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TRANSPORT FOR LONDON
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# CLIMATE ADAPTATION FOR LONDON TRANSIT

## Creating a basis for flood adaptation investment in the London Underground

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# I. EXECUTIVE SUMMARY

**The Problem:** Adverse weather events like extreme rainfall and subsequent flooding are occurring more frequently in the greater London area, which results in service delays and infrastructural damage to the London Underground (the Underground, LU, or "The Tube").

In the short-term, a severe storm may disrupt train service and inconvenience commuters and operations staff at Transport for London, but these are not the only impacts. Flooding, which will increase in frequency and severity with climate change, will also have long-term impacts on the Underground's assets, with freshwater deteriorating tunnels, rails, concrete bench-walls, cables, rolling stock, and more.


***Figure 1**: Flooding at Pudding Mill Lane station (DLR) in July 2021*

**Recommendation:** To adapt to a future impacted by climate change, TfL needs to identify and fortify vulnerabilities in the London Underground network to mitigate flood risks and improve resiliency. This is not in place of, but in tandem with achieving its decarbonization and electrification goals that TfL has already outlined. Our findings and recommendations for next actions are structured into the following categories:

1. **Frameworks on climate adaptation and resilience** and the current status of TfL's efforts and future plans
2. **Flood cost modeling** using case studies from New York and Boston to identify methodologies.

1. **Frameworks on Climate Adaptation and Resilience**

| Finding | Recommendations |
|---|---|
| TfL is embedding adaptation as a main criterion in business planning for maintenance, renewals, and enhancements of its assets, as evidenced in its Climate Action Plan released in March 2023. | **Utilize data on asset exposure and vulnerability in the business planning process** via the asset-based flood cost model described below to allow the benefits of adaptation measures to be better understood. |
| | **Outline a budget envelope for adaptation spending** that is then integrated into the asset areas' funding profiles and associated with meeting certain criteria. |

2. **Flood Cost Modeling**

| Finding | Recommendations |
|---|---|
| TfL currently only uses lost customer hours (LCH) in estimating costs borne out of floods and other climate-related events (only rarely able to incorporate attributable financial cost of asset damage). | **Implement an asset-based flood cost model,** borrowing from the analysis that Martello et. al. conducted in partnership with the MBTA. |
| | **Merge LCH into the flood cost model** by either building a model time of how LCH arises from weather-related damage, or how LCH arises from weather events. This allows LCH to be incorporated into the above-described asset-based cost model. |

## Conclusion

Extreme weather is occurring more frequently and will continue to do so with climate change. It is crucial for TfL to simultaneously adapt and mitigate existing infrastructure to improve resilience against flooding. With focused and efficient business planning, cost modeling, and adaptation investments, Transport for London can lead the way in climate adaptation for modern transit infrastructure.

# II. INTRODUCTION

On July 12, 2021, a sudden rainstorm resulted in unprecedented flash floods in London, flooding streets, homes, and low-lying areas of the city. The disruption to the London Underground was significant. Of the 11 lines of the Tube, 8 were shut down, including Euston Station, one of London's major rail stations.[1] 30 Tube stations were fully or partially closed as a result of the rain. The storm dumped the equivalent of one month's worth of rain on the capital city in one hour.[2] Given the severity, the storm was considered a one-in-100-year flooding event. Except, another storm of similar magnitude hit London again just thirteen days later, flooding the Underground and disrupting services again. The cost of these storms to TfL was £2 million.[3]

One year later, in July 2022, the United Kingdom faced extreme heat waves, this time requiring the Tube to preemptively shut down certain lines due to the specter of rails buckling due to the high temperatures.[4] On lines that were still operating, such as the Central Line, commuters had to endure temperatures of up to 36˚C (97°F) on platforms in a system that usually does not need (or have) air conditioning.

Individually, these extreme weather events are anomalous. But together, along with their increasing frequencies, adverse weather events are proving to be early signs of the

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[1] Gareth Davies, "London Flooding: Tube and Rail Networks Suspended after Month's Worth of Rain Falls in a Day," *The Telegraph*, July 13, 2021, https://www.telegraph.co.uk/news/2021/07/13/uk-weather-london-southern-england-hit-torrential-rain-floods/.

[2] Isabella Kwai, "Fierce Storm Inundates London, Bringing City to a Standstill," *The New York Times*, July 13, 2021, sec. World, https://www.nytimes.com/2021/07/13/world/europe/uk-london-floods.html.

[3] Transport for London, "Pan TfL Flooding Review July 2021 V6," 2021.

[4] Megan Specia, "England's Transportation Network Strains Under the Heat," *The New York Times*, July 18, 2022, sec. World, https://www.nytimes.com/2022/07/18/world/europe/uk-heat-tube-luton-airport.html.

impending climate crisis and impacting transit infrastructure and service reliability in detrimental ways.

More than two-thirds of the world's largest cities are coastal cities that are vulnerable to rising sea levels resulting from climate change, exposing millions of people to the risk of extreme weather events including flooding and storms. At the same time, over the next few decades, the number of cities exposed to extreme temperatures will nearly triple. By 2050, more than 970 cities will experience average summertime temperature highs of 35˚C (95°F).[5]

In response to rising temperatures, cities are making large investments in mitigating climate change by systematically reducing carbon emissions, whether it is through expanding mass public transit to decrease single-vehicle trips or transitioning to low-emission or all-electric rolling stock and fleets. However, it is just as critical that the investment cities make to transition towards a zero-carbon world are resilient to the existing and future extreme weather events resulting from climate change. Public transportation systems have been important when providing individuals access to jobs, education, health and more. These same systems, though, are vulnerable to extreme weather events like flooding and urban heat, which are predicted to increase in both intensity and frequency.

Most transportation modes depend on the functionality of a supporting network of infrastructure and as such, are vulnerable to extreme events.[6] During these extreme events, the structural integrity and safety of this infrastructure can be compromised, which can cause serious consequences.[7] By reducing, deviating or even canceling travel for

[5] "Adaptation & Water," C40 Cities, https://www.c40.org/what-we-do/scaling-up-climate-action/adaptation-water/.

[6] OAR US EPA, "Climate Change Impacts on Transportation," Overviews and Factsheets, October 19, 2022, https://www.epa.gov/climateimpacts/climate-change-impacts-transportation. https://www.epa.gov/climateimpacts/climate-change-impacts-transportation

[7] Max Didier et al., "A Compositional Demand/Supply Framework to Quantify the Resilience of Civil Infrastructure Systems (Re-CoDeS)," *Sustainable and Resilient Infrastructure* 3, no. 2 (April 3, 2018): 86–102, https://doi.org/10.1080/23789689.2017.1364560. https://www.tandfonline.com/doi/full/10.1080/23789689.2017.1364560

passengers, goods and services, these flood events affect the transportation network and its connectivity.[8]

Ensuring that necessary infrastructure is resilient is important for a few reasons. First, if public transit systems cannot operate during extreme weather events, ridership will drop, resulting in less ability to reduce carbon emissions. Second, if ridership drops, organizations operating and maintaining these public transit systems will lose revenue, which is needed to sustain itself. Beyond this economic disruption, failing public transportation systems can lead to ripple effects like a loss to social systems and the fabric holding a citizenry together[9] [10].

In response to extreme weather events resulting from climate change, like flooding and overheating, cities across the world are investing in adaptation mechanisms intended to reduce the harsh effects of such weather events. **Adaptation** is the ongoing process organizations undertake to make physical or organizational changes that enable climate resilience in the present and in the future. **Resilience,** a similar and important yet subtly different idea, is the response to and the ability to recoup losses and recover with stability after a natural disaster. Resilience includes the adaptation of livelihoods and infrastructure, the anticipation of vulnerability in climate and extreme scenarios, absorption of the effects and response for recovery and response when the actual events occur.[11]

## Problem Statement:

Adverse weather events are early signs of the impending climate crisis, which are expected to increase in frequency in coming decades. Despite this, Transport for London (TfL), the organization responsible for the Underground, does not have a holistic view of how 2021 floods or 2022 heat wave "cost" TfL in damages, repairs, and lost revenue. ***How can TfL***

[8]Aditya Rebally et al., "Flood Impact Assessments on Transportation Networks: A Review of Methods and Associated Temporal and Spatial Scales," Frontiers in Sustainable Cities 3 (2021), https://www.frontiersin.org/articles/10.3389/frsc.2021.732181.
[9]Xin Dong et al., "Vulnerability of Urban Water Infrastructures to Climate Change at City Level," *Resources, Conservation and Recycling* 161 (October 1, 2020): 104918, https://doi.org/10.1016/j.resconrec.2020.104918.
[10]Michal Wisniewski, "The Role of Integral Model of Critical Infrastructure Safety in Industry 4.0," 2021, https://doi.org/10.35808/ersj/2410.
[11]"Department for International Development," GOV.UK, March 7, 2023, https://www.gov.uk/government/organisations/department-for-international-development.

***develop climate change-related adaptation based on financial and ridership data that they have?*** What are the financial impacts of adverse weather events on the London Underground, and how can the agency estimate them for future events?

## Background | Transport for London

**Overview**

TfL, created in 2000, is the executive body within the Greater London Authority responsible for London's transport system. Its authority extends across a wide array of transit systems, including rail, bus systems, taxis, roads, cycling provisions, and the London Underground. TfL leads the development and implementation of the Mayor of London's Transport Strategy, as well as managing, maintaining, and expanding London's Transit system. TfL is a conglomerate of a number of predecessor organizations, has an operating budget of greater than ₤10B, and a staff of nearly 30,000. This vast and wide-ranging organizational structure allows for TfL's impressive management capabilities, but can make internal coordination more difficult.

**Organizational Structure**

TfL is organized into two primary directories, each with a variety of responsibility for different modes of transit: London Underground (responsible for running the underground rail network, including the Elizabeth Line), and Surface Transport (responsible for the Dockland Light Railway, bus systems, trams, Dial-a-Ride, London Overground, London River Services, etc.) Ultimately, these entities represent a wide array of services, whether directly operated, contracted, or licensed.

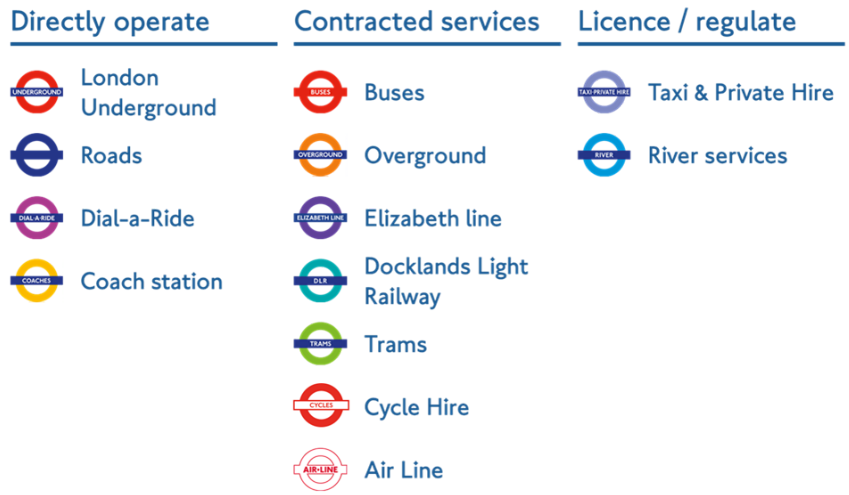


***Figure 2:** Breakdown of TfL services and mode of delivery*[12].

**London Underground**

The London Underground is the focus of this analysis for a variety of reasons. Firstly, the operation of the London Underground is completely under the purview of TfL, simplifying the organizational aspects of implementing climate adaptation measures. Secondly, underground systems are, for fairly evident reasons, more prone to flooding during extreme rainfall events and the short and long-term ramifications thereof. Thirdly, choosing a single portion of London's transit network simplifies and focuses our analysis. Finally, a considerable portion of our analysis and recommendations relies on transferring processes and learnings from other transit systems, and these kinds of adaptation analyses have been more thoroughly investigated in the case of underground rail.

# Background | Climate

From 1990 to 2021, there has been significant research dedicated to rainfall-induced flood vulnerability and specifically on how to make transportation systems more resilient to flood vulnerability. An extensive review of all studies on natural disaster vulnerability in this time period has shown that flooding is the most pertinent natural disaster investigated. Additionally, transportation is among the most critical categories of infrastructure in regards to flood resilience.

[12]Transport for London, "TfL Adaptation Reporting Power," 2021. Transport for London. https://tfl.gov.uk/corporate/about-tfl/adapting-to-climate-change

## *Climate change projections in the London area*

Climate change no longer exists solely in the future, and we are already experiencing its effects across the globe. Each region of the planet will experience a unique set of effects, depending on its particular idiosyncrasies. The implications and potential damages of climate change motivate adaptation investment, and projections of the severity of these changes are crucial in informing the manner and extent of necessary adaptation investments.

The London region of the UK is no exception to climate impacts, with summers expected to grow hotter and drier, and winters expected to grow wetter and warmer[13]. Crucially, heavy rainfall events are expected to become much more frequent (as compared to light rainfall events). Even though summer months are projected to experience less total rainfall, both winter and summer are projected to experience an increase in extreme rainfall events.[14] London is estimated to see a 20 - 30% increase in the intensity of its winter and summer precipitation extremes (5- and 25-year rainfall events) by 2070, compared to a 2009 baseline, with the possibility of a near 40% increase in the most pessimistic scenarios[15]. The increase in intensity of extreme rainfall events increases the risk to critical transit systems that underpin London's economy. These systems were often not designed for the kind of heavy rainfall events that will be seen more frequently in the coming decades. Flooding will become more frequent, and interruptions and repairs will become more commonplace.

## *Climate Adaptation and Mitigation in the Transportation Sector*

The two key strategies to address global climate change are mitigation and adaptation. **Mitigation** entails limiting current and future greenhouse gas (GHG) emissions in order to tackle the fundamental causes of climate change. **Adaptation** involves taking deliberate actions to reduce the adverse impacts of climate change as well as to harness any beneficial opportunities that may arise. The pace of mitigation impacts the need for adaptation. International negotiations have left us at a goal of 1.5 degrees to 2 degrees

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[13]Glenn Watts et al., "Climate Change and Water in the UK – Past Changes and Future Prospects," *Progress in Physical Geography: Earth and Environment* 39, no. 1 (February 1, 2015): 6–28, https://doi.org/10.1177/0309133314542957.
[14]Ibid.
[15]Hayley Fowler and Marie Ekström, "Multi-Model Ensemble Estimates of Climate Change Impacts on UK Seasonal Precipitation Extremes," *International Journal of Climatology* 29 (March 15, 2009): 385, https://doi.org/10.1002/joc.1827.

celsius of temperature increase. At the 21st Conference of Parties held by the UN in 2015, 195 nations adopted the Paris Agreement.[16] This landmark agreement includes the aim to strengthen global response to climate change by specifically “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”

The minimization of temperature increases will hopefully help to avoid catastrophic and irreversible outcomes. However, current and unavoidable temperature increases already expose natural and human systems to significant adverse consequences. These adverse consequences, including extreme weather events like flooding, extreme heat and droughts, require significant adaptation from individuals, governments and private companies.

This precise need for adaptation has given rise to increased investment in economic and scientific analysis. **Economic analysis** is increasingly used to provide insights to decision-makers on the cost and effectiveness of adaptation, the most optional resource allocation between adaptation and mitigation as well as the timing of these responses and their distributional implications in terms of who wins and loses from such responses.

The geographic implications of mitigation and adaptation are also critical. While mitigation creates benefits felt globally, adaptation is enacted and enjoyed by local actors. Global emissions reductions serves as a public good, creating an incentive for every country to freeride. These misaligned incentives make substantial mitigation extraordinarily difficult, barring serious international coordination. On the other hand, local entities have an incentive to implement adaptation policies because the benefits are felt directly by those who take on those adaptation actions. Barriers to adaptation primarily include financial knowledge or resources, and personnel capacity to implement such measures.

Adaptation to climate change is now widely acknowledged as a complementary response to greenhouse gas (GHG) mitigation, as witnessed in the outcomes of the climate change negotiations at Bali (2007), Copenhagen (2009) and Cancun (2010). However, an act of adaptation can look vastly different based on the hazard it aims to address and the

[16]United Nations Intergovernmental Committee on Climate Change, “FAQ Chapter 1 — Global Warming of 1.5 °C,” n.d., https://www.ipcc.ch/sr15/faq/faq-chapter-1/.

vulnerability of the economy, people or assets. All adaptation measures can loosely be sorted into the following categories[17]:

**Reactive Adaptation:**
Reactive adaptation works to fight the immediate negative consequences of climate hazards, aiming to protect quality of life and the city's systems during climate-related disasters and afterwards. For example, sandbags to divert water or temporary water-purchasing during a drought are forms of reactive adaptation. Reactive adaptation can be effective for short-term aberrations, but the costs can be high if repeated interventions are needed.

**Preventative Adaptation:**
Preventative adaptation reduces the negative consequences of climate hazards in order to avoid these hazard events from becoming disasters. For example, this could include the construction of flood walls or installation of energy-efficient AC in public buildings.

**Transformative Adaptation:**
Transformative adaptation actions grapple with the root causes of climate risk and ensure climate hazards are less likely or less severe by implementing fundamental changes to the city's systems. These actions could be expanding the city's green infrastructure to reduce the risk of flooding or implementing new building codes that require cool roofs. These types of actions deliver greater protection from risk and reduce the need for any preventative or reactive actions. The costs of these actions, however, may be higher and their design a bit more complex.

There are several elements that impact an institution's adaptive capacity, or its ability to adjust to climate variability and extremes in order to moderate potential damages or cope with its consequences.[18] In order to invest in adaptation, it is helpful for an institution to understand the costs and benefits of that investment. Beyond driving business decisions,

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[17]C40, "Climate Action Planning Guide: Identifying Adaptation Strategies," n.d., https://www.c40knowledgehub.org/s/guide-navigation?language=en_US&guideArticleRecordId=a3s1Q000001iaiLQAQ&guideRecordId=a3t1Q0000007lEWQAY.
[18]United Nations, "UN Framework Convention on Climate Change: Glossary of Key Terms," n.d., https://www4.unfccc.int/sites/NAPC/Pages/glossary.aspx.

understanding these costs and benefits can provide normative guidance on policy tools. Resources across an organization will have to be allocated between different adaptation strategies as well as between adaptation and mitigation and understanding this analysis can inform these decisions.

# III. ADAPTATION

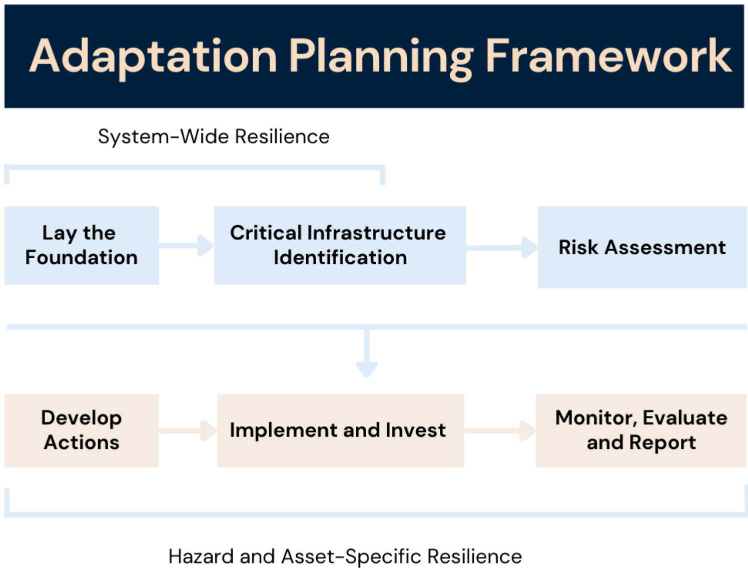
## Framework for TfL to Plan its Adaptation to Flooding

In order to incorporate adaptation planning into infrastructure planning and investment decisions, our team developed an adaptation planning framework TfL can utilize to benchmark their efforts. Incorporating insights from existing planning frameworks in the climate adaptation field, these steps can be used to measure against best practices and identify existing gaps Tfl may have in its adaptation planning, both in terms of system-wide resilience as well as hazard-specific resilience (i.e. flooding vulnerability for specific business areas like the London Underground).

The overarching process cities are recommended to take by leading practitioners and researchers includes the following steps:

1. Laying a foundation
2. Identifying critical infrastructure
3. Conducting a risk assessment
4. Developing adaptation actions and investments
5. Implementing and Investing
6. Monitoring, Evaluating and Reporting.

The following chapter will walk through the substance of this framework, identify steps TfL has taken within this framework, limitations of these steps and/or any gaps the organization should fill through additional or deeper investments or process changes.




While describing each recommended step, this section will indicate how the Adaptation Planning Framework can be tailored for transportation entities like TfL; it will also lay out the actions TfL has already taken in these directions and any limitations it may face in this regard.

## *Step 1: Lay the Foundation*

In this step, cities should **define and scope the planning effort**, **form a team** to execute said effort, and **review existing data,** plans, studies, maps, and other resources. In order to develop buy-in, it will be critical that the entity that champions the importance of adaptation is involved in the planning process.

For transportation entities, a primary team to lead this effort can include representatives from throughout the agency, including planners, engineers, data scientists, operators and community engagement representatives.


**TFl's Existing Steps & Opportunities**

TfL has already laid the foundation for adaptation. Through its 2023 Climate Adaptation Plan that was released this March, its team has developed an internal collaborative team to tackle its adaptation efforts which has defined and scoped its effort as the entity that leads and implements the Mayor's Transport Strategy, specifically Policy Number 9. [19]

TfL's team has collected and reviewed existing information including data on the financial, health, safety and social impacts of the 2021 floods and established clear overarching goals, including the following:

1. Deliver an efficient and reliable transport network that provides an attractive alternative to car use, while playing our part in adapting London to climate impacts
2. Protect TfL staff, contractors, and customers
3. Reduce the financial impact of climate change and make the most of any financial opportunities arising from climate change and/or climate change adaptation

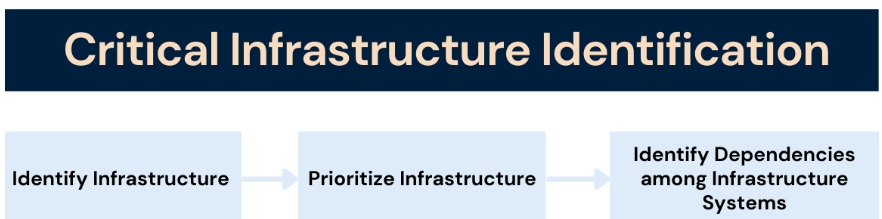
Under six developed themes (leadership & governance, organization and people, risk management, information management, capital and operational delivery, and collaboration, community and reporting), TfL has come up with goals as well as outcomes that are measurable that it would like to achieve in the short-term, medium-term and long-term.[20]

[19]Transport for London, "Climate Change Adaptation Plan," 2023, https://content.tfl.gov.uk/tfl-climate-change-adaptation-plan.pdf.
[20]Goals are broad statements that describe a desired end state, what the community seeks to achieve through implementing resilience solutions for critical infrastructure. Objectives are specific, measurable statements that support the achievement of a goal.

In terms of laying the foundation, while TfL has outlined steps to incorporate adaptation training for all its staff in the short- and medium-term, it could also  be helpful for TfL to identify and communicate to its entire organization which team is leading its climate adaptation planning processes.

Additionally, while TfL has collected and reviewed existing data, developing a more in-depth data collection strategy which would define what information needs to be collected, how and when it will be gathered, and what participants and partners should be involved in this process. This strategy would essentially spell out what must be gathered to better understand TfL's systems and their adaptation gaps.

### *Step 2: Critical Infrastructure Identification*




In this step, cities should identify and prioritize infrastructure and evaluate dependencies among infrastructure systems. The National Infrastructure Protection Plan (NIPP) has stated that

> *"Effective risk management requires an understanding of the criticality of assets, systems, and networks, as well as the associated dependencies of critical infrastructure that is essential to enhancing critical infrastructure security and resilience."*

For transportation entities, this step can leverage any existing asset management system it may have. After identifying key infrastructure, which would involve describing characteristics of key infrastructure, and developing mapping products and other visualizing, cities can begin prioritizing infrastructure for adaptation planning and investments. For transportation authorities, planning teams can prioritize between different assets: underground rail, light-rail, bus, roads, etc.

Below are considerations cities can incorporate when evaluating the impact different infrastructure assets have on their community.

*Table 1: Considerations when Prioritizing Infrastructure*

| Key Considerations | Descriptions |
|---|---|
| Safety Impact | Effect of the system/asset on loss of life, well-being of individuals in the community, the environment, and the physical condition of other infrastructure systems |
| Context | Value of the system/asset to the identity of the community, region or nation; importance of the system, asset as a priority attribute to the community, region or Nation |
| Operational Impact | Effect of the system/asset on the overall network's ability to operate and on other dependent assets |
| Economic Impact | Effect on economic growth of community if asset experienced long-term disruption or degradation |
| Service Impact | Impact disruption could have on services infrastructure provides to community |

**TfL's Existing Steps & Opportunities**

For its 2023 Climate Adaptation Plan, TfL conducted an interdependency assessment, and identified co-dependencies with the following sectors: wastewater, energy, risk management, emergency services, national infrastructure owners, and the public at large[21]. It identified that TfL's operations depend on the following sectors: digital technology, regulator and government departments, contractors and supply chain and future workforce skills.

TfL's interdependency assessment is limited in that it does not incorporate the following analysis that some practitioners recommend:

[21]Transport for London, "TfL Climate Change Adaptation Plan 2023," March 2023, https://content.tfl.gov.uk/tfl-climate-change-adaptation-plan.pdf.

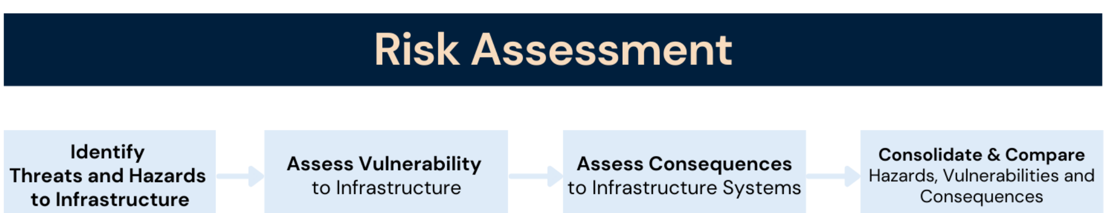
➔ Consider the primary and secondary sources or providers of resources and services required or used by an infrastructure asset to operate. For example, TfL may want to consider energy dependency for an asset in the LU. In that case, it would need to identify who the electrical power distribution provider is and where the primary and secondary substations for the infrastructure asset are located.

➔ Consider the backup sources of resources that are needed to sustain operations of the infrastructure asset in the event of a damaging event. For example, if TfL is considering the energy dependency for an asset in the LU, it would need to identify any on-site backup generators in the event of any significant incident, or disruption to supply chains.

➔ Consider impacts that could occur on downstream infrastructure assets and essential services upon disruption or degradation. For example, an electric outage could halt operations for ticketing for LU, preventing passengers from riding services and impacting the ability of information systems to monitor operations.

TfL may also want to identify key infrastructure or prioritized assets by granular safety, operational, societal, economic or service impacts, which could be useful.

### *Step 3: Risk Assessment*




A climate risk assessment essentially seeks to analyze the likelihood of future climate hazards and the potential impacts of these hazards on cities spatially, and their residents. Conducting a risk assessment is fundamental in order to accurately prioritize action and investment into climate adaptation.

As seen above, the first step in a risk assessment is to **identify the threats and hazards to infrastructure**. While all hazards and threats could be analyzed, a transportation entity may want to evaluate the likelihood that specific hazards will occur that may be more frequent in their areas. Defined hazard recurrence rates, the frequency of recorded history events or predictions can be used to determine the likelihood of a hazard.

The next step in a risk assessment is to **assess how vulnerable infrastructure assets are to the identified hazards.** A vulnerability assessment would entail evaluating the specific hazards, with the specific goal of identifying areas of weakness. Some elements of vulnerability that transportation entity like Tfl could consider includes:

➔ <u>Recoverability</u>: the ability of an asset to easily recover from a disruptive event; an assessment of the asset's ability to return to normal operations taking into account its dependence on outside services (such as energy supply), the capacity at which it is operating, and its own robustness.
➔ <u>Proximity:</u> vulnerability based on an asset's geographic nearness to other susceptible assets.
➔ <u>Redundancy:</u> vulnerability based on whether or not an asset represents a single point of failure within its overall system.

The third step in a risk assessment is to **assess the consequences of these hazards**. Consequences may be measured in the following ways:

➔ <u>Human</u>: injury, illness, loss of life
➔ <u>Economic:</u> costs associated with loss of infrastructure, business, continuity, and replacement or maintenance costs
➔ <u>Mission:</u> reducing trust in the transportation entity's mission or ability to deliver on it)

The last step in a risk assessment would be to **consolidate the above analyses** to consider impacts system-wide by comparing each threat/hazard, vulnerability, and consequence scenario in order to prioritize them based on which pose the highest risk.

**TfL's Existing Steps & Opportunities**

TfL has already conducted an in-depth climate risk assessment. Their team has identified 333 climate risks within the assessment. Precipitation is the hazard with the greatest number of identified risks. Temperature is the hazard with the next greatest number of identified risks.

Some of TfL's most at-risk assets are:

- ➔ Bridges and viaducts
- ➔ Drainage – track, civil infrastructure, buildings, and highways
- ➔ Rolling stock
- ➔ Signaling systems

The following graphs already developed by TfL are very useful in demonstrating the severity of climate risk by the organization's various business areas. As seen below, TfL's Rail and Trams will experience the largest quantity of the identified climate risks with London Underground Experiencing the next largest quantity. However, London Underground will experience the largest amount of the most severe climate risks. Additionally, precipitation is the hazard associated with the largest quantity of climate risks, which will be experienced mostly by London Underground and Rail and Trams.

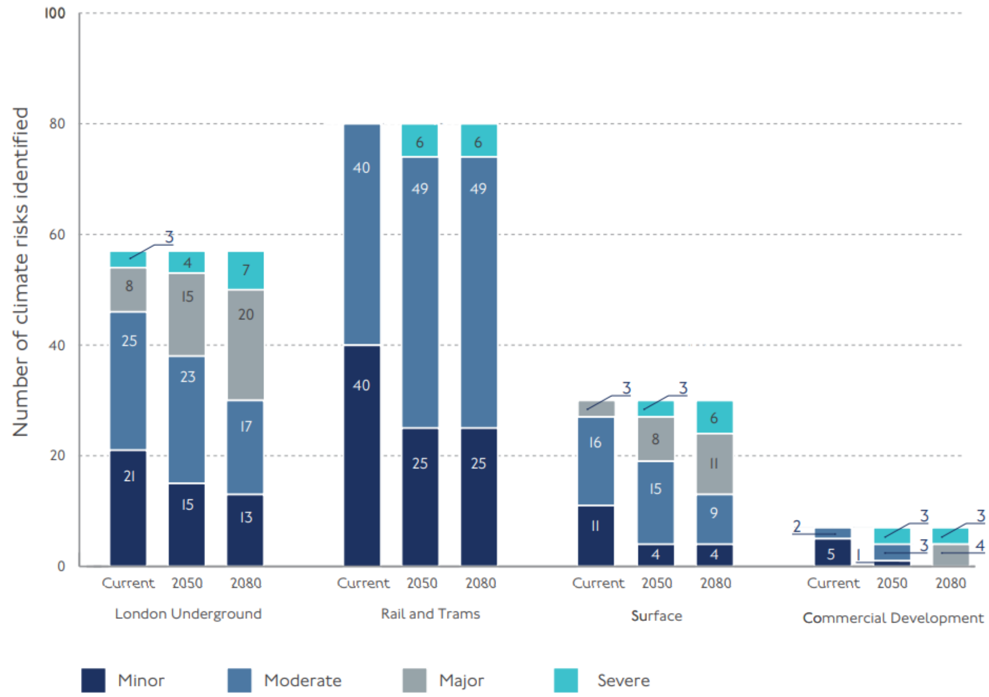



***Figure 3***: *Change in Severity of Climate Risk Over Time by Business Area*[22]

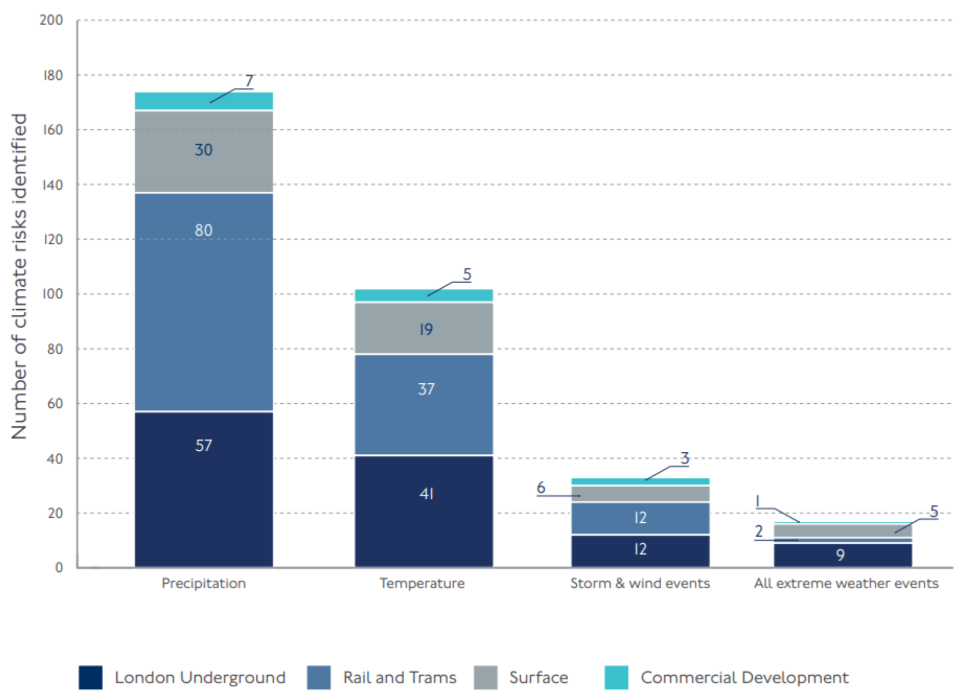


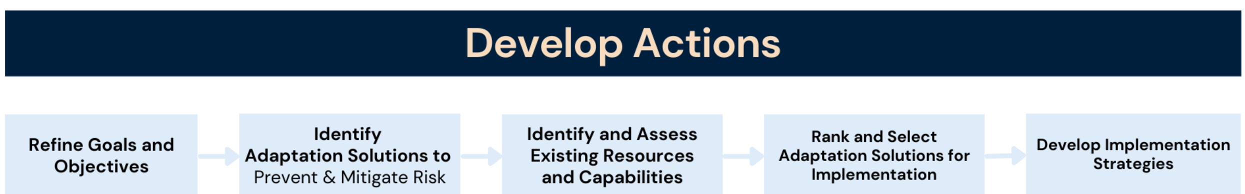

***Figure 4***: *Climate Risks by Business Area*[23]

[22]Transport for London.
[23]Ibid.

Conducting a more granular level risk assessment for these business areas (Rail, Tram and LU) and hazards (precipitation) would be helpful. A granular level risk assessment would entail analysis of just precipitation as a hazard and evaluation of how vulnerable each asset area within LU is to flooding.

## *Step 4: Develop Actions*

The next step would be to develop actions to address risk and enhance infrastructure adaptation by identifying and prioritizing potential solutions. Before identifying specific solutions to invest in, it is helpful for transportation entities to **revisit their overarching vision and refine any previous goals and objectives.**




Adaptation solutions can be policies, strategies, plans, codes and ordinances, programs to increase adaptation, and/or actual infrastructure projects that replace assets or add new components. Cities need two types of adaptation solutions:

1) <u>Systemic-resilience solutions</u>: Actions that increase the adaptive capacity of a city, regardless of the hazard exposure(s) the city might face.[24] [25]
2) <u>Hazard-specific solutions</u>: Actions that reduce the impact of a specific hazard or enhance a city's ability to recover from that hazard[26]

When developing actions, cities can identify the level of ambition, or the tolerable risk level, for each of the climate risks analyzed in the assessment.

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[24]*Adaptive capacity* is the potential or ability of a system, region, or community to adapt to the effects or impacts of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes.
[25]"IPCC - Intergovernmental Panel on Climate Change," https://archive.ipcc.ch/ipccreports/tar/wg2/index.php?idp=643.
[26]Focused adaptation, 2021 report, c40 and mckinsey sustainability, <u>Microsoft Word - C40-McKinsey Press Release_DRAFT_7.14.21 (1).docx</u>

Some solutions more relevant to transportation entities include:

- ➔ Update codes and standards: Based on the hazards, and vulnerabilities identified in the risk assessment process, entities can update relevant internal or external (contractual) codes and standards to mitigate the greatest risks.
- ➔ Invest in Information Management Systems: Entities can update their internal systems to better track costs of extreme weather events and vulnerability of assets to identified hazards.
- ➔ Invest in robust infrastructure: Entities can use the data and insights generated through the risk assessment process to identify measures that will reduce the vulnerability of key infrastructure to threats and hazards.
- ➔ Update infrastructure maintenance and capital improvement programs: Entities can use the list of prioritized assets and list of associated dependencies to inform maintenance, renewal and replacement priorities for service providers.
- ➔ Develop continuity and contingency plans: Critical infrastructure owners and operators can use information about dependencies to create resourceful, reflective, and flexible plans that help maintain services to critical infrastructure during emergency situations.

**TfL's Existing Steps & Opportunities**

Throughout its 2023 Climate Adaptation Strategy, TfL has already developed a series of goals and objectives that largely work towards system-wide resilience. Goals and objectives that are most relevant for flood vulnerability for the London Underground are shown below.

*Table 2: TfL's Current Flood Adaptation Goals and Key Results*

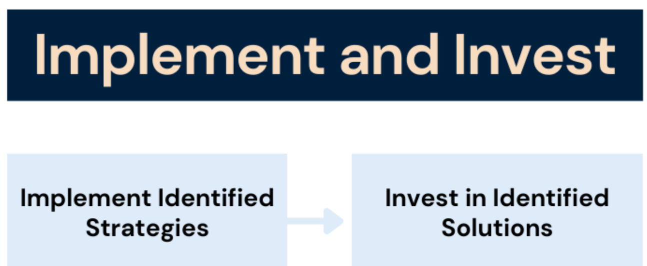
| Category of Change | Flood Adaptation Goals for LU | Measurable Key Result (KR) | Time-Frame |
|---|---|---|---|
| **Leadership and Governance** | Update the SHE management system to include climate risk and adaptation more comprehensively | KR: Completed upgrade within identified time-frame | Short-Term |
| **Leadership and** | Create a budget specifically for | KR: Presence of | Short-Term |

| | | | |
|---|---|---|---|
| **Governance** | adaptation measures, e.g. SuDS installation | budget will allow for dedicated funding for adaptation | |
| **Leadership and Governance** | Integrate adaptation into business planning and create a programme to continually review processes | KR: Growth of business cases made for adaptation investment | Medium-Term |
| **Risk Management** | Develop the ERM framework to fully include climate risk and adaptation measures | KR: Presence of new framework | Short-Term |
| **Risk Management** | Obtain and continually improve the data required for risk modeling, for example through amending existing asset condition reporting and performance reporting systems | KR: Utilization rate of updated asset condition reporting or performance reporting systems | Long-Term |
| **Information Management** | Review information gathered in TfL's performance reporting systems to determine if it is sufficient for adaptation decision-making | KR: Completed quarterly review of performance reporting systems | Short-Term |
| **Information Management** | Develop a process to ensure that TfL embeds the use of research findings to make the most cost effective business decisions | KR: Growth of business cases utilizing research | Short-Term |
| **Capital and operational delivery** | Develop high-level principles for trackside green infrastructure management in collaboration with the Rail Safety and Standards Board (RSSB) and other rail sector stakeholders | KR: Reduced Flooding in tracks by a certain percentage | Short-Term |
| **Capital and operational delivery** | Ensuring climate risk and climate projection scenarios are included across procurement processes and in contract clauses and works information | KR: New policies including risk projections and scenarios in these processes | Medium-Term |

Some of the opportunities in TfL's actions laid out include:

- Internally identify specific action tailored for **most frequently predicted hazards** and specific assets in each business area
- Internally identify specific **teams responsible** for said actions
- Internally **create and track key results** of each action
- For updating procurement and contracts, **identify and require what criteria triggers a work order for replacement or repair** and triggers a new or larger contract for replacement or repair

## *Step 5: Implement and Invest*




Transportation entities can implement the identified adaptation solutions through a variety of funding sources, including traditional mechanisms like taxes, fees, and bonds as well as grants from federal and state government agencies or philanthropic organizations. Public-private partnerships could also be considered to develop innovative financing mechanisms to help distribute risk across parties.

In order to implement various solutions, a responsible party (specific agency or team) should be identified. Collaborators, partner agencies or private sectors can also be identified to assist in the implementation of the solution. These two partners can work together to provide input on the steps for implementation as well as in establishing a timeframe for each solution and potential barriers to implementation, whether regulatory, monetary or political.

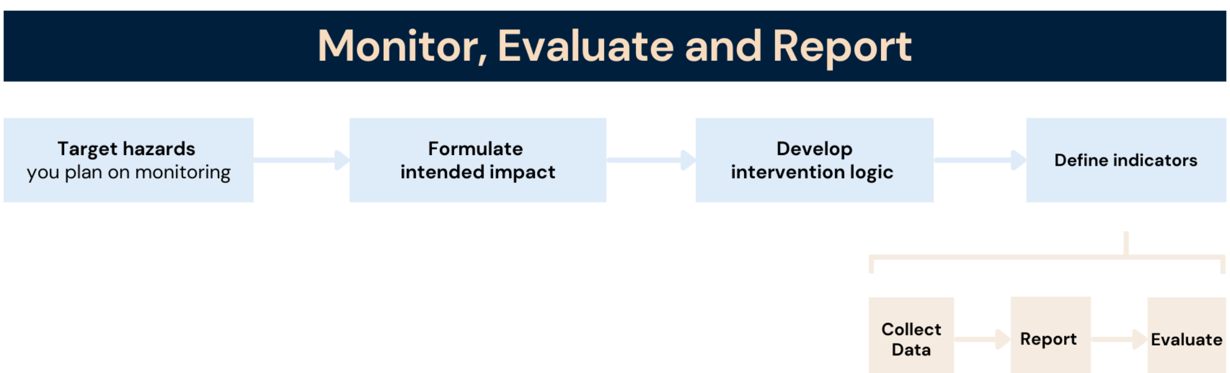
**Steps Taken by TfL & Opportunities**

TfL has identified types of funding sources that could be leveraged for adaptation. These sources include:

- ➔ Passenger fares income: historically this has been the largest single source of TfL's income, but was significantly impacted by the pandemic in 2020/21 and 2021/22
- ➔ Other income: including commercial activity and income from the Congestion Charge
- ➔ Grant income: including funding grant from the Department for Transport (DfT)
- ➔ Prudential borrowing (the amount and profile of which has been agreed with the DfT) and cash reserves

Opportunities include setting aside a budget specifically for adaptation, which can be developed once information management systems are updating and business planning processes incorporate risk and cost estimates of adaptation.

## *Step 6: Monitor, Evaluate and Report (MER)*[27]




In order to ensure accountability, transparency, and improvement in the adaptation initiatives set out in cities' adaptation plans, practitioners and experts recommend that a monitor, evaluate and report phase should be conducted. MER can also help cities or specifically transportation entities make the case for future adaptation actions by helping communicate the results and demonstrating the tangible benefits of adaptation.

Some of the challenges of MER are that climate hazards can be unpredictable and there is an inherent incompatibility between the long-term nature of climate change and the far shorter time-span of project management cycles. In a similar vein, adaptation actions can be costly and more structural actions may take time to deliver a return. Additionally,

[27] C40, "Climate Action Planning Guide: Identifying Adaptation Strategies."

adaptation actions are diverse and may be implemented by various teams, which makes city-wide monitoring of changes in risk difficult. Lastly, unlike mitigation and greenhouse gas reduction, adaptation cannot be measured by a single metric. For example,

The first sub-phase within the MER is monitoring – a continuous practice that uses the systematic collection of data on specific indicators to provide management of an ongoing intervention. The steps within the monitoring include the following:

➔ Target the hazards you plan on addressing and monitoring.
➔ Formulate intended impact: Risk reduction to the city's assets, people and environment from climate hazards achieved by the adaptation actions. Risk reduction entails reducing exposure, vulnerability and increasing a city's adaptive capacity.
➔ Develop an intervention logic: Tie specific actions to their immediate output, outcome and final impact. The output is tangible improvement from the initial situation or baseline. The outcome is the change that the output generates. The impact is any medium or long-term effect of the outcome. Impacts can be categorized as society (people), economy (assets) or environment (nature).[28]
➔ Identify indicators to measure the outputs, outcomes and impact: The outcome indicator should be relative to the hazard (i.e. the percentage of rainfall that leads to unacceptable flooding) and the impact indicator should also (i.e. number of assets damaged, cost of asset damage)[29]. Cities or transportation entities can set realistic and aspirational targets for each indicator to keep goals on track.
➔ Data collection: Critical to a data collection plan is a description of each indicator that is being measured, the baseline and target, data sources and methods to collect that data. A plan should also specify who will be collecting data, how frequently and to whom it will be reported.

The next phase of MER is **reporting** in order to present data and insights publicly and internally increase visibility over time. The following phase in MER is to **evaluate** by assessing the causality between adaptation actions and the observed effects. Ideally, evaluation helps create recommendations that improve the design, more efficiency

[28]United Nations, "2005 World Summit Outcome | Resolution 60/1 | UN Peacemaker", https://peacemaker.un.org/node/95#.
[29] Indicators should be: Clear (precise and unambiguous); Relevant (appropriate to the subject at hand); Economic (available at reasonable cost); Accepted (Accepted as a relevant measure by stakeholders); and Monitorable (Amenable to independent validation).

allocates resources and implementation of actions, policies and processes. Since climate-related events are unpredictable, evaluation should be conducted by monitoring hazard events and comparing their intensity with similar events previously. However, in order to understand the benefits of adaptation actions in the absence of a hazard, modeling could be used to predict different adaptation scenarios and potential impacts for various hazard scenarios. The value of this type of modeling is demonstrated in Section Y.

**TfL's Existing Steps & Limitations**

TfL has not publicly created a MER plan yet. It could be useful to hone in on one hazard (precipitation and flooding), and one business area (LU) and develop a preliminary MER framework (in addition to the adaptation planning steps) to identify which internal and external challenges TfL experiences when doing so. This could then assist building out MER for other hazards and other business areas.

Our team has developed a sample matrix to track actions, outputs, outcomes and impacts. Other matrices that can support TfL with its MER plan are shown below, including a data collection table and intervention logic table.

*Table 3: Sample Indicator Matrix*

| Action | Output | Output Indicator | Outcome | Outcome Indicator | Impact | Impact Indicator |
|---|---|---|---|---|---|---|
| Installing floodgates | Floodgates installed | # of floodgates installed | Reduced flooding from heavy rainfall | % of heavy rainfall leading to flooding | Reduced exposure to flooding | People: injured<br>Assets: # of assets damaged, cost of repairs or replacement |
| Installing Sustainable Underground Drainage Systems | SUDS installed | # of stations with SUDS installed | Reduced flooding from heavy rainfall | % of heavy rainfall leading to flooding | Reduced exposure to flooding | Same as above |

| | | | | | | |
|---|---|---|---|---|---|---|
| (SUDS)[30] | | | | | | |
| Adapting assets (hardening, elevating) | Assets at risk retrofitted | Number of assets retrofitted | Protection of assets from flooding | % of assets protected from floods | Reduced vulnerability to flooding | Same as above |

*Table 4: Sample Data Collection Matrix*

| | Indictor | Baseline | Target | Data Source | Collection Method | Who will collect | Time period | Cost | Who will analyze | Target use |
|---|---|---|---|---|---|---|---|---|---|---|
| Output | # of tracks damaged | 3 in 2017 | 3 per year | - | - | - | - | - | - | - |
| Outcome | % of tracks recovered | 10% | 40% | - | - | - | - | - | - | - |

*Table 5: Deconstructing Intervention Logic*

| Hazard | Sample Action | Output | Outcome | Impacts |
|---|---|---|---|---|
| Rainfall | Convert recreational and open spaces to water squares | Additional water retention area | Reduction of floods due to rainfall | Reduced exposure to flooding |
| Storm surge / Sea level rise | Installing flood gates | Flood gates installed | Reduced storm surge flooding | Reduced exposure to flooding |

[30] Sustainable urban drainage systems aim to mimic 'natural' drainage by adopting techniques to deal with surface water runoff locally, through collection, storage, and cleaning before allowing it to be released slowly back into the environment.

## Summary | TfL's Adaptation Planning & Our Framework

TfL has successfully implemented many elements of our Adaptation Planning Framework, including laying a foundation for adaptation planning, conducting an in-depth risk assessment and developing goals and outcomes. Understanding the bigger picture adaptation planning process is valuable for TfL to continuously tie its strategies and actions to its larger vision. In the coming sections, our analysis will hone in on information management and risk management specifically, as tools that can generate TfL's adaptive capacity and ability to respond to precipitation and flooding in the London Underground.

*Table 6: Adaptation Planning Matrix*

| | Laying the Foundation | Critical Infrastructure Identification | Risk Assessment | Develop Actions | Implement + Invest | MER |
|---|---|---|---|---|---|---|
| **Level of Completion** | ✔ | ✖ | ✔ | ✔/✖ | ✖ | ✖ |
| **TfL steps taken** | Developed Climate Adaptation Plan; established and chair the quarterly Transport Adaptation Steering Group | Conducted interdependency analysis | Has conducted an in-depth risk assessment fully | Has identified actions as goals | No investments beyond replacing / repairing damaged assets | - |
| **Gaps** | Lack of in-depth data collection strategy (who, what, when, etc) | Has not identified key infrastructure or prioritized assets by safety, operational, societal, economic or service impacts | Has not evaluated risk experienced by each asset within London Underground | Has not identified actions for specific hazards or specific assets.<br><br>Has not identified specific teams responsible for actions in plan. | Funding strategy not created | No MER plan created |
| **Opportunities** | Develop a system-wide data collection strategy as it relates to the 2023 Climate Adaptation Plan | Based on risk assessment, prioritize assets that are most vulnerable to risk based on impact (Conduct this for flooding as a hazard specifically) | Analyze just precipitation as a hazards and evaluating how vulnerable each asset within LU is to that hazard.Conduct this for flooding as a hazard specifically | Internally create key results for each of the actions that are hazard and assets-specific. | Identify funding sources for both system-wide resilience strategies and hazard-specific resilience investment | Develop a MER plan for one hazard / one set of assets (LU) to develop a precedent that can be used for other hazards and assets in different business areas |

# IV. EXISTING CASE STUDIES: INFRASTRUCTURE CLIMATE ADAPTATION INVESTMENT

## Flood Control Devices - New York City Transit[31]

In October 2012, Hurricane Sandy hit the East Coast of the United States, causing widespread devastation in its wake. Flooding from Sandy especially damaged assets of the New York City subway system, submerging several stations in Manhattan and seven of eight East River tubes in up to 14 feet in water.

The severity of flooding was unprecedented and caused significant damage and required full shutdowns and overhauls of the East River tubes over the course of 8 years. Losses were estimated at $5 billion, and the Federal Transit Administration provided $5.8 billion in grants for repairs and resiliency projects. Overall, New York City Transit spent $350 million on 3,500+ flood control devices that have to be manually deployed ahead of a storm.

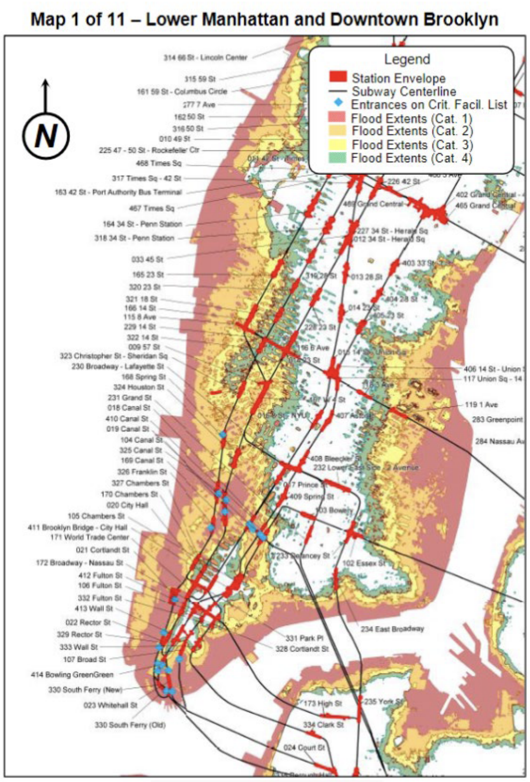



***Figure 5**: Sea, lake, and overland surge map showing station envelopes and flood zones.*

[31]Elizabeth Keating, "Hurricane Preparedness: NYC Transit Can Improve Oversight Of Flood Control Devices – Final Report," 2022. https://mtaig.state.ny.us/Reports/2022-04.pdf

New York City Transit (NYCT) took on several actions to restore the system and make it resilient to future storms; it implemented a series of flood prevention measures to mitigate water intrusions in yard portals, sidewalk vents, and manholes, including deploying inflatable plugs and constructing floodgates to seal off subway entrances and street-level ventilation gates. The agency also installed steel doors and raised entrances to subway stations in flood-prone areas to prevent water ingress.

These were the steps taken by NYCT to mitigate flooding from storm surges after Hurricane Sandy:

1. Initiated a program to identify assets under NYCT's purview that were vulnerable to flooding
2. Proactively designed, procured and installed hardening measures to protect those areas
3. Established response protocols in order to activate or deploy hardening measures in advance of forecasted storms


***Figure 6****: "Marine door" deployment measure in activated mode at a NYC subway station*

## *Lessons Learned by NYC Transit*

The Office of the Inspector General of the Metropolitan Transportation Authority (MTA), NYC Transit's parent agency, conducted a review of NYCT's flood control program measures in October 2022. While deployable solutions are flexible and adaptive, NYCT's operations run into the challenges of deployment response, asset management, and maintenance.

1. NYCT should improve asset data management and procedures in order to support the maintenance and deployment of flood protection devices

2. NYCT should improve training provided to employees and contractors who are deploying and removing devices
3. NYCT needs to establish efficient deployment routes and timelines to improve extreme weather planning

## *Applicability to TfL*

London and New York City have differing priorities for flood control; our analysis is focusing on long-term adaptation due to sudden rainfall, while NYC's efforts so far are for forecasted storms, although the NYC subway also faces issues of sudden rainfalls causing underground flooding disrupting operations.

That said, TfL and the Underground can still reference NYC Transit's approach in identifying vulnerabilities and using a combination of active and passive hardening measures to fortify the system from flooding under a rapid timeline.

1. **Identify assets** that are prone to flooding in vulnerable areas (see *Addressing Vulnerabilities* section in Appendix I)
2. Determine whether **passive hardening measures** or **active deployable solutions** are appropriate
3. **Establish response protocol** for predictable storms - how will the LU's staff deploy protection measures?

| **Active Hardening Measures** | |
|---|---|
| *Advantages* | *Disadvantages* |
| Requires minimal adaptation of existing infrastructure | Requires advanced knowledge of potential flooding |
| Faster and cheaper to design and implement vs. passive hardening measures | Require personnel to deploy and remove equipment |

## Flood Cost Modeling – Boston T[32]

As a coastal city replete with rivers, ponds, and marshland, the city of Boston is no stranger to flooding, and the Massachusetts Bay Transportation Authority (MBTA) has been working to fortify the Boston's subway system (the "T") from flood risks from both sea level rise and inundated rivers and marshes. Climate change will not only cause sea level rise, but will also exacerbate Boston's exposure to tropical storms and the resulting storm surge. Underground rail systems are among the most vulnerable infrastructure systems to flood damage, and Boston will need to invest heavily in adaptation measures to keep the lines nearest the coast operational and usable.

Understanding the future potential flooding and associated costs for the T is the first step in taking appropriate adaptive measures, and Martello et. al. at Massachusetts Institute of Technology offer a thorough methodology to model asset damages resulting from future flooding. In order to inform the total cost estimates of water ingress into the transit network, the MIT team:

1. **Analyzed and modeled flood and sea level rise vulnerabilities** throughout the network
2. Obtained **unit replacement costs of assets** within the system
3. Estimated via a survey of experts how flood depth would correspond to the damage to assets (known as **depth-damage curves**)[33]
4. **Modeled system-wide and line-specific cost distributions** as a result of various flooding scenarios

This framework was then used to **estimate total discounted future cost** due to flood damages under different sea-level rise scenarios (e.g. +.07 meters in sea level from 2000 baseline, +.43 m, .749 m, etc.) and storm scenarios (e.g. 1 in 10 year storm event, 1 in 50 year storm event, etc.). This analysis was generally conducted via a probabilistic approach, using estimated distributions for uncertain variables and Monte Carlo simulation to arrive at a numeric result.

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[32] Michael V. Martello, "Climate Change Adaptation Planning and Decision Making for Transit Infrastructure.," *Doctoral Thesis, Massachusetts Institute of Technology*, 2023.
[33] Michael V. Martello, Andrew J. Whittle, and Hannah R. Lyons-Galante, "Depth-Damage Curves for Rail Rapid Transit Infrastructure," *Journal of Flood Risk Management* 16, no. 1 (2023): e12856, https://doi.org/10.1111/jfr3.12856.

In order to understand flood risk throughout the system, Martello et. al. build a hydraulic model of the MBTA system, treating tracks as a network of pipes with various ingress points. The diameters and gradients of the “pipes” were assembled via track geometries, and the ingress points (stations, service entrances, etc.) were assembled via a manual survey and categorized based on shape and size. With this information and a set of assumptions about the hydraulic behavior of tunnels and ingress points, a full hydraulic model can be assembled of the system. This allows for a **time-dependent calculation of flood depth** at each point in the system as a function of flood depth at the ingress points. The mathematical details of the cost calculation (as a function of flood depth) won’t be covered in this section, as we offer an in-depth example in the next section that applies to TfL.

# V. FLOOD COST MODELING FOR TfL

One attractive feature of the flood cost modeling method that Martello et. al. employ is that it translates generally well to other use cases, both underground rail as well as in other infrastructure systems that could suffer from flooding. The authors of this analysis for the MBTA specifically note this benefit, and encourage its application in other settings. In order to implement this analysis, the only requirements are the following:

1. **Hydraulic model of the system** in question that correlates surface flooding with system intake and flood depths;
2. **Replacement cost of assets** within the system; and
3. **A future flood risk model**. Assumptions must be adjusted for new settings.

## *Model Inputs*

| **Hydraulic model of the London Underground:** | | |
|---|---|---|
| An underground rail system can essentially be modeled as a network of pipes, given the geometry of the pipes (diameter, direction, length, and depth at each point), interconnection nodes (stations or intersections), portals into the system (station entrances, tunnel openings, etc.), and a set of assumptions. This allows a time-dependent flood model of the system to be built that correlates surface flooding depth at different portals with system flow and flooding. In the case of the LU, the only portion of the inputs that needs to be newly-generated is an audit of portals into the system before the model can be constructed. | | |
| **Inputs:** | **Source:** | **Status:** |
| Track geometry | TfL | Available |
| Portal audit | TfL | Needs to be conducted |

| Replacement cost of assets within the London Underground: | | |
|---|---|---|
| Assets can be separated into two sub-categories: linear assets (those which exist along a tunnel at regular intervals, i.e: track, signals, electrical), and point assets (those which exist at nodes in the system, i.e: stations). Linear assets are then expressed on a per-unit-length basis. Tunnels (with linear assets), and nodes (stations and other point assets) are analyzed separately in regards to their depth-damage function. For a complete analysis, a complete list of vulnerable assets along with replacement costs must be known for each section (tunnel or node) of the network. | | |
| **Inputs:** | **Source:** | **Status:** |
| List and location of assets | TfL | Available |
| Asset replacement costs | TfL | Available |

| Future Flood Risk Model: | | |
|---|---|---|
| This portion of the analysis may be the most regionally dependent in terms of methodology, as different regions experience flood risk due to climate change in various ways and due to various driving factors. Whereas Boston's flood risk is primarily due to sea-level rise and storm surge, London's risk comes via heavy rainfall and groundwater seepage. TfL is already using climate change projections from the Met Office, but rainfall projections still need to be converted into surface flood projections. | | |
| **Inputs:** | **Source:** | **Status:** |
| Climate / rainfall projections for the London area | Met Office | Available |
| Flood risk model | Research partners | Needs to be conducted |

## *Assumptions*

In addition to assembling model inputs, some assumptions must be adjusted for this methodology to apply to the London Underground.

**Salinity of flood water**

Water salinity greatly impacts the depth-damage functions for various assets. Tunnel inundation from storm surge of coastal saltwater will be considerably more damaging than freshwater flooding due to rainfall or ground-water seepage. Previous studies have attempted, through surveys of experts, to determine the relative damage caused via freshwater flooding as opposed to salt water. On average, survey responses indicated that freshwater would cause less than a third (31%) of the damage caused by a saltwater flood. However, high variance in estimated values and lack of consensus among experts prevents high confidence in this scaling factor[34].

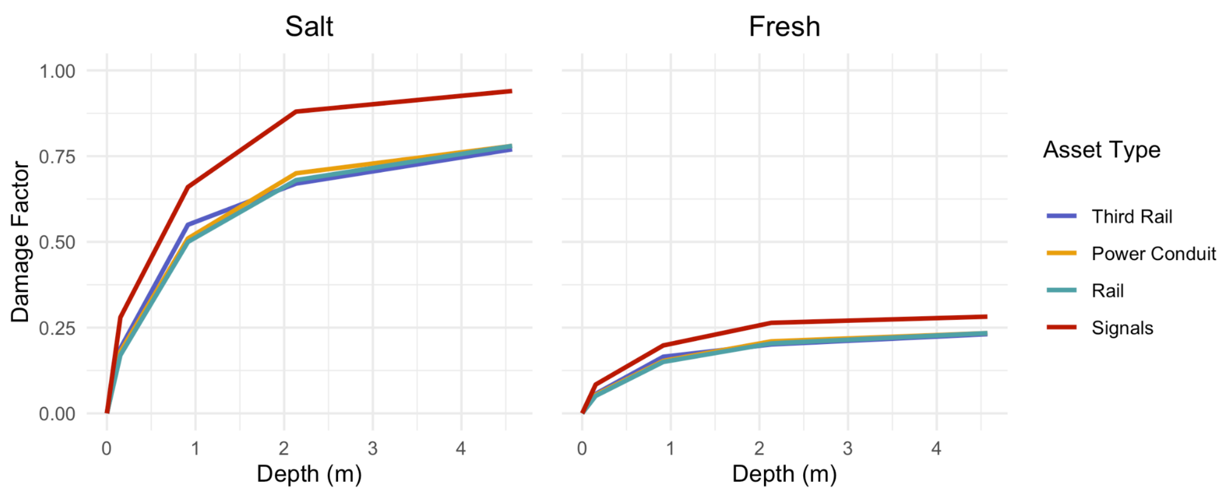



***Figure 7:*** *Estimated depth damage curves for saltwater and freshwater, assembled by Martelo et. al. via surveys of experts. Fresh water depth-damage factors are estimated at 30% of respective saltwater depth-damage factors.*

**Uniformity of flooding**

Unlike in the case of sea level rise, London's flood risk is driven by highly-localized storm events. These rainfalls tend to be highly localized and unpredictable, which presents a tricky puzzle in determining aggregate future flood risk across the entire London Underground system. TfL should work in partnership with Thames Water to understand

[34] Martello, Whittle, and Lyons-Galante.

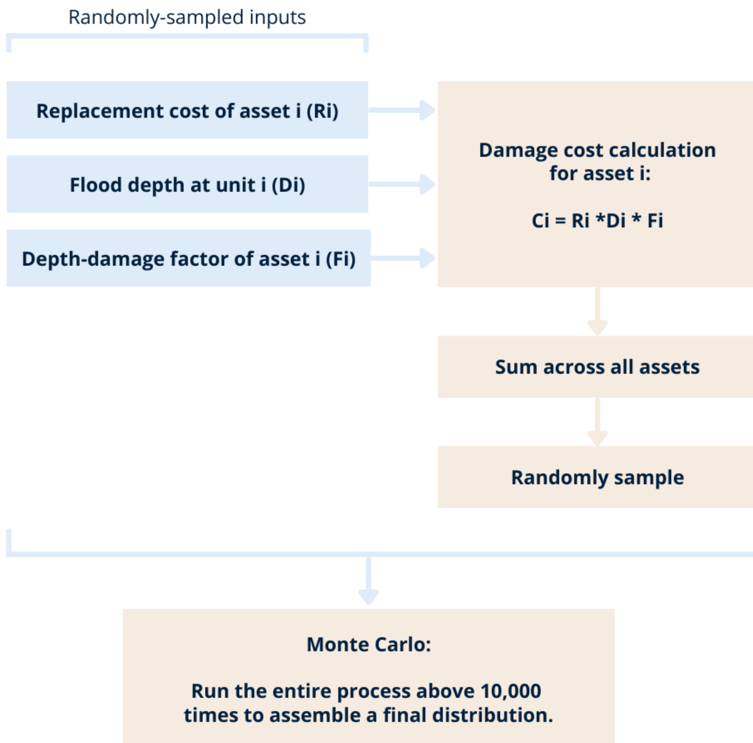
and build a model of average surface flood risk as it relates to portals into the LU system. This model, in concert with Met Office projections for rainfall events as a result of climate change, should allow TfL to arrive at what matters for business planning: an aggregate model of all future financial risk due to flooding discounted to the present.

## Asset-Based Flood Cost Model Example

As an exercise to explore how this methodology translates to the context in the London Underground, we will go through the process of **calculating a flood damage damage probability distribution for one portion of the London Underground system**. For the purposes of this toy analysis, we choose the section of the Metropolitan Line from Baker St. to Great Portland St, as this was among the more heavily-flooded lengths of track during the 12th of July Flooding, according to the Pan-TfL Flooding Review[35]. This toy analysis will not be precise, as it relies on imprecise (though not unreasonable assumptions) – rather, the purpose is to display a simple example of the modeling process that can be refined and extrapolated.

[35] Transport for London, “Pan TfL Flooding Review July 2021 V6.”

*Modeling Process:*




**Replacement costs of linear assets:**
In the case of their MBTA flood cost modeling, Martello et. al. price assets by reverse-engineering publicly-available bids on replacement or installation projects within the Boston subway system, converting all costs to 2023 dollars. We were unable to extract similar asset replacement cost information for TfL via public documents, so we used the asset replacement costs from the MBTA under the assumption that they are fairly similar to replacement costs for assets in the London Underground. The linear asset costs are as follows:

*Table 7: Estimated replacement costs and standard deviations of linear assets within the MBTA*

| Transit Asset | Replacement Cost (£M/km) | Standard Deviation (£M/km) |
|---|---|---|
| Heavy Rail Track | 9.5 | 2.5 |
| Light Rail Track | 3.4 | 0.9 |
| Heavy Rail Signal | 4.9 | 1.3 |

| | | |
|---|---|---|
| Light Rail Signal | 3.3 | 0.9 |
| Light Rail Catenary | 7.7 | 2.0 |
| Duct Bank | 5.0 | 1.3 |
| Tunnel Lighting | 2.2 | 0.6 |
| Tunnel Structure | 138.4 | 36.7 |

Four linear assets were included in this analysis: heavy rail, third rail, signals, and duct bank. Adjusted sets of assets can be used in future analyses.

**Depth-damage factors**

The depth-damage factor is the estimate of the portion of the asset's replacement cost incurred via flood damage, and corresponds directly with flood depth. Depth-damage factors are sampled directly from the fresh water depth-damage curves shown in figure 7. These curves are built around estimated depth-damage factors at flood depths of 0.5 feet (0.15 meters), 3 feet (0.91 meters), 7 feet (2.13 meters), and 15 feet (4.57). For depths other than these values, the damage factor is taken as a linear interpolation of the depth damage factors for depths immediately above and below that damage factor (in other words, taking a point from one of the lines shown in the chart in figure 7).

**Asset damage cost calculation**

The overall damage cost of the system is calculated as follows:

$$\sum_{i=1}^{N} R_i f_{dd_i}(d_i)$$

Where $R_i$ is the sampled replacement cost of assets at unit $i$ (a segment of a tunnel or a station at which a flood depth is calculated according to the hydraulic model), and $f(di)$ is the sampled depth-damage curve at unit $i$.

For this example analysis, we will calculate this value for a single $i$: the segment of the Met Line described earlier. We assume constant flood depth along this line (a hydraulic model may result in varying flood depths along a distance of track, in which case it would be split into units representing subsegments of that track, each with constant depth). Given the replacement costs of assets described above, the track length between Baker St and Great

Portland St stations (0.92 km), and depth-damage curves for the four linear assets in question, we can calculate a single sample cost value for the damage at a given depth di as follows:

1. Estimate a replacement cost for each asset by sampling from a normal distribution $N(1.45C_{est}, 0.38C_{est})$, where $C_{est}$ is the point estimate replacement cost of the asset (see table 6). This uncertainty behavior is drawn from real-world variability in rail projects (Martelo et. al.).

2. Estimate the depth-damage factor for each asset by taking the expected depth-damage factor from the depth-damage curve, and sampling from a beta distribution $f_{dd}(d) \sim beta(\alpha, \beta)$, where:

$$\alpha = (1/k - 1) f^*_{dd}(d)$$

$$\beta = (1/k - 1)(1 - f^*_{dd}(d))$$

   $k$ is an uncertainty parameter, and is set to 0.4, and $f^*_{dd}(d)$ is the expected depth-damage factor.

3. Calculate a single sample cost for each asset-type by multiplying the sampled factors above, and sum cost across all assets.

**Cost distribution via Monte Carlo sampling**

A final damage cost likelihood distribution is assembled via a Monte Carlo simulation. We calculate 10,000 sample costs according to the process described above, generating a set of unique estimates. To approximate this distribution, we generate a beta distribution based on the minimum, maximum, mean, and standard deviation of the sample set generated via monte-carlo. In a model with more than one analysis unit, the monte carlo simulation would be performed for the entire system.

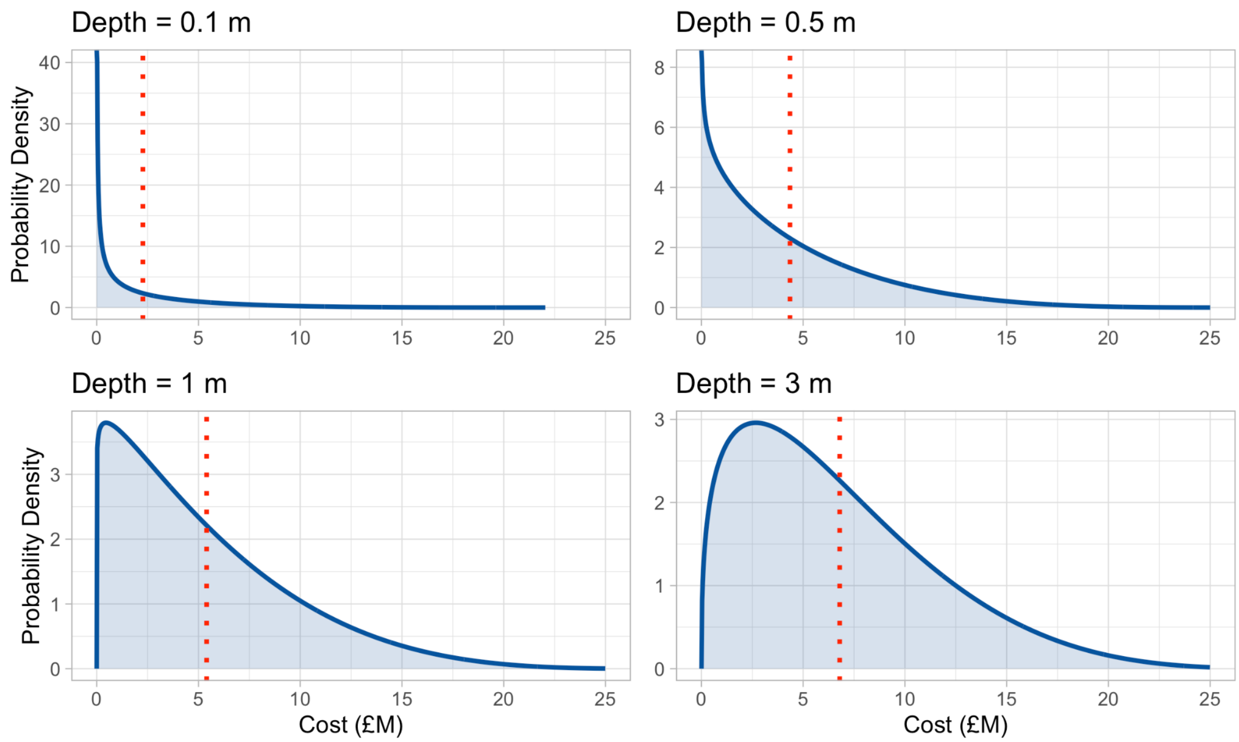



***Figure 8:*** *expected losses in asset damage under flood depths of 0.1, 0.5, 1, and 3 meters for the Met Line segment from Baker St to Great Portland St, given the noted assumptions regarding asset replacement costs, asset types, depth-damage curves, and variable uncertainties and distributions. Expected values are shown by the red line.*

**Calculating expected annual costs**

There is a large amount of uncertainty in the damage cost estimation of a single unit of the system for a single flood. However, this model isn't designed for cost accounting a single event – rather, it is designed to **generate probabilistic risk estimation over a long series of years**. Estimating costs over a large number of years, each with a flood exceedance probability (FEP), allows us to understand total expected costs across the system as a function of climate-change-exacerbated flooding. A major benefit of having a systematic model is that we can not only calculate this expected cost, but understand how we can mitigate that cost via controllable inputs. For example, one could test which portal into the system has the greatest impact on the total incurred costs, allowing for the prioritization of adaptation measures with the greatest expected benefits.

Given system flood risk projections, annualized expected losses can be calculated as the discounted expected costs due to flooding over a series of years. This can be done through a similar Monte Carlo process, sampling from a distribution of possible flooding scenarios for each year to calculate resultant costs. As stated above, this lifetime flood cost analysis is the real strength of this methodology. With this information available, TfL is able to much more effectively optimize its investment in adaptation strategies.

## Comprehensive Flood Cost Model Proposal

Transit systems like the MBTA that face coastal flooding from storm surge face much more asset-based damage due to flooding as a result of climate change than the London Underground. Firstly, they face saltwater flooding, which can be much more detrimental to assets (particularly electrical) than fresh water flooding. Secondly, storm surge from tropical storms can generate monumental amounts of water with the potential to completely inundate underground rail tunnels with enough sea level rise. The adaptation decisions that transit agencies operating systems facing coastal flooding will be dominated by the question of asset damages. TfL, however, will face a much more complicated set of costs due to climate change – it is not immediately obvious whether more cost will be incurred via asset damage, lost ridership, additional labor, or some other source. This is why we propose TfL approach a **comprehensive flood cost model, combining the asset-based flood cost model above with other models for separate sources of cost.**

### *Lost Customer Hours*

TflL currently uses Lost Customer Hours (LCH), a metric used to capture the direct and economic costs resulting from TfL service disruption, as its primary method of costing flood events. Costs of service disruption and lack of ridership due to flooding or extreme rainfall are captured by modeling the resultant LCH, which have a monetary value. LCH is a complex metric, using a passenger assignment model to estimate multi-order transit network effects of a service disruption, and the resulting financial and economic losses.[36]

In order to incorporate LCH into a comprehensive model that includes asset-based costs, LCH must first be modeled with respect to the same climate models that drive asset damage cost estimation. It should be possible to do this with some degree of confidence, by associating station service disruptions with rainfall and flood likelihood. Our team

[36] MarkM C. P. Massachusetts Institute of Technology Perelmuter, “Quantifying Passenger Impact of Disruptions on Metro Lines” (Thesis, Massachusetts Institute of Technology, 2020), https://dspace.mit.edu/handle/1721.1/127595.

conducted a surface-level feasibility analysis of this idea by linking a dataset of LCH due to extreme weather data with rainfall data in the london-area.

Another possible method for linking LCH and station closure is to link station closure with the extent of station damage. If experts within TfL can make some set of reasonable estimations of resulting station closure times after a flood event at various stations (along with some estimation of uncertainty), LCH could be estimated as a direct result of flood depths according to the hydraulic model discussed in the previous section.

## *Labor Costs*

Flood events generate additional labor hours for TfL employees and contractors, sometimes in large quantities. Even though employees and contractors are a short-term constant, long-term labor costs are elastic and will grow to reflect any increase in the frequency or severity of flood events. Including projected labor costs in a comprehensive flood cost model would allow TfL to account for this portion of climate-change-related costs, but is more difficult than incorporating LCH. Firstly, TfL does not currently do activity-based costing, meaning that granular data does not exist on what additional labor results from flood events. Secondly, labor costs are likely more difficult to confidently correlate with flood events than asset damage or station closure. Lastly, labor costs are, at least to some extent, contained in asset replacement cost estimates.

Upon looking at the labor contracts between TfL and some of the companies contracted for temporary workers (Matchtech group, Morson International, Rullion Engineering Personnel), it does not appear that any of the contracts detail the substance of timesheets, except for the following language: "*There is also an option to include any specific details on the timesheet and invoice, e.g. Payroll Number, Job Number, up to 4 unique pieces of information per Temporary Workers. TfL requests that the Service Provider confirms if this would be appropriate for their Company, in the above letter of acceptance.*"

These contracts do require that invoices include a series of items, including "a detailed description of the Services and/or Deliverables". If TfL is able to adjust these contracts for temporary workers and full-time workers to detail out clearer requirements in time-sheets and work-orders and subsequently adjust the internal systems for time-sheets and work-orders, it would greatly ameliorate the data gaps of costs attributed to extreme weather events.

If labor costs are to be included in TfL’s flood cost modeling, TfL will have to first address the primary issue described above: the lack of activity-based costing. Adopting activity-based costing would require a drastic shift in TfL’s labor management processes and data systems. This is a massive and difficult change – even if investment can be secured and stakeholders aligned, the change will take a long time to make. Several TfL employees have told us in meetings that improvement and modernization of the LU’s data systems has been on the wishlist for some time, but hasn’t happened yet. This is another argument for why the investment in LU’s data system might make sense, but it is not evident that flood cost modeling alone is a good argument for making what would be a considerable investment.

# VI. FINDINGS AND RECOMMENDATIONS

This section summarizes key findings on how TfL has addressed climate adaptation through information management and risk management. Our findings focus on how TfL can generate adaptive capacity to anticipate and respond to system-wide climate threats, particularly rising precipitation and flooding vulnerability in the London Underground.

These findings incorporate insights gathered from case studies from other cities as well as from documents TfL has provided, existing data available and meetings with TfL team members.[37]

## *Risk Management in the Business Planning Process*

TfL is embedding adaptation as a main criteria in business planning for maintenance, renewals and enhancements of its assets. In order to save money by avoiding excessive repairs and renewals, and help maintain service reliability and revenue generation, TfL is creating a business plan based on the outcomes in the Mayor's Transport strategy.

TfL has developed two criteria to incorporate adaptation into business planning. One has been generated to evaluate just adaptation investments, and another is focused on evaluating the necessity for asset renewals in particular. [38] For asset renewals specifically, outcomes are assessed against six Asset Management Objectives (AMOs), including: Safety, Service, Customer & Staff Capacity & Growth, **Environment** and Financial.

[37] Flooding Report, Business planning document, Climate Adaptation Plan, Adaptation Reporting Power (*Risk Assessment in Adaptation Reporting Power,* Task force for Financial Climate Disclosure
[38] See Appendix II and III.

**Gaps**

- The business planning criterion does not include a criteria for investment in preemptive maintenance
- The business planning criterion does not define Environment as an AMO.
- The business planning criterion does not incorporate the impacts of extreme weather events on assets, which would require using the following data in its criteria: data on asset vulnerability, data on asset degradation rates, or cost estimates for specific adaptation measures
- The business planning criterion does not delineate a budget associated with meeting the criterion
- The criterion does not differentiate between degradation forecasts and additional degradation due to climate change
- The criterion relies on standards and procedures for assets that are not updated to incorporate the risk and vulnerability of assets to hazards

**Recommendations**

- **Utilize data on asset exposure and vulnerability in the business planning process**, ideally via the asset-based flood cost model described in section V. This allows the benefits of adaptation measures to be better understood.
- **Outline a budget envelope for adaptation spending** that is then integrated into the asset areas' funding profiles and associated with meeting certain criteria.

## *Cost Estimation*

TfL currently only uses LCH in estimating costs due to floods and other climate-related events (only rarely able to incorporate attributable financial cost of asset damage).[39] However, this method falls short on two fronts. Firstly, LCH doesn't capture other important costs, such as asset damage or cost of labor resulting from weather events. Second, the LCH model doesn't allow TfL to understand total future costs of climate-related events such as flooding, as there is no model linking LCH to weather events in a probabilistic manner.

[39]TfL used LCH for its analysis of the flooding events of 12th and 25th July 2021 and their implications for its networks. Its analysis looked at the impacts and health and safety implications of the events and also identified some of the attributable financial costs.

## Gaps

- ➔ Lack of ability to attribute asset costs to flood events and other climate-related events
- ➔ Lack of ability to estimate total discounted future cost of flood damage incurred by the London Underground (or other transit systems). Without this information regarding the total cost of climate-change-exacerbated events, it becomes much harder to justify adaptive measures in the business planning process.
- ➔ Lack of ability to track cost impacts of adaptation measures. Since TfL currently does not employ a model that correlates system variables (e.g. water inflow rate at a station opening) with resulting costs (e.g. flood damage), it cannot model the total avoided cost of a given adaptive measure.

## Recommendations

- ➔ **Implement an asset-based flood cost model,** borrowing from the analysis that Martello et. al. conducted in partnership with the MBTA. This will require TfL to adopt a surface flood risk model and form a hydraulic model of the UG.
- ➔ **Merge LCH into the flood cost model** by either building a model time of how LCH arises from weather-related damage, or how LCH arises from weather events. This allows LCH to be incorporated into the above-described asset-based cost model

# VII. CONCLUSION

Adverse weather events like extreme rainfall and subsequent flooding are occurring more frequently in the Greater London Area, resulting in service delays and infrastructural damage to the Tube. In the short-term, a severe storm may disrupt train service and inconvenience commuters and operations staff within LU, but these are not the only impacts. Flooding, which will increase in frequency and severity with climate change, will also have long-term impacts on the Underground's assets, deteriorating tunnels, rails, concrete bench walls, cables, rolling stock, and more.

Planning for and adapting to this new reality requires both a shift in the high-level organizational vision and strategy and improved cost modeling and analysis on-the-ground to identify priorities for adaptation investments.

Throughout the Climate Adaptation Strategy published in March 2023, TfL has developed a series of goals and objectives that largely work towards system-wide resilience. To further manage business planning risk, generating activity-based costing for labor will allow TfL to attribute damages in costs to extreme weather events, which can be directly used in making business cases for targeted adaptation investments.

By looking at the efforts underway in New York City and Boston, TfL can jump-start its own efforts to make its infrastructure more resilient. Building a flood cost model for the London Underground will not only offer financial validity to adaptation investments, but will serve as a valuable precedent for TfL's analyses for other hazards and business areas. Developing this model will create space to utilize evidence in driving adaptation decision-making, which will be necessary as these extreme weather events become more frequent.

With focused and efficient business planning, cost modeling, and adaptation investments, Transport for London can lead the way in climate adaptation for modern transit infrastructure.

# VIII. APPENDICES

## Appendix I: Addressing Vulnerabilities Through Active Hardening Measures (Deployable Flood Protection Devices)

1. Categorize the types of water intrusion points into the system and quantify them.
   *Example*:

| Location | Intrusion Type | Qty | Intrusion Type | Qty |
|---|---|---|---|---|
| Station 1 | Sidewalk Vent | 3 | Manholes | 12 |
| Tunnel portal 1 | Portal | 2 | Fan Plant | 2 |

2. Identify where permanent**, passive hardening measures** can protect multiple penetration spots, such as seawalls/levees or other constructed barriers
3. Where water penetration locations *cannot* be permanently sealed or covered, **deployable (active) hardening measures** should be activated in the event of a storm.

These devices are currently in use within New York City's subway system:

| Type | Purpose | Notes | Time to Deploy | # Used in New York |
|---|---|---|---|---|
| Mechanical closure device | Covers sidewalk vents necessary for airflow into the subway system. Vulnerable to above-ground water flowing | Permanently installed, but require personnel to activate and reset after | < 1 minute per location with crew of 7 | 2230 |
| Deployable vent cover | Where MCDs cannot be used, these reusable are applied over existing grates utilizing watertight gaskets | Covers should be stored near their protection locations, but may also be in centralized warehouses.<br><br>Usually custom-made for specific grates, must be manually installed. | 28 minutes per location with crew of 6 | 680 |
| Stop logs | Modular walls reminiscent of aluminum logs. Used to seal off door frames of subway entrances and assets like elevators | Mounting plates are permanently installed, but logs must be stored nearby or in a central warehouse.<br><br>Bespoke to each location. | 50 minutes per location with crew of 11 | 50 |
| Station Entrance/Portal Flex Gate | Water resistant membrane that rolls up into the enclosure when not in use. Used to seal off subway entrance stairwells.<br><br>Portal gates are larger versions meant for doorways and garage openings. | Permanently installed at locations but must be manually set up and taken down. | 45 minutes per device | 75 |

| | | | | |
|---|---|---|---|---|
| Watertight Hatches | Steel plates that seal off openings where water penetration may bypass other protective measures. | Hatches are stored at needed locations and need to be manually deployed. Due to size and weight, supporting equipment must also be stored onsite. | 5 minutes per location with crew of 4 | 150 |
| Watertight Marine Doors | Large steel doors that are used to seal off large portals and entrances. | Permanently installed at locations and custom-made for each location. Are capable of withstanding much more water than simple membranes, and should be used where more water is anticipated. | 10 minutes per location with crew of 5 | 150 |

# Appendix II: Business Planning Criteria - General

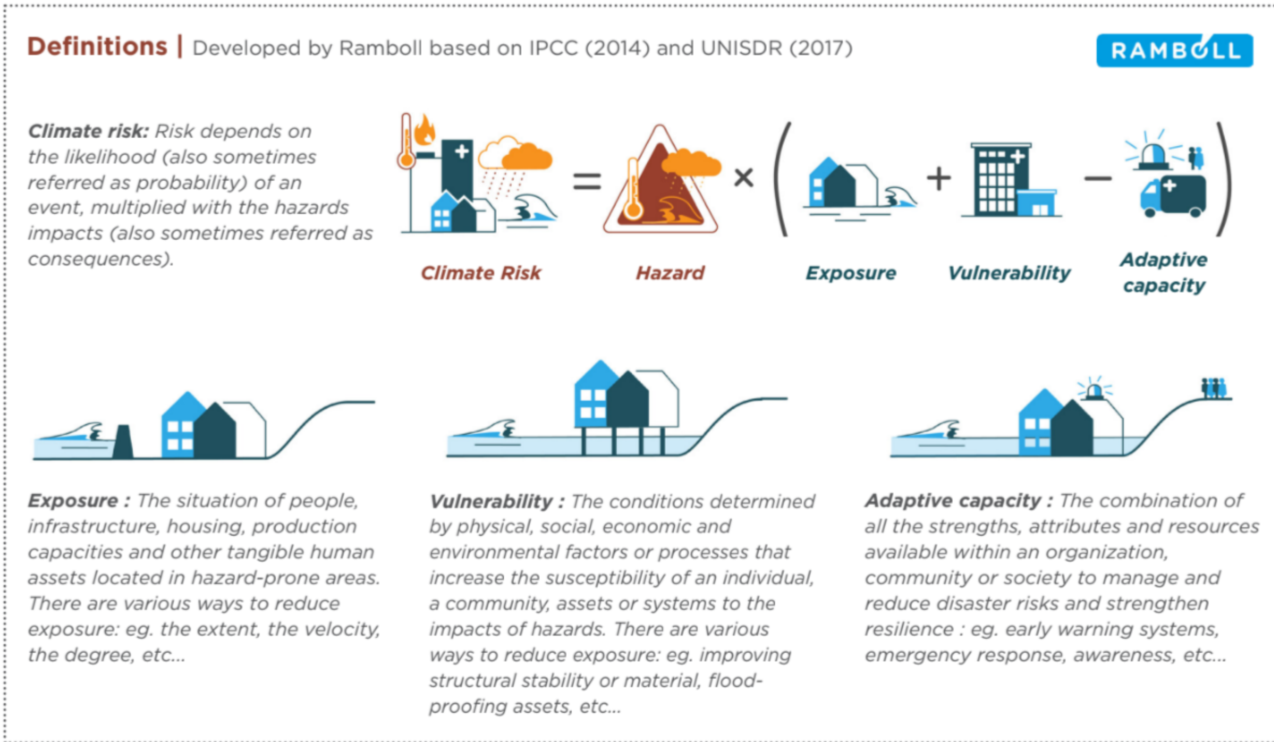
| Score | | Strategic outcome | |
|---|---|---|---|
| **Transformational Gain** | **5+** | across multiple strategic locations, minimizing impacts for 10,000+ people or more | direct, speedy, and permanent impacts |
| | **5-** | | indirect, slow to realize, temporary impacts |
| **Significant Gain** | **4+** | at a key strategic location, minimizing impacts for 1-10,000 people | direct, speedy, and permanent impacts |
| | **4-** | | indirect, slow to realize, temporary impacts |
| **Modest Gain** | **3+** | at a local level, minimizing impacts for <1,000 of people | direct, speedy, and permanent impacts |
| | **3-** | | indirect, slow to realize, temporary impacts |
| **Neutral Impact** | **2** | Insignificant change compared to doing nothing | - |
| **Decline** | **1-** | A significant detrimental impact at a local network level (<1,000 ppl) | - |
| | **1+** | A highly significant detrimental impact at a strategic network level (1,000+ people) | - |

# Appendix III: Business Planning Criterion - Asset Renewal

| Level of Service | Asset Management Objective description | Climate change adaptation qualitative scale |
|---|---|---|
| **5. Excellent** | **Industry Leading** – Assets exceed the corporate environmental targets that have been set | All climate risks mitigated to within tolerance limits; high confidence in risk assessment accuracy and comprehensiveness |
| **4. Good** | **Progressive** – Assets on track to meet the corporate environmental targets that have been set; environment embedded in decision making | All current climate risks mitigated to within tolerance limits; some risks above tolerance limits remain in longer term (2050s and beyond) assessments but plans in place to address this |

| Level of Service | Asset Management Objective description | Climate change adaptation qualitative scale |
|---|---|---|
| **3. Average** | **Baseline** – Baseline environmental performance of assets is known, and a plan is in place for improvement | Some current climate risks above tolerance limits but plans are in place to address this; some risks above tolerance limits remain in longer term (2050s and beyond) assessments with plans being developed to address this |
| **2. Poor** | **Action required** – Baseline environmental performance of assets being established, and an improvement plan are under development | Existing plans insufficient to mitigate current risks beyond tolerance thresholds to within tolerance limits |
| **1. Very Poor** | **Unacceptable** – No activity underway to understand baseline or develop an improvement plan | No mitigation actions in place for current asset climate risks beyond tolerance thresholds; known large gaps in risk assessment |

# Appendix IV: Deconstructing Climate Risk[40]




[40] C40, "Climate Action Planning Guide: Identifying Adaptation Strategies."

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