first strategy focused on ensuring transportation does not shut down outright. By redirecting or blocking as much floodwater as possible and generating backup electricity, subways can remain operable or begin operation after a big storm as quickly as possible with no interruptions. One such project proposed to integrate stormwater management into future street reconstruction projects by allowing stormwater to seep into the ground rather than flow into sewer systems, wastewater treatment plants, or into subway entrances and vents.[22] One example would be the inclusion of bioswales, or "planted areas in the sidewalk designed to capture stormwater from the adjacent roadway,"[23] into sidewalks. Another initiative focused on tunnel protection. Installing floodgates and raising tunnel entrances and ventilation structures above flood elevations could provide protection for electrical and mechanical equipment against failure, and allow subway and other underground transportation systems to continue operations.[24] Although it is critical to prevent disruptions in subway service, the suggested initiatives are not the best option for that. Focus could instead be on methods to prevent flood water from entering subway entrances and tunnels or even protecting electrical systems.

In the off-chance that preventative measures fail during a flood, and after subway systems are potentially disrupted by a flood, the second strategy prioritized restoring subway systems as

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[22] Ibid, 183.
[23] Ibid.
[24] Ibid, 184.

quickly as possible while providing alternative transportation services. Rather than attempt to return subway systems to regular service, the city believed that the most important concern was to provide alternative, temporary transit services when subway lines are disrupted. The city implemented requirements to limit vehicles entering Manhattan to have three or more occupants to further prevent a surge in traffic after Sandy into the central business district.[25] Another initiative proposed more pedestrian and bike paths to increase mobility within the city and lessen the pressure on increased road traffic after the storm. Creating alternative services to subway systems are important in the case that flooding disrupts service, but as aforementioned, without any preventative measures in place, flooding will 100 percent happen and returning the subway to regular service should be the priority when that occurs.

The last strategy of the proposal was to expand transportation services to decrease the load and reliance on the city's current public transport system. Two initiatives that were considered include expanding the city's Select Bus system and expanding the ferry service. These two initiatives would decrease the current reliance on underground systems, such as the subway, and would serve as an alternative for when these underground systems are disrupted.[26] This strategy is the most likely to work in the long term, as a decreased reliance on the subway system would lead to less of an impact on commuters who rely on public transportation in any flood event. However, this project is the least feasible and looks to be the least important to the city since, when flooding occurs without preventative measures, much of the money will be spent on repairing and rebuilding damaged systems already in place.

[25] Ibid.
[26] Ibid, 188.

Funding for PlaNYC

Funding for these SIRR resiliency initiatives largely came from city, state, and federal public funds. The projected $19.5 billion cost would cover "both capital expenditures and study costs" and only those associated with the first phase of each project, such as repairing all of the damage done by Superstorm Sandy.[27] The funds would expand to cover housing, business, and city agency recovery and resiliency. $5.5 billion of the existing funds come from the city's capital, $1.8 billion from community development block grants, and around $2.3 billion from federal aid in the Sandy Supplemental Aid Package.[28] Additionally, the city expected to receive $1.8 billion more from federal grants, additional funding from the Robert T. Stafford Disaster Relief and Emergency Assistance Act, and will save costs through cross-sector resiliency efforts.[29] However, because damages to the city infrastructure were so severe, the city concluded that they needed more money than they had to fund the recovery and resiliency efforts—at a gap of $4.5 billion. As of March 2021, a total of around $3.7 billion has been allocated to the Metropolitan Transit Authority (MTA) by the Federal Transit Administration for Sandy recovery, relief, and resilience.[30]

Success of the Plan

As of May 2019, only around 54 percent of the $14.7 billion in allocated federal grants has been used by the city.[31] Of that $14.7 billion, $10.5 billion was provided by the Federal Emergency Management Administration (FEMA) and of that $10.5 billion, only 43 percent of

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[27] Ibid, 401.
[28] Ibid, 403.
[29] Ibid.
[30] "FTA Funding Allocations for Hurricane Sandy Recovery and Resiliency | FTA," accessed December 15, 2021, https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/fta-funding-allocations-hurricane-sandy-recovery-and.
[31] "Safeguarding Our Shores: Protecting New York City's Coastal Communities from Climate Change."

those funds have been used across all sectors.[32] Despite the estimates that "every federal grant dollar dedicated towards flood mitigation can save $6 in future disaster costs,"[33] nearly half of the allocated funds have not been used, partially because of strict guidelines on documentation and reviews implemented by the federal government. In particular, the Department of Transportation has only used 42.2 percent of FEMA grants, which totals to around $300 million; and large scale coastal projects, like the East Side Coastal Resiliency plan and Hunts Point Lifelines plan, have only utilized 14 percent of allocated funds.[34] In addition to the lack of utilization of federal grants, completion dates for these projects continue to get pushed into the future. Nearly a decade out from Sandy, the nature of the complete projects, delayed timelines, and many outstanding projects demonstrate how little the city prioritizes flood risk. Though it is clear that climate change will make NYC more vulnerable to storms, the government has not provided many solutions to combating flooding.

MTA Initiatives

Post-Sandy, the MTA proposed multiple initiatives for repairing subway systems and implementing long-term flood protection plans. The MTA recruited six architectural and engineering design firms to develop a series of plans that could protect vulnerable subway stations, tunnels, storage yards, and other equipment during the next major storm or flood event.[35] They established the Sandy Recovery and Resiliency Division, which was dedicated to managing all of the projects that aided recovery after Superstorm Sandy. Under this division, the MTA hoped to address these specific projects: repairing several subway tubes under the East River, mitigating floods at several subway car yards, designing flood prevention equipment to

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[32] Ibid.
[33] Ibid.
[34] Ibid.
[35] "Fix&Fortify Sandy Recovery Work," accessed December 21, 2021, http://web.mta.info/nyct/service/FloodMitigationWorkBeginsat7DowntownStations.htm.

entrances at low-lying Lower Manhattan subway stations,[36] and installing a $15.7 million sea wall on the eastern side of the Rockaways.[37] Most of these projects have either only recently been finished, or have not been completed as of December 2021, nearly ten years after Sandy. It is important to note that, during this same time, construction of the Second Avenue Subway was taking place. Although funding probably came from another source, the first phase of this project was completed in 2017 and the subway line was open before many of the outstanding repairs that needed to be done from Sandy had been completed or even started. The F Line East River Tunnel Project concluded in March 2021, earlier than the timeline projected but still nine years after Superstorm Sandy hit NYC.[38] The project replaced 4365 feet of subway track, installed a Cable Management Rack System (CMRS) for the length of the Rutgers Tube, laid new signal and communication cables, and repaired 250 feet of tunnel where the cables are housed.[39] Additionally, Chinatown's East Broadway station was significantly upgraded with platform renewals, wall tile replacements, platform edge replacements, and leak mitigations.[40] The escalated timeline was possible due to the COVID-19 pandemic and decreased usage of the subway for much of 2020.[41]

Despite the progress that the MTA has made on the F Line East River Tunnel Project, several other projects are still outstanding, including the Coney Island Yard, 207th Street Yard, Rockaway Line, and Staten Island Railway projects. The Coney Island Yard and 207th Street

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[36] Ibid.
[37] "Rebuilding the Rockaways After Hurrican Sandy," accessed December 21, 2021, http://web.mta.info/nyct/service/RebuildingRockawaysAfterHurricanSandy.htm.
[38] Jose Martinez, "MTA Touts Tunnel Fixes But Sandy Subway and Rail Repairs Still Have Long Way to Go," THE CITY, April 6, 2021, https://www.thecity.nyc/2021/4/6/22370970/mta-touts-tunnel-fixes-but-sandy-subway-and-rail-repairs-still-have-long-way-to-go.
[39] "MTA Announces Completion of Sandy Resiliency Work in F Line's East River Tunnel," MTA, accessed December 21, 2021, https://new.mta.info/press-release/mta-announces-completion-of-sandy-resiliency-work-f-lines-east-river-tunnel.
[40] Ibid.
[41] Ibid.

Yard projects are the only two projects with an estimated completion date, whereas the Rockaway Line and Staten Island Railway projects are substantially behind schedule with no projected completion date. The Coney Island Yard Project is at around 50 percent completion, still needing work to be done installing new drain structures and storm-surge protection, and elevating power and signal cables.[42] The project is expected to finish by September 2022. The 207th Street Yard project in Upper Manhattan is around 52 percent complete, and still requires work to be completed in perimeter walls and gates, replacing damaged track, and erecting buildings to house signal equipment.[43] The project is expected to be substantially completed by November 2023. Though the sea wall has been erected by the Rockaways, there has not been significant progress on any other front. Structural repairs and replacement of cable and signal equipment has not yet begun, nine years after Sandy.[44] The Staten Island Railway is facing a similar reality—their project is 17 months behind schedule.[45] The unexpected COVID-19 pandemic has only served to delay Sandy repair and recovery projects more than it had before. With an increasing number of obstacles and obvious lack of commitment from the MTA to complete Sandy repairs before other projects, it is imperative to devise a solution that can be implemented quickly, or move away from relying on one catch-all solution to flood prevention to instead enact more localized initiatives.

Flex-Gate Project

The city has also looked to flood resiliency projects designed outside of the SIRR. Some of these projects are already in the process of being implemented, while others have been considered but not yet executed. Flex-Gate, developed by ARUP and ILC Dover, is one project

[42] Martinez, “MTA Touts Tunnel Fixes But Sandy Subway and Rail Repairs Still Have Long Way to Go.”
[43] Ibid.
[44] Ibid.
[45] Ibid.

that has already begun implementation across the city. Flex-Gate is "a fabric-based gate installed at the top of a subway entrance that can be deployed quickly and withstand flooding associated with Category 2 hurricanes."[46] The outside layer of the gate is made of the same watertight fabric material in NASA spacesuits, while the inside has Kevlar webbing.[47]Able to be deployed in five to ten minutes by one to two people and inspired by the rolling doors over NYC storefronts,[48] the advantages of Flex-Gate are that it replaces traditional flood barriers, eliminates the need for post-storm clean up within subway stations and tunnels, and only requires a one-time installment.[49] When deployed, the gate stretches horizontally across the station entrance and stairwells, creating a seal that traps most water and has few leaks.[50] It is able to be deployed in winds up to 60 MPH, can withstand one-foot high waves moving at five feet per second, and provides a barrier against 16 feet of water.[51] In 2016, Flex-Gate was already installed in 14 stations and 50 more were anticipated in Lower Manhattan, where flood risk remains the highest in the city, by the end of the year.[52] However, only 23 Flex-Gates were eventually installed.[53] Though already effective, Flex-Gates should be installed on a larger scale to waterproof subways completely. Not only should they be installed on subway entrances, but also on any vents at street level. Portal Flex-Gates, which function more similarly to garage doors, were also

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[46] "Protecting New York's Subways against Future Flooding - Arup," accessed November 10, 2021, https://www.arup.com/en/projects/mta-8-stations-resiliency.
[47] Laura Bliss, "New York City Is Trying Really Hard to Waterproof the Subway," *Bloomberg.Com*, August 19, 2016, https://www.bloomberg.com/news/articles/2016-08-19/new-york-city-mta-aims-for-flood-resiliency-with-tunnel-plugs-flex-gates-and-vent-covers.
[48] Joel Rose, "To Flood-Proof Subways, N.Y. Looks At Everything From Plugs To Sheets," *NPR*, October 8, 2015, sec. Joe's Big Idea, https://www.npr.org/2015/10/08/446600221/to-flood-proof-subways-n-y-looks-at-everything-from-plugs-to-sheets.
[49] "Protecting New York's Subways against Future Flooding - Arup."
[50] Ibid.
[51] "How We Created Flex-Gate®," ILC Dover, September 19, 2018, https://www.ilcdover.com/2018/09/18/how-we-created-flex-gate/.
[52] Bliss, "New York City Is Trying Really Hard to Waterproof the Subway."
[53] "How We Created Flex-Gate®."

considered for rail and vehicle tunnels.[54] Different Flex products were also considered for first-floor businesses and housing complexes.[55] In total, the Department of Transportation allocated around $437 million to implement flood barriers in stations and replace watertight seals to equipment rooms in 2017.[56] The Flex-Gate project cost around $20.4 million to install.[57]

Resilient Tunnel Plug Project

The Resilient Tunnel Plug (RTP) project was developed in 2007 by ILC Dover to assess the feasibility of an inflatable plug system to plug tunnels.[58] The RTP is an alternative means to seal underground tunnels to prevent flooding from storm surges and floods.[59] These barriers, created with a three-layer plug made from Vectran fabric in a cylindrical shape with two spherical caps, are stored in a container on the roof of a tunnel until they need to be deployed.[60] The RTPs are not meant to be utilized as a permanent solution to flooding, but can provide a temporary solution to contain flooding until more permanent measures can be taken. As opposed to traditional flood barriers implemented in tunnels, the advantage of an RTP system is that it only requires one installation and can be deployed quickly. The system must have the strength to withstand the forces of a flood, create a sufficient seal within the tunnel, be stored without impeding tunnel traffic, and work after long-term storage.[61] The RTP system has undergone successful testing and is a potential option that the city is considering for implementation. The inflatable plug is a low-cost option for flood prevention in comparison to other options, such as

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[54] Ibid.
[55] "How We Created Flex-Gate®."
[56] "Statewide Transportation Improvement Program (STIP) for Region 11" (New York State Department of Transportation, November 6, 2017), https://www.dot.ny.gov/programs/stip/files/r11.pdf.
[57] Ibid.
[58] Eduardo M. Sosa et al., "Large-Scale Inflatable Structures for Tunnel Protection: A Review of the Resilient Tunnel Plug Project," *Journal of Infrastructure Preservation and Resilience* 1, no. 1 (December 2020): 11, https://doi.org/10.1186/s43065-020-00011-0.
[59] Ibid.
[60] Ibid.
[61] Ibid.

the Flex-Gate. In 2012, during the testing phases of the RTP, the cost of each plug was around $400,000.[62] If as many inflatable plugs were installed as there are Flex-Gates, the total cost would be $10 million, or half the cost of the Flex-Gate. Additionally, the unit cost of the plugs are expected to decrease after ILC Dover moves past the testing phase.[63]

Storm Surge Barriers

Storm surge barriers have been continuously considered for New York City harbors since a 2009 conference on their applicability.[64] Storm surge barriers are structures in rivers that protect urban areas from flooding, and usually consist of movable gates that open for shipping and tidal flows and close for flooding events.[65] Installing these flood barriers are quite expensive, and most existing barriers have been implemented after flood disasters. Despite their cost, storm surge barriers have many advantages. Aside from the ability to prevent coastline flooding from storms, storm surge barriers also reduce the length of coastline and reduce the height of supplemental floodwalls.[66] Multiple barrier systems that can open and close may provide several environmental benefits by increasing the turnover of water and dispersal of pollutants, as wind drives water out of enclosed spaces.[67] However, these movable barrier systems may also harm the environment by interrupting water salinity, temperature, nutrients, and migration patterns of fish and shellfish.[68] Installing these surge barriers will also require an investment into an adequate flood warning system in order to signal gate closure, and flood risk perception may

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[62] Luke Abaffy, "Pressurized Tunnel Plug Claims to Be Affordable Alternative to Permanent Floodgates," accessed December 15, 2021, https://www.enr.com/articles/5292-pressurized-tunnel-plug-claims-to-be-affordable-alternative-to-permanent-floodgates.
[63] Ibid.
[64] Jeroen C.J.H. Aerts et al., "Cost Estimates for Flood Resilience and Protection Strategies in New York City," *Annals of the New York Academy of Sciences* 1294, no. 1 (2013): 1–104, https://doi.org/10.1111/nyas.12200, 49.
[65] Ibid.
[66] Ibid.
[67] Ibid.
[68] Ibid.

decrease if people believe that floods will decrease when barriers are installed.[69] Due to these concerns, many barrier systems have been proposed for New York City, but none have been implemented. The following are projects that have been proposed across different coastal areas around the city.

The Verrazano Narrows Barrier, located in the tidal-influenced straight that separates Staten Island and Brooklyn, was designed by engineering firm Arcadis and implements sliding sector gates that have been utilized in the Netherlands.[70] The East River Barrier, developed by Parsons Brinckerhoff and sited between the Whitestone and Throgs Neck Bridges between the Bronx and Queens, was designed to use hydraulic operating flap gates that would normally lie underwater and deployed during a hurricane.[71] Developed by Halcrow, the New York-New Jersey Outer Harbor Barrier, between Sandy Hook and Rockaway Peninsula, is designed to withstand Category Three hurricanes.[72] The Arthur Kill Barrier, designed by Camp Dresser & McKee, runs between the Upper New York Bay and Raritan Bay.[73] All barriers would be sited in heavily trafficked waterways and in optimal places with minimal need for land-based levees. During installation and operation, the barriers would have a minimal impact on marine traffic, but could have a significant effect on tidal flows.[74] Cost of these barriers would come from three components: initial construction of the barrier, maintenance of the barrier, and any extra flood protection needed in addition to the barrier. Based on existing barriers, the cost of the NYC barriers would come to $80 million to $6.9 billion each, and a cost per unit meter width at $0.04 million/meter and $2.37 million/meter.[75] Periodic maintenance would be projected at

[69] Ibid, 50.
[70] Ibid, 59.
[71] Ibid, 61.
[72] Ibid, 64.
[73] Ibid, 56.
[74] Ibid.
[75] Ibid, 69.

approximately five to ten percent of invested capital, which would put the cost at $3 million/year to $100 million/year.[76] The cost of each proposed NYC barrier would be a couple of billion dollars per barrier. Despite the proposed barriers, none have been implemented in the city, even after Superstorm Sandy.

The most recent proposed project is the $119 billion six-mile-long sea wall that would span from the Rockaways to New Jersey south of Staten Island.[77] One of five proposed initiatives to protect NYC's coastlines, the sea wall is heavily debated. Though it would be able to protect coastlines from flooding, the barrier could trap sewage and toxins and change the "natural flow of sediment and salt in rivers," affecting marine life.[78] Though these sea barriers may seem to be extremely effective at first, they may not be the best option for the city. The project would take 25 years to complete, a timeline that we may not be able to afford with climate change steadily increasing sea level, storm frequency, and subsequently flooding, every year. Sea level rise may also increase maintenance on these sea walls, building taller and taller walls each year with rising water levels. Instead of barricading the city from the inevitable, there may be other solutions that are better suited to prepare the city from flooding.

Case Studies Around the World

Although Superstorm Sandy was one of New York City's worst unprecedented storm events in the past few hundred years, several cities around the world have experienced major flooding and storm events in their histories. Many of the projects proposed after Superstorm Sandy have taken inspiration from some of these cities that are prone to flooding, and in

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[76] Ibid, 73.
[77] Anne Barnard, "The $119 Billion Sea Wall That Could Defend New York … or Not," *The New York Times*, January 17, 2020, sec. New York, https://www.nytimes.com/2020/01/17/nyregion/the-119-billion-sea-wall-that-could-defend-new-york-or-not.html.
[78] Ibid.

particular, those that have had far more experience than NYC in dealing with flooding and storm events. The following cities—Tokyo, Copenhagen, and Rotterdam—not only have extremely successful general flood prevention systems, but also have effective stormwater management for underground transportation systems similar to the NYC subway system. Here, it is critical to examine the different strategies in place for each city and their applicability to New York City.

Tokyo, Japan

Japan has a long history of exposure to storms, tsunamis, flash floods, and river floods. As a result, much of Japan's focus on resiliency in their urban spaces is on flood management. Now with climate change and sea level rise threatening the country, flood control is only becoming more important. Because of its high priority, flood control within Japan is largely split into two categories: preservative and protective. Preservation manages reducing the probability of flooding through efforts like water discharge systems, and protection pertains to preparedness for flood events.[79] Much of the resiliency efforts are managed by the central government, but local governments have been granted 30 percent autonomy in "budget allocation for projects undertaken at the prefectural or municipal levels,"[80] pressuring local governments to help in the process of developing resilient infrastructure and flood prevention. Greater Tokyo is one of the most densely populated cities in the world and home to 26 percent of the country's population.[81] The urban landscape, built to accommodate the population of the city, now has reduced the land's capacity to store excess water and is prone to flooding and subsequent damage from these floods.[82]

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[79] Prerna Singh et al., "Lessons from Case Studies of Flood Resilience: Institutions and Built Systems," *Transportation Research Interdisciplinary Perspectives* 9 (March 1, 2021): 100297, https://doi.org/10.1016/j.trip.2021.100297.
[80] Ibid.
[81] Ibid.
[82] Ibid.

Initiatives in Japan

Throughout Japan's history, there have been many general attempts to reduce coastal and inland flooding due to storm surges. The Ministry of Land, Infrastructure, and Transport (MLIT), and Water and Disaster Management Bureau are dually responsible for administration and planning surrounding rivers and coastal areas.[83] Legislation was introduced throughout the 20th century and into the 21st century to manage flooding. The Flood Fighting Law (1946) designated 209 rivers as critically important for land conservation and entrusted the central government with managing them, while local governments were responsible for flood fighting and implementing easy-to-understand warning systems.[84] In 1978, the central government implemented comprehensive flood control measures to mitigate their effects in at-risk cities and especially in those that had undergone rapid urbanization, such as Tokyo.[85] Most recently, the Specified Urban River Inundation Prevention Act that went into effect in 2003 attempted to further delegate more specific roles for river and sewerage administrators. The creation of the National Strategy for Risk Management of Large-Scale Flood Disasters led to the widening of river channels, development of permeable lands, and construction of detention basins and discharge channels to hold flood water.[86]

Tokyo Specific Innovations

Tokyo is one of the world's most densely populated cities with a rapidly growing urban landscape. It is also situated on a plain that is intersected by five river systems that swell during each rainy season.[87] The rapidly growing urban landscape has made the city's residents and built

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[83] Ibid.
[84] Ibid.
[85] Ibid.
[86] Ibid.
[87] Diego Arguedas Ortiz, "The Underground Cathedral Protecting Tokyo from Floods," accessed December 19, 2021, https://www.bbc.com/future/article/20181129-the-underground-cathedral-protecting-tokyo-from-floods.

environment more vulnerable to floods and sinking. While more general prevention of floods within the city is important, it is equally as important to address potential flooding of underground systems, such as the Tokyo Metro system. Millions of people rely on the subway system to commute to and from work and school each day. The Tokyo Metro system has already been equipped with various measures of resiliency, and the central government and private companies are in the process of implementing more action. Some of the action that is in the process of being implemented is constructing anti-flooding mechanisms to seal ventilation ducts that can withstand pressures of six meters of water, fitting water-tight doors to entrances of stations, and installing flood gates at the entrance of tunnels where trains on the surface descend underground.[88] The goal of these reactive measures is to prevent water from entering any underground ingress.

Japan has also looked towards an alternative to the traditional approach for combating underground flooding. Completed in 2006, the Metropolitan Area Outer Underground Discharge Tunnel (MAOUDC) or G-Cans Project is a 3.9 mile (6.3 km) long system of tunnels and cylindrical chambers 72 feet (22 m) underground that protects North Tokyo from flooding and is the largest diversion flood water facility in the world.[89] Water from smaller rivers in North Tokyo is sucked into the 229 feet (70 m) tall and 98.4 feet (30 m) diameter cylindrical tanks[90] and is diverted to the larger Edo River and eventually overflowed into the sea.[91] Before being pumped into the Edo River, the water is stored in a pressure controlled tank that is 580 feet (177 m) long, 256 feet (78 m) wide, and 59 feet (18 m) tall, and has 59 pillars of 500 tons that support the

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88 "Technologies Supporting the Future: Flood - Japan's Regional Strength," JapanGov, accessed October 18, 2021, https://www.japan.go.jp/regions/resilientjapan/flood.html.
89 Ortiz, "The Underground Cathedral Protecting Tokyo from Floods."
90 Brandon Blackburn-Dwyer, "Massive Tokyo Flood Protection System Might Not Be Big Enough," Global Citizen, accessed December 19, 2021, https://www.globalcitizen.org/en/content/japan-flood-control-superstructure-china-tokyo/.
91 Ortiz, "The Underground Cathedral Protecting Tokyo from Floods."

ceiling and break up incoming water.[92] From here, four turbines pump water at a rate of 200 tons per second into the Edo River.[93] When there aren't flood events in the city, the G-Cans is used as a spot for tourists, highlighting the importance of flood management and magnificence of Tokyo's flood resiliency efforts.[94] Overall, the project cost around 230 billion yen ($2 million) and was presumably government funded.[95] It is estimated that the MAOUDC has cut flood damage in Tokyo by half.[96] Though only an indirect way of relieving pressure off subway flooding, the MAOUDC is an effective method for underground and above ground flood prevention.

In addition to these reactive measures, a disaster response plan has been implemented to deal with major flooding to determine how far in advance trains should stop operating to evacuate passengers safely and minimize interruption of subway service.[97] One method that is being utilized is observing meteorological data to predict where and when flooding will occur and how severe the flooding will be. Distribution of rain can be measured in 3D using the Global Precipitation Measurement (GPM), or data acquired by satellites of different nations to observe precipitation on a global scale.[98] The GPM carries a Dual-frequency Precipitation Radar (DPR), one of the world's most advanced meteorological instruments that emits radio waves in two different frequencies and can distinguish rain from ice and the size of raindrops.[99] Other meteorological observation techniques are employed to observe life cycles of storms. Monitoring and Prediction System of Extreme Phenomena (MPSEP) processes real-time data and predicts

[92] Blackburn-Dwyer, "Massive Tokyo Flood Protection System Might Not Be Big Enough."
[93] Ibid.
[94] Ibid.
[95] Shingo Ito, "The Underground 'Parthenon' Protecting Tokyo from Floods," accessed December 19, 2021, https://phys.org/news/2020-10-underground-parthenon-tokyo.html.
[96] Blackburn-Dwyer, "Massive Tokyo Flood Protection System Might Not Be Big Enough."
[97] "Technologies Supporting the Future."
[98] Ibid.
[99] Ibid.

instances of localized rainfall and winds, which has the possibility of detecting torrential rainfall early.[100] Combined with physical implementations of resiliency, these predictive methods can help determine which areas are most at risk, what stations and tunnels may need to be closed down, and which stations and trains can stay open if possible in order to have the safest and least amount of interruption of the entire system as possible.

Due to the high priority of flood prevention in Japan, there have not been many setbacks in implementing resilient plans. With a focus on longer term and predictive measures, the central government has implemented successful strategies for flood resilience. Though there is not much information on funding distribution for these flood resiliency projects or where the money comes from, it seems that Japan utilizes mostly public funding. Due to their long history with flooding and storms, the Japanese government is dedicated to flood resilience and is very inclined to spend money on flood prevention initiatives because of Japan. Not only have they been supporting their own country's projects, but they have also been funding flood relief projects for several other countries around the world.[101]

Applicability to New York City

Currently, it is impossible for New York City to have the same level of dedication and precision in planning for flood resilience as Japan does because the city has not had the same long history with flooding and storm surges. Japan has been planning for flooding preemptively through the preservation of bodies of water and creation of more channels by which water can flow through safely to the sea. However, it is not too late for New York City to implement some of these changes. The city could implement some flood water dispersion method into the sea that

[100] Ibid.
[101] "Japan-World Bank Program for Mainstreaming Disaster Risk Management in Developing Countries Portfolio," Text/HTML, World Bank, accessed December 19, 2021, https://www.worldbank.org/en/data/interactive/2020/03/01/tokyo-drm-hub-portfolio.

does not necessarily have to be as dramatic as the G Cans system. Additionally, it would be important to implement meteorological solutions that map in real time which areas are prone to flooding and how much they will flood. These maps would assist in efficiently closing down subway systems only when necessary and deploying alternative transportation methods for those areas. Finally, it is most difficult to conceptualize building up commitment and enthusiasm for flood and climate resilience in New York City. Following in Japan's footsteps, the government must first be willing to fund many of the flood prevention projects, but also the residents of the city must be aware of the importance of flood prevention. Making these spaces accessible as tourist attractions could make flood resilience more appealing.

Copenhagen, Denmark

Denmark will experience sea level rise and more frequent and severe extreme weather events due to climate change. In the most optimistic scenario, sea level will rise around 3.9 to 23.6 inches (0.1 to 0.6 m), and 11.8 to 35.4 inches (0.3 to 0.9 m) in the most pessimistic scenario.[102] As we approach this future of uncertainty, we need to strategize potential preventative efforts for flooding and other resiliency efforts. Rather than forming plans after a disaster has already happened, we need to have a plan already in place by the time an inevitable disaster comes.

Innovations in Copenhagen

Within Denmark's capital city, Copenhagen, climate adaptation plans have already been put in place in the face of disaster by local municipalities. In 2011, the Copenhagen Climate Adaptation Plan (CAP) was published with a goal to maintain the current sewer system's service

[102] "Integrating Adaptation in the Design of the Metro of Copenhagen — Climate-ADAPT," accessed October 19, 2021, https://climate-adapt.eea.europa.eu/metadata/case-studies/integrating-adaptation-in-the-design-of-the-metro-of-copenhagen.

level of 10-year rain events by disconnecting buildings and streets from sewers and local management of stormwater runoff, directing surplus stormwater to areas that do not cause harm, and enlarging sewers to meet the 10-year service level.[103] However, shortly after the plan was announced, a cloudburst of approximately 150mm flooded city basements and streets with a damage of 6 billion Danish kroner (approximately $0.9 billion).[104] Flood management subsequently became a higher priority for the city after the cloudburst event, and the Copenhagen Cloudburst Management Plan (CMP) was thus introduced in 2012. The goal of the plan is to prevent flooding in extreme weather events, where flooding will not exceed more than 3.9 inches (0.1 m) in urban areas and "more frequently than once in 100 years, except areas designated for flooding."[105] To do so, the city will discharge runoffs to the harbor through underground tunnels or streams, incorporate "water breaks" that divert runoff away from sewers, and modify streets to transport diverted water and to provide areas of controlled flooding.[106] The 2015 Climate Adaptation and Investment Statement (Implementation Plan) extended the budget of the project to 11 billion Danish Kroner (nearly $1.6 billion).[107] Some other systems for flooding and rainwater management include retention of water through subsurface infiltration beds, green roofs, and permeable paving, handling treatment of water as close to the source as possible, and diverting it away from sewer systems to lower the chance of combined sewer overflows.[108] Models, risk mapping, monitoring and early warnings for floods are also utilized.[109]

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[103] Li Liu and Marina Bergen Jensen, "Climate Resilience Strategies of Beijing and Copenhagen and Their Links to Sustainability," *Water Policy* 19, no. 6 (July 18, 2017): 997–1013, https://doi.org/10.2166/wp.2017.165.
[104] Ibid.
[105] Ibid.
[106] Ibid.
[107] Liu and Jensen, "Climate Resilience Strategies of Beijing and Copenhagen and Their Links to Sustainability."
[108] DI - Confederation of Danish Industry, *Climate-Adapted Cities: Solutions from Copenhagen* (Cph.: DI - Confederation of Danish Industry, 2014).
[109] Ibid.

In general, flood management in Copenhagen has been combined with various other resiliency efforts in a "holistic approach to adaptation and transformation" to resilient cities.[110] Combining these different systems for a broader climate adaptation plan allows for the most resilient future. The Copenhagen metro in particular has had consistent climate adaptation planning since the first line was designed in the mid-1990s.[111] Expected increase in mean sea level, flooding, and more frequent extreme weather events that can impact metro infrastructure, operation, and passenger safety has encouraged Metroselskabet, the Copenhagen metro company, to implement a climate adaptation plan in place for the metro system.[112] By integrating climate change adaptation early in the planning process, only minor adjustments are needed as circumstances change. Metroselskabet has outlined an extensive plan for improving metro resiliency. The plan includes: installing drainage systems in entrances to underground stations, above ground tracks, and tunnels where above ground trains go underground; implementing flood gates where metro systems are connected to other systems; waterproofing technique rooms and electrical and mechanical installations and raising the doorstep of technique rooms to 0.98 feet (0.3 m); and building gabion walls, or walls made from a cage filled with rocks, along above-ground metro stations up to 6.6 feet (2.3 m) high.[113] The goal of these applications is to limit the impact and spread of floods as much as possible by attempting to prevent flooding entirely or mitigating it as much as possible. In addition to these efforts, the plan utilizes calculations of expected highest water level from heavy rainfall and storm surges for each station and considers a one in 2,000 year flooding event.[114]

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[110] DI - Confederation of Danish Industry, *Climate-Adapted Cities*.
[111] "Integrating Adaptation in the Design of the Metro of Copenhagen — Climate-ADAPT."
[112] Ibid.
[113] Ibid.
[114] Ibid.

The main stakeholder of the climate adaptation plan for the Copenhagen Metro is Metroselskabet, with additional funds from the city of Copenhagen, central Danish government, and the city of Frederiksberg totaling a cost of 22.4 billion Danish Kroner (approximately $3.5 billion).[115] The project was initially approved in 2009, and finished and put into operation in 2019.[116] Since the project was implemented when the metro line was first built, resiliency and willingness to improve flood prevention systems seem to come by easier. As a result, the cost of the project did not seem like a large issue for Metroselskabet. Rather than needing to restore old subway systems, building a new, resilient system is more cost-effective and efficient.

Applicability to New York City

Considering that the Copenhagen metro system was only recently developed, it is difficult to compare the city's initiatives to the ones implemented or proposed in New York City after Superstorm Sandy. After experiencing an extreme flood event, the Copenhagen metro system was created with flood management systems already in place. This does not seem like the best option for NYC because of what seems like previous difficulty that the city faced in accomplishing large-scale projects. Rather than focus on one overarching repair to make the entire subway system more resilient, the city should instead focus on lower budget solutions to flood prevention underground, such as waterproofing electrical and mechanical systems and raising the doorstep to these technical rooms. Additionally, New York City could also focus on the preservation of above-ground stations and above-ground flood management by utilizing gabion walls. This way, projects are more likely to be approved and require a shorter amount of time and less service disruptions to complete. The city, similar to Copenhagen, already has a climate resilience plan in place under PlaNYC. However, it could be more useful if the plan had

[115] Ibid.
[116] Ibid.

a specific committee or section dedicated to address flood management issues. Annually, the CMP creates solutions to prevent flooding from surpassing more than 3.9 inches (0.1 m). If PlaNYC was able to propose such a strict guideline to flood prevention, then the city may be more enthusiastic and committed to flood resilience.

Rotterdam, Netherlands

Initiatives in the Netherlands

The Netherlands largely sits below sea level and more than 55 percent of the country is in a flood zone.[117] For this reason, flood prevention is critical for the survival of the country. This also indicates that the Dutch are extremely experienced in dealing with and managing floods. As of 2012, the country also spends around 1.15 billion Euros ($1.3 billion) per year on water control.[118] For much of history, the Dutch used elaborate mosaics of dikes as flood protection, but after serious floods in 1916 and 1953, the country came to the conclusion that building and reinforcing dikes was no longer possible in densely populated areas and instead used dams to seal off flood-prone rivers.[119] The government declared that all flood defenses across the country needed to be strong enough to resist a one in 10,000 year flood as a result of the 1953 floods.[120] In transitioning away from the usage of dikes to prevent flooding, the Dutch government turned to utilizing natural materials and mimicking natural systems to prevent flooding. These particular solutions, such as levees that mimic rocky coasts and using living organisms as natural buffers are referred to as soft solutions.[121] One such project is the Sand Engine, a "28 million-cubic-yard

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[117] Singh et al., "Lessons from Case Studies of Flood Resilience."
[118] Andrew Higgins, "Lessons for U.S. From a Flood-Prone Land," *The New York Times*, November 15, 2012, sec. World, https://www.nytimes.com/2012/11/15/world/europe/netherlands-sets-model-of-flood-prevention.html.
[119] Ibid.
[120] Ibid.
[121] Cheryl Katz, "To Control Floods, The Dutch Turn to Nature for Inspiration," Yale E360, accessed October 25, 2021, https://e360.yale.edu/features/to_control_floods_the_dutch_turn_to_nature_for_inspiration.

[25.6 million-cubic-meter] heap of dredge sediment" spread along the shore.[122] As the tides push against the mound of sand, ocean currents rearrange the sand into a 12 mile long buffer that can protect the coastline against erosion.[123] The project cost 59.13 million Euros ($67 million). In 2009, the Water Act established two authorities to manage the country's water resources.[124] At the national level, the Minister of Infrastructure and Water Management would be responsible for major water systems, including the marine environment and flood control. At the local level, 23 democratically elected water boards are responsible for regional water management and flood prevention.[125]

Rotterdam Specific Innovations

Rotterdam, located in the delta of the Rhine and Meuse Rivers, is the second largest city in the Netherlands and also one that takes initiative in climate adaptation projects. The municipality extensively advertises their climate adaptation strategies to residents to involve them in the design process.[126] With a history of flood prevention methods involving windmills, mechanical pumping, and dikes, the city of Rotterdam established Delta Works, a committee that has developed standards for urban planning and applications of flood protection since the 1953 flood.[127] One project that Delta Works spearheaded was the Maeslantkering (Maeslant barrier), a moveable storm surge barrier near Rotterdam, that was finished in 1997 and used once in November 2007.[128] The project cost 11.47 billion Euros ($13 billion). The city also established the Rotterdam Climate Initiative, which "operationalizes the municipality's aim to make

[122] Ibid.
[123] Ibid.
[124] Singh et al., "Lessons from Case Studies of Flood Resilience."
[125] Ibid.
[126] Liping Dai, Rebecca Wörner, and Helena F. M. W. van Rijswick, "Rainproof Cities in the Netherlands: Approaches in Dutch Water Governance to Climate-Adaptive Urban Planning," *International Journal of Water Resources Development* 34, no. 4 (July 4, 2018): 652–74, https://doi.org/10.1080/07900627.2017.1372273.
[127] Singh et al., "Lessons from Case Studies of Flood Resilience."
[128] Higgins, "Lessons for U.S. From a Flood-Prone Land."

Rotterdam 100 percent climate-proof by 2025"[129] and where city policymakers devised two strategies to respond to flood risk: regional-preventative strategy and local-adaptive strategy.[130] The regional-preventative strategy entails reducing the probability of fluvial and coastal risk and implementing solutions in urban water defenses.[131] The local-adaptive strategy focuses on integrating flood management measures with other urban functions and promoting flood resilient architecture.[132] In addition to these preventative projects, Rotterdam is focused on resiliency, and the city anticipates the possibility of floods by "regularly monitoring interruptions in transportation networks to assist in planning for evacuation and recovery."[133] The program 3Di is able to make various water-based calculations.[134] The "Room for the River" project, which aimed to build flood retention zones, widen riverbeds, excavate floodplains, and create paths for water to drain, marked a shift from just anticipation of extreme weather events to resiliency in the face of these events.[135] The long-term view when creating flood control policies and approach that balances defensive and adaptive measures makes Rotterdam successful in flood control management.

Many Rotterdam climate adaptation projects are funded by Sewage levies.[136] Because flooding is such a large concern for Rotterdam and the Netherlands in general, the city sets aside a sum of money to ensure any program's long-term efficacy. Between 2016-2020, we expect to see the government investing 5.8 million Euros ($6.75 million) into rainwater collection and

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[129] Dai, Wörner, and van Rijswick, "Rainproof Cities in the Netherlands."
[130] Singh et al., "Lessons from Case Studies of Flood Resilience."
[131] Ibid.
[132] Ibid.
[133] Ibid.
[134] Katz, "To Control Floods, The Dutch Turn to Nature for Inspiration."
[135] Singh et al., "Lessons from Case Studies of Flood Resilience."
[136] Dai, Wörner, and van Rijswick, "Rainproof Cities in the Netherlands."

processing.[137] However, the success of the Dutch flood prevention system does not necessarily mean that it is possible elsewhere.

Applicability to New York City

After the devastating Superstorm Sandy hit New York City, many engineers suggested implementing Dutch flood protection measures for the city of New York, such as large coastal barriers that can be closed in events of extreme weather.[138] Although it seems like it may work at first, the approaches that the Dutch and US governments have towards disasters are completely different. The Dutch focus more on disaster prevention and avoidance, whereas the US focuses more on post-disaster relief.[139] In the US, the typical response to an extreme weather event is to provide aid for the community that needs it, rather than create legislation that could prevent this devastation from happening again. Whereas there is possible implementation of Dutch flood protection, such as utilizing flood proof entrances to subway stations, cost and funding might still be a large issue.[140] The city and state governments are less likely to provide funding or grants for something with a large upfront cost. When a government does not prioritize creating a climate adaptation plan, they are less likely to agree to fund one such plan, especially if other issues may seem to be more pressing. As a result, it is more likely for New York City to implement underground flood resiliency initiatives, such as waterproofing subway entrances and tunnels, and onshore coastal preventative measures, like greener and softer shorelines. In an effort to make NYC more passionate about climate adaptation and resilience, the state government should implement annual budgets that can then fund different climate resiliency projects that arise throughout any given year. By prioritizing climate resilience by means of an annual budget for

[137] Ibid.
[138] Higgins, "Lessons for U.S. From a Flood-Prone Land."
[139] Ibid.
[140] Ibid.

(not-so-unexpected) emergencies, it will not be as difficult to tackle flooding and storm surges as it was during Superstorm Sandy.

What Can We Do?

The aftermath of Superstorm Sandy saw devastation across New York City. The city utilized federal grants to oversee projects in an attempt to rebuild, recover, and fortify the city for future catastrophes. However, only around half of the allocated funds have been used and many of the projects completed have largely only been repair work with no focus on resiliency efforts. As a result, similar storm events after Sandy have similarly flooded the city. This past summer in August 2021, Hurricane Ida created unexpected flooding in subway stations across the city. Though the subway systems were fortified, subway service was halted for several days due to flash flooding. Many criticized NYC officials, stating that they did not prepare for this storm as much as they could have, but officials claimed that the unpredictability and difference to Sandy made Ida difficult to prepare for.[141] As opposed to coastal flooding seen in Sandy, Ida brought heavy rainfalls and inland flooding in unprecedented areas. Nine years after Superstorm Sandy, it is clear that the resiliency efforts proposed after the storm and government response are not enough to protect the city from another extreme weather event. For the future, New York City should focus on how to prevent flooding rather than reactive action that can be taken.

Coastal Flood Prevention

Flood prevention does not start at the subway entrance. To prevent flooding from reaching the underground subway in general, resilience needs to start off-shore. At this point, it seems as though storm barriers, no matter how effective they may be for the city, will likely not

[141] McKinley, Rubinstein, and Mays, "The Storm Warnings Were Dire. Why Couldn't New York Be Protected?"

be approved by the city because of how controversial they are. Large-scale, expensive, and time-consuming projects are difficult to approve due to the unpredictable nature of the projects and whether or not the benefits will outweigh the harmful aspects of the project. Instead, what is more feasible in New York City is to have soft shorelines like Rotterdam and across the Netherlands. Rather than build higher and higher levees each year with rising sea levels, natural buffers are utilized to protect coastlines against erosion. In the Netherlands, sand dredge was dumped along the coast and relies on tides to rearrange the sand into a buffer to protect the coastline.[142] In New York City, the Billion Oyster Project, founded by Murray Fisher and Pete Malinowski, aims to place oysters along the New York Harbor to create reefs that protect shorelines from erosion, flooding, and storm damage.[143] In addition to these off-shore options, one on-shore option is to create a greener landscape along the shorelines by blending floodwalls and gates into parks.[144] These landscapes would not only protect the city from coastal flooding, but also serve as a good retention system for stormwater and heavier rainfall. The proposed East Side Coastal Resiliency (ESCR) project is one example of this landscape.

On-Street Flood Prevention

As we move inland, the areas most likely to flood next are streets. With poor wastewater management in gutters and along streets, heavy rainfall is likely to result in on-street flooding. In order not to overwhelm existing wastewater treatment, it is imperative to address on-street flooding either by creating or dedicating channels to store and carry stormwater like in Tokyo and across Japan or by creating stormwater management systems that utilize urban landscapes to the city's advantage like in Copenhagen. Some methods utilized in Copenhagen are the retention

[142] Katz, "To Control Floods, The Dutch Turn to Nature for Inspiration."
[143] "Oyster Reefs," Billion Oyster Project, accessed December 22, 2021, https://www.billionoysterproject.org/reefs.
[144] "Project Background - ESCR," accessed December 17, 2021, https://www1.nyc.gov/site/escr/about/project-background.page.

of water in subsurface infiltration beds, green roofs, and permeable pavement on streets.[145] Though New York City is unlikely to mimic the G-Cans system from Tokyo, the city has already begun integrating subsurface infiltration beds into sidewalks. Rather than trickle down the street, much of rainwater can be stored in these beds, decreasing flooding and also providing green spaces across the city. These different stormwater management initiatives can be used to target what specific neighborhoods are more vulnerable to. For example, if a neighborhood's streets are flat and water is likely to pool in certain areas, it might be useful to establish infiltration beds along these streets. However, in Manhattan and especially in more crowded areas, it might be more useful to install green roofs on taller buildings to prevent flooding. In areas with a lot of roads or highways, it might be more useful to install permeable pavements for stormwater retention. The city should take advantage of utilizing urban landscapes for their stormwater management.

Underground Flood Prevention

Finally, when stormwater reaches subway entrances, it has already decreased in volume dramatically due to the actions taken on the coast and on the streets. At this stage, it is important not to have water enter subway station entrances and vents. Flex-gate is a good option for all subway station entrances and vents because it is virtually watertight and only needs to be installed once. However, the cost for each gate is extremely high and these gates may be difficult to fit on pre-existing entrances. The city has already started implementing these gates on several stations vulnerable to flooding and should continue installation on existing subway entrances that are difficult to renovate. Another option would be to change the way that station entrances look architecturally, where entrances have a roof and some sort of step in front of the entrance above

[145] DI - Confederation of Danish Industry, *Climate-Adapted Cities*.

ground level that helps prevent water from going down the steps. If water reaches the tunnel, a Resilient Tunnel Plug can be used to block water from flooding the tunnels. A relatively cheap option compared to the Flex-gate, the inflatable plug only needs to be installed once and can be deployed at any moment. As a last resort option, the inflatable plug is meant to be a temporary solution despite how much they can handle. If every flood prevention system from the coast to the tunnel is working properly, RTPs only need to be deployed sparingly. These plugs can also be used to prevent other disasters from spreading, such as fire or gas.

Flood Mitigation Methods

When every flood prevention system fails and the subway systems are flooded, then the next priority is to return service as quickly and efficiently as possible. To do that, we need to see what affects people and their productivity the most after subway service has been disrupted. On any average day, around 46 percent of all commuters in New York City use the subway for transportation.[146] After Superstorm Sandy, the percentage decreased to 11 percent, and 55 percent of users switched transportation systems after Sandy.[147] When asked, individuals ranked their preference for what scenario they preferred most to least, and that was to cancel work, work from home, and finally change transportation modes.[148] After Sandy, the city provided alternative shuttle options for disrupted subway lines and although switching transportation modes is the least preferred option, these alternative transportation modes are necessary to return service to subways as quickly as possible. Since cancelling work was the preferred option after subway disruptions, it would be important to restore service to the subway systems as efficiently as possible to return life back to normal. The first most effective scenario to return productivity

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[146] Elham Hajhashemi et al., "Using Agent-Based Modeling to Evaluate the Effects of Hurricane Sandy's Recovery Timeline on the Ability to Work," *Transportation Research Part D: Transport and Environment* 77 (December 2019): 506–24, https://doi.org/10.1016/j.trd.2019.08.011, 508.
[147] Ibid.
[148] Ibid, 512.

after Sandy was to recover the NYC subways a day earlier than they were.[149] The second most effective scenario was to recover power a day earlier.[150]

Though this paper focuses largely on providing several solutions to avoid disruptions in subways so that the first most effective scenario can transpire during future disasters, it is also important to address the recovery of power systems. One obvious solution would be to waterproof as much of the power grid system as possible, which would cost a lot of money and time and maybe even need to disrupt the service. Another solution could be to implement microgrids. Microgrids are "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid."[151] They are able to be connected to and disconnected from the grid and operate separately from it. The advantage of using these microgrids is that they can operate during emergencies and when the main electrical grid is down. In the case of Superstorm Sandy, where around eight million homes and businesses lost power because of outages at substations,[152] microgrids would be able to prevent blackouts from occurring on such a large scale.

Funding for Projects

None of these solutions would be possible without funding and a government willing to implement all of these projects. Climate resilience needs to be at the forefront of city operations so that it can continue to be included in the conversation for allocating funds. Due to the geography and climate of the countries, flood prevention is a widely discussed topic in Japan, Denmark, and the Netherlands, and all have some budget allocated to addressing these issues and

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[149] Ibid, 518.
[150] Ibid.
[151] Dan T. Ton and Merrill A. Smith, "The U.S. Department of Energy's Microgrid Initiative," *The Electricity Journal* 25, no. 8 (October 2012): 84–94, https://doi.org/10.1016/j.tej.2012.09.013.
[152] Hajhashemi et al., "Using Agent-Based Modeling to Evaluate the Effects of Hurricane Sandy's Recovery Timeline on the Ability to Work," 515.

for proposed projects that arise throughout the year. However, given that the United States is a large country and fairly polarized when it comes to climate change and what to do with federal tax money, it may be difficult to implement these changes on a federal scale. Instead, New York City could raise money for a local annual budget from an insurance surcharge.[153] This insurance surcharge, already used in disaster-prone states such as Florida, Louisiana, and Texas, can be offered to owners with high-value properties and used to fund resilience efforts across the city. The benefit of paying this insurance surcharge would be the benefits of the flood resiliency projects. Another mechanism to encourage more people (and not just government officials) to interact with the idea of climate resilience is by creating public facing projects. This could take shape in the form of added green spaces in the city or along the shores, as well as tourist attractions. The more that climate resiliency and adaptation is included in the conversation about urban planning, the better prepared New York City will be against the increased and more intense storm surges across the Northeast.

Conclusion

Despite many reports and projects initiated throughout the years after Superstorm Sandy, it has been difficult to implement many of these flood protection plans in New York City. Much of the current flood management system is reactive, where focus is placed on strengthening systems for removing water from tunnels and subway stations rather than preventing water from reaching the tunnels and stations. Thus, it is impossible to think about flood prevention of the underground subway systems in isolation. Solutions that prevent flood water from reaching underground in the first place concern issues of wastewater management and coastal protection. Flood management is inherently an issue of the urban landscape as a whole, and to prevent

[153] "Safeguarding Our Shores: Protecting New York City's Coastal Communities from Climate Change."

flooding is to make cities greener, more resilient, and adaptive to future climate change related storm events and other emergencies that are only becoming more common. Rather than continue to think only reactively as New York City has been doing before, it is necessary to come up with solutions that can mitigate damage to the city as much as possible as sea level rises and as storms become more frequent and violent. Consequently, it is important to prioritize systems that the city should focus on in their resiliency efforts—what will help the city retain the most functional and bounce back the fastest? Is flood prevention in the subway the most important thing we should be focusing on when it comes to climate resilience? Although the subway system does transport a large portion of NYC commuters per day, we should also think about how much we actually rely on the subway system and whether or not we should decrease that reliance on the subway. This decreased reliance suggests less of an impact on commuters if subway service is disrupted. The gradual transition from subway service to focusing on other public transportation systems, such as improving the current bus system, increasing pedestrian walkways and bike paths, and decreased reliance on personal vehicles can also help in the long term. It may become more and more impractical to use an underground subway system as sea levels continue to rise. Until that point, it is necessary to continue to provide the best service possible to those who rely on the subway.

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