Informing New York City Subway Flooding Solutions Through Sociotechnical Infrastructure Management

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by

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Abstract

Urban flooding is an urgent problem to be solved as climate change intensifies its threat, and urban subway systems need to prepare for potential flooding. Since the subway network is part of an interconnected infrastructure system, it is necessary to formulate comprehensive plans for infrastructure maintenance and management. Based on official reports, project plans, news, announcements from the government, and relevant research, I have established a comprehensive framework to assess infrastructure management to deal with flooding in New York City (NYC). Drawing from the experience in London and Tokyo I also explore whether their practices can be lessons for NYC in general drainage method, monitoring and maintenance, and mapping and public awareness. From the perspective of infrastructure management, this study helps NYC clarify the gaps in current infrastructure management, including necessity to improve sewage design standards, upgrade the monitoring system, and develop an active mechanism to engage the public.

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Chapter 1 Introduction & Background

Overview

Urban flooding is an urgent problem to be solved, and climate change intensifies its threat. Underground transport infrastructure, especially urban subway systems, can be vulnerable under such threats and need to prepare for the potential flooding scenarios due to their underground location and huge flow of daily users. Hurricane Sandy in 2012, for example, brought NYC a devastating impact, including inundation of the city surface, urban closure and traffic disruption. It is estimated that of the $41.9 billion in losses it caused, $5 billion came from the subway system, which hints at the strong connection between urban flooding events and underground transit infrastructure, showing the necessity of urban drainage improvement (Vermeij, 2016). A direct improvement to relieve such hazards is to implement mechanical strengthening actions. Unfortunately, a simple review of the infrastructure from an engineering perspective would be insufficient to address all of the issues. Instead, a comprehensive plan to deal with the vulnerability of the underground transit infrastructure and related elements of the sewer system is needed. Construction of an extensive framework can enlighten the evaluation and consideration of the status and needs to improve infrastructure in the future.

My research is qualitative, relying heavily on secondary data and information. Resources I utilized come from the government's official reports, project plans, news and articles and literature review of related studies. First, I would like to build a comprehensive framework assessing the physical infrastructure from the perspective of prevention, implementation and recovery, with the consideration of social, financial and political factors as well. This is enlightened by the literature review. Then I will show how NYC performs under extreme events and judge its sustainability of infrastructure and social aspects. I am going to focus on NYC,

diving into details by examining its performance, especially under Hurricane Sandy. By analyzing NYC's infrastructure management based on the framework, I will try to identify NYC's good and bad performance and get some potential policy improvements by learning from the other two cities.

Framework Construction

To analyze and assess the management performance of NYC, a framework inspired by studies on grey infrastructure is applied with a context of sociotechnical systems. "Sociotechnical systems" was coined by Eric Trist, Ken Bamforth and Fred Emery, empathizing both social and technical aspects of an organization. Basically, this theory is based on the interrelatedness of social and technical aspects of a subject and accentuates the joint optimization of both aspects. In the context of infrastructure, Chini et al. (2017, p. 4) also use this term to describe "the interaction of complex systems between both human and non-human components". In this paper, it is used as a foundation of tight bonding of physical infrastructure and policy and management.

The framework will be used to evaluate the management system from main dimensions on general drainage strategy, monitoring and maintenance, mapping, response ability, recovery and public education. Both formal reports and plans and informal news reports will be collected to diversify the information of the study.

Research Question

Facing the urban flooding triggered by climate change, metropolitan areas around the world take action. Sharing a similar geographical location and aging infrastructure, NYC can

reflect on Tokyo and London's cases and figure out its distinctive strategy. This research will build a comprehensive framework to evaluate NYC's performance on infrastructure management and go through a policy transfer to propose some potential improvements NYC may be able to adopt in the future. From the perspective of infrastructure management, this study helps NYC clarify the gaps in current management and indicates possible improvement directions in the future. The importance of the study is that it can provide a systematic analysis on infrastructure management for reference, which helps NYC to see the difference between NYC's and the other two cities' plans and may learn some experience from the monitoring system of the infrastructure and engagement of the public.

Background

Flooding Risk and Subway Systems

In the study of floods affecting the subway system, water itself is an inevitable research subject. The impact of flood hazard on the subway system includes hydrological changes, geological structure and space use. It also challenges the city's disaster early warning system, response ability and decision-making ability in case of disaster, as well as post-disaster recovery.

Based on the past flooding events, inundation risk of flooding seems closely related with the subway failure record. There have been inundation risk assessments implemented for several of the major subway systems around the world. The original Analytic Hierarchy Process (AHP) and Triangular Fuzzy Numbers AHP (TFN-AHP) are two popular assessments used. Liu et al. (2020) compares these two models in the case of Shenzhen's subway and found the flooding risk matches subway failure.

Outdated Infrastructure in NYC

Although the connection between subway failure and urban flooding is well known, there is still a gap in knowledge, especially from the perspective of resilience. Forero-Ortiz and Martínez-Gomariz (2019) outline the potential hazards of global underground transportation systems and pointed out the knowledge gap in understanding the impact of water on subway networks. They emphasize the importance of "studying water related hazards in the subway system to fill this by ensuring service availability through operation quality and integrated connectivity with the city transport network" (p. 1252).

Besides, the growth of infrastructure all over the world cannot keep up with the growth of population and urban area and the expenditure on infrastructure maintenance and renewal is not comparable to the growth of GDP (see figure 1 & 2). The same infrastructure needs to be responsible for more and more citizen density. Whether it can really rely on the repair on the original basis to meet the current needs is a question worthy of consideration (Saulnier & Varella, 2013).

Situation of Tokyo and London

The London Underground (LU) network has a busy subway network as NYC does, whose subway and drainage infrastructures share a similar long history and both are threatened by subway flooding. To deal with the potential hazards, LU is keeping updating its policies and exploring new possibilities such as building a cyber network. As another city suffering from urban flooding, Tokyo chose to build a comprehensive underground labyrinth of drainage pipes, which is called the Metropolitan Area Outer Underground Discharge Channel. All cities of New York, London and Tokyo are concerned about and acting under climate change.

Type of infrastructure	World GDP (approximate %) Years 2000–2010	World GDP (approximate %) Years 2020–2030	Difference in average annual infrastructure expenditure (as % of GDP)
Road	0.38	0.29	−23
Rail	0.09	0.06	−33
Electricity	0.22	0.24	+9
Water (only OECD countries, Russia, China, India, and Brazil)	1.01	1.03	+2

Data source: OECD (2006)

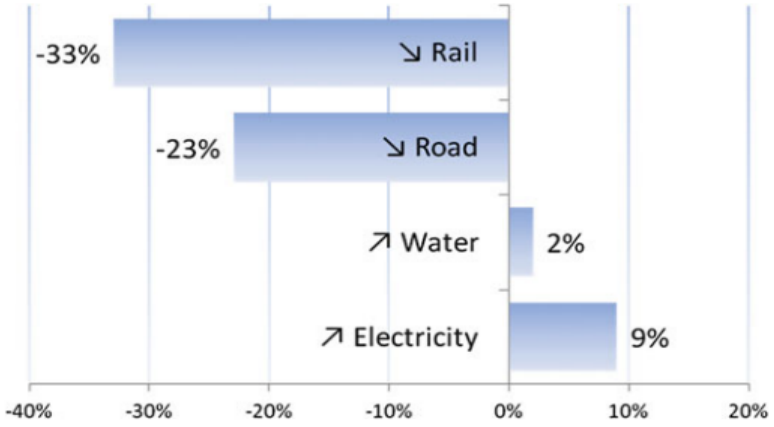

Figure 1 Graphical interpretation of the differences in average annual infrastructure expenditures (Saulnier & Varella, 2013).

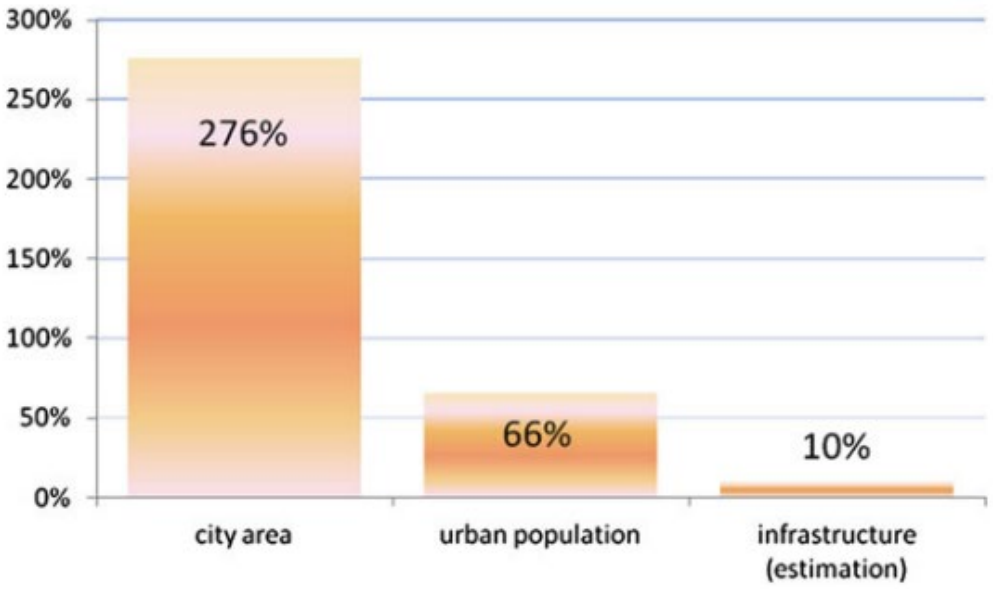

Figure 2 Estimated (1) urban population, (2) city area, and (3) infrastructure global growth by year (Saulnier & Varella, 2013).

Build a Framework

Framework construction is the foundation of the methodology of this thesis. It relies on a qualitative method that studies multiple sources of reports and plans to extract indices. To emphasize the diversity of data sources and increase the comprehensiveness, I collect reports and studies from all three cities. This framework helps to set up the stage for future comparison.

Most government reports and plans I collect are comprehensive plans. They can be helpful as they can cover both the existing physical conditions and the social aspects. Besides, from these documents I can identify the current emphasis of planning. Major organizations involved include MTA in NYC, LUL in London and Edogawa River Office (江戸川河川事務所ホーム) in Tokyo.

Table 1. Framework

Property of Infrastructure	Index
Technical aspects	Monitor and maintenance of existing condition
	Mapping
	Vulnerability management
	Response ability during extreme events

Social Aspects	Recover ability after a disaster
	Public Awareness & Participation

Referential Resource

NYC would be my study area. While given the same threats and similar geographical circumstance they are facing, London and Tokyo can provide some practice reference when we talk about NYC's actions. In NYC, the Stormwater Resiliency Plan (SRP) is the report I refer to frequently. London Sustainable Drainage Action Plan is the formal reference I cite for the case study of London. For Tokyo, the information comes from the official project plan of Metropolitan Area Outer Underground Discharge Channel (首都圏外郭放水路), Tokyo Sustainability Action and The Action Plan for 2020.

Table 2. List of Formal Plan Reference

City	Plan	Agency
NYC	Stormwater Resiliency Plan	Mayor's Office of Resiliency
	Long-Term Control Plan	DEP
	Green Infrastructure Plan	PlaNYC DEP
	Financial District and Seaport Climate Resilience Master Plan	EDC Mayor's Office of Climate

		Resiliency
	2021 10-year Capital Plan	DEP
London	London Sustainable Drainage Action Plan	Greater London Authority (GLA)
Tokyo	The Action Plan for 2020	Tokyo Metropolitan Government

Chapter 2 Literature Review

Overview

The subway system is a part of the interacted underground infrastructure system. It is not comprehensive to consider it as an independent system, especially when we are discussing the performance of this system in urban flooding. The inundation of the subway system, which can threaten public health, existing infrastructure and socioecology, is one of the consequences of urban flooding in the whole city. Localized hazards, including flooding, are responsible for extensive damage to infrastructure and livelihoods (UNDRR 2019).

However, the subway system's subsided space and the high dependence on the underground drainage system require it to have a slightly different strategy from that used for surface flooding scenarios. Unfortunately, such differences challenge this urban underground infrastructure management a lot with the requirement of a more sophisticated and comprehensive plan for both infrastructure maintenance and planning management under extreme conditions. Therefore, in order to analyze the flooding problem of the subway, we must start from the overall toughness of the city and its several underground infrastructures including the subway system. After clarifying some basic concepts and their effectiveness, I will try to figure out some important characteristics to be used when building a framework for future analysis.

Infrastructure

"Infrastructure is the set of fundamental facilities and systems that support the sustainable functionality of households and firms" (NYC Environmental Protection, 2021). The infrastructure discussed in this thesis is mainly physical infrastructure. As it is defined, urban physical infrastructure (UPI), is a complex set of systems and networks that provide important

services for cities. However, UPI is vulnerable to climate change. Bobylev (2013) examines physical components of infrastructure including power poles, bridges, flood barriers, and sewers and analyzes their characteristics and development trends of convergence, sustainability, resilience, flexibility, connectivity, interdependence, and other features. On the conclusion of climate change as the main threat to urban physical infrastructure, Bobylev suggests UPI deserves more importance, and that infrastructure adaptation should be included when formulating plans and developing relevant legislation and updated building codes for future development. In conclusion, despite its vulnerability, infrastructure is an inevitable component and has potential to help cities adapt to climate change.

Critical Infrastructure (CI)

The U.S. Critical Infrastructure Protection Act of 2001 defines "Critical Infrastructure" as systems and assets vital to the United States, whether physical or virtual, so that the failure or destruction of such systems and assets will affect security, particularly national economic security. Among the infrastructures, the Transportation system sector is also considered as Critical Infrastructure by the Cybersecurity and Infrastructure Security Agency (CISA).

Recognizing the importance of these CIs, we need to maintain their good status and plan a sustainable development for them. Masood and his group (2016) have some thoughts on the future development and suggest that the future verification of critical infrastructure will involve two major issues, which are resilience to unexpected or uncontrollable events and adaptability to changes in future infrastructure structure and / or operations. Masood's group explores the future scenario in their research, asking such questions on the 'future proof' of infrastructure assets validation of critical infrastructure in the future; preparation for uncertainty of future events; and

related management practices? They also held two industrial seminars in the UK, gathering views from the UK infrastructure and construction industries and government policymakers, as well as summarizing the lessons learned from the workshop and proposing a framework to link future validation to asset management considerations. These questions and the assessment method can also be applied to other cities' consideration of CI development.

Since CI plays such a vital role, how can we improve the sustainability of both CIs themselves and the systems they support? Vamvakeridou-Lyroudia et al. (2020) propose a comprehensive and participatory approach to the interconnected CIs. The main objectives of their proposed methods are: (I) to provide scientific evidence to better understand how future climate conditions affect the normal operation of interconnected CIs in urban areas during their life; (II) assessing the cost-effectiveness of different adaptation measures; (III) involving local stakeholders and operators in the joint design of methods and the assessment and evaluation of adaptation measures; (IV) combining computational modeling with advanced 3D visualization technology to effectively involve stakeholders in decision-making; (V) Including risk assessment and damage assessment functions jointly designed by end users and local stakeholders; (VI) integrate all the above components into a specially designed cloud platform as the end-user decision support system, (VII) verify the end-user and local stakeholders' decision support system. All these suggestions can help to maintain the CI system.

Critical Underground Infrastructure (CUI)

Underground infrastructure can be defined as a group of underground structures that are physically or functionally interconnected. Critical Underground Infrastructure is an underground

structure or a group of underground structures that are vital to the function of the community (Linkov et al., 2006).

Underground infrastructure, limited by the underground condition, can be even more vulnerable and dangerous than surface infrastructure, especially under extreme weather. Jiang and Tang (2021) summarize 378 underground infrastructure failures related to rainstorms in China between 1994-2018. They found the failure of UI has increased significantly since 2010 and the ability of underground infrastructure to withstand rainstorms depends on the performance of nearby existing drainage facilities. Besides extreme weather conditions, geographical features also affect the failure rate of underground infrastructure, with factors such as highly concentrated rainfall and thick layered unsaturated coarse-grained soil, for example, causing a higher failure rate.

UI's vulnerability comes not only from that surface water flooding into the tunnel, the groundwater level is another cause. Colombo, Gattinoni and Scesi (2018) studied Milan's hydrological hazards of underground infrastructure caused by the rise of groundwater level. Different scenarios for the aquifer system are considered: (1) the recharge probability distribution describing the current conditions; (2) It is expected that the pumping rate of oil wells will decline by years in the next 15 years; (3) prediction shows a rising trend in the next 15 years. Flood disasters increased with the increase of infrastructure depth, especially in the northern center of the study area. To deal with Milan's water level rising problem, Gattinoni and Scesi did research to discuss the effectiveness of different solutions in 2016. With modeling scenarios showing that the groundwater level will rise significantly (1m-10m), they evaluated 3 solutions: a reduction of the recharge, an increase of pumping rates in the shallow aquifer that arising from geothermal systems, and the construction of a draining tunnel. Their conclusion is that the first

two nonstructural solutions can easily manage the short-term rise of the groundwater, but far from enough in the long-term. Thus, this problem needs to be solved by superimposing the effects of multiple solutions.

Beyond Infrastructure

Importance of response system

Subway system is an important part of urban underground space. It is located underground, which will not only bring it more challenges in hydrology, but also have higher requirements in asylum and evacuation. Papasian cited Srikanta Herat's explanation, who is the senior academic program officer at the United Nations University (UNU), that "modeling catastrophic events is essential to establish emergency measures in the design of underground infrastructure, including evacuation, emergency flood control and transportation." Coastal megacities are vulnerable to floods because there may be a variety of situations, such as rainstorms combined with tides or sea tides caused by wind or earthquakes. Physical infrastructure improvement can help to some degree, but there can always be accidents. It is not possible to completely eliminate hazards. To prepare a hazard event that "goes beyond the design level of infrastructure solutions", Papasian proposes that the focus should include improving response mechanisms as well as reducing vulnerability to save lives.

Comprehensive Suggestions

To deal with the deteriorating urban flooding scenario, Antin (2009) put forward some general policy suggestions, enlightening me to consider from the following four directions: 1. Establish a decision-making team composed of experts and stakeholders; 2. Create targeted risk assessment charts to provide reference for construction and flood control projects; 3. After

completing the risk assessment, in addition to maintaining physical barriers such as dikes and dams, it should also support comprehensive development and construction, including the application of green infrastructure; 4. Strengthen public awareness and education to make the public aware of risks and have the ability to escape. Through these suggestions, we can extract several key elements: decision-making team, assessment system, comprehensive development and public participation. These features consist of a large part of the infrastructure management.

Framework Reference

Urban Physical Infrastructure Adaptation Framework

Bobylev (2013) focuses on climate change adaptation options of physical infrastructure, including sewer conduits, flood barriers, and so on. He considered UPI characteristics and development trends from interconnectivity, interdependence, convergence, sustainability, efficiency, vulnerability, resilience, critical elements, evolution, and flexibility in the climate change adaptation context and provides some recommendations for adaptation. His paper lists many key features of infrastructure that could not only be functional but also vulnerable. Thus, characteristics such as interdependence can be potential indicators of the evaluation framework.

Green Stormwater Infrastructure Strategy Efficiency Evaluation Framework

Luan et. al. (2019) applies the Storm Water Management Model (SWMM) to evaluate Green Stormwater Infrastructure (GSI) with the case study of Western New City of Zhuhai in China. The study uses four indicators—runoff volume control, peak flow reduction, pollutant removal, and economic cost—to conduct a Multi-Criteria Decision Analysis with the use of Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). In conclusion, the

TOPSIS assessment indicates that the cost weight has significant impact on the multi-criteria decision-making and all strategies may be classified into three categories: effectiveness, cost, and stability. As a paper discussing the evaluation framework of green stormwater infrastructure, it also emphasizes the significance of effectiveness, cost, and stability in policy-making progress that could be potential indexes. Though my framework would be used to evaluate the physical infrastructure, the elements Luan's teams summarized can also provide a very meaningful reference when dealing with the same urban flooding problem.

Chapter 3 Understanding and Evaluating Flood Risks and Responses

Overview

The protagonist of this thesis, NYC, has a lot of flood control experience and its own unique policies in history. Besides it, Tokyo and London, both highly urbanized and with similar geographical conditions and several aging status quo, may provide some reference for NYC to improve its management that it may take some features from the other two cities. Learning from London and Tokyo's experience of dealing with subway flooding, I will do a policy transfer study in terms of NYC's performance on monitoring and maintenance of infrastructure management, as well as increasing public awareness.

NYC

As a city with a long history of industrialization, NYC has planned the urban infrastructure earlier than most parts of the world. But this also brings an inevitable problem that, after a hundred years, many of the existing urban infrastructure cannot keep up with the modern design concept. Let alone continue to support the development of NYC in the future. According to Regional Plan Association (RPA), "up to 20 percent of all NYC subway station entrances — more than 400 in total — could be affected by an extreme rain scenario, also known as a 'once-a-century' flood event" (2021). For the subway system, it is very necessary to live in harmony with water and this harmony generally requires the subway to adapt to the water, not the opposite. Even without considering the flood zone threatened by sea-level rise, a rainstorm may pose a threat to the whole NYC subway system, whether it is in the waterfront or not. Because rainwater will interfere with underground signals and require the closure of the electrified rails. On a dry day, the Metropolitan Transportation Authority (MTA) moves about 14 million gallons

of water out of the subway system to avoid the interference of groundwater (Hu & Barnard, 2021). According to the MTA, the current pumps and drainage system were designed to handle a maximum rainfall rate of 1.75 inches per hour. The MTA is trying various methods to increase the resilience of the subway system. In 2008, MTA installed subway gates to prevent rainwater from overflowing through the entrances. However, this measure is still far from enough to deal with the waterlogging under extreme events. In 2011, Hurricane Irene caused a 2-day closure; Hurricane Sandy limited the capacity of the subway for 5 days in 2012, and left reconstruction work for the impaired tunnels till 2020; Hurricane Ida, again, shut down the NYC subway and could cost up to $100 million dollars.

History

1904: This is the remarkable year when the first official subway system in NYC was opened. It is operated by Interborough MRT as a 9.1-mile-long subway line with 28 stations connecting the region between City Hall and 145th street (MTA, 2013）.

1999: Flooding happened in the subway system due to a rainfall of 2.5-4.0 inches over 2, by which time MTA's drainage system can handle 1.5 inches of rainfall per hour (Chen, 2007).

2004: Hurricane Francis brought another flooding event within the subway system with a rainfall of over two inches of rain per hour (Chen, 2007).

2007: According to Mike Lombardi, head of Metro operations at NYC Transit, 13 million gallons of groundwater need to be pumped from the system every day (Donohue, 2007).

2008: Queens implemented a new elevated grate, some of which are completely sealed to prevent water ingress (Dunlap, 2008).

2011: Hurricane Irene sweeps through NYC. It forced the city to shut down its subway system for two days though no flooding happened (Feis, 2011）.

2012: Hurricane Sandy hit NYC and its underground infrastructure. This is one of the worst storms the city has ever seen. This hurricane limited the capacity of the subway for 5 days, and left reconstruction work for the impaired tunnels till 2020. Besides, this disaster unmasked some huge defects hidden in the subway system (New York Times, 2012). In the same year, MTA explored the possibility of using "tunnel plugs" to deal with next extreme weather conditions. This action was led by a team of engineers from West Virginia University who kept developing the new technology for five years (Donoho, 2012).

2021: Hurricane Ida, again, shut down the NYC subway and cost up to $100 million dollars (Goose, 2021).

How does urban flooding impact the underground transport system? A common inconvenience is that rainwater will interfere with underground signals and require the closure of the electrified rails. On a normal dry day in recent years, the MTA moves about 14 million gallons of water out of the subway system (Hu and Barnard, 2021). Besides, the pumps and drainage system were designed to handle a maximum rainfall rate of 1.75 inches per hour (MTA, 2007).

In 2008, MTA installed subway grating to prevent rainwater from overflowing through the entrances. However, this measure is still far from enough to deal with the waterlogging of the subway. In NYC, there are usually two ways to mitigate flood risk: structural and nonstructural. Structural measures include engineering solutions to reduce or avoid the possible impact of floods, such as the construction of dikes and tidal barriers. Several ways that can be directly applied are to install standby power supply for the water pump system to reduce or avoid the possibility of infrastructure damage in the event of power failure, and to clean up the flooded tunnel faster. Alternatively, flood gates and raised entrances are installed for stations, which can

enable the underground transportation system to continue to operate even during floods (Cronin & Cronin, 2016). Nonstructural measures do not target physical construction, but try to reduce risks and impacts through policies and laws, public awareness and education.

Although many transportation and other basic infrastructure systems in the metropolitan east coast area (MEC) area are located at an altitude of 6 to 20 feet above the current sea level, they are completely within the range of 8 to 20 feet above the sea level of coastal storm surge expected by tropical storms and temperate storms in the East. The region has spent about $100 billion on infrastructure every decade (Klaus, Edelblum &Arnold, n.d.).

In NYC, MTA has invested $2.6 billion in resiliency projects since Hurricane Sandy, including fortifying 3,500 subway openings like vents, staircases, and elevator shafts against flooding. While, these engineer methods cannot solve the problem of dead flooding from the root. NYC has introduced the Green Infrastructure Plan since 2010 to drain the street rainwater, preventing stormwater from entering the city's underground system.

Though we see some investment after the impacts of hurricanes, the general lack of funding to do the upgrading of the subway system is an obstacle to implementing all the methods we discussed before. Even though a 3 trillion infrastructure bill would be provided by the Biden Administration to maintain and improve the infrastructure in the United States, not a lot of them would go into the subway system (Probasco, 2022). According to the bill, the $1.2 trillion bill is allocated mainly for highways and other infrastructure projects. $550 billion is in the form of new spending. Even among them, about $50 billion would be shared by cybersecurity and climate change. This funding is used to protect infrastructure from the emerging problems met, which are cybersecurity attacks and disasters often closely connected with climate change, such as flooding, wildfires, coastal erosion, and droughts and other extreme weather events. Besides,

$39 billion would go to general public transit. This funding would be shared nationwide to upgrade and expand public transit systems, including to create new bus routes to increase accessibility to all citizens. After levels of dispersal, the amount that can go to maintain or improve the subway system can be minimal.

Approximately 60 percent of NYC's sewer system is in the Combined Sewer System, which is common to older, more developed US cities. But such treatment often causes combined sewer overflows during significant rain events. There exist mitigation plans of CSO, such as the Long-Term Control Plan (LTCP). LTCP projects typically involve sewer and wastewater treatment plant upgrades, and the implementation of green infrastructure. NYC Green Infrastructure Program has led to over 10,000 green infrastructure projects constructed or currently in construction by 2021 (Mayor's Office of NYC, 2021).

Tokyo

Tokyo's struggle against floods can be traced back to its history. Located on a plain, the city consists of five noisy river systems and dozens of rivers, which expand naturally every season. Intensive urbanization, rapid industrialization and careless water intake have led to the sinking of some areas and exacerbated the vulnerability of cities. Its geographical feature as an island even in the future amplifies the natural hazards' impact on it. Typhoon Catherine struck Tokyo in 1947, destroying about 31,000 houses and killing 1100 people; Ten years later, typhoon Kakogawa (aka IDA) destroyed the city, with about 400 mm (15.7 inches) of rainfall in a week. Streets, homes and businesses were flooded, as well as the subway system.

Tokyo Metro Co., Ltd. consists of nine lines with an operating mileage of more than 195.1 kilometers and 179 stations, which are used by 7.07 million passengers every day. The

operation concept of Tokyo Metro is that safety equals safety plus service. In terms of security, it is particularly committed to responding to natural disasters. In view of the recent extreme weather events, the countermeasures against rainstorms are particularly important. According to the latest flood disaster forecast released in 2009, 17 lines, 97 stations and 147 km tunnels in the metropolitan area will be completely submerged under the water (Aoki, Yoshizawa, & Taminato, 2016). Nowadays, the damage caused by extreme weather is increasing and Tokyo Metro, which manages many subways under the Japanese capital, continues to strengthen preparations for flood prevention.

Even though Japan has been coping with floods for centuries, the current system in Tokyo did begin to take shape after the war. Japan chose to build a comprehensive underground labyrinth of drainage pipes in Tokyo, which crisscross with subway lines and natural gas pipelines. Among them, the Metropolitan Area Outer Underground Discharge Channel, also called G-Can project, completed in 2006 is an international example of Japan's flood control project and is the largest underground flood diversion facility in the world. This project cost $3 billion and 13 years. G-cans are connected to five major rivers in Japan through five huge vertical shafts. Whenever there is flooding, the water will flow into these huge drainage shafts up to 230 ft high and into the huge reservoir 72 ft deep underground through 3.9 miles of underground drainage pipes. After the storm subsided, the water in the reservoir can be pumped into the Edo River at a total speed of 53,000 gallons per second and finally into Tokyo Bay (Patowary, 2013). Walking into the ground of the city, just like you take a birthday cake, you will find an underground maze of tunnels, next to crisscross subway lines and natural gas pipelines (Ortiz, 2018).

However, in recent years, there are concerns on that Japan's high urbanization, rapid industrialization, and large-scale exploitation of water resources have led to surface subsidence and a more fragile urban drainage system, which lead to a reducing discharge ability of this system. The Japanese capital now has dozens of dams, reservoirs and dams (Patowary, 2013).

Like NYC and London, flood control mechanisms are also considered in Tokyo. In addition to increasing the number of flood control barriers, the entrances of the station have agreed to be rebuilt according to the design of complete flood prevention, so as to achieve a better sealing effect. Flood gate is also installed at the entrance of the tunnel to prevent water from entering from all angles.

In addition to engineering preparation, Tokyo has also adjusted its decision-making system and formulated an action schedule, Disaster Response Plan, to deal with major floods. Based on the calculation of the predicted time of the initial disaster, the plan specifies a sequence to determine how long the train should stop running in advance in order to complete the passenger evacuation (The Government of Japan, 2022). Such reference standard practices help personnel take more effective action in the face of flood emergencies.

Flood control projects in dense coastal areas often ignore the impact on the quality of urban design. Important underground infrastructure, such as hydraulic systems, water networks, civil buildings, transportation, energy supply and soil systems, is particularly important in shaping the urban environment and integrating resilience (Krishnan et al., 2019). However, the complexity and resource intensity of these engineering fields make it a challenge to integrate them into design measures. In the planning process, this hinders the active cooperation between the design and engineering communities. Lin’s study presents a collaborative design engineering practice aimed at finding spatial solutions for the flood prone Edogawa area of Tokyo, Japan.

They proposed 3 several elements which are important: A team including urban planning experts, hydraulic engineers, water resources managers and landscape designers; Combination of hydraulic engineering solutions and spatial planning methods provides two alternative strategies for the selected site and evaluation of the urban design quality of each alternative and the effectiveness of reducing flood risk.

London

The London Underground (LU) network is one of the busiest subway networks in the world, with more than 3.5 million people commuting between 270 stations in the city every day (Carrington, 2016). However, much of London's subway infrastructure came from the Victorian era, which indicates both the advanced development of modern London and hidden dangers in the old subway system. In particular, several most popular stations with the largest passenger flow, such as Waterloo, King's Cross and London Bridge are also stations with the most vulnerability. Flash floods and water pipe bursts after heavy rains often cause subway delays and other negative effects, including a train trapped in 2007 and frequent line closures in 2015. Ian Uttley, a senior drainage engineer at LU, was cited by Carrington, saying that “You can’t get an asset more vulnerable to flooding than a network of underground tunnels.”

LU’s report points out that 85 stations of London underground are facing high risk and rising flood risk. Among them popular stations including Waterloo, King's Cross and London Bridge are considered to be the most vulnerable stations under the test of the crisis (Carrington, 2016). According to the report, water pipe rupture affects the pipeline on average five times a year. Frequent closures and delays also cost the subway and the wider economy millions of pounds. In 2012, 3 million liters of water accidentally flowed into the ventilation shaft between

Mile End and Stratford, forcing the Central Line of LU to close for 26 hours, resulting in an additional cost of £ 4 million （5 million dollars）.

According to the same report, at present, the biggest risk faced by London Underground comes from mountain torrents and water pipe bursts after rainstorms. Flooding often causes delays, including a train trapped in 2007 and frequent line closures in 2015. As another major factor, water pipe rupture affects the pipeline five times a year on average.

London Underground Limited (LUL) has published a quantitative risk assessment (QRA), "assessing the risk of significant hazards that may lead to the death of customers and other members of the public" (LUL, 2001). In addition to the public health concern, closures and delays have resulted in millions of pounds of economic losses for the subway and the wider economy. In 3m liters of water went into a ventilation shaft between Mile End and Stratford by accident, forcing the Central line to be closed for 26 hours, resulting in an additional £ 4 million cost.

Funding problem is also seen in the London case. In 2014, the guardian revealed that the government's funds for dealing with the impact of global warming in the UK were almost halved, and the number of staff working on this issue was reduced from 38 to 6 (Carrington, 2016).

Advanced metro’s interest is currently focusing on extreme weather events and hazards due to climate change, considering the increase in high-magnitude events frequency. An influential precedent is Transport for London (TfL), the integrated transport authority who has established action plans for enduring extreme weather events in their metro system (Forero-Ortiz & Martínez-Gomariz, 2020).

Chapter 4 Methodology & Findings

General Planning of Urban Drainage

In NYC, tanks and tunnels are the main types of construction adopted to serve as temporary water storage in extreme weather. The CSO retention tank collects CSO emissions during wet weather and pumps them back to the wastewater treatment facility after a rainstorm when the sewer system has capacity. There are four CSO storage tanks in NYC: Erie Creek, Flushing Creek, and the Jamaica Bay tributaries: Perdegart Basin and Spring Creek.

The CSO storage tunnel is also able to accommodate sewage and rainwater during most storms through underground large-diameter pipes or tunnels, which is similar to a retention tank. However, there are currently no existing CSO storage tunnels in NYC. Newtown Creek and Flushing Bay LTCP recommend CSO tunnels (NYCDEP, 2018).

In the strategy of softening the coastline, we can also read NYC 's preference for green infrastructure. NYC has implemented a green infrastructure plan since 2010 to reduce combined sewage overflows by transforming streets, sidewalks and public and private properties (Liao, Deng& Tan, 2017). The goal is to "reduce an additional 3.8 billion gallons of CSO production per year; obtain the first 2.5 centimeters of rainfall from 10% of the impervious area of the basin through green infrastructure and combined sewers; and provide substantial and quantifiable sustainability benefits, such as cooling cities, reducing energy use, improving real estate value and clean air" (NYCDEP, 2010).

London's policy is also highly similar to that of NYC, with a high emphasis on green infrastructure. In the 7-layer drainage hierarchy proposed in the SuDS in London, a guide, 2 steps are used, green roof and tree trench, to delay the accumulation of surface water flow (2016). However, huge drainage infrastructure projects are also proposed. To improve the flood

control, the Thames Tideway Scheme was proposed. The Thames River tunnel will be 25 kilometers long, passing through central London to collect, store and transport almost all untreated sewage and rainwater flowing into the estuary. The project started in 2016 and is planned to be completed in 2025 with an estimated cost of about £ 5 billion ($6.6 billion).

Unlike the other two cities, Tokyo's underground infrastructure for flood control is widely admired and Japanese authorities believe it has proven highly effective. When it comes to rainwater treatment in Tokyo, the project that has to be mentioned is the G-Cans. Since its completion, this huge infrastructure project has undertaken the task of storing water and releasing floods for Tokyo under extreme rainfall. Nakamura and Oosawa (2021) examined and confirmed the flood control effect of underground facilities on the rainfall generated by typhoon Hagibis in Tokyo in 2019. They discuss the advantages of underground regulation reservoirs in urban areas for the two aspects of cost and land acquisition and think that the underground reservoir has significant advantages in both aspects. That is why I agree with their recommendation of underground infrastructure utilization.

Monitoring & Maintenance

Infrastructure is very expensive, including in NYC. Adding new infrastructure and consistently monitoring and maintaining the status of the existing infrastructure requires NYC to spend a lot of money on it every year. DEP's 2021 10-year capital plan includes $4.6 billion for sewer improvements and the agency has committed $3.8 billion in sewer upgrades across the city over the past 10 years. There is currently an unprecedented focus on southeast Queens with approximately $2 billion of investment for a comprehensive drainage system. Historically, NYC has been spending money on infrastructure. But whether this huge amount of money is used

efficiently and accurately in the places where it is most needed is questionable. Because NYC has never had a system that can monitor the status of infrastructure in real time, the choice of infrastructure upgrading and maintenance projects is often passive. But with the progress of technology, perhaps sensors and modeling can help NYC gradually get out of this blind spot for the infrastructure status.

London began to explore in this direction a few years ago. Aiming to build a model that can help evaluate the current situation of infrastructure in a timely manner and help people better understand the situation, LUL directed the Underground M3 project. This new exploration on the monitoring of aging infrastructure uses computer vision and miniature electromechanical sensors in conjunction with research institutions including Cambridge University, and intends to fundamentally change the basic mode of existing condition assessment and monitoring methods. LUL and participating researchers proposed that the future monitoring system will include wireless sensor network (WSN), and will be designed around the ability of autonomous nodes. According to them, nodes contained within the network will integrate specific sensing capabilities with communication, data processing and power supply.

According to the University of Cambridge, "Underground M3 system" is a comprehensive research project implementing this methodology, funded by the EUROCORES Programme Smart Structural Systems Technologies(S3T). The main objective of the project is to develop a system that uses a hierarchical approach to monitor the extent and rate of deterioration. The system would be composed of two parts: “Micro-detection using advances in computer vision” and “Micro-monitoring and communication using advances in micro electromechanical system (MEMS) and wireless communication”. The project also carries the hope of London to use potential low-cost technologies to reduce the costs associated with scrapped structures,

which is very important to the feasibility of repair and reuse. Moreover, they can also improve the safety level by improving the early warning ability of disasters.

Following the Underground M3 project, Soga et al. (2012) used computer modeling, MEMS and WSN to build a new basic model of existing methods for infrastructure condition assessment and monitoring. Their paper describes the actual deployment and testing of these innovative monitoring tools in the London subway, Prague subway and Barcelona subway tunnels. The vision of the underground M3 project is to use computer vision technology and widely installed micro detectors to install low-cost and low-power wireless sensors on key components of the infrastructure. These sensors may be constructed into an economical and feasible general wireless sensor network monitoring system to provide key decision support capabilities for system administrators. Therefore, the challenge of the project is to verify the ability of recently developed computer modeling technology in the underground environment and demonstrate a large number of small, low-cost sensors that can be used and integrated into large engineering systems to improve performance and prolong life, while continuously assessing and managing uncertainty and risk.

I think this monitoring project is a project worth learning from and adoption in NYC. First of all, with very good resources, NYC can obtain sufficient scientific and technological talents to work in relevant technology research and development through cooperation with universities and technology enterprises. As pointed out in the London's model, at present, sensors and modeling can achieve relatively high accuracy and controllable cost. In the long run, it would be a cost-effective choice and can help NYC accurately locate the fragile infrastructure when spending money.

Although through different methods, Tokyo also maintains real-time monitoring of its infrastructure. As mentioned before, the G-Cans project is the centerpiece of the drainage system in Tokyo now. The project built around 2000 is equipped with working base stations on the site of its five reservoirs. According to Edogawa River Office's public G-Can project tour, Tokyo's G-Can project includes a specific control center site as part of the overall project. at the station of the project as well. The staff can not only monitor the condition of the underground reservoir in real time during the flood, but also enter the underground space for maintenance during the dry period. However, this project may not be of great reference value to the monitoring and maintenance of NYC's old infrastructure. Because it was built close to now, the monitoring equipment was considered. And the drainage system in NYC is relatively scattered, unlike Tokyo, which is surrounded by this single project. However, if NYC have new infrastructure construction plan, Tokyo's pattern of on-site monitoring can be a helpful reference.

Mapping

In addition to monitoring the infrastructure itself, it is also very important to map external hazards, such as floods. NYC has the requirement of mapping as well. Since the pass of Local Law 172 in 2018, which requires the city to map the vulnerable region under flood risk, NYC keeps doing mapping and modeling and updates the plans and maps every 4 years (Mayor's Office of Resiliency, 2021). These timely updated and well-informed maps not only help to inform people, but also provide researchers in this direction with detailed and reliable materials for their research, so as to make contributions to better prevent urban waterlogging in the future.

NYC devoted a lot of effort to coastal stormwater management. According to mapping, the city found the lower Manhattan is at great risk and the coastal area vulnerable and may be

inundated in the future. There is a lot going on to protect the waterfront. A recent example is the plan of Lower Manhattan Coastal Resiliency (LMCR). NYC Economic Development Cooperation (NYCEDC) and the Mayor's Office of Climate Resiliency (MOCR) released the Financial District and Seaport Climate Resilience Master Plan to protect Lower Manhattan from the urgent threat of climate change. With an estimated cost of $5 to $7 billion, a more resilient shoreline of Lower Manhattan is going to be implemented to withstand severe coastal storms and rising sea levels. Lower Manhattan is indeed an area that deserves special protection in terms of economic significance and disaster risk. However, in addition to rising sea levels, the risk of urban waterlogging may also come from short-term rainfall caused by extreme weather. The Stormwater Resiliency Plan includes a flooding map under extreme scenarios and we can see the flooding can happen everywhere.

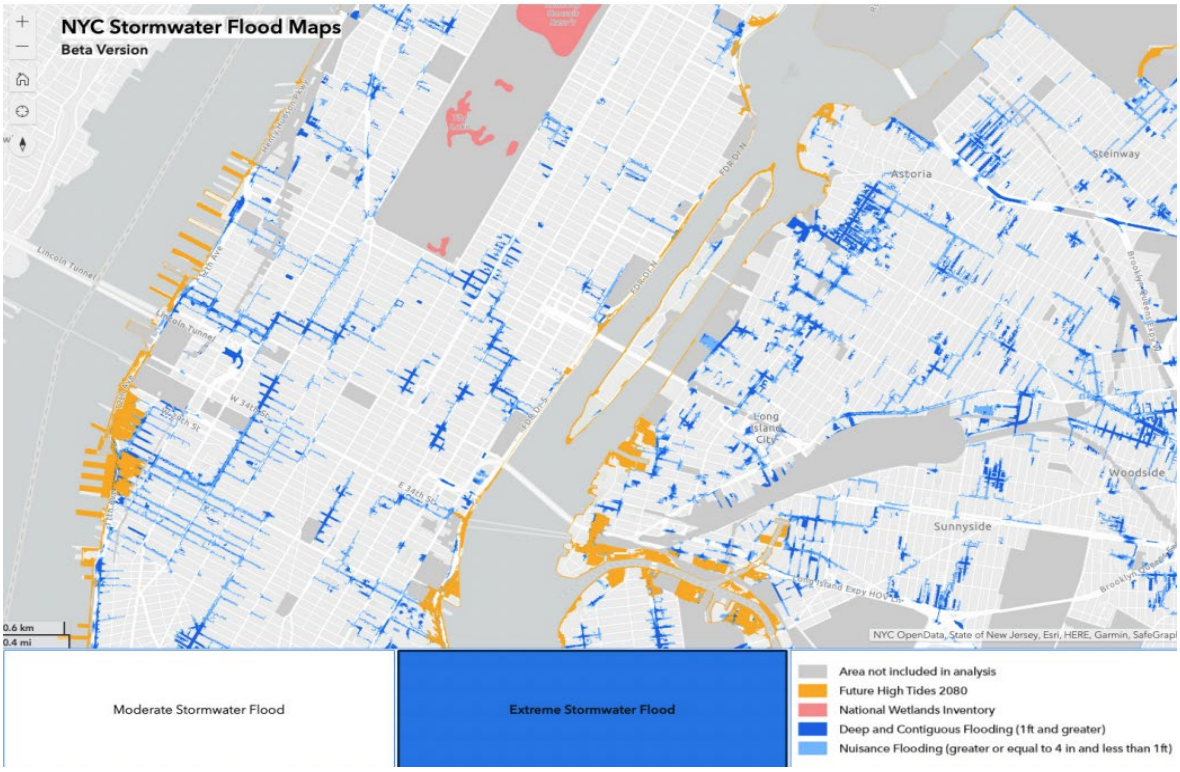

Figure 3 NYC stormwater flood map. Depicted here is the "extreme stormwater flood" scenario. Public maps can be accessed at NYC.gov/resiliency

London pays attention to mapping work as well to better evaluate the economic benefits the SuDS plan can bring to London. According to Ossa-Morenoa, Smith and Mijicb (2016), although the technical performance of SuDS is generally very good, in many places, the absorption rate of large-scale SuDS is very slow, mainly due to reasons outside the engineering field. Thus, Ossa-Morenoa, Smith and Mijicb study the strategic role of the transformation of SuDS in managing the environmental risks of urban infrastructure at the catchment level. They take the Decoy Brook basin in London, UK as an example. They adopt the methodology to assess the SuDS retro-fitting scheme in London by applying a stakeholder participatory approach to do SuDS mapping and do economic assessment of both the flood mitigation and wider benefits of selected SuDS schemes. They concluded that as long as the general principles are suitable for local conditions, the SuDS mapping and economic evaluation methods proposed in the planning stage can be used in cities around the world.

The demand for mapping is going on in all cities, and I think NYC is one of them that has done very well. What NYC can improve may be the combination of modeling of vulnerable infrastructure and flood mapping, and come out with a comprehensive mapping method that considers both infrastructure vulnerability and external disasters.

Vulnerability of Infrastructure System

Infrastructure needs to be monitored and maintained because their effectiveness will be reduced under the influence of various vulnerabilities. Obviously, aging is an inevitable cause. In addition to the impact of time on the material itself, the original design concept of infrastructure may also be outdated. Precipitation intensity-duration-frequency (IDF) curves were used by

NYC to design its sewer system. The standard design criterion is to use the intensity-duration values based on a storm with a 5-year return period to calculate how large the sewer pipes need to be sized to appropriately manage stormwater. Certain older areas of the city are designed with a shorter period, 3 years. The sewer design flow is then determined by application of an equation using a runoff coefficient, a rainfall intensity determined from an equation derived from the IDF analysis, and the contributory drainage area. The IDF curve currently used by NYC is based on historical data from 1903-1951. While currently, the precipitation trends are markedly different from a century ago. NYC Wastewater Resiliency Plan presents a map showing the difference:

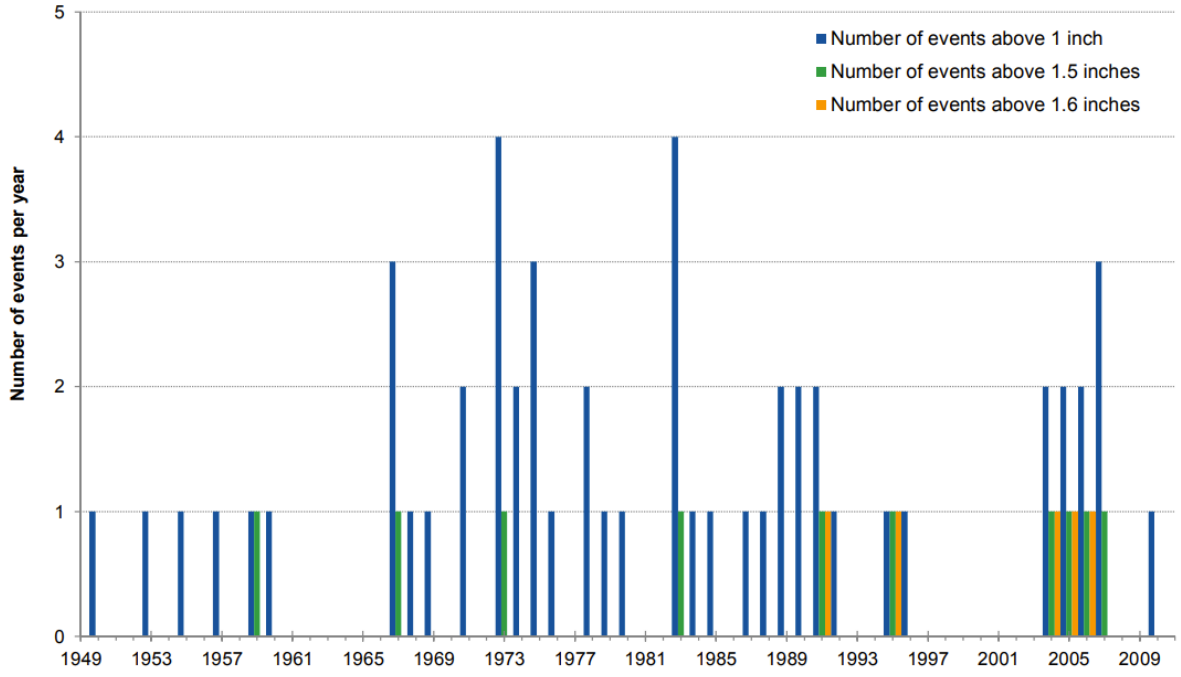

Figure 4 Number of Large Rainfall Events Each Year since 1948 (Mayor's Office of Resiliency,2020)

We can see that both the number of events and the amount of precipitation in a single event increased in general, which implies that the design criteria may be outdated and need a redesign.

Vulnerability comes not only from an infrastructure system itself, but also from the high interdependence between infrastructure, whose significance is often underestimated by people. Such interdependency can bring the subway system extra indirect damage. Future disaster risk reduction strategies should be able to address interdependent infrastructure issues in order to reduce collateral damage. At present, the plans proposed by the NYC government and relevant public welfare companies focus more on reducing direct damage than indirect damage (Hamaguchi & Kim, 2014). Hamaguchi and Kim's study suggests that indirect damage to the construction sector is greater than direct damage, the new plan must reduce indirect damage, focusing on interdependencies between sectors, such as reducing the size of feeder segments of the power sector.

However, research on interdependent infrastructure faces data collection challenges because they require data from different sectors, which are sometimes distributed in different jurisdictions. Rinaldi, Peerenboom and Kelly (2001) point out that interdependent infrastructure research lacks data. After studying Hurricane Sandy's effect on NYC, they suggest that future research on Sandy must improve its methods to estimate the damage caused by the risk of interdependence in the transport sector, such as power outages.

This interdependence of infrastructure troubles London as well. Faramehr and his group (2019) believe that although the interdependencies between infrastructures are usually obvious and interrelated under normal operation, they show great diversity when the system is interrupted under extreme events such as flooding, depending on the specific scenario. They raised the example that if there is a lack of appropriate tools to assess and quantify the track flood caused by water pipe burst, which is a cross sectoral failure that may affect the operation of two urban infrastructure systems, railway and water supply.

Not only with water systems, the rail system is also connected with electricity. Goldbeck, Angeloudis and Ochieng (2019) believe that increasing interdependency among CIs will exacerbate the impact of destructive events through cascading failures, blocked asset repair and network congestion. Current resilience assessment methods cannot fully capture the impact of this interdependence, because they tend to model asset reliability and network flow respectively, and usually rely on static flow allocation methods. Therefore, they develop an integrated dynamic modeling and simulation framework, which combines the network and asset representation of infrastructure systems, and uses rolling planning scope to model the best response to interruption. Their case study of the London Underground and power network shows that the proposed method can be used to evaluate the resilience of urban scale infrastructure systems to local flood events, and estimate the value of resilience loss triangle of different levels of risk exposure and repair capacity. After looking at studies on the vulnerability caused by interdependency in London, I totally agree with Rinaldi, Peerenboom and Kelly that NYC need more research in this direction to improve its infrastructure management.

The G-Cans project in Tokyo seems to have a different assessment of vulnerability. Bobylev (n.d.) believes that the project reduces vulnerability to natural disasters, but it cannot be considered sustainable. Because the project consumes a lot of land and energy, but only solves the consequences of floods. This imbalance between input and output may also be considered a manifestation of vulnerability. I think this is what we need to consider when considering NYC infrastructure, especially for new projects. Can the benefits of infrastructure expansion offset the consumption of space and energy in a place like NYC? Even if NYC is determined to complete such a project, once it cannot ensure the balance of gain and loss, the subsequent maintenance and management will become a new vulnerability in the future.

Response Ability

Our infrastructure can be vulnerable and once the hazard presents, the built environment is not the only victim. Since we cannot completely avoid such damage, what can we do? The ability to deal with these disasters is partially reflected by the city's ability to respond. The Stormwater Resiliency Plan believes that it is very important for all departments to respond positively, clarify the division of labor and mutual cooperation, and clearly define the responsibilities of all departments. Cross sectoral coordination arising from a major rainfall event in 2007 led to the establishment of a flood mitigation working group and the development of a flash flood emergency plan managed by NYC Emergency Management (NYCEM). Several of the main institutions involved in the response system include the Department of Environmental Protection, which is responsible for cleaning the interior of the catch basin, monitoring the weather and initiating the flash flood emergency plan; NYCEM managing the community emergency response team (CERT); MTA responding to flash flood emergencies affecting subways, buses, commuter Railway Assets, bridges and tunnels. In addition, the Department of Transportation (DOT), the Department of Health (DSNY), the fire department (FDNY), the police station, the community affairs group, the community affairs unit (CAU) in the mayor's office and other departments perform their respective duties.

In addition to clarifying the responsibilities of government departments, the time management of decision-making under extreme events can also reflect the situation of the response system in NYC to some extent. Schofer, Chan and Cohen (2012) introduce the decision analysis model of institutional decision-making under the background of uncertain events and subsequent consequences. In addition to constructing an inherently complex situation whose results depend on decisions and events with uncertain results, the model also provides valuable

insights into the risks borne by bus operators, which depend on their exposure to assets, people and customers and their ability to protect them. They concluded that reducing the preparation time required for weather event preparation and allowing institutions to receive more and more accurate weather forecasts can significantly save costs.

Challender (2016) studies how NYC performed during Hurricane Sandy and suggests that the response to Hurricane Sandy can be divided into two main time frames - the preparation phase, during which the city can take advantage of the slow onset of the storm to prepare and the immediate response phase, which began even before the storm left New York. Challender examines the destruction of key underground infrastructure and residential areas during Hurricane Sandy, as well as the immediate response and ongoing initiatives of disaster prevention officials and communities to create a more resilient city and coastline. He believes that in addition to the storm hardening key systems and protecting tunnels from water infiltration, there are a large number of problems related to land use, enhancing community resilience, and updating emergency preparedness plans and flood maps that need to be solved. Further research can be on technologies such as reverse 911 calls and multilingual press conferences to attract citizens at the personal level, rather than providing meteorological information through conventional channels.

Recover ability after a Disaster

For the occurrence of catastrophic events, we have measured the capacity of the infrastructure system and the effect of human response before and during the disaster. While. after a disaster, a very important measure index is the ability to recover from damage. And this recover ability may be even more difficult to achieve than expectation.

The South Ferry subway station on line 1, a three-year-old subway station when Hurricane Sandy hit, took five years to recover from the impact of the disaster. The 15 million gallons of water poured into the subway station in 2012 brought it more than $340 million in repair costs (Creag, 2017).

What is underlined this cost of time and money? Hashash et al.(2014) propose that Hurricane Sandy had several major geotechnical consequences, including (I) storm surges that changed the coastal landscape of the area, resulting in new entrances, erosion and soil erosion of the coastline, showing how swamps, sand dunes and barrier islands affect soil erosion patterns and the resulting damage; (II) storm surge damage to coastal communities reveals the vulnerability of residential building foundations not built in accordance with modern flood control standards; (III) the destruction of nonstructural components by floods has led to the discontinuation of many underground structures and underground infrastructure. Their paper introduces the observation results of the characteristic damage of geotechnical infrastructure and the change of geological environment in the affected area collected and recorded by the Geer (Geotechnical extreme event survey, www.geerassociation. ORG) team. From the perspective of geotechnical engineering, Hashash and his group discuss the key transformation in the future urban planning, that is, elastic but sustainable design for extreme natural events.

Recovery rate is an important indicator of disaster consequences. The results show that the recovery rates vary from district to district in NYC, which may reflect the differences in infrastructure resilience and exposure conditions. Zimmerman (2014) analyzes the impact and recovery of rail transit, takes the recovery of more than 20 subway lines as a physical measure, and takes the passenger volume of stations as a user or social measure. The analysis of line restoration shows that within a few weeks after the storm, almost 80% of the lines are fully

restored, almost 20% of the lines are partially restored, and there are few complete pauses, indicating that the restoration ability is very strong. The passenger volume measured at the station is compared with the level and change rate during the storm and in different time periods of the previous year. The high correlation of passenger volume in one day before and after the storm indicates that there is little redistribution of passenger volume between stations between these two time periods. However, the rate of change shows that within two weeks after the storm, the passenger volume of the whole system has decreased by 14-16% compared with the same time period of the previous year, and then recovered, which may reflect the slow speed of social recovery compared with the recovery of physical transportation system (Zimmerman, 2014) The long-term service quality impact is caused by equipment damage, such as water damage and salt water corrosion.

London's discussion on the resilience of infrastructure has even stepped forward to discuss the recovery at the network level. Yadav, Chatterjee and Ganguly (2020) think that natural disasters, including floods, can cause catastrophic failures in interdependent urban transport network-of-networks (NoNs). As infrastructure systems become more intelligent, the threat of targeted cyber physical attacks is increasing as well. Thus, they develop a hypothesis driven elastic framework for non-operators of urban transport, which we demonstrated on the London Railway Network (LRN) and find that topology attributes designed to maximize efficiency rather than robustness make the network more vulnerable to complex natural target interruptions, including cascading failures. By the end of their paper, they suggest that the principles of network science can be used to formulate the organizational principles of recovery after interruption. This conclusion is also very enlightening for NYC. Since we realize that the recovery after the disaster comes more from social difficulties than from engineering difficulties,

NYC's next consideration of recovery capacity can also be formed on the aspect of a whole transport network.

Public Awareness and Participation

Public participation is an indispensable part in any way. In the SuDS, they pointed out that the GLA department should lead the production of sustainable drainage guidelines and good practice examples for individual homes, small apartment buildings or local communities, and implement at least five pilot modifications of green sustainable drainage measures. At the same time, through incentive schemes, individuals or local communities are encouraged to implement their own sustainable drainage programs. While NYC's Stormwater Resiliency Plan has a different approach. It emphasizes more on revealing the flood vulnerability maps to the public and builds online interactive maps showing citywide flood vulnerability (Mayor's Office of Resiliency, 2021).

To help citizens better protect themselves from a flooding event, both Tokyo and NYC prepare convenient guidance. Tokyo has a special flood emergency manual for citizens. NYC also has a Flooding Quick Reference Guide to provide guidance for citizens facing the threat of floods. Although both cities have prepared convenient reference manuals, I think one thing NYC can learn from the reference manuals of Tokyo is to use more simple illustrations. Because although NYC's manual lists the actions that can be taken very concisely, there is no schematic diagram to teach people what to do. But we should be aware that this manual should not only be aimed at literate people. Large and dense texts will also make readers not interested in reading at ordinary times, resulting in the failure of this manual to play its due guiding role. Therefore, I

strongly suggest that NYC add cartoon schematic diagrams in guidance manuals of flood control and disaster prevention to make it more attractive and easier to understand.

Besides, in the comparison of citizen participation in NYC and London, I found that London's policy of increasing public education contains more active methods, such as using benefits to encourage citizens to build their own GI. Thus, citizens can be active participants in dealing with the urban flooding problem. Increasing citizens' knowledge of green infrastructure also contributes to the increase of small-scale private infrastructure. Compared to NYC's emphasis on providing a platform where people can play with interactive maps, London's promotion provides more incentives that NYC should take into account as well.

Chapter 5 Conclusion & Recommendation

In general, I find that NYC does not bet on a large central underground infrastructure like Tokyo or London. This is reasonable as NYC has five boroughs splitted by the Upper Bay and several rivers. And within each borough, there are smaller scale drainage projects under construction as well. This is actually a good phenomenon, which shows that New York City does not blindly follow the trend, but formulates flood discharge strategies according to local conditions and its own independent conditions.

However, from the perspective of technology, NYC still has great room for progress. From the perspective of monitor and maintenance, NYC does not have a monitoring system or projects assessing the exact condition of the infrastructure, which can provide referential data for both governments and the public. Though it seems to be a good choice for Japan to monitor the working conditions of underground drainage facilities in real time through the monitoring room of G-Cans project, this strategy may not be useful for NYC. Due to the geographical conditions of NYC divided by waterways and the application of the CSO system, it is difficult to establish a centralized underground reservoir in NYC, let alone build corresponding monitoring facilities and special monitoring base stations to make interventions. However, the choice of London to establish a cyber network to monitor the existing underground infrastructure facilities and update the infrastructure situation to relevant departments in real time through this system seems very promising.

Furthermore, this network of monitoring systems can be combined with the very complete flood risk map that FEMA has made now. According to the guidance of the flooding map, priority should be given to subway stations exposed to high risk. These subway stations are

like those short boards in the barrel theory. We can gradually expand the detection scope through small-scale monitoring and installation in high-risk subway stations, such as the South Ferry Station I discussed before, and finally achieve the monitoring of underground infrastructure across whole NYC. Once this network is built, it would contribute a lot to the prevention of infrastructure vulnerability.

Vulnerability is an inevitable problem for infrastructure. Both NYC and London have realized that the strong dependence between infrastructure will bring vulnerability to the underground infrastructure system and have conducted research and evaluation on this dependence. This will enable them to better understand the weaknesses of infrastructure and put forward more targeted solutions. The inspiration from Tokyo is the necessity to choose between sustainability and vulnerability and maximize benefits. How to offset the cost and prevent the imbalance which could be a future vulnerability is another thing NYC should think thoroughly.

The bad news for NYC is that the vulnerability of its infrastructure system not only comes from the physical aging of the infrastructure system and the interaction between the infrastructure systems, but also from the impact of not updating the management in time. The data of rainfall and population growth are very perfect in the archives, but few people analyze them in several plans. From the perspective of infrastructure maintenance, the growth rate of infrastructure in New York City is not as fast as the increase of urban population, and the investment in infrastructure is out of proportion to the overall GDP growth. From the perspective of new infrastructure, the design standards of drainage infrastructure in New York failed to be adjusted in time according to the changes of rainfall patterns, and the outdated design standards could not provide sufficient drainage capacity. Therefore, it is the urgent mission of New York to

readjust the infrastructure design standards and increase infrastructure investment according to the current model and considering the extreme weather under climate change.

In terms of public education, the three cities have given corresponding plans. Comparing the different ways of improving public participation proposed by Stormwater Resiliency Plan and London Sustainable Drainage Action Plan, I can find that London is more inclined to stimulate the subjective initiative of the public and make GI closer to the lives of residents than NYC does. London's approaches not only give residents more access to GI, but also makes use of the phenomenon that people are more concerned about things around them to improve citizens' acceptance and understanding of GI. At the same time, London also considers using interests to encourage residents to actively participate in the construction of GI, so that GI is no longer supported by the public sector or large private sector alone. NYC has done a good job in information disclosure, but there is still room to learn from London in mobilizing enthusiasm. After all, those excellent online map platforms open to citizens can only be meaningful when there is an opportunity for residents to use them. Besides, using more schematic illustrations to make the guidance manual more attractive and clearer to users is another potential improvement NYC can learn from Tokyo.

In addition to improvements on physical infrastructure management, the popular solution of using green and blue infrastructure to mitigate flooding risk and the following subway failure seems potential as well. Continue the construction and maintenance of Green Infrastructure (GI) to perfect the green and blue infrastructure is meaningful as Catalano de Sousa, Montalto and Gurian (2016)'s study on the rainwater collection performance of bioretention facilities in Queens, NYC has verified the stability of GI's performance on cutting runoff in both extreme and non-extreme. The combination of green and grey infrastructure would be the future of

subway flooding control. After all, in addition to reducing flood risk, green infrastructure in urban space can also provide advantages including water conservation, energy conservation due to reduced cooling use, improved air quality and carbon sequestration.

Adjusting measures to local conditions is the key point of urban planning. Learning from other cities and do a policy transfer is one of them. What to do next is to analyze more on current management and what is suitable next. After Takemoto (2011) compared Bangkok and Japan's flood water management, he concluded that the development of a city does not necessarily affect the existing flood management capacity, nor does it necessarily affect its climate adaptation system. By comparing the different scenarios in Bangkok and Tokyo, he believes that for Tokyo, because they have established urban planning and watershed management systems, it is a key challenge to figure out how to manage future climate risks and create a method to deal with the uncertainty in long-term planning. To deal with subway flooding and other hazards under climate change, every city has its own strategy. While, during the exploration of a city's own choice, learning experience from other cities is a shortcut. NYC has done a lot, but it can still further improve itself by learning from the measures of others.

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