Climate change and interdependency risks for London's land based transport sector

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| Climate change and interdependency risks for London's land based transport sector |
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Glossary

| **Term** | **Definition** |
| --- | --- |
| **Adaptation** | The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. (TfL ARP3) |
| **Cascading impacts** | Cascading impacts occur when impacts in one or more parts of an interconnected system may trigger impacts in other parts of the system. For example, flooding can cause direct damages to power infrastructure which then cascades through to other sectors such as transport, increasing risk across the system. (CCRA3 Technical Team). |
| **Climate hazard** | The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. (IPCC AR5). |
| **Climate risk** | The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence. (IPCC SR1.5). |
| **Co-dependency** | Areas where the transport sector both contributes to the interdependency risk as well as being impacted. |
| **Downstream interdependency** | Transport operations are also critical for other sectors, such as health (for example, ambulances requiring road access), education (for example, travel to/from school) and employment. |
| **Emerging interdependency** | An interdependency that could not currently be realised because the infrastructure asset or pathway is not currently present (e.g. electrified fleets) but is expected to be in place within the time periods used in the climate assessment (2050s, 2080s). |
| **Interdependency** | For the purposes of this project, an interdependency is defined as an organisational interface where a climate induced risk is shared by multiple sectors, leading to increased vulnerability. |
| **Intra-dependency** | Impacts to one part of the LBTS can also cascade across the sector as London’s LBTS depends on the smooth running of each LBTS organisation. For example, rail station closures due to flooding could increase road traffic and affect bus service reliability, or flooding of network management control centres could result in major network disruption. In addition, flooding of transport networks can affect the ability of staff to reach their workplaces and so affect service reliability. |
| **Resilience** | The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation. (IPCC AR5) |
| **Upstream interdependency** | The London LBTS and its operations are also impacted by other sectors. For example; power supply, telecommunications, water supply and wastewater services. If these are vulnerable to climate change, then London LBTS operations will also be affected. London’s LBTS is also dependent on its supply chain to operate efficiently. If the supply chain is vulnerable to climate change impacts, operations will be affected. |

# Executive Summary

In accordance with the Climate Change Act 2008, TfL voluntarily reports on the actions it is taking to adapt to climate change as part of its Adaptation Reporting Power (ARP) submissions. In the third round of reporting (ARP3), organisations worked together at the sector scale to develop common approaches to risk assessment and reporting of climate risks and adaptation actions. The challenge at ARP4 is to expand the analysis to explore how climate hazards impact on interdependencies between assets and services in different infrastructure sectors (e.g. transport, water and drainage, power and telecoms).

London’s land-based transport sector (LBTS) is already being affected by severe weather events that are becoming more frequent and more intense. Climate change will increase the likelihood of climate and weather-related hazards such as; heatwaves, drought, rising sea levels, flooding (all sources), wildfires and subsidence. Climate hazards that impact upon one organisation’s assets can then lead to cascading impacts to other organisations. The congested nature of London’s infrastructure increases both the likelihood and potential magnitude of these cascading impacts. Therefore, climate interdependency risks represent a complex problem for the LBTS as these risks cascade across organisational boundaries.

This project combines system mapping with a climate risk assessment for the LBTS’ upstream interdependencies. This draws on guidance from the UK government and Defra[[1]](#footnote-2) to use a systems approach to understand, analyse, and respond to the complex problem of assessing interdependencies and climate risk. A high level of stakeholder engagement has taken place throughout the project to co-develop an understanding of interdependencies, climate hazards and risk reduction actions. The system mapping has provided the platform for the climate interdependency risk assessment which follows a standard methodology consistent with Defra’s reporting guidance and work undertaken in ARP3.

The work represents a continuation and expansion of collaborative approaches to climate adaptation and resilience in London. This approach to sharing knowledge and best practice has been recognised within the London Climate Resilience Review and provides a strong platform to encourage multi-sector engagement beyond ARP4.

Findings

A total of 114 climate interdependency risks have been identified and scored against the likelihood of this pathway occurring and the potential magnitude of an impact or consequence across three time horizons: present-day, 2050s and 2080s. Overall findings for the London LBTS and its upstream interdependencies are summarised below:

Climate hazards

* Surface water flooding driven by higher and more intense rainfall.
* Fluvial flooding caused by higher rainfall in upstream catchments.
* Landslides driven by higher and more intense rainfall and drought impacts on soil moisture.
* High temperatures impacting on the power and telecoms sectors, along with impacts from wind and associated debris.
* Sea level rise coupled with storm surges and extreme high tides mean that tidal flooding remains a significant risk for London.

**Interdependencies**

* Power sector interfaces score highly due to high levels of interdependency and the multiple climate hazards affecting power assets.
* Urban drainage and civil infrastructure interfaces also score highly due to likelihood scores for flood hazard impacts and high consequence scores.
* The telecoms interface is a medium level risk, although this may vary significantly according to each LBTS organisations individual configuration. However, reduced confidence in these scores is noted due to the limited information available from both the telecoms sector and the LBTS regarding vulnerability. The telecoms sector’s dependency on the power sector is also noted but not assessed directly within this project.

**Trends across time horizons**

Overall trends suggest that surface water flooding already poses a major risk to London and this is only likely to increase in future. Other climate hazards such as high temperatures and heatwaves, high winds, fluvial and tidal flooding will increase in severity into the 2050s. Climate interdependency risks increase significantly in the 2050s as decarbonisation, electrification and changes in climate hazards lead to greater impacts from the power sector. Impacts from damage to civil structures, banksides and slopes and vegetation interfaces also increase within the 2050s and are primarily driven by increased precipitation. Rising sea levels into the 2050s and beyond may limit the ability of tidal flood defences to continue to protect LBTS assets situated within the Thames Estuary.

**Actions**

Key risk reduction actions have also been identified for the LBTS along with proposed timings, with priorities to:

* **Continue to support cross-sectoral collaboration** beyond the LBTS and prioritise engagement where knowledge gaps exist, such as with the telecoms sector.
* **Improve data sharing** across organisations, with the ultimate aim of creating shared risk registers.
* **Explore co-funding opportunities for resilience measures which deliver co-benefits**, particularly for green infrastructure solutions which can reduce the risk from multiple hazards such as flood management and urban cooling.
* **Share and develop best practice on the maintenance of green infrastructure** which presents an increasingly important adaptation solution yet remains poorly understood in regard to management and maintenance.

**Conclusions**

Overall, the project presents both a significant contribution to ARP4 submissions for the LBTS, and also provides a new approach to assessing climate interdependency risks. Combining a systems approach with the established climate risk assessment process has ensured an innovative and rigorous process to the collation and analysis of climate interdependency risks. Undertaking stakeholder engagement across all stages of the project has created a co-learning process which has developed cross-sectoral relationships and a shared understanding of the risks facing London’s infrastructure.

Outputs from this assessment have focused on the key interfaces which have been identified as priorities by stakeholders. This presents a more pragmatic approach than a purely hypothetical assessment of all potential cascading failures across a system which has typified previous analysis of climate and interdependency risk. At the same time, the system mapping that has been undertaken ensures that the value of collective thinking and ‘brainstorming’ of potential risks is not lost but has been synthesised to a more manageable output.

Developing a more complete understanding of how climate interdependency risks will impact on London beyond the LBTS will require the support of actors beyond TfL and the TASG. We highlight the following recommendations:

* Greater regulatory commitment to co-ordinating cross-sectoral working groups. TfL and the TASG have taken a lead in this regard to the benefit of the transport sector and other sectors. However, the ‘pulling power’ of one organisation or sector to convene and address a multi-sectoral problem is limited. Making the ARP a requirement rather than a voluntary process would go some way to addressing this.
* The creation of opportunities for co-funding of appraisals for climate adaptation across regulatory groups in each sector.
* Standardising the use of data sharing tools to support in identifying pressure points across the entire system. Stakeholders highlighted that this approach needs to be streamlined to minimise wasted time leading to redundant efforts.
* Dissemination of best practice guidance for the maintenance and management of green infrastructure given its prominence in climate adaptation.

We also discuss specific actions which could be taken forward by TfL in relation to key climate interdependency risks (telecoms, pipe bursts, distribution network, flood defences) which have been identified through the risk assessment.

# Introduction

The project aims to provide a joined-up approach to support the assessment of interdependencies within ARP4 for the wider Transport Adaptation Steering Group (TASG).

## Project context

The Climate Change Act 2008 gives the Secretary of State the power to direct reporting authorities to produce reports on what they are doing to adapt to climate change and associated governance processes. The power is referred to as the “Adaptation Reporting Power”, or ARP. The ARP identifies current and future climate risks, together with proposed adaptation measures, and reports on progress since previous ARP submissions.

Transport for London (TfL), Network Rail, National Highways, High Speed 2 (HS2), High Speed 1 (HS1), Defra (and others) have continued to work together as part of the Transport Adaptation Steering Group (TASG) to deliver joined-up approaches to their ARP4 submissions. This project is a continuation of these attempts to take a collaborative approach to climate adaptation and resilience across London. This collaborative approach to sharing knowledge and best practice has been recognised within the London Climate Resilience Review.

## Interdependencies

London’s LBTS is already being affected by severe weather events that are becoming more frequent and more intense. Climate change will increase the likelihood of climate and weather-related hazards such as; heatwaves, drought, rising sea levels, flooding (both surface water and fluvial), wildfires and subsidence. Climate hazards that impact upon one organisation’s assets can then lead to cascading impacts to other organisations, known as interdependencies.

The congested nature of London’s infrastructure increases both the likelihood and potential magnitude of these cascading impacts. This means that multiple organisational interdependencies must be considered, where assets or processes beyond the LBTS may be impacted by climate hazards and impact the transport sector.

*“London can be viewed as a system made up of many interdependent and interconnected parts. London’s transport infrastructure is dependent on energy infrastructure which is dependent on water infrastructure and vice versa; disruption to one part of the system has cascading effects.”*

London Climate Resilience Review Interim Report, pg. 8[[2]](#footnote-3).

Understanding and managing climate hazards in relation to these organisational interdependencies is one of the London LBTS’ biggest challenges. Therefore, a key focus for the LBTS and TASG in ARP4 is to:

* identify both upstream and downstream interdependencies that exist between assets and services in different infrastructure sectors (e.g. transport, water and drainage, energy and telecommunications)
* Identify how climate hazards (e.g. flooding, drought and heatwaves) affecting upstream interdependencies will impact the delivery of transport services.

## Project aim and approach

This project supports TfL and the LBTS to update their ARP4 submissions through improving their understanding of interdependencies, climate hazards and risk reduction actions to enable a resilient transport network and continuity of service for Londoners.

Climate interdependency risks represent a complex problem for the LBTS as these risks cascade across organisational boundaries. The UK government recommends taking a systems approach[[3]](#footnote-4) to understand, analyse, and respond to complex problems. Our system mapping has provided the platform for the analysis of interdependencies and the climate interdependency risk assessment. Stakeholder engagement is central to this approach and has taken place throughout the project in the form of system mapping focus groups and three workshops.

This project report outlines the key findings and is structured as follows:

* Section 2 provides an overview of the project method across the system mapping and climate interdependency risk assessment.
* Section 3 presents the results from the climate interdependency risk assessment for key LBTS interdependencies.
* Section 4 discusses the proposed actions for climate interdependency risk reduction
* Section 5 presents the recommendations and next steps.

# Method

This project combines system mapping with a climate risk assessment for the LBTS’ upstream interdependencies. This section outlines the approach used to identify interdependencies and climate risks for the LBTS and how those outputs were used to inform the risk assessment. The scoring method used for the risk assessment itself is also discussed.

Systems approaches provide a structured co-learning process, bringing together interested parties to work through complexity and uncertainty. This enables them to see the bigger picture, share knowledge and experience and consider different perspectives. This is key to informing more holistic considerations and recommendations that can account for interdependencies, identify and manage trade-offs, and avoid unintended negative impacts from interventions.

In line with the Defra guidance, we have used Participatory Systems Mapping (PSM)[[4]](#footnote-5) within our stakeholder engagement approach. PSM is used to develop a qualitative visual representation of a system through a facilitated co-learning process with stakeholders. It shows the elements that make up the system and how the behaviour of the system is affected by the causal relationships between these elements. It is a collaborative process that draws on experiences and knowledge from across a diverse group of perspectives. PSM promotes discussion between participants and builds a shared understanding of a system, which also encourages buy-in for further action planning.

Using a systems approach for interdependency analysis has provided the platform for the climate interdependency risk assessment. The risk assessment follows a standard methodology consistent with Defra’s reporting guidance and the ARP3 assessment.

The overall method is shown in Table 2.1 highlighting the contribution of stakeholder engagement through the project, along with the key tasks and outputs in each step. A full list of the stakeholders who engaged with the project is presented in Appendix A.

Table .: Project overview

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| --- |
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| |  |  |  |  |  | | --- | --- | --- | --- | --- | | **Stakeholder engagement and system mapping** | **Task** | **Key activities** | **Outputs** | | | **System mapping** | | | | * Project report * Chapter for ARP4 report | | Creation of causal loop starter system maps | 1  Review existing documentation to establish system frameworks | * Review and summarise existing documentation * Establish understanding of systems and system framework * Stakeholder identification |  | | Creation of integrated system map | 2  Collation and analysis of interdependencies | * Interdependencies collation * Workshop 1: Interdependencies analysis | | **Risk assessment** | | | | | Assess climate risk | 3  Risk assessment | * Workshop 2: Climate risk analysis * Climate risk assessment for upstream interdependencies | * Risk assessment spreadsheet * Key risks infographic * Key actions infographic | | Identify actions and stakeholders | 4  Development of actions to mitigate risks | * Identification of actions * Workshop 3: Agree key risks, actions and stakeholders involved in mitigation of risks | | Identify priorities and unintended consequences | 5  Prioritisation framework | * Risk assessment analysis and framework to prioritise actions * Presentation to validate findings | |

### Step 1: Review of existing documentation to establish system frameworks

The first step of the PSM approach was to develop a high-level scoping map which delineated the boundaries of the system. This was created after a desk review of relevant documentation (see Appendix B for further details). This map helped to identify the key system areas and stakeholders to engage with.

Simple sub-system maps were then created for each relevant sector using an online, open-access software called Kumu. Maps were drafted for the following sub-systems:

* Environmental management
* LBTS – rail and sponsored services (including underground)
* LBTS – roads
* Land use and planning
* Power
* Telecoms
* Water

Figure 2.1 shows a sub-system map for the LBTS road system in Kumu with key processes and climate hazards. Appendix C provides a description on how to read system maps.

Figure .: Example sub-system map for LBTS - roads

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

### Step 2: Collation and analysis of interdependencies

Online focus groups with stakeholders from each sector were held to review the sub-system maps drafted in Step 1. This step validated the relationships between elements and how they were impacted by climate hazards to identify interdependencies with the LBTS.

Participation in the focus groups was strong overall but varied across different sectors. Key omissions at this stage included the telecoms sector, the Port of London Authority (PLA) and the aviation sector. Sub-system maps were therefore reviewed with internal experts for these sectors instead.

Once sub-system maps for each sector had been reviewed and updated, they were combined into an integrated system map for analysis​. This included analysing the map to identify upstream and downstream connections and synthesising individual pathways into ‘hotspot’ areas using filtering tools (see Figure 2.2).

Figure .: Hotspot map for ‘drainage and flooding’ showing key climate hazards and interdependency pathway

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

A range of stakeholders from across multiple sectors then attended the in-person’ integration’ workshop held in January 2024.

**What is an integration workshop?**

*The purpose of an integration workshop is to bring together stakeholders from across the component sub-systems to review the integrated system map. This allows stakeholders to move beyond siloed thinking and to share different perspectives together on system-wide concerns. Holding these events in-person encourages conversations across the stakeholder group, developing relationships which can also bring value beyond the immediate project.*

In the workshop, stakeholders were asked to review the interdependency hotspots and identify key impact pathways, from climate hazards through to key assets and processes in other sectors and then the LBTS. The maps were also used to highlight key organisational interfaces (e.g. urban drainage capacity) which represented the point where the risk transferred to the LBTS from another sector.

This ensured a collaborative approach to collation of the interdependencies affecting the LBTS through including the perspectives, experiences, and knowledge of stakeholders from across multiple sectors. Outputs informed the identification of 10 key organisational interfaces to summarise the LBTS’ priority interdependencies (Table 2.2).

Table .: List of organisational interfaces (green circles indicate interfaces linked to vegetation and the natural environment)

| Icon | Organisational interface | Description and assets included | Asset owners |
| --- | --- | --- | --- |
|  | Power grid resilience | The capacity of the power grid as a whole and its resilience to changes in demand. | National Grid |
|  | Power network - linear infrastructure | The resilience of linear assets such as pylons and overhead power lines primarily within the transmission network. | National Grid |
|  | Power network - substation assets and cables | The resilience of substation assets and underground cables within both the distribution and transmission network. | National Grid and UK Power Networks. |
|  | Telecoms network | The resilience of telecoms assets such as masts, cables, street cabinets, exchange centres and data centres. | Multiple external providers, including; BT, Sky, Motorola, EE, Nokia, Vodafone |
|  | Civil structures | The integrity of civil structures in close proximity to LBTS assets which are maintained by other landowners e.g. bridges, tunnels. | Primarily boroughs but also other private landowners. |
|  | Pipe bursts | The resilience of water company pipe assets which are in proximity to LBTS infrastructure. | Thames Water and Affinity Water. |
|  | Urban drainage system and combined network | The capacity of the urban drainage system and the combined network maintained by other landowners. | All owners of drainage assets including; Boroughs, Thames Water, private landowners |
|  | Vegetation and green infrastructure | The management of lineside and roadside vegetation in close proximity to LBTS assets maintained by other landowners. | Any landowners responsible for maintaining green infrastructure; Boroughs, GLA, private landowners, Environment Agency |
|  | Banksides and slopes | The management of land maintained by other landowners near to rail or road infrastructure where there is potential for landslides. | Private landowners, Environment Agency, Boroughs. |
|  | FRM assets | The resilience of flood risk management (FRM) assets such as the Thames Barrier and upstream flood defences. | Environment Agency |

Outputs from the integration workshop also led to the creation of an interdependency [system map](https://kumu.io/SystemsECP/arp4idmmpsmv3-cra#cra-map) (Figure 2.3), summarising all interdependency pathways to be used within the climate interdependency risk assessment. Filtering tools where then applied to enable analysis centred around either organisational interfaces or climate hazard.

Figure 2.4 illustrates how the outputs from the system mapping enabled upstream interdependency risks to be identified for use in the risk assessment. This example filters on pipe bursts as a key organisational interface, which impacts on LBTS assets such as; highways, roads and streets, rail infrastructure, and built environments. The impact pathway includes ground movement caused by climate hazards such as low rainfall or temperature variation, as well as more direct impacts from low temperatures on pipe bursts. The map also highlights key stakeholders (in this example, Thames Water and Affinity Water) responsible for each interface through the coloured bars around each interface node.

The climate interdependency risk assessment was structured so that each individual causal pathway from left to right on the map (from **climate variable** through to **assets impacted**) represents a climate interdependency risk to be scored. The ID for each risk relates to its organisational interface (1-10) and which risk it represents within the pathway. In this example there are 9 risks (6A to 6I). Further detail on how to use the filtering functions of the system map can be found in Appendix C. Definitions and the categorisation of climate variables and assets were agreed with TfL in advance of the risk assessment and can be found in Appendix D.

Figure .: Interdependency systems map

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

Figure .: Interdependency pathway for climate hazards

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

### Step 3: Climate interdependency risk assessment

Once the system mapping outputs had been used to structure the risk assessment, a high-level risk score was assigned for each interdependency pathway. The headings used in the risk assessment spreadsheet are presented in Table 2.4, highlighting where the system mapping outputs have been used to inform the climate interdependency risk assessment.

Stakeholders from the TASG then attended an online workshop in February 2024 to review the preliminary likelihood and consequence scores for each of the 10 interfaces within the risk assessment. Feedback and insights from stakeholders were used to inform the risk scoring for all three time periods, through their knowledge of adaptation actions and operational procedures which could affect the risk severity. This helped to ascertain the likelihood and consequences of upstream interdependencies impacting on the LBTS.

Further clarification calls were then held with non-LBTS stakeholders to review the risk severity associated with their relevant organisational interfaces. For example, climate interdependency risk scores relating to tidal flooding were reviewed with the Environment Agency to validate our assumptions regarding the likelihood of climate hazards impacting on their assets.

### Climate interdependency risk assessment scoring approach

The risk assessment was informed by the method used by TfL for its ARP3 Climate Change Risk Assessment. The risk to the LBTS was based on assessing the likelihood and consequence of the interdependency impact pathways occurring. Risks were assessed for three time horizons: current risk (2020s), risk in the 2050s and risk in the 2080s. This methodology was discussed and agreed with TfL and presented to stakeholders at the workshops.

The likelihood score and the highest of the three consequence scores were multiplied together to calculate the overall risk severity:

Likelihood x Consequence = Risk

* Likelihood: Likelihood of the impact pathways that were identified in the systems map occurring (informed by UKCP18 climate projections and workshop output)
* Consequence: Consequence of the impact pathway occurring in relation to: safety/health/environment, financial impact, performance
* Risk: Risk levels range from minor to severe and are assessed on a 5x5 matrix (Table 2.3)

Table 2.3: summarises the thresholds for categorising the overall risk severity on a scale from ‘minor’ to ‘severe’, in line with Network Rail’s ARP3 methodology.

Table .: Thresholds for categorising overall risk score

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **​** | | **Consequence​** | | | | |
| Low (1)​ | Medium (2)​ | High (3)​ | Very High (4)​ | Critical (5)​ |
| **Likelihood**​ | Almost Certain (5)​ | moderate​ | major​ | major​ | severe​ | severe​ |
| Likely (4)​ | moderate​ | moderate​ | major​ | major​ | severe​ |
| Possible (3)​ | minor​ | moderate​ | moderate​ | major​ | major​ |
| Unlikely (2)​ | minor​ | moderate​ | moderate​ | moderate​ | major​ |
| Highly Unlikely (1)​ | minor​ | minor​ | minor​ | moderate​ | moderate​ |

Table .: Overview of risk assessment approach

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Heading** | **Description** |  |
| 1 | ID | Numerical and alphabetical identification of each interdependency risk |  |
| 2 | Organisational interface | Key point at which TfL and the LBTS become dependent on the resilience of assets or services owned by others (e.g., electricity supplied by the National Grid) | Outputs from systems map |
| 3 | Climate variable | Lists the variables agreed with TfL that are most relevant to their interdependencies and align with those in their ARP3 report, such as precipitation, sea level rise and extreme high temperatures | Outputs from systems map |
| 4 | Climate projections  (90th percentile, RCP 6.0, 2050s) | Summarises the projected changes to each of the climate variables in the 2050s |  |
| 5 | Climate projections  (90th percentile, RCP 6.0, 2080s) | Summarises the projected changes to each of the climate variables in the 2080s |  |
| 6 | Impact description | Describes the full impact pathway based on the systems map | Outputs from systems map |
| 7 | Asset | Lists the broad asset type within the LBTS that the impact description refers to, such as rail infrastructure or the built environment | Outputs from systems map |
| 8 | Narrative | Summarises the information that was considered when determining the likelihood and consequence scores for each of the three time periods including any evidence of adaptation that was identified or any further information required | Risk assessment (present, 2050 and 2080) |
| 9 | Likelihood | This score indicates the likelihood of the impact description (impact pathway) occurring on a scale from 1 (highly unlikely) to 5 (almost certain) | Risk assessment (present, 2050 and 2080) |
| 10 | Consequence | This score indicates the severity of the potential consequence (or impact) on different asset types (split into the three types of consequence: safety/health/environment, performance, and financial), of the impact pathway occurring on a scale of 1 (low) to 5 (critical) | Risk assessment (present, 2050 and 2080) |
| 11 | Risk score | Overall risk score based on multiplication of the likelihood score with the highest consequence score across the three consequence categories | Risk assessment (present, 2050 and 2080) |

Notes: These headings are used in the climate interdependency risk assessment spreadsheet template.

Likelihood scores

The likelihood that the whole upstream interdependency pathway would be affected by climate hazards was scored using a 5-point scale from ‘almost certain’ to ‘highly unlikely’. The definitions of likelihood used were taken from the TfL ARP3 Climate Change Risk Assessment methodology. Table 2.5 shows the definitions used for the 5-point likelihood scale.

Table .: Likelihood categories

| Score​ | Likelihood​ | Definition​ |
| --- | --- | --- |
| 5​ | Almost certain​ | The risk is in the process of materializing and may already be under active management as an event​ |
| 4​ | Likely​ | Past events have not been fully resolved, effective mitigations not yet identified, control weaknesses are known and are being managed ​ |
| 3​ | Possible​ | Past events satisfactorily resolved, mitigations are in place or are on track to be in place, control improvements are under active management​ |
| 2​ | Unlikely​ | Events are rare, required mitigations in place, controls are effective​ |
| 1​ | Highly unlikely​ | No known event or if known extremely rare, extreme industry-wide scenarios​ |

Source: TfL Climate Change Risk Assessment (ARP3)

Likelihood scores were assigned to each pathway based on professional judgement and scores for the 2050s and 2080s also considered whether there was any evidence of adaptation plans or measures that could decrease the likelihood. Evidence was identified from:

* The current climate baseline and UKCP18 data.
* Reviewing ARP3 reports, risk assessments and climate change adaptation plans.
* Reviewing publications by the UK Climate Change Committee (CCC), particularly their 2023 adaptation report to the UK Parliament and the sector briefings produced for UK Government’s third Climate Change Risk Assessment (CCRA3)[[5]](#footnote-6).
* Insights provided by the TASG stakeholders in the February 2024 workshop and in follow up conversations with other sectors.

Consequence scores

TfL’s ARP3 scored consequence on a single 5-point scale from ‘critical’ to ‘low’. Consequence scores were broken down into three categories to provide a more detailed consideration of different types of consequences, in line with Network Rail’s ARP3[[6]](#footnote-7). The three consequence categories were agreed with TfL as: safety/environment, performance, and financial consequences. Table 2.6 shows the definitions of consequence used in the 5-point scale in this project. These definitions were developed based on those used by Network Rail in its ARP3 risk assessment, TfL’s corporate risk assessment methodology, and from discussion and agreement with members of the TASG and TfL.

Consequence scores were assigned using professional judgement that was informed from the same sources as the likelihood scores, specifically stakeholder engagement and a literature review of ARP3 reports and CCC reports.

Table .: Consequence categories and definitions

| Score​ | | Safety / environment ​ | Financial[[7]](#footnote-8)​ | Performance ​ |
| --- | --- | --- | --- | --- |
| 5​ | Critical​ | Life changing / multiple health issues leading to prosecution. Multiple fatalities leading to prosecution. Major long-term / large scale environmental harm leading to prosecution​ | £££££​ | Unplanned and severe disruption to more than one main route resulting in station/road/track closures and negative media coverage of TfL​ |
| 4​ | Very high​ | Significant health issue leading to adverse regulatory outcome. Single fatality leading to adverse regulatory outcome. Significant long-term/large scale environmental harm leading to adverse regulatory outcome​ | ££££​ | Unplanned disruption on more than one route for over a week resulting in station/road/track closures​ |
| 3​ | High​ | Moderate health issue leading to regulatory action. Major injuries leading to regulatory action. Moderate environmental harm leading to potential regulatory action​ | £££​ | Unplanned disruption on at least one route for up to a week resulting in station/road/track closures​ |
| 2​ | Medium​ | Minor health issue with potential for regulatory action. Minor injuries with potential for regulatory action. Minor localised/short term environmental harm with potential for regulatory intervention​ | ££​ | Unplanned disruption on one route for up to day ​ |
| 1​ | Low​ | Minor health issue. Minor injuries or minor localised environmental harm​ | £​ | Planned disruption on one route for up to a day​ |

Source: Adapted from TfL Climate Change Risk Assessment (ARP3) and Network Rail ARP3

### Climate projections

Climate projection data was used primarily to inform scoring across the different time horizons used in the risk assessment. In line with the climate projections used to inform the TfL ARP3 Climate Change Risk Assessment, data for the CRA in this project were obtained from the United Kingdom Climate Projections 2018 (UKCP18). UKCP18 projections are developed by the Met Office and are the latest set of climate projection data for the UK. Projection data was obtained for one medium-high greenhouse gas emissions scenario, RCP6.0, to be consistent with TfL’s ARP3 report. Projection data were obtained for the 2050s and the 2080s for both temperature and precipitation variables. For sea level change, data for a high greenhouse gas emissions scenario, RCP8.5, were obtained for the same time periods. RCP8.5 was used for sea level data because the UKCP18 Marine Projections do not include data on sea level rise for the RCP6.0 scenario. The 90th percentile values were used from data from the probabilistic projections UKCP18 product. Values for 20- and 100-year return periods were used from data from the probabilistic extreme’s product from UKCP18.

Probabilistic projection data, with the exception of sea level rise, were obtained for the London administrative region, as available from the UKCP18 user interface. Due to data availability from location of tide gauges, sea level rise data were obtained for the closest gauge to London, Sheerness.

The climate hazards of higher wind speed and lightning were also included in the risk assessment. The Met Office’s UKCP18 factsheet on wind was used to summarise expected changes in near surface wind speeds across the 21st century and the associated confidence in those projections[[8]](#footnote-9). Projections for lightning are not available so we derived a description for projected trends over the 21st century from TfL’s recommended list of climate hazards.

The key climate projection headlines for London over the 21st century are[[9]](#footnote-10):

* Warmer, wetter winters and hotter, drier summers.
* Increase in frequency of extreme weather events, e.g., heatwaves and storms.
* Sea level rise.

More detail on the climate baseline and projection data used in this project can be found in Appendix E. It includes a summary of which climate hazards were used to inform the risk assessment and where they were sourced.

### Key assumptions for risk assessment

* **Worst case scenarios** – during the second workshop stakeholders were encouraged to consider worst case scenarios when scoring consequences under RCP 6.0 for the 2050s e.g., locations and examples which could be more severe. This relates to 90th percentile aligning to ARP3 and ARP4 risk assessments.
* **Adaptation** – if evidence of present or planned adaptation was found, either in reviewed documents or from discussions with stakeholders, then this was considered in the likelihood scoring. Evidence of adaptation was assumed to moderate the likelihood of the impact pathway occurring and/or the consequence of it occurring, for example due to upgrading assets, changing maintenance or operation regimes, or installing SUDs. If there was no evidence of adaptation found then an un-adapted future was assumed, noted in the narrative, and reflected in the likelihood and/or consequence scores. For example, if it was assumed that assets would be replaced like-for-like and that current maintenance and operation procedures would continue.
* **Scoring of cascading interdependencies** – to create a manageable scope for the risk assessment, we have limited our assessment to score direct risks from interdependencies. E.g. where the impacts cascade directly from one sector such as water to transport, rather than power to water to transport. To fully risk assess cascading interdependencies across multiple sectors would require in depth knowledge of likelihood and consequence for assets and services in other sectors e.g. the exact nature of vulnerability between all power and all telecoms assets. This is beyond the scope of a project funded by the transport sector alone, although we recommend that this approach is taken once other sectors have matured in their understanding of interdependencies.
* **Coverage -** the risk assessment does not cover every possible interdependency, but instead focuses on the key interfaces that have been highlighted as being of greatest concern for the London LBTS through the system mapping. The risk assessment focuses on upstream interdependencies with other sectors rather than those within the LBTS which are well understood. Whilst the scope of the risk assessment scoring is on upstream interdependencies, co-dependencies and downstream interdependencies are discussed within the narrative in Sections 3.8 and 3.9.

### Step 4: Development of actions to reduce risks

A longlist of risk reduction actions was collated by the project team in response to the findings from the risk assessment. These considered actions such as; collaborative approaches to data sharing and governance, targeted investments in resilience measures, the sharing of best practice and exploration of co-funding approaches. All stakeholders were then invited to attend an online workshop in March 2024.

Key climate interdependency risks to organisational interfaces and a visualisation of the impact pathway from the system map were presented along with a draft list of risk reduction actions.

Stakeholders were asked to help develop a list of risk reduction actions for the LBTS using a Miro Board, grouped in accordance with the categories from the ARP3 adaptation plan. To encourage innovative thinking, we added an additional ‘magic wand’ category where we asked stakeholders to consider actions they would like to see implemented regardless of barriers. A follow-up Microsoft Form was sent to participants to review the co-developed list of actions and to provide an indicative low, medium, or high priority score against each action for the different climate interdependency risks identified.

### Step 5: Prioritisation framework

Table 2.7 summarises our prioritisation framework to identify key actions to reduce climate interdependency risks:

* Step 1 identified a longlist of actions for reducing risks which was informed from Workshop 3
* Step 2 applied the prioritisation criteria following the method used by Climate Adapt[[10]](#footnote-11) to create a shorter list of priority actions
* Step 3 identified the timing of the priority actions by assessing the level of stakeholder engagement, skills and resources, and regulatory support required.

This allowed each action to be reviewed against a set of prioritisation criteria to provide a structured method for identifying key actions and recommended delivery for the LBTS. The final list of prioritised actions was reviewed and agreed with TfL.

Table .: Overview of method for prioritising actions for reducing climate interdependency risks

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Step 1: Identify actions for reducing climate interdependency risks** | | | | | | | | | | | | | |
| **Climate hazard** | | | **Key interdependency risk** | | | **Level of control** | | | | **Recommended action** | | | |
| e.g., surface water flooding | | | Identify key risks from climate risk assessment | | | Identify if the risk is within LBTS control or influence | | | | What should be done to mitigate the risk | | | |
| **Step 2: Prioritising actions** | | | | | | | | | | | | | |
| **Criteria** | Sub-criteria | | | | | | | | | | | | |
| **Risk level** | Timeframes: is the risk current or emerging? | | | | | | | | | | | | |
| **Risk level** | Severity: is the risk rated major or severe? | | | | | | | | | | | | |
| **No regret** | Actions which are worthwhile no matter the extent of future climate change | | | | | | | | | | | | |
| **Low regret** | Actions with relateively low associated cost but benefits for risk mitigation under climate change could be relatively high | | | | | | | | | | | | |
| **Win-win options** | Actions which delover the desired results in terms of minimising risks but also have significant contribution to other social, environmental or economic goals across organisations | | | | | | | | | | | | |
| **Flexible or adaptive options** | Actions that can be adjusted easily if circumstances change compared to initial projections | | | | | | | | | | | | |
| **Multiple benefit options** | Actions which provide synergies with other outcomes such as climate change mitigation, disaster risk reduction, environmental management or sustainability | | | | | | | | | | | | |
| **Step 3: Use framework to identify timing of priority actions** | | | | | | | | | | | | | |
| **Timing of priority actions** | | | | | | | | | | | | | |
| Is the action within the LBTS level of control? | | | | | | | | | | | | | |
| Are skills and capabilites currently available to deliver this action? | | | | | | | | | | | | | |
| Are the actions aligned with the current regulatory cycle? | | | | | | | | | | | | | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | **Prioritisation criteria** | | | | | | | **Timing of priority actions** | | | **Outcome** |
| **Risk type** | Recommended action | Categorisation | Risk level | No regret | Low regret | Win-win | Flexible or adaptive options | Multiple benefit options | Prioritisation | T1 (engagement) | T2 (resourcing) | T3 (policy) | Timing outcome |
| **General** | Create shared risk registers to identify joint risks and co-create/co-fund risk mitigation where a single solution can deliver benefits for wider interfaces | Information management | n/a | yes | yes | yes | yes | yes | high | no | no | no | long-term |

# Findings

A total of 114 climate interdependency risks have been identified and scored across three time horizons; present-day, 2050s and 2080s, with the full risk assessment provided as a separate spreadsheet. This section summarises our key findings and discusses the climate interdependency risks and trends which are of most relevance to the LBTS.

We summarise below the key sectors or systems which the LBTS is dependent on, and the key climate hazards identified through the stakeholder engagement, risk assessment and reviews of relevant documentation (such as ARP3 reporting and CCRA3 research).

## Power

Primary risks relate to power grid capacity and resilience during periods of high demand, such as for cooling during extreme high temperatures. Other risks relate to the resilience of linear and substation assets as part of transmission and distribution networks to climate hazards such as flooding and high temperatures**[[11]](#footnote-12)**. Power sector risks are also considered within the wider context of climate mitigation. Decarbonisation of heating and the increased electrification of assets and fleets into the 2050s increases vulnerability. Cascading failure could impact on power supplies critical for operation of track infrastructure, signage and street lighting on highways and roads, as well as air conditioning and cooling within built environments such as stations and depots.

## Telecoms

Primary risks relate to damage to telecoms assets, such as data centres, exchange centres and street cabinets, due to flooding. There is also concern about the potential for damage to telecoms masts and cables due to high winds. Failures could affect the ability of transport staff and emergency responders to communicate and in rare cases could impact communication with emergency responders. However, engagement with the telecoms sector has been limited in comparison to other sectors and there is less information regarding how climate change will affect the frequency and magnitude of outages of the telecoms network in future**[[12]](#footnote-13)**. This suggests a key area for further research and collaboration and provides a lower level of confidence in our risk scores.

## Water

Primary risks relate to pipe bursts as a result of ground movement caused by reductions in soil moisture content and temperature variation**[[13]](#footnote-14)**. Pipes are also directly impacted by low temperatures, although this h is assessed to decrease over time as temperatures rise. Bursts can lead to track, road and station closures through flooding and tunnel ingress, as well as interruption to supply (ITS) events. Other wider risks to water resources and water quality are considered to have a less significant impact on the LBTS and have not been included within the risk assessment. Prioritisation of water supplies for public services and statutory requirements to maintain supply (e.g. through bottled water) means that drought risk impacting on water availability to the built environment is not considered as a key risk to the LBTS. The overwhelming of the combined network during periods of heavy rainfall is also considered within the urban drainage interface.

## Environmental management

Primary risks relate to the operation of Flood Risk Management (FRM) assets such as the Thames Barrier and upstream flood defences and the potential impacts from tidal and fluvial flooding. Banksides and hillslopes near to rail and road infrastructure can also be managed by private landowners with the potential for both drought and high rainfall to reduce slope stability and cause landslides. Similarly, lineside vegetation can be managed by any private landowners and may be impacted by increased leaf and tree fall due to a lengthened growing season coinciding with more storm events. These impacts can lead to speed restrictions, track closures and health and safety risks on roads and for built environments (e.g. station platforms). The management of vegetation, particularly during drought periods where water restrictions may impact on maintenance and lead to die-off is considered to be an emerging risk due to the planned increase in green infrastructure as an adaptation measure. This increases the potential for maladaptation due to damage to road surfaces, the blocking of drainage systems and wildfire risk.

## Land use and planning

Primary risks relate to maintenance of the drainage network and the contribution of urban runoff during periods of intense rainfall, leading to surface water flooding which may cause track, road and station closures. Within the area of urban planning and maintenance, flood or weathering related damage to civil infrastructure such as bridges and tunnels may also impact on transport infrastructure. As discussed above, the adoption of green infrastructure practices across London will bring benefits to infiltration, carbon sequestration and urban cooling but must be carefully managed to avoid unintended consequences outlined in Section 3.4.

## Summary of key findings and risks

Figure 3.1 below presents an infographic summarising the key findings from the climate interdependency risk assessment. The highest severity climate interdependency risks are shown along with the organisational interfaces which are most impacted for each of these. Analysis of the climate interdependency risk assessment shows the number of risks which meet the threshold of ‘major’ or ‘severe’ for each of the main climate hazards identified. This provides a high level overview of how risk profiles change over the three time horizons assessed – present day, 2050s and 2080s. A breakdown of the analysis for each of the climate interdependency risks and organisational interfaces is provided in Appendix F.

Figure .: Trends in total risk severity for each climate hazard, and the affected organisational interface across the three time horizons: today, 2050s, and 2080s.

**This figure shows the number of key climate interdependency risks per climate hazard type for three time horizons: the present, 2050ss and 2080. Key climate interdependency risks are those that meet a risk score of major or severe. The risk numbers are sorted into 5 categories: 0, 1 to 4, 5 to 8, 9 to 12, and 13 plus. Also listed are the organisational interfaces that are potentially most affected by each climate hazard.  
Surface water flooding and high temperatures and heatwaves are the climate hazards with the most major or severe risks, with multiple organisational interfaces being affected. 
The risk numbers for each climate hazard are: 
Surface water flooding: Today: 5 to 8, 2050s: 13 plus, 2080s: 13 plus; Organisational interfaces impacted are: Urban drainage systems and combined network, Telecoms network, Power network (substation assets and cables), and Civil structures. 
High temperatures and heatwaves: Today: 0, 2050s: 5 to 8, 2080s: 13 plus; Organisational interfaces impacted: Power grid resilience, Power network (substation assets and cables), Power network (linear infrastructure), Telecoms network. 
High wind and storms: Today: 1 to 4, 2050s: 1 to 4, 2080s: 5 to 8; Organisational interfaces impacted: Power network (linear infrastructure), Telecoms network, Vegetation and green infrastructure. 
Fluvial flooding: Today: 1 to 4, 2050s: 5 to 8, 2080s: 9 to 12; Organisational interfaces impacted: Flood risk management assets, Telecoms network, Cilvil structures, Power network (substation assets and cables). 
Tidal flooding: Today: 0, 2050s: 1 to 4, 2080s: 5 to 8; Organisational interfaces impacted: Flood risk management assets, Power network (substation assets and cables), Civil Structures. 
Ground movement: Today: 1 to 4, 2050s: 1 to 4, 2080s: 5 to 8; Organisational interfaces impacted: Pipe bursts, Power network (substation assets and cables). 
Landslides: Today: 1 to 4, 2050s: 1 to 4, 2080s: 1 to 4; Organisational interfaces impacted: Bank sides and slopes. 
Drought and wildfires: Today: 0, 2050s: 0, 2080s: 1 to 4; Organisational interfaces impacted: Vegetation and green infrastructure, Urban drainage systems and combined network, Power network (substation assets and cables). **

*Note: for the full description of climate hazards, please see the full detailed project report available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

Overall findings from the risk assessment are also summarised below:

Climate hazards

* Surface water flooding driven by higher and more intense rainfall.
* Fluvial flooding caused by higher rainfall in upstream catchments.
* Landslides driven by higher and more intense rainfall and drought impacts on soil moisture.
* High temperatures also impact the power and telecoms sectors, along with impacts from high winds and associated debris.
* Sea level rise coupled with storm surges and extreme high tides suggest that tidal flooding remains a significant risk for London.
* Ground movement (e.g. through subsidence) may lead to widespread impacts on subterranean assets across multiple sectors but is considered a medium-risk due to the slow onset of impacts.
* Drought and wildfires represent an emerging risk, with the latter a particular concern for the power sector.
* Groundwater flooding was acknowledged as a concern although knowledge of potential impacts on assets was limited. This lack of confidence is reflected in the scoring where it is grouped with fluvial flooding and impacts from increase average rainfall.
* Climate hazards such as frozen precipitation and low temperatures are anticipated to reduce in significance over time, as projections indicate a warming trend in winters through the 21st century.

**Interdependencies**

* Power sector interfaces score highly due to high levels of interdependency and the multiple climate hazards affecting power assets.
* Urban drainage and civil infrastructure interfaces also score highly due to likelihood scores for flood hazards and high consequence scores.
* The telecoms interface has been scored as a medium level risk, although this may vary significantly according to each LBTS organisations individual configuration. However, reduced confidence in these scores is noted due to the limited information available from both the telecoms sector and the LBTS regarding vulnerability. The telecoms sector’s dependency on the power sector is also noted but not assessed directly within this project.
* Impacts from vegetation and pipe bursts generally received lower scores due to evidence of adaptation measures and lower consequence scores.
* Impacts from FRM assets were scored lower due to high levels of proposed adaptation for the Thames Barrier reducing likelihood, despite high consequence scores.

**Trends across time horizons**

* Overall trends suggest that surface water flooding already poses a major risk to London, and this is only likely to increase in future.
* Other hazards such as high temperatures and heatwaves, high winds, fluvial and tidal flood are not considered major at present, but will increase into the 2050s.
* Climate interdependency risk increases significantly in the 2050s as decarbonisation, electrification and changes in climate hazards lead to greater impacts from the power sector.
* Impacts from damage to civil structures, banksides and slopes and vegetation interfaces also increase within the 2050s and are primarily driven by increased precipitation.
* Rising sea levels into the 2050s and beyond may limit the ability of tidal flood defences to continue to protect LBTS assets situated within the Thames Estuary.

## Priority upstream interdependencies for the LBTS

This section provides greater detail on the interdependencies themselves and is structured around the 10 organisational interface categories as defined above in Table 2.2. The narrative below provides a summary of the highest severity risks for each interface from the risk assessment for the 2050s along with key assumptions and trends. Summary tables refer to L (likelihood) and C (consequence) scores where the highest of three consequence scores used to calculate the total risk severity is presented.

Visualisations of each interface are included in Appendix G and can be read along with the sections below.

### Interface 1: Power grid resilience

#### Explanation of interface and key pathways

The resilience of the power grid is essential to providing reliable electricity supply for the London LBTS. This is primarily dependent on the National Grid electricity transmission network maintaining capacity. However, as decarbonisation increases the proportion of renewable energy supplied to the grid from new distributed generators connecting directly into the distribution network may also impact on the resilience of the grid[[14]](#footnote-15).

Climate interdependency risks relate to increases in high temperatures[[15]](#footnote-16) which can increase cooling loads in summer. This may lead to a shift in the demand profile from a winter heating to a summer cooling system, placing strain on grid capacity. In future scenarios this is also likely to be coupled with overall increased demand due to decarbonisation (e.g. large-scale switch from gas boilers to heat pumps. If grid capacity is insufficient to cope with demand peaks during heatwaves, then this could lead to short term blackouts and loss of power required for LBTS assets.

Previous examples of this relationship include the 9th August 2019 power outage, which led to traffic light failures in London[[16]](#footnote-17). However, it is worth noting the complexity of the relationship between power and transport and the multiple factors and elements within the system that may be affected[[17]](#footnote-18)[[18]](#footnote-19). For example, impacts to rail infrastructure from the power outage noted above were caused in part by lightning strikes, but also by failure within other elements of the system, which were not the responsibility of the National Grid. This included the failure of several smaller embedded generation power stations and vulnerabilities within the Thameslink fleet, which required a manual reset after shutdown. This highlights how decarbonisation and electrification are likely to increase vulnerability within both the power and transport sectors. Although it is unlikely that this same scenario would be replicated, there remains the potential for other pathways of vulnerability to emerge as climate hazards occur more frequently and energy systems become more complex and integrated.

#### Summary

Table .: Highest risk severity for 2050s for power grid resilience

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 1A | Extreme high temperatures | Higher cooling loads placing greater strain on the grid leading to cascading impacts to power supply for rail. | Rail infrastructure – tracks, boundaries, crossings | 4 | 4 | 16 |
| 1B | Extreme high temperatures | Higher cooling loads placing greater strain on the grid leading to cascading impacts to power supply for roads. | Highways and roads – predominantly street lighting, traffic lights and signage | 4 | 4 | 16 |

The highest severity risk relates to cascading impacts to power supply as a result of extreme high temperatures impacting on grid capacity. The severity is driven by higher likelihood in the 2050s due to the increasing dependency of electrified vehicles and systems and roads e.g., smart motorways increasingly reliant on electricity. This also leads to high consequence scores for health and safety, due to potential loss of power for active traffic management and variable road signs. Loss of power for critical rail infrastructure is also a significant risk if overhead line electrification (OLE) cannot be maintained, leading to performance impacts from track closures and loss of service.

Other climate interdependency risks which have been scored are:

* Loss of power to signalling systems leading to track closures and service disruption
* Loss of power or inability to maintain electric vehicle fleets if charging points are no longer able to operate.
* Loss of power to the built environment, which may impact staff health and wellbeing (e.g. lack of air conditioning) as well as to cold storage and supply chains (e.g. loss of cooling in depots).

### Interface 2: Power network – linear infrastructure

#### Explanation of interface and key pathways

Impacts to linear infrastructure within the power network operated by National Grid can also lead to cascading impacts to power supply for the London LBTS. These assets include pylons and overhead power lines, which can be located outside of London as part of the wider transmission network. Due to London being a net importer of electricity, impacts may occur in geographically disparate locations, which then cascade through to assets in London.

Climate hazards that impact this interface include:

* Extreme high temperatures, which can impact on asset integrity – in particular the sagging of transmission lines, with much of the older network only designed to be resilient to 30 degrees Celsius. However, newer assets are designed to be resilient to 40 degrees Celsius, reducing likelihood scores (as informed by National Grid stakeholders).
* Increased lightning strikes, which can directly impact linear infrastructure and prevent staff from responding to incidents.
* Higher wind speeds during storm events leading to debris, which can damage overhead power lines and cables.
* Higher average rainfall over a season leading to increased catchment runoff and higher river levels leading to fluvial flooding which can damage linear assets.
* Surface water flooding which may be exacerbated by preceding low rainfall / drought conditions and hardened soils in combination with storm events leading to flash flooding. This can impact foundations for linear infrastructure as well as access for maintenance or response.

#### Summary

Table .: Highest risk severity for 2050s for power network – linear infrastructure

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 2M | Higher wind speeds | High winds and storms impacting on linear infrastructure (overhead power lines, cables), both directly and indirectly via debris which may be exacerbated by increased vegetation growth. Cascading impacts to power supply for rail infrastructure (e.g. tracks). | Rail infrastructure – tracks, boundaries, crossings | 4 | 4 | 16 |
| 2N | Higher wind speeds | High winds and storms impacting on linear infrastructure (overhead power lines, cables), both directly and indirectly via debris which may be exacerbated by increased vegetation growth. Cascading impacts to power supply for highways and roads. | Highways and roads – predominantly street lighting, traffic lights and signage | 4 | 4 | 16 |

The highest severity risks identified are in relation to higher wind speeds and debris impacting on overhead power lines and cables. These risks are also dependent on the management of vegetation, which may be the responsibility of other landowners beyond the power sector. Consequence scores assume a loss of power and are therefore considered to be similar to those outlined in Section 2.3.1 for power grid capacity and resilience. However, the overall scores are different due to a difference in likelihood and adaptation responses within the power sector and the climate variables involved (e.g. wind rather than temperature).

Scores for the present day are highest for climate interdependency risks impacted by high wind speeds, with fluvial flood risk also of moderate concern. Risk severity generally trends upwards for both likelihood and consequence in the 2050s and 2080s.

### Interface 3: Power network - substation assets and cables

#### Explanation of interface and key pathways

Impacts to power network assets such as substations and underground cables (which London has a higher proportion of relative to overground cables), can also lead to cascading impacts to power supply for the London LBTS.

These assets are vulnerable to a high number of climate hazards, including:

* Extreme high temperatures impacting on asset integrity within substations and performance thresholds for transformers, circuit breakers and cables which may be temperature limited.
* Frozen precipitation leading to more freeze-thaw weathering and erosion leading to ground movement and impacts to structural foundations and asset integrity for substations and underground cables.
* Larger diurnal or short-term temperature variation causing ground movement and impacts to structural foundations and substation asset integrity.
* Higher average rainfall over a season leading to increased catchment runoff and higher river levels leading to fluvial flooding which can damage substation assets. This also includes the potential for groundwater flooding and impacts on power tunnels which carry cables as part of the transmission and distribution network.
* Surface water flooding caused by a combination of low rainfall / drought and hardened soils in combination with storm events leading to flash flooding, impacting on asset integrity and access.
* Storm surges, sea level rise and extreme tides separately or in-combination causing tidal flooding if FRM assets are overtopped, impacting on asset integrity and access.

#### Summary

Table .: Highest risk severity for 2050s for power network – substation assets and cables

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 3A | Extreme high rainfall in a single event | Extreme rainfall leading to surface water flooding. Can be exacerbated if occurring in summer after a period of low rainfall or drought leading to reduced soil moisture. Impacting on asset integrity and access. Cascading impacts to power supply for rail infrastructure (e.g. tracks). | Rail infrastructure – tracks, boundaries, crossings | 4 | 4 | 16 |
| 3B | Extreme high rainfall in a single event | Extreme rainfall leading to surface water flooding. Can be exacerbated if occurring in summer after a period of low rainfall or drought leading to reduced soil moisture. Impacting on asset integrity and access. Cascading impacts and loss of power for road signage. | Highways and roads – predominantly street lighting, traffic lights and signage | 4 | 4 | 16 |
| 3E | Extreme high temperatures | Extreme high temperatures impacting on asset integrity within substations and performance thresholds for transformers, circuit breakers and cables which may be temperature limited. Cascading impacts to power supply for rail infrastructure (e.g. tracks). | Rail infrastructure – tracks, boundaries, crossings | 4 | 4 | 16 |
| 3F | Extreme high temperatures | Extreme high temperatures impacting on asset integrity within substations and performance thresholds for transformers, circuit breakers and cables which may be temperature limited. Cascading impacts and loss of power for road signage. | Highways and roads – predominantly street lighting, traffic lights and signage | 4 | 4 | 16 |

The highest severity climate risks relate to extreme high temperatures and variables leading to surface water flooding. Likelihood scores are lower relative to those for linear assets, to account for redundancy within the network and the LBTS’ own distribution assets (e.g. substations, cables owned by TfL) which mean that supply can be more easily switched if required. This increased resilience results in impacts which are more localised and shorter in duration.

The high temperature scenarios reflected in 3E and 3F also present the potential for wider in-combination impacts with power grid capacity and resilience. For example, in an extreme scenario where high cooling demand was placed on the grid, both the higher demand and the impacts to asset integrity could increase the overall risks to power supply for the LBTS.

We see a trend for risk increase across all time horizons, which can be attributed to both projected climate change (increase in temperatures, droughts, precipitation) and a lack of adequate action.

### Interface 4: Telecoms network

#### Explanation of interface and key pathways

Many LBTS operations are dependent on the telecoms network operated by external providers, such as BT, Sky, EE, Motorola and others. The resilience of this external network is then essential for enabling communications between staff and from staff to the public. In some cases, communications with emergency services are also reliant on the external network. However, not all LBTS organisations will be equally affected by a telecoms outage, as there are some examples of telecoms systems which are entirely separate from external providers (e.g. the GSM-R system used by the Elizabeth Line[[19]](#footnote-20)). Impacts to the LBTS are broadly categorised as the loss of ability to communicate with staff and road users on highways and road and with staff and passengers in built environments (especially stations).

Climate hazards which impact telecoms include:

* Fluvial flooding caused by increased catchment runoff and higher river levels leading to damage and functioning of telecoms assets (exchange centres, street cabinets, data centres) critical to the network.
* Surface water flooding caused by combination of low rainfall / drought and hardened soils followed by storm events and flash flooding leading to damage to telecoms assets (exchange centres, street cabinets, data centres) critical to the network.
* High winds and storms impacting on telecoms assets (masts, cables) critical to the network.
* Extreme high temperatures impacting on assets such as underground cables and cooling requirements for exchange and data centres.

It is also noted that the telecoms sector has a high level of dependency on the power sector (e.g. to provide cooling) and the three interfaces discussed above, although the scoring of these risks is beyond the scope of this risk assessment.

#### Summary

Table .: Highest risk severity for 2050s for telecoms network

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 4B | Extreme high rainfall in a single event | Extreme rainfall leading to surface water flooding. Can be exacerbated if occurring in summer after a period of low rainfall or drought leading to reduced soil moisture. Leading to damage to telecoms assets (exchange centres, street cabinets) critical for communications and passenger safety. | Built environments - buildings, stations, depots, head offices and property/developments | 4 | 4 | 16 |
| 4F | High average rainfall over season | Fluvial flooding caused by increased catchment runoff and higher river levels. Leading to damage to telecoms assets (exchange centres, street cabinets) critical for communications and passenger safety. | Built environments - buildings, stations, depots, head offices and property/developments | 4 | 4 | 16 |

Due to lack of information surrounding each LBTS organisation’s relationship with external telecoms providers and a lower level of engagement with stakeholders from within the telecoms sector, risk scores are provided with a lower level of confidence.

The highest risk severities have been assigned to both surface water flooding and fluvial flooding risks to telecoms assets, with consequence scores driven by health and safety concerns. For example, failure of communication systems in stations preventing information from reaching passengers and safe evacuations. The potential for cascading disruption across multiple stations means that performance impacts are assessed to be higher for built environments on the rail network than for highways and roads. However, there are also safety risks on high speed roads and the potential that emergency services cannot be called on time.

It is worth noting that there are currently changes in the way that telecoms and emergency communications networks are being configured, with the current Tetra trunk network being replaced by Long Term Evolution (LTE), as well as the copper wire (Public Switched Telephone Network (PSTN)) comms networks being discontinued. However, it is expected that prioritisation of service would take place for emergency service communications if a shared network was used. This has been reflected in risk scores related to emergency service callouts.

​Increasing severities from present day through to the 2050s and 80s are primarily driven by higher likelihood scores associated with projections increasing for wind, temperature and precipitation. Some adaptation has been noted in regard to resilience measures (e.g. ‘Cells-on-wheels’ moveable masts which can be used during a hazard event[[20]](#footnote-21)). In addition, potential adoption of the Future Rail Mobile Communication System (FRMCS)[[21]](#footnote-22) would provide industry standardisation which may benefit joint adaptation approaches, although this could also lead to a more concentrated risk position.

### Interface 5: Civil structures

#### Explanation of interface and key pathways

The congested nature of infrastructure within London means that many LBTS assets are in close proximity to civil structures ] owned by boroughs or other private landowners. Impacts to these structures can then trigger cascading impacts to rail and road infrastructure through debris being washed into tunnels or onto carriageways and access roads forcing road, track and station closures.

Climate hazards that impact this interface include:

* Higher average rainfall over a seasonleading to increased catchment runoff and higher river levels causing fluvial and/or groundwater flooding**.** Leading to damage to civil structure foundations and asset integrity through tunnel water ingress or sudden bridge collapses in extreme cases.
* Frozen precipitation and freeze-thaw weathering leading to ground movement and damage to civil structure foundations and asset integrity (e.g. bridges, subways).
* Large diurnal and short term temperature changes causing weathering and erosionleading to ground movement and damage to civil structure foundations and asset integrity.

Fluvial flooding and tidal flooding are considered as the primary flood risk due to their erosion power and ability to move material at a larger scale than surface water flooding.

#### Summary

Table .: Highest risk severity for 2050s for civil structures

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 5C | High average rainfall over season | Higher average rainfall over season leading to increased catchment runoff and higher river levels causing fluvial and/or groundwater flooding. Leading to damage to civil structure foundations and asset integrity through tunnel water ingress or sudden bridge collapses in extreme cases. Damage to track infrastructure potentially leading to closure. | Rail infrastructure - tracks, tunnels, boundaries, structures | 4 | 5 | 20 |
| 5D | High average rainfall over season | Higher average rainfall over season leading to increased catchment runoff and higher river levels causing fluvial and/or groundwater flooding. Leading to damage to civil structure foundations and asset integrity through tunnel water ingress or sudden bridge collapses in extreme cases. Damage to highways, roads and streets potentially leading to closure. | Highways, roads, streets, access points, carriageways, pavements, cycleways, street lighting, traffic lights and signage | 4 | 4 | 16 |

The highest severity risk for this interface relates to impacts from fluvial flooding and the potential to erode or damage civil infrastructure and wash debris onto roads and tracks leading to high consequence scores for health and safety. Likelihood scores are high due to the many roads and tracks that are in close proximity or traverse structures owned by other organisations within London. Consequence scores are slightly higher for rail infrastructure due to the assumption that a lower proportion of road assets are dependent on third party civil infrastructure.

General trends for present, 2050s and 2080s are for likelihood scores to increase driven by increased precipitation and fluvial flooding.

### Interface 6: Pipe bursts

#### Explanation of interface

Pipe bursts are a key upstream interdependency for the LBTS, with the sector dependent on the resilience of water company (primarily Thames Water and Affinity Water) pipe assets which are in proximity to LBTS infrastructure. In general, stakeholders highlighted that Thames Water assets are located nearer to rail infrastructure and Affinity Water to highways infrastructure.

Climate hazards that impact this interface include:

* Low temperature events which lead to low water temperatures increasing pipe brittleness and vulnerability to bursts.
* Greater diurnal and short-term temperature variation due to an increase in both cold and hot temperature extremes. These impacts can both cause deterioration of pipes through movement of the ground around pipes or direct impacts to the assets themselves.
* Low rainfall and drought can also lead to soil moisture changes and ground movement as a result of reduced groundwater levels, impacting on brittle pipes. The high proportion of clay soils within London are also more vulnerable to changes in soil moisture.

Bursts on water mains and distribution network assets are a particular concern in London due to the congested nature of infrastructure. Asset age and material (e.g. high proportion of cast iron mains) also increase their susceptibility to bursts. Examples of these risks occurring include the burst water main on Blackfriars Road in January 2020 which temporarily closed Southwark tube station and diverted bus routes. Impacts of pipe bursts on the LBTS can be categorised primarily as:

* Bursts which lead to surface water flooding events leading to the closure of highways and roads, as well as stations if access roads are impacted.
* Bursts which impact directly on track infrastructure or lead to tunnel water ingress and closure of tracks.
* Bursts which cause interruption to supply (ITS) events for built environments (e.g. offices, stations) where water is not available for customers or staff.

#### Summary

Table .: Highest risk severity for 2050s for pipe bursts

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 6A | Large diurnal temperature range | Increased diurnal temperature variation and cycling causes ground movement and direct impacts to pipes leading to bursts. May impact directly on track infrastructure or lead to tunnel water ingress and closure of tracks. | Rail infrastructure - tracks, tunnels, boundaries, structures | 3 | 4 | 12 |
| 6D | Low rainfall / drought | Low rainfall and drought can also lead to soil moisture changes and ground movement as a result of reduced groundwater levels, impacting on brittle pipes. May impact directly on track infrastructure or lead to tunnel water ingress and closure of tracks. | Rail infrastructure - tracks, tunnels, boundaries, structures | 3 | 4 | 12 |

* The highest risk severities are associated with an increase in climate driven changes to soil moisture and ground movement leading to high likelihood scores. Consequence scores primarily relate to performance impacts for infrastructure if tunnels or tracks become flooded as a result of bursts.
* However, as with all interdependencies assessed, in many cases climate hazards exacerbate existing risks to pipes and may not be the primary cause of the failure. In particular, the location of bursts on the network determines consequences, as a burst in proximity to a busy part of the line or station would have greater impacts.
* Scores for this interface are comparably lower than others due to the prominence of managing leakage and bursts within Affinity Water and Thames Water’s adaptation plans. However, as these plans do not extend beyond 2050 the risk is assessed to increase again beyond this point. Likelihood scores also increase for drought/low rainfall and diurnal temperature variation risks due to projections indicating an increase in these climate variables. Conversely, low temperature risks decrease over the time period due to warming temperatures.

### Interface 7: Urban drainage system and combined network

#### Explanation of interface and key pathways

If urban drainage systems and the combined network are overwhelmed, this can lead to surface water flooding impacting on the LBTS. This interface covers all external organisations that own drainage assets above ground and considers the combined sewer network owned by Thames Water and other organisations which operates in Central London. This interface considers urban drainage capacity but also the requirements for better maintenance and accurate data on the network, which were highlighted as a key issue. In recognition of the intersectoral challenge posed by surface water flooding, TfL and other organisations such as Thames Water, the Greater London Authority and the Environment Agency already work together as part of the London Surface Water Flooding Strategic Group.

Climate hazards that impact this interface include:

* Low rainfall and drought leading to reduced soil moisture and hardened ground, which is more susceptible to surface water flooding during high rainfall storm events. This leads to high levels of urban runoff impacting on urban drainage.
* An increase in sea level rise, extreme high tides, storm surges either individually or in combination leading to elevated tide levels. This can lead to tidal locking limiting outfalls and sluices used to discharge from the drainage and sewer network, reducing drainage capacity and contributing to surface water flooding.
* Higher average temperatures could also lead to a lengthened growing season and increased vegetation growth and die-off in drought impacting on maintenance of drainage network (due to blocking of gullies) and contributing to surface water flooding.

Surface water flooding can cause significant disruption to the LBTS’ operations with impacts grouped under the following categories:

* Impacts to earthworks (road and rail embankments and cuttings) potentially causing collapse and loss of service.
* Impacts to built environments by preventing access to stations and workplaces, as well as leading to health and safety risks through increased slips, trips and falls.
* Impacts to infrastructure through flooding of tracks and tunnel water ingress leading to loss of service.
* Impacts to the road network through closures and diversions required, as well as slippery surfaces leading to a rise in accidents.

#### Summary

Table .: Highest risk severity for 2050s for urban drainage system and combined networks

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 7K | Sea level rise / extreme high tides / storm surges | Tidal locking limiting outfalls and sluices from drainage and sewer network, contributing to surface water flooding. Impacts to built environments and access to stations and workplaces. | Built environments - buildings, stations, depots, head offices and property/developments | 4 | 4 | 20 |
| 7I | Sea level rise / extreme high tides / storm surges | Tidal locking limiting outfalls and sluices from drainage and sewer network, contributing to surface water flooding. Impacts to infrastructure (tracks, tunnel water ingress) and loss of service. | Rail infrastructure - tracks, tunnels, boundaries, structures | 4 | 4 | 20 |

Urban drainage and surface water flooding cover a number of complex system interactions with climate risks. Primarily, surface water flooding occurs during periods of intense rainfall on impermeable surfaces such as concrete or hardened soils. However, due to many of London’s drainage network outfalls being located along the Thames estuary, potential in-combination interactions with higher tides are expected to increase in frequency. This is already noted as an issue by Thames Water and can lead to sewer flooding as well[[22]](#footnote-23).

Likelihood scores for these risks assume that tidal locking occurs in conjunction with a period of high rainfall and runoff. Consequence scores are weighted towards performance impacts and are highest for built environments and infrastructure, which if flooded may lead to disruption and loss of service, in addition to health and safety risks.

Scores generally increase from the present day through to the 2080s due to the projected increase in climate hazard, although they are balanced somewhat in the 2050s due to planned uptake of Sustainable Drainage Systems (SuDS) as an adaptation measure (e.g. 7,000 hectares of SuDS planned as part of Thames Water’s DWMP).[[23]](#footnote-24)

### Interface 8: Vegetation and green infrastructure

#### Explanation of interface and key pathways

Green infrastructure assets are owned and managed by stakeholders such as; London Boroughs, the Environment Agency, and private landowners. Vegetation can provide benefits through shading, carbon sequestration, runoff attenuation and improvements to soil health and structure. Trees in urban areas can also provide an amenity and recreation benefit and improve air quality. However, if these assets are poorly managed and in close proximity to rail or road infrastructure then they can negatively impact on operations.

Climate variables that impact this interface include:

* Higher average temperatures and higher average rainfall leading to an extended growing season. This increases the likelihood of leaves being on trees when autumn and winter storm events occur, increasing the overall risk of leaf fall onto tracks, roads and station platforms. This can also increase the growth of vegetation and tree roots which can damage road surfaces or impact on building structures.
* Higher wind speeds leading to more tree and leaf fall onto tracks (which could cause problems to wheel adhesion and risk derailment), roads and station platforms.

There is also the potential for maladaptation in the planting of trees and other green infrastructure as part of LBTS and external initiatives and strategies (e.g. the London Plan) to increase shading. However, if vegetation is not managed appropriately then this leads to an increase in likelihood for the hazards above.

Impacts to the LBTS can be categorised as:

* Impacts to built environments through the risk of leaf fall onto station platforms presenting a safety risk through increased slips, trips and falls.
* Impacts to highways and roads through larger debris on carriageways leading to road closures and disruption, and leaf fall reducing tyre adhesion and so increasing accident risk. Tree roots and growth may also damage road surfaces leading to additional maintenance costs.
* Impacts to infrastructure as a result of tree fall onto tracks leading to line closures and disruption and fines e.g., Network Rail can be fined by Train Operating Companies if trains cannot be run. Leaf fall can also reduce wheel track adhesion, and damage wheels, leading to speed restrictions and delays.

#### Summary

Table .: Highest risk severity for 2050s for vegetation and green infrastructure

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 8D | Higher average rainfall and higher average temperatures combined with storm events | Increased length of growing season to coincide with autumn/winter storm events leading to increased risk of leaf fall onto tracks reducing wheel track adhesion and causing delays if the line is closed due to a tree across the tracks. | Rail infrastructure - tracks, tunnels, boundaries, structures | 4 | 4 | 16 |

The highest risk severities for this interface are associated with the risks of leaf fall onto tracks, with consequence scores driven by performance impacts due to delays. Likelihood scores are increased due to policy drivers for ‘greening’ London, although evidence of adaptation measures to manage impacts from tree and leaf fall are also considered (e.g. fences to trap leaves).

However, risk severity still increases across the time horizons due to projected changes for in-combination climate hazards whereby higher rainfall and temperatures lead to an extended growing season to coincide with storm events.

### Interface 9: Banksides and slopes

#### Explanation of interface and key pathways

In some cases, LBTS assets such as tracks and roads run adjacent to riverbanks or slopes which are managed by other organisations such as London Boroughs, the Environment Agency and other private landowners. Damage to these slopes or banks (e.g. in the form of landslides) can cause impacts to the LBTS. This is a particular concern within London due to the high proportion of clay soils which are prone to landslides in time of heavy rainfall or after drought.

Climate hazards which impact on this interface include:

* High average rainfall over a season which may increase soil moisture leading to landslide risks.
* Low rainfall/drought leading to low soil moisture and reduced vegetation cover, impacting on slope stability and increasing landslide risk.

#### Summary

Table .: Highest risk severity for 2050s for banksides and slopes

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 9A | High average rainfall over season | Higher rainfall may increase landslide risk. Landslide impacts to critical rail infrastructure (e.g. tracks, tunnels). | Rail infrastructure - tracks, tunnels, boundaries, structures | 4 | 4 | 16 |

The highest risk severities for this interface were associated with landslide risks caused by either low rainfall/drought conditions or high rainfall. Rail infrastructure were given higher consequence scores due to the relatively greater performance impacts and disruption associated with route closures on rail networks, with the assumption that road users would have more alternative diversion options.

The general trend is towards increased risk from present day to 2080s due to the lack of identified adaptation across the non-LBTS organisations and increasing projections for precipitation.

### Interface 10: FRM assets

#### Explanation of interface and key pathways

Many organisations within the LBTS have critical assets located along the Thames Estuary that are protected by flood defences, such as the Thames Barrier operated by the Environment Agency and The Embankment. However, climate change might require these defences to be used more frequently and their levels to be raised and increases the likelihood of tidal flooding events impacting on the LBTS. This interface also considers FRM assets which are required in upstream areas where fluvial and flash flooding in valleys can also occur (e.g. Teddington).

The climate hazards that impact on this interface are sea level rise, storm surges and extreme high tides. These have been grouped within the risk assessment based on their in-combination contribution to tidal flooding as a hazard. If overall tide levels rise beyond the level accounted for within the design of the Thames Barrier and other defences within the Thames Estuary (TE) 2100 plan then overtopping would occur.

#### Summary

Table .: Highest risk severity for 2050s for FRM assets

| ID | Climate variable | Impact description | Asset | L | C | Total |
| --- | --- | --- | --- | --- | --- | --- |
| 10D | Sea level rise / extreme high tides / storm surges | Tidal flooding caused by higher tide levels leading to overtopping of FRM assets and defences impacting on earthworks e.g. stability of rail and road embankments and cuttings | Earthworks | 2 | 5 | 10 |

The highest risk severities were associated with overtopping of FRM assets impacting on earthworks leading to tidal flooding and damage to road and rail assets. Consequence scores are driven by performance and financial impacts due to the potential for large scale damage across the estuary if key flood defences were to fail. Scores have assumed that adaptation measures included within the Thames Estuary 2100 plan will be implemented (e.g. flood defences downstream of the Thames Barrier will have been raised by a further 100cm to 150cm by 2070) and therefore the likelihood is considered to be low. Similarly, fluvial flood risk scores have assumed the implementation of the River Thames Scheme[[24]](#footnote-25).

This means that the risk profile does not increase significantly across the 2050s time horizon, as although projections for sea level rise increase, further adaptation measures are expected to manage the increasing hazard. However, high consequence scores mean that overall risk will increase significantly if tidal flood defences are not funded or implemented as currently planned.

Other impacts to the LBTS that have been scored include**:**

* Impacts to highways and roads through closures
* Impacts to infrastructure such as tunnels, tracks and crossings causing line closures and service disruption
* Impacts to built environments through station closures and damage to control centres, depots and stations.

## Co-dependencies

In several cases, TfL and other members of the LBTS also own assets which may contribute to areas of interdependency identified above. These function as a two-way relationship where the LBTS also contributes to the organisational interface and management of risk.

Key examples of these co-dependencies include:

* **Vegetation management** – LBTS stakeholders also maintain their own lineside and roadside green infrastructure assets. Pruning and management of vegetation takes place as part of maintenance programmes. Management of green infrastructure is significant for climate change adaptation due to the shading provided by trees which help to mitigate against the impacts of high temperatures on track infrastructure and rolling stock. Other benefits include water attenuation and lowering of the urban heat island effect. TfL also manage green infrastructure as part of the Healthy Streets approach[[25]](#footnote-26) to improve shading on streets. If vegetation is not managed appropriately this can impact on the LBTS and other sectors.
* **Civil structures –** LBTS assets such as tunnels, roads and bridges can also be damaged and lead to impacts to pipes or cables owned by other stakeholders such as Thames and Affinity Water.
* **Urban drainage capacity** – LBTS stakeholders maintain their own drainage assets which also contribute to the overall capacity of the system. This means that the potential for the combined network to become overwhelmed is also dependent in part on the LBTS maintaining their own drainage assets to reduce the total volume of runoff. Water quality impacts from overflowing drainage and highways runoff can also constitute a significant downstream interdependency for catchment management. This is an issue especially in outer London where the drainage network empties directly into rivers, rather than into treatment plants.

## Downstream interdependencies

Downstream interdependencies may arise when rail or road services are impacted by a climate hazard compromised and are unable to deliver goods or services as required for other users. These interdependencies were not included within the scope of the risk assessment. However, they were still collated and discussed with stakeholders during focus groups to understand the cascading impacts from the transport sector to other sectors. These are categorised as follows:

* **Impacts on staff availability -** disruption or closures to rail or road networks leading to cascading impacts across multiple sectors, including but not limited to power, water and telecoms if staff are unable to get to work.
* **Supply chain impacts** - the transport network is critical to providing supplies of fuel, chemicals and other materials which are required for the operation of assets such as power stations, treatment works, ports and airports.
* **Waste disposal -** many other sectors rely on the transport sector and the maintenance of highways and roads for waste disposal from sites. Inability to dispose of waste may lead to public health and environmental risks.
* **Access for emergency services -** closures to highways and roads will impact on the ability of emergency response units to respond in a timely manner with resulting impacts to health and safety.
* **Access to health services** **-** closures to highways and roads will impact on hospitals due to delayed admission or access for patients.
* **Access to airports -** Over 2 million passengers a year use public transport to travel to Heathrow Airport, with many of these journeys dependent on LBTS rail or road assets[[26]](#footnote-27). Road or rail closures can lead to economic impacts through delayed or missed flights.
* **Train operating companies (TOCs) -** track or station closures may mean that TOCs cannot run their services.
* **Local businesses** - kiosks and shops inside stations or nearby may be impacted by station closures with resulting economic impacts to communities.
* **Power grid back up capacity -** Greenwich power station owned by TfL and other embedded generation operated by the LBTS can provide back-up capacity for the wider grid during times of high demand.

# Prioritised actions

A total of 52 actions were co-created by stakeholders to reduce the risk from climate hazards to the key organisational interfaces and adapt to climate change. This section summarises our priority actions and the timescales we recommend for delivery.

The long list of actions is outlined in Appendix H and have been grouped following the TfL’s ARP3 categorisation, with the number of actions in each category indicated with the number of actions in each category indicated below:

* Capital and operational delivery (5)
* Collaboration, communication and reporting (5)
* Information management (10)
* Leadership and governance (15)
* Organisation and people (6)
* Risk management (11)

We have applied our prioritisation framework (see Table 2.7) to identify high priority actions that can be implemented over the short (1 year), medium (2-4 years) and longer-term (5+ years). Our priority actions to do not include a cost-benefit analysis and will require additional consideration of funding mechanisms for implementation.

The objective for delivering these priority actions is two-fold:

1. Deliver more impactful actions to address the key climate interdependency risks identified in this study
2. Reduce redundancy across organisations from duplicated investments in adaptation

Figure 4.1 summarises our priority actions for reducing climate interdependency risks. It follows the climate interdependency risk infographic (see Figure 3.1) through linking the relevant climate hazards and organisational interfaces to the recommended actions. This indicated potential stakeholders who could be involved in implementing actions.

Short-term actions are include those which are within the LBTS level of control, considered to have sufficient skills and capacity available to implement, and align with current regulatory and planning cycles. Medium-term actions focus on areas which are already in development but may require additional capacity building, stakeholder engagement or regulatory support to implement efficiently. Longer-term actions include those where there is no precedent and require a greater level of coordination, resourcing and co-funding.

Delivering the shorter-term actions would build collaboration and communication across organisations to help facilitate delivering the longer-term actions. For example, sharing outputs from current research on landslide and embankment failure could help inform adaptation measures within organisations (short-term action). This could help inform training for trackside maintenance colleagues to understand the benefits (and risks) of green infrastructure to reduce landslide risk (medium-term). This could then inform the development of best practice of vegetation and green infrastructure (medium-term), which feeds into the establishment of urban greening initiatives to adapt to future climate hazards (longer-term action).

We highlight the importance of green infrastructure related actions. Interventions such as tree planting, SuDS and other nature-based solutions form an essential part of the net zero agenda and adaptation to multiple climate risks, such as flooding and heat. Additional benefits can also be derived such as improved air quality, amenity and biodiversity. Therefore, these actions scored highly against the prioritisation criteria, as they represent win-win and/or multiple benefit options and can be seen as priority investments. However, actions to address maintenance and management are just as important to avoid any unintended consequences for other climate hazards or organisations. For example, discussions with the GLA and previous engagement between the transport sector and Forestry Commission have pointed to potential adaptation through planting tree species that do not hold leaves during the storm season[[27]](#footnote-28). Developing a clear set of principles for green infrastructure management for London’s asset owners would also provide guidance on the relative prioritisation of different trade-offs (e.g. safety v carbon sequestration or biodiversity). These actions need to be deployed in the most effective way possible to ensure adaptation to a variety of climate related risks.

Creating a culture of multi-sector collaboration can avoid unintended consequences from adapting to one climate risk in one organisation whilst creating a risk to another organisation’s asset. For example, stakeholders referenced an example where the diversion of flood water from temporary works within the transport sector led to the collapse of a National Grid-owned tower along a riverbank. Therefore, we also highlight the need to improve sharing of data between the LBTS group and other sectors. In this regard, risks from pipe bursts in the water sector could be addressed through an improved understanding of network vulnerabilities. This could be achieved through using existing data exploring vulnerabilities to flooding within the TfL network (such as outputs from the London Comprehensive Review of Flood Risk (LCRFR)), coupled with Thames Water’s own network map which shows key receptors and their locations relative to pipe assets.

In the long term, our assessment has shown the need for a shared risk register or database. This will support cross-sectoral collaboration and help organisations to recognise the challenges that climate impacts can have across multiple sectors at any one time. Through a shared risk register, opportunities to respond to and mitigate risks can be jointly identified and solutions co-created and co-funded. This approach would also support the delivery of more co-ordinated investments in climate adaptation and resilience, leading to greater efficiency.

Establishing a shared risk register, and beyond that the collective recognition of risks and funding of solutions across sectors will require support beyond TfL and the TASG from regulatory bodies and increasing alignment of regulatory planning and investment cycles and determinations. For example, at present organisations identify risks and seek funding for reductions discretely to their relevant regulator. Where there is a shared or common risk that can be addressed for multiple organisations or sectors at the same time, we propose that a joint investment approval process that allows regulatory bodies to make joint determinations, underpinned by a robust shared risk register, would be effective. This enables a more granular understanding of common benefits. It also avoids redundancy of solutions and delivers a more effective and efficient solution for all customers.

Figure .: Infographic showing prioritised actions for key climate interdependency risks

The figure shows the recommended actions from the interdependencies project for three time frames: short-, medium- and long-term. A total of 52 actions were co-created by stakeholders to reduce the risk from climate hazards to the key organisational interfaces and adapt to climate change. This figure summarises the priority actions and the timescales recommended for delivery. The priority actions have been grouped according to the six themes from the TfL Climate Change Adaptation Plan: Capital and operational delivery; Collaboration, communication and reporting; Information management; Leadership and governance; Organisation and people; and Risk management. Each action was further categorised for the main climate hazard it relates to (All climate hazards, surface water flooding, high temperatures and heatwaves, high winds and storms, drought and wildfires, landslides, tidal flooding).  

The priority actions for the short term (1 year) are: 

For the risk management theme:  

Collect data during maintenance visits on assets most at risk from surface water flooding (related climate hazard: surface water flooding); 

For the leadership and governance theme: 

Incentivise a larger role for NBS, NFM and green corridors to help London’s road and rail sector adapt to multiple climate risks and deliver co-benefits in areas such as biodiversity and amenity (related climate hazard: all climate hazards),  

Contribute to GLA SuDS marketplace initiative (related climate hazard: surface water flooding); 

For the information management theme: 

Ensure the outputs of Network Rail research into landslide and embankment failure are shared with other asset owners to inform their own risk and adaptation measures (related climate hazard: landslides),  

Exploring data sharing models to improve current methods of sharing data. Consider contributing to Digital Twins such as CreDo (related climate hazard: all climate hazards); 

For the organisation and people theme: 

Train sponsors and project managers on the importance of keeping SuDS in project design (related climate hazard: surface water flooding); 

For the collaboration, communication and reporting theme: 

Collaborative communications, warnings between organisations and working together to mitigate impacts. Build on collaborative examples such as the Surface Water Flooding Strategic Group and the Infrastructure Operators Adaptation Forum (related climate hazard: all climate hazards); 

For the capital and operational delivery theme: 

Contribute to Thames Estuary 2100 plan updates including risk assessments and benefits assessments to support upgrading of flood defences (related climate hazard: tidal flooding). 

The priority actions for the medium term (2 to 4 years) are: 

For the risk management theme:  

Ensure planning assumptions for extreme heat are aligned across power, rail and road organisations (related climate hazard: high temperatures and heatwaves), Understand existing and future adaptation of the assets London’s road and rail sector rely on (related climate hazard: all climate hazards); 

For the leadership and governance theme: 

Lobby for changes to building regulations to manage risk from high temperatures.  

(related climate hazard: high temperatures and heatwaves), Open-access tools for making the business case for investing in green infrastructure and nature-based solutions (related climate hazard: all climate hazards), Join up adaptation investment to avoid unnecessary redundancy (related climate hazard: all climate hazards); 

For the information management theme: 

Developing best practice for management of vegetation and green infrastructure. For example, building on existing conversations with Forestry Commission and sharing across sectors (related climate hazard: all climate hazards);  

For the organisation and people theme: 

Training for trackside maintenance colleagues to understand the benefits (as well as risks) of green infrastructure to reduce landslide risk (related climate hazard: landslides); 

For the collaboration, communication and reporting theme: 

Contribute to reporting for all sectors currently undertaking their own interdependencies study and prioritise where there are knowledge gaps, such as telecoms sector (related climate hazard: all climate hazards); 

The priority actions for the long term (5 plus years) are: 

For the risk management theme:  

Investigate co-funding opportunities for vegetation management to mitigate shared risks to assets (related climate hazard: drought and wildfires), Invest in co-funding models for asset adaptation which have shared risks (related climate hazard: all climate hazards); 

For the leadership and governance theme: 

Establish urban greening initiatives to adapt to temperature fluctuations. TfL’s Green Infrastructure and Biodiversity Plan could support this (related climate hazard: high temperatures and heatwaves), Create shared risk registers to identify joint risks and co-create/ co-fund risk adaptation where a single solution can deliver benefits for wider interfaces (related climate hazard: high winds and storms); 

For the organisation and people theme: 

Develop understanding of the design/ operation and performance of non-traditional solutions. For example, implementation issues and business case opportunities (related climate hazard: high temperatures and heatwaves). 

# Conclusions and next steps

## Summary and recommendations

Overall, the project presents both a significant contribution to ARP4 submissions for the LBTS, and also provides a new approach to assessing climate interdependency risks. Combining a systems approach with the established climate risk assessment process has ensured an innovative and rigorous process to the collation and analysis of climate interdependency risks. Undertaking stakeholder engagement across all stages of the project has created a co-learning process which has developed cross-sectoral relationships and a shared understanding of the risks facing London’s infrastructure.

Outputs from this assessment have focused on the key interfaces which have been identified as priorities by stakeholders. This presents a more pragmatic approach then a purely hypothetical assessment of all potential cascading failures across a system which has typified previously analysis of climate and interdependency risk. At the same time, the system mapping that has been undertaken ensures that the value of collective thinking and ‘brainstorming’ of potential risks is not lost but has been synthesised to a more manageable output.

The findings provide a platform for further exploration of climate change and interdependency risks for the London LBTS. However, we also note the varying levels of confidence in risk scoring (e.g. lower for telecoms risks) and the need to review this scoring periodically as more data becomes available. Nevertheless, this project presents a summary of much of the available evidence on climate interdependency risks to key infrastructure assets for the London LBTS.

Developing a more complete understanding of how climate interdependency risks will impact on London beyond the LBTS will require the support of actors beyond TfL and the TASG. We highlight the following recommendations:

* Greater regulatory commitment to co-ordinating cross-sectoral working groups. TfL and the TASG have taken a lead in this regard to the benefit of the transport sector and other sectors. However, the ‘pulling power’ of one organisation or sector to convene and address a multi-sectoral problem is limited. Making the ARP4 a requirement rather than a voluntary process would go some way to addressing this.
* The creation of opportunities for co-funding of appraisals for climate adaptation across regulatory groups in each sector.
* Standardising the use of data sharing tools to support in identifying pressure points across the entire system. Stakeholders highlighted that this approach needs to be streamlined to minimise wasted time in configuration leading to redundant efforts.
* Dissemination of best practice guidance for the maintenance and management of green infrastructure given its prominence in climate adaptation.

We also recommend conducting a cost-benefit analysis for the recommended actions to further support the prioritisation of actions and highlight the potential for multi-benefit solutions benefitting both the transport sector and others.

## Next steps

Our immediate recommendations for next steps for TfL are to encourage implementation of the short term actions identified in Section 4 which are applicable to all members of the LBTS.

Specific actions which could be progressed in the short term to address priority interdependencies include:

* Further engagement with the telecoms sector who are currently beginning their own ARP4 reporting progress with support from the Electronic Communications Resilience and Response Group (ECRRG) who engaged with this project. Undertaking an internal review of TfL’s own vulnerabilities would also be a starting point and would support the reporting process for the telecoms sector.
* Further engagement with Thames Water on mapping network vulnerabilities for TfL roads and rail.
* Data sharing and collaboration with UK Power on specific vulnerabilities within TfL’s distribution network.
* Supporting the Environment Agency with ongoing work to assess the risks and benefits of upgrading the Thames Barrier and other flood defences.
* Investigate the issue of groundwater flooding further. For example, the potential impacts of any chalk stream abstraction reductions upstream and any associated increase in groundwater levels and risks to subterranean assets.

This project sets a precedent in multi-sector collaboration to identify climate interdependency risks for the London LBTS. However, to fully assess cascading interdependencies across multiple sectors in London would require in depth knowledge of likelihood and consequence for assets and services in other sectors e.g. the exact nature of vulnerability between all power and all telecoms assets. This is beyond the scope of a project funded by the transport sector alone, although we recommend that a co-ordinated approach should be undertaken once all sectors have matured in their understanding of interdependencies.

1. Stakeholder summary

Table A.1: List of stakeholders who engaged with the project (attendance highlighted in grey)

| Stakeholder | System mapping focus groups | Workshop 1 - System mapping integration | Workshop 2 - Climate risk assessment | Workshop 3 – Risk reduction actions | Other (e.g. follow-up calls, forms, email exchanges) |
| --- | --- | --- | --- | --- | --- |
| Transport for London | **yes** | **yes** | **yes** | **yes** |  |
| HS2 | **yes** |  | **yes** | **yes** |  |
| HS1 | **yes** | **yes** | **yes** | **yes** |  |
| Department for Transport | **yes** | **yes** | **yes** | **yes** |  |
| National Highways | **yes** | **yes** | **yes** | **yes** |  |
| Network Rail | **yes** | **yes** | **yes** | **yes** |  |
| Office of Rail and Road (ORR) | **yes** |  | **yes** | **yes** |  |
| Defra | **yes** |  |  |  |  |
| National Grid | **yes** | **yes** |  | **yes** |  |
| UK Power Networks |  | **yes** |  | **yes** |  |
| Environment Agency | **yes** | **yes** |  |  | **yes** |
| Greater London Authority | **yes** | **yes** |  |  | **yes** |
| Affinity Water |  | **yes** |  | **yes** | **yes** |
| Thames Water | **yes** | **yes** |  |  | **yes** |
| Heathrow Airport |  |  |  |  | **yes** |
| Electronic Communications Resilience and Response Group (ECRRG) |  |  |  |  | **yes** |
| Motorola |  |  |  |  | **Y es** |

1. Documents reviewed

Table B.2: Documents reviewed

| Title | Type of document | Available online |
| --- | --- | --- |
| TfL Adaptation Reporting Power Submission 2021 | PDF | Y |
| TfL Adaptation Risk Assessment | Excel | Y |
| Network Rail Third Adaptation Report - December 2021 | PDF | Y |
| HS2 Climate Change Adaptation and Resilience | PDF | Y |
| National Highways Preparing for climate change on the strategic road network - third adaptation report under the Climate Change Act | PDF | Y |
| Affinity Water - Climate Change Adaptation Report 2021 | PDF | Y |
| Affinity Water Adaptation Report Addendum Report Part 2 Climate Change Interdependencies MM Document | PDF | Y |
| PLA - Climate Change Adaptation Report  Third Round Update | PDF | Y |
| Climate Change Adaptation Report National Grid Electricity Transmission July 2021 | PDF | Y |
| Third Round Climate Change Adaptation  Report National Grid Gas October 2021 | PDF | Y |
| Thames Water Climate Change Adaptation Report for 2015-2020 | PDF | Y |
| CCC Understanding climate risks to UK infrastructure  Evaluation of the third round of the Adaptation  Reporting Power - July 2022 | PDF | Y |
| Cadent Climate Change Adaptation Report Third Round Response December 2021 | PDF | Y |
| UKPN Climate Change Adaptation Report 16 December 2021 | PDF | Y |
| TechUK Report to DEFRA under the Adaptation Reporting Power Third Round December 2021 | PDF | Y |
| Heathrow Climate Change Adaptation Report  Third Round Progress Report January 2022 | PDF | Y |
| ITRC Resilience study research for NIC Systems analysis of interdependent network vulnerabilities Final Report April 2020 | PDF | Y |
| LoTAG Adaptation Risk Workshop slides | PPT | N |
| Borough workshop outputs | Excel | N |
| Interdependencies categories for risk assessment (Climate assessment) | Excel | N |
| NIC System analysis of interdependent network vulnerabilities | PDF | Y |
| WSP Interacting risks in infrastructure, the built and natural environments | PDF | Y |
| Defra Summary of responses and government response | Webpage | Y |
| Defra NAP3 and the fourth strategy for climate adaptation reporting | PDF | Y |
| Defra NAP3: Annex 1: Climate risks and opportunities | PDF | Y |
| SGN 3rd Round Climate Adaptation Report 2021 | PDF | Y |
| Environment Agency adaptation report: Living better with a changing climate | PDF | Y |
| NHS-UK health security agency: Health and care adaptation report 2021 | PDF | Y |

1. How to read and use system maps

Two system maps have been created for the purposes of this project.

1. The [**integrated system map**](https://kumu.io/SystemsECP/arp4idmmpsmv2-integrated#integrated-interdependency-map) which includes all key interdependencies and processes across the various sub-systems. Variations of this map were used within the system mapping focus groups and the integration workshop to collate and analyse interdependencies. Nodes or processes which were not considered to be relevant to the LBTS have not been included. This map functions as a stakeholder engagement tool and a record of conversations that took place across the project and is not intended as a final project deliverable in itself.
2. The [**climate interdependency risk** **system map**](https://kumu.io/SystemsECP/arp4idmmpsmv3-cra#cra-map) which contains only the relevant upstream interdependencies and simplified impact pathways used in the climate risk assessment. We recommend using this map in conjunction with the reviewing the risk assessment spreadsheet and summary findings in Section 3.
   1. Guide to using the integrated system map
      1. Basic principles

Systems maps comprise of nodes and links. To read a systems map, it is important to understand the nodes and links in the following ways:

* **Nodes** represent system functions or factors of which there can be more or less. For example, there can be more or less disrupted journeys, or an increase/decrease in the number of staff able to reach their workplace. Categories of nodes are shown in the legend and classified by colour and shape. In this case nodes have simply been classified as climate hazards, infrastructure, environment and social and economic according to their role within the system. More information on each node is provided on a panel to the left of the map which can be opened by clicking on three dots on the left of the map (close to the ‘L’ of Legend). The panel may be closed by clicking these dots when it is open – which creates more space for the map to be seen. When you click on a node, these three dots appear to vibrate, drawing attention to their location.
* **Links** represent correlations. Positive correlation links are shown using green arrows (more of A leads to more of B), negative correlation links using red arrows (more of A leads to less of B) and complex correlations using blue arrows. Complex interactions (or those which are uncertain due to lack of information) are shown in blue and represent interactions where there is no clear correlation one way or the other. Note that therefore green does not necessarily equal good and red does not equal bad.
  + 1. How to use the map – exploring the system

The integrated system map covers a total of seven sub-system areas identified through document review and the stakeholder engagement process. The map is structured so that the key LBTS sub-systems are at the centre of the map, with the other sub-systems around them. When the map is opened, the viewer is presented with the overlays for the sub-systems only. The key interdependency ‘hotspots’ which were used for analysis during the integration workshop can then be selected using the filter in the top left of the page (Figure C.1).

Figure C.1: ‘Hotspot’ filter

**The screenshot shows the filters that can be selected within the systems maps to filter for different types of interdependencies hotspots. 
The available hotspot categories are: 
Hotspot Drainage and flooding A;
Hotspot Drainage and flooding B;
Hotspot Green infrastructure A;
Hotspot Green infrastructure B;
Hotspot Power and operations A;
Hotspot Power and operations B;
Hotspot Power and operations C;
Hotspot Staff and supply chains;
Hotspot Water A.
Hotspot Water B
Overlay
**

* + 1. How to read the map – detailed analysis

Hovering over a node will background all nodes not immediately linked to that node – thereby indicating the links relevant to that node. This effect is held by clicking the node and then the focus button (a circle with four marks like a compass) on the right-hand side of the map. Once the focus mode has been activated then the focus can be expanded or contracted with the arrows that have appeared. Clicking on the focus button again will exit the view.

When a node has been selected, clicking on the ‘focus’ button in the right-hand menu gives two options; to look at 1) the downstream impacts of the node or 2) the nodes upstream which impact the selected node - these can be selected using the ‘node impacts’ and ‘node impacted by’ buttons at the bottom right of the screen, respectively.

* 1. Guide to using the climate risk interdependency system map
     1. How to use the map – exploring the risk assessment

The definitions of the categories and how these have been used to structure the risk assessment are also discussed in Section 3 of the main report. The basic principles and approaches to exploring this system map are the same as for the integrated system map outlined above.

However, the main difference in this map is that there are multiple filters present. These can be found in the top left of the map. They can be used as follows:

1. **Headings –** this filter is set to show all nodes by default. However, this filter can be used to analyse the nodes according to their headings within the risk assessment spreadsheet (e.g. pathways, hazards, asset types).
2. **Interface** – this allows users to filter by organisation interface (Column B in the risk assessment spreadsheet). Appendix H shows how this filtering has been applied to each of the interfaces.
3. **Risk –** this allows users to filter by climate risk instead. This approach has informed the key risks infographic and discussions at Workshop 3 with the wider group to understand how multiple interfaces can be impacted by the same risks and therefore mitigated by similar actions.

The ‘stakeholders’ button in the bottom right of the screen can also be toggled on and off to remove the stakeholder tagging around the interface nodes.

1. Categories used in risk assessment

Table D.3: Categorisation of climate variables

|  |  |
| --- | --- |
| **Climate variable** categories used in the assessment | **Other climate variables included within** these categories |
| Extreme high rainfall in a single event | Storm event. Heavy rain/cloudburst |
| Extreme high temperatures | Extreme high temperature (in the short-term, e.g. a few days). Long hot, dry summer. |
| Extreme high tides |  |
| Frozen precipitation | Snow. Ice. Hail. Sleet. Change in freeze-thaw cycles. |
| High average rainfall over season | High rainfall over a season or longer. Increase in mean annual precipitation. |
| Higher average temperatures | Higher average temperature (in the long-term, i.e. over a season or longer). |
| Higher wind speeds | Likely increase in the frequency and intensity of high wind events (with some uncertainty).  Change in wind and storminess |
| Large diurnal temperature range | Large diurnal temperature range (in the short-term, e.g. a few days) |
| Lightning | Increases in the number of lightning days are projected for all four seasons, with the largest projected increases occurring in summer, associated with storms. |
| Low rainfall / drought | Increase in the number of dry days per year, especially in summer.  Drier summers. Low rainfall (over a long period of time but not necessarily leading to water use restrictions).  Drought (three or more dry winters, leading to water supply restrictions).  Increase wildfire risk. |
| Low temperatures | Extreme low temperature (in the short-term, e.g. a few days) |
| Sea level rise | Extreme high tides. |
| Storm surges | Changes in storm frequency. |
| The following climate variables were not recorded as being of significant risk to interdependencies and were not included within the risk assessment. | Fog Change in extreme winter temperature  Other extreme weather events Change in solar radiation exposure Adhesion Sun glare |
| Table D.4: Categorisation of asset types | |
| **Asset type** | **Other assets** included |
| Built environments - buildings, stations, depots, head offices and property/developments | Control centres.  Plants. Fixed plants. Portable transportable plant.  Depot plant. Sub-stations. Station assets (approaches, signs, lifts, PA, interchanges, etc.). Devco types. Tenanted Estate.  Comms system  Mechanical, electrical and communications.  ITS.  Tech and Networks. |
| Bus fleet and vehicles |  |
| Highways, roads, streets, access points, carriageways and pavements | Cycleways.  Street lighting. Access points. |
| (Rail) Infrastructure - tracks, tunnels, boundaries, structures | Bridges & viaducts.  Structures (e.g. bridges, footbridges, cycle bridges, bridge components, culverts, signals, gantries, retaining walls, buildings, road restraint systems and tunnels). OLE. Level crossings, on-street running of trams. Civils' structures. On track machines - renewals.  On track machines - seasonal and incident. On track machines - track treatment. On track plan and mobile plant. Third rail systems. Deep tube tunnels.  Sub- surface tunnels. |
| Earthworks | Geotechnical (e.g. embankments and cuttings) |
| Signalling system |  |
| Rolling stock | Impacts to rolling stock from climate hazards are largely direct and have therefore been excluded from the interdependency risk assessment |
| People\* | Impacts on customers and workforce (e.g. roadworkers, traffic officers etc.) H&S/Welfare Maintenance staff and equipment Passengers TfL Staff |
| Included as part of organisation interface nodes due to co-dependency e.g. urban drainage, vegetation impacts and substation assets (see Section 2.4) | Drainage (e.g. gullies, outfalls and culverts, soakaways, ponds, pipes and ditches and channels) . Power Distribution Electrical Power supply (excluding rail) Power supply (non-rail infrastructure) Vegetation. Green assets (trees, other vegetation). |
| \*Impacts to customers and staff safety are captured within the health and safety impacts in the consequence scoring. Similarly, increased congestion through cascading disruption within the transport sector is covered within performance impacts and is a relevant consequence for all interdependencies identified. | |

1. Climate baseline
   1. Climate change in the context of London
      1. Influences on climate in London

London, as part of Southern England, is within the part of the UK closest to continental Europe. Therefore, the city can be subject to continental weather influences that bring cold spells in winter, and hot, humid weather in summer.**[[28]](#footnote-29)**

Due to London’s location within a relatively sheltered area, between the Chiltern Hills to the north and the North Downs to the south, the regional climate is slightly milder than the rest of Britain. More specifically for London, the city is influenced by the urban heat island (UHI) effect.**[[29]](#footnote-30)**&**[[30]](#footnote-31)** The UHI effect is most conspicuous overnight in cold spells with light winds from late autumn to early spring, when temperatures in central London can be over 5°C higher than in the outer suburbs and surrounding rural areas.29

Following the Clean Air Act of 1956 and a decline in heavy industry, there has been an increase in sunshine duration over the London area, particularly during the winter months.29

* + 1. Current climate - general trends

General trends in the area, based upon observed data for the period 1981-2010 , include:

* Mean annual temperature in London is 11.01°C.
* January is the coldest month, with mean temperature of 5.01°C for the period.
* July is the warmest month, with mean temperature of 18.12°C for the period.
* Peak rainfall events are observed during autumn months.
* Mean annual rainfall for the period is 638.61mm.
* Average number of days with ground frost is 91 days per year.
  + 1. Current temperature

Based upon observed data from 1980-2010, January is the coldest month, with a mean monthly temperature of 5.01°C. July is the warmest month with a mean monthly temperature of 18.12°C over the same period.

At the Greenwich Observatory station, situated within central London, the average annual maximum temperature was observed to be 15.34°C for 1981-2010, whilst the annual average minimum temperature was observed to be 7.84°C for the same period.32

The highest daily maximum temperatures recorded in the south and southeast of England were recorded at Heathrow and St James’s Park, where both locations reached 40.2°C on 19th July 2022.29

* + 1. Current precipitation

Rainfall is generally well distributed throughout the year, with an autumn peak. In addition, there are significant amounts in the summer associated with showery, convective rainfall. This is due to the additional heat from the London UHI leading to shower development in summer.29

Due to the city’s sheltered location between the Chiltern Hills and the North Downs, observed annual average rainfall in London is lower than the south and southeast region of England. For the 1981-2010 period of observed values at Greenwich Observatory, July was the month with the lowest average rainfall at 34.55mm, whilst October had the highest average rainfall at 61.06mm.**[[31]](#footnote-32)**

Intense rainfall events have been recorded throughout London, with a noteworthy example occurring in Hampstead, Greater London, where 169mm rainfall fell within 2.5 hours on 14 August 1975.29

* + 1. Current sea level and observed sea level rise

In London, the risk from sea level rise (SLR) is growing. The high water mark at London bridge has increased by 1.5m since 1780.**[[32]](#footnote-33)**

The rivers Thames and Lea are the two main tributaries in London, where the land elevation rises to an eroded hilly landscape towards the north and south of the city. This concentrates landward-encroaching SLR from the North Sea to the river banks of the Thames.**[[33]](#footnote-34)**

The key structure protecting the city of London from increasing tide levels and storm surges is the Thames Barrier. The barrier opened in 1982 following an extreme flooding event in 1953. The aim of the barrier is to prevent high tides and storm surges from travelling upstream and damaging infrastructure and people in central London. It is expected to be operational until 2070, at which time it must be replaced.34 The Thames Barrier was not intended to protect against sea-level rises cause by climate change. At time of construction, the barrier was expected to be used 2-3 times per year. This has increased, whereby the current annual usage is 6-7 times.**[[34]](#footnote-35)**

* + 1. Projected climate summary

The overall projected climate change trends for London over the 21st century include:

* There is an increased chance of warmer, wetter winters and hotter, wetter summers.
* There is an increased risk of sea level rise.

In line with the scenario used for the Transport for London Climate Change Risk Assessment, climate projection data from the United Kingdom Climate Projections 2018 (UKCP18) for one greenhouse gas emissions scenario, RCP6.0**[[35]](#footnote-36)**, for the 2050s and 2080s time periods for both temperature and precipitation. For sea level change, data were available only for RCP8.5, and were obtained for the same time periods. The UKCP18 projections were developed by the UK Met Office using the Met Office Hadley Centre climate model and a selection of other global climate models and are the latest set of climate projections for the UK.

The projections presented are both probabilistic projections and probabilistic extremes, outlined in Table E.5. Probabilistic projections present a range of values for the climate variable, based on the output of multiple runs of the climate models.

Probabilistic projection data, with the exception of SLR, were obtained for the London administrative region, as available from the UKCP18 user interface. Due to data availability from location of tide gauges, SLR data were obtained for the closest gauge to London, Sheerness.

Due to availability, probabilistic extreme data values were obtained at the 25km spatial resolution on the UKCP18 tool, grid reference 537500, 187500 to represent London.

Table E.5: Climate projection data obtained for the risk assessment

| Climate variable | Data source | Emissions scenario | Time period | Spatial scale | Value |
| --- | --- | --- | --- | --- | --- |
| Summer (JJA) minimum air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Summer (JJA) maximum air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Summer (JJA) maximum air temperature extreme | UKCP18 - Probabilistic projections of climate extremes (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Grid reference: 537500, 187500 | 20- and 50-year return periods |
| Summer (JJA) mean air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Winter (DJF) minimum air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Winter (DJF) maximum air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Winter (DJF) mean air temperature | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Summer (JJA) mean precipitation | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| Winter (DJF) mean precipitation | UKCP18 – Anomalies for probabilistic projections (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Administrative region | 90th percentile |
| 1-day total summer (JJA) precipitation | UKCP18 - Probabilistic projections of climate extremes (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Grid reference: 537500, 187500 | 20- and 50-year return periods |
| 1-day total winter (DJF) precipitation | UKCP18 - Probabilistic projections of climate extremes (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Grid reference: 537500, 187500 | 20- and 50-year return periods |
| 5-day total summer (JJA) precipitation | UKCP18 - Probabilistic projections of climate extremes (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Grid reference: 537500, 187500 | 20- and 50-year return periods |
| 5-day total winter (DJF) precipitation | UKCP18 - Probabilistic projections of climate extremes (25km) over UK, 1961-2100 | RCP6.0 | 2050s, 2080s | Grid reference: 537500, 187500 | 20- and 50-year return periods |
| Annual sea level change (m) | UKCP18 – Sea level anomalised for marine projections around UK coastline, 2007-2100 | RCP8.5 | 2050s, 2080s | Tide gauge location: Sheerness | 90th percentile |

* + 1. Projected temperature change

Three temperature variables were analysed: changes in the mean seasonal air temperature, maximum air temperature and minimum air temperature, presented in Table E.6. Data was obtained for seasonal values for summer (June, July, August) and winter (December, January, February). The projections are shown in Table E.6 and summarised graphically below (Figure E.2 and Figure E.3).

It should be noted that these projected mean, maximum and minimum temperatures are the modelled data for the typical range of future temperatures during each season, and that peaks and troughs in actual observed data will occur outside of these, resulting in heatwaves and cold snaps. The general trend is an increase in seasonal temperatures. While winters, on average, will become warmer, the Met Office consider that cold snaps may still occur to the same low temperatures that have been experienced in past decades, however it may be that these occur less frequently.

Table E.6: Projected temperature change

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Climate variable** | **Season** | **Observed baseline mean seasonal temperature (1981-2010) (°C)** | **2050s (2040-2069) projected temperature change (°C) under RCP6.0, 90th percentile** | **2080s (2070-2099) projected temperature change (°C) under RCP6.0, 90th percentile** |
| Air temperature (mean) | Summer (JJA) | 17.34 | +2.86 | +5.57 |
| Air temperature (max) | Summer (JJA) | 22.11 | +3.39 | +6.55 |
| Air temperature (min) | Summer (JJA) | 12.57 | +2.52 | +4.92 |
| Air temperature (mean) | Winter (DJF) | 5.24 | +2.09 | +3.61 |
| Air temperature (max) | Winter (DJF) | 8.11 | +1.99 | +3.41 |
| Air temperature (min) | Winter (DJF) | 2.36 | +2.34 | +4.09 | |

Source: UKCP18

E.2: Projected temperature change (Summer)

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

E.3: Projected temperature change (Winter)

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

* + 1. Projected temperature extremes

Seasonal temperature extremes were obtained for the summer months (JJA), presented in Table E.7.

The trend shows an increase in temperature extremes across all return periods, and with increasing intensity through time. In London this is likely to result in more intense and longer heatwave events in future decades, which may occur more frequently within any given year.

Table E.7: Projected temperature extremes for the summer season (JJA) for 1 in 20, 50 and 100 year return period events for a 1981-2000 modelled baseline based upon RCP6.0, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Modelled baseline (1981-2000) (°C)** | **2050s (°C)** | **2080s (°C)** |
| 20-year return period | | | |
| Maximum summer air temperature (JJA) | 35.05 | 38.82 | 42.04 |
| 50-year return period | | | |
| Maximum summer air temperature (JJA) | 35.92 | 39.72 | 43.05 |
| 100-year return period | | | |
| Maximum summer air temperature (JJA) | 36.50 | 40.29 | 43.69 |

* + 1. Projected precipitation change

Table E.8 provides the baseline precipitation data for summer and winter (observed mean seasonal rainfall, mm) as well as the projections of how much this is anticipated to change by (percentage change) under RCP6.0 by the 2050s and 2080s.

Table E.8: Projected precipitation change

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Climate variable** | **Season** | **Observed mean baseline seasonal precipitation (1981-2010) (mm)** | **2050s (2040-2069) projected precipitation change (%) under RCP6.0, 90th percentile** | **2080s (2080-2099) projected precipitation change (%) under RCP6.0, 90th percentile** |
| Precipitation (mean seasonal) | Summer (JJA) | 146.12 | +11.14 | +0.77 |
| Precipitation (mean seasonal) | Winter (DJF) | 162.59 | +18.78 | +33.45 |

Source: UKCP18

Figure E.4 and Figure E.5 respectively show the projected mean seasonal summer and winter rainfall in mm and include the percentage change in relation to the baseline period.

The observed mean total annual rainfall was 640.08mm for the London administrative region between 1981 and 2010. A +3.65% change is projected in mean total annual rainfall for the 2050s and a +5.69% change is projected for the 2080s.

Figure E.4: Projected precipitation change (Summer)

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

Figure E.5: Projected precipitation change (Winter)

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

The projected trend in rainfall shows that both summers and winters are expected to be wetter in the 2050s and 2080s. For winters, the rate of change increases through time from the 2050s to the 2080s. For summers, the rate of change decreases through time. This means that over time, despite both summer and winter experiencing wetter conditions, winter is expected to see a greater increase in seasonal average rainfall compared to the seasonal baseline, than that of summers.

There are few projections for snowfall, however with a trend of warmer winters it may be that snow events become less frequent. The capacity of a warmer atmosphere to carry more water could potentially lead to heavy snowdrops of wetter snow, as ‘wet’ Atlantic storms meet cold Arctic weather fronts.[[36]](#footnote-37)

* + 1. Projected precipitation extremes

In addition to the averages projected by climate models, rainfall events are projected to become more intense due to a warmer atmosphere being able to carry more water.

Projections of total precipitation over a 1-day and 5-days period associated with a 1 in 20, 50 and 100-year return period have been extracted from the UKCP18 probabilistic extremes tool and estimated for a baseline period and future RCP6.0 scenario for the 2050s and 2080s. Results for summer are presented in Table E.9 and Table E.10. Results for winter are presented in Table E.11 and Table E.12

Projections show an increase in intense, and multi-day precipitation events for both summer and winter seasons. Results in the below tables indicate that 1-day precipitation events are more intense during summer across all return periods than during winter. Contrastingly, 5-day precipitation events are projected to be more intense during winter. The trend towards increases in multi-day precipitation amount is likely to increase the likelihood and magnitude of fluvial flooding in London across both seasons.

Table E.9: Projected 1-day precipitation extremes for the summer season (JJA) 1 in 20, 50 and 100 year return period events for a modelled 1981-2000 baseline based upon RCP6.0, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Modelled baseline (1981-2000) (mm)** | **2050s (mm)** | **2080s (mm)** |
| 20-year return period | | | |
| 1 day total precipitation summer (JJA) | 49.12 | 50.89 | 53.83 |
| 50-year return period | | | |
| 1 day total precipitation summer (JJA) | 61.81 | 64.05 | 67.65 |
| 100-year return period | | | |
| 1 day total precipitation summer (JJA) | 72.86 | 75.36 | 79.36 |

Table E.10: Projected 5-day precipitation extremes for the summer season (JJA) 1 in 20, 50 and 100 year return period events for a modelled 1981-2000 baseline based upon RCP6.0, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Modelled baseline (1981-2000) (mm)** | **2050s (mm)** | **2080s (mm)** |
| 20-year return period | | | |
| 5 day total summer (JJA) | 68.2 | 72.82 | 78.52 |
| 50-year return period | | | |
| 5 day total precipitation summer (JJA) | 75.59 | 80.85 | 87.46 |
| 100-year return period | | | |
| 5 day total precipitation summer (JJA) | 81.24 | 86.87 | 94.15 |

Table E.11: Projected 1-day precipitation extremes for the winter season (DJF) 1 in 20, 50 and 100 year return period events for a modelled 1981-2000 baseline based upon RCP6.0, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Modelled baseline (1981-2000) (mm)** | **2050s (mm)** | **2080s (mm)** |
| 20-year return period | | | |
| 1 day total precipitation winter (DJF) | 33.18 | 36.96 | 40.44 |
| 50-year return period | | | |
| 1 day total precipitation winter (DJF) | 41.40 | 45.96 | 50.06 |
| 100-year return period | | | |
| 1 day total precipitation winter (DJF) | 48.77 | 53.92 | 58.62 |

Table E.12: Projected 5-day precipitation extremes for the winter season (DJF) 1 in 20, 50 and 100 year return period events for a modelled 1981-2000 baseline based upon RCP6.0, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Modelled baseline (1981-2000) (mm)** | **2050s (mm)** | **2080s (mm)** |
| 20-year return period | | | |
| 5 day total precipitation winter (DJF) | 68.24 | 76.44 | 84.19 |
| 50-year return period | | | |
| 5 day total precipitation winter (DJF) | 75.49 | 84.38 | 92.97 |
| 100-year return period | | | |
| 5 day total precipitation winter (DJF) | 80.88 | 90.14 | 99.32 |

* + 1. Projected sea level rise

Table E.13 summarises the projected sea level rise from UKCP18 marine data, relative to the observed baseline (1991-2010) derived from the National Oceanography Centre. It shows that sea level is projected to increase by 0.43m in the 2050s, and up to 0.82m in the 2080s.

Figure E.6

summarises these increases graphically. For both the observed baseline and future projections, the closest available tide gauge, Sheerness, was used to represent SLR in London.

Table E.13: Projected annual sea level change (m) relative to an observed 1991-2010 baseline, based upon RCP8.5, 90th percentile

|  |  |  |  |
| --- | --- | --- | --- |
| **Climate variable** | **Observed baseline mean sea level (1991-2010)** | **2050s (2040-2069)** | **2080s (2040-2069)** |
| Sea level (m) | 0.13 | +0.43 | +0.82 |

Source: National Oceanography Centre (baseline); UKCP18 (projections)

Figure E.6: Projected sea level rise

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

1. Risk assessment analysis

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Figure F.7: Summary of risk scores by interface

Figure F.8: Summary of risk scores by climate hazard

1. System map visualisations

*For this figure, please see the full, detailed, but not fully accessible project report, which is available upon request from* [*katherinedrayson@tfl.gov.uk*](mailto:katherinedrayson@tfl.gov.uk) *and* [*friederikeholz@tfl.gov.uk*](mailto:friederikeholz@tfl.gov.uk)*. Please note that a reply may take several days.*

.9: Interface 1: Power grid resilience

.10: Interface 2: Power network - linear assets

**Figure G.11: Interface 3: Power network – substation assets and cables**

**Figure G.12: Interface 4: Telecoms**

.13: Interface: Civil structures

**Figure G.14: Interface 6: Pipe bursts**

**Figure G.15: Interface 7: Urban drainage system and combined network**

**Figure G.16: Interface 8: Vegetation and green infrastructure**

**Figure G.17: Interface 9: Banksides and slopes**

**Figure G.18: Interface 10: FRM assets**

1. Prioritisation framework

Table H.14: High priority actions with scoring criteria

| Risk type | Recommendation action | ARP3 category | No regret | Low regret | Win-win | Flexible or adaptive | Multiple benefits | Is this action likely to be within the LBTS level of control? | Are skills and capabilities likely to be currently available to deliver this action? | Is this action aligned with the current regulatory cycle? | Outcome | Organisational interface |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| General – applicable to all climate hazards | Collaborative communications and warnings between organisations to work together to adapt to impacts. Build on collaborative examples such as the Surface Water Flooding Strategic Group and the Infrastructure Operators Adaptation Forum (IOAF). | Collaboration, communication and reporting | yes | yes | yes | yes |  | Yes | Yes | Yes | Short term, medium-high priority | All |
| General – applicable to all climate hazards | Exploring data sharing models to improve current methods of sharing data. Consider contributing to Digital Twins such as CreDo. | Information management | yes | yes | yes | yes | yes | Yes | Yes | Yes | Short term, high priority | All |
| General – applicable to all climate hazards | Incentivise a larger role for NBS, NFM and green corridors to help the LBTS adapt to multiple climate risks (e.g. flooding, heat) and deliver co-benefits in other areas such as biodiversity and amenity. | Leadership and governance | yes | yes |  | yes | yes | Yes | Yes | Yes | Short term, medium-high priority | All |
| Landslides | Ensure the outputs of Network Rail research into landslide and embankment failure are shared with other asset owners to inform their own risk and adaptation measures. | Information management | yes | yes | yes | yes |  | Yes | Yes | Yes | Short term, medium-high priority | Banksides and slopes |
| Surface water flooding | Contribute to GLA SuDS marketplace initiative. | Leadership and governance | yes | yes |  | yes | yes | Yes | Yes | Yes | Short term, medium-high priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding | Train sponsors and project managers on the importance of keeping SuDS in project design. | Organisation and people | yes | yes |  | yes | yes | Yes | Yes | Yes | Short term, medium-high priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding | Collect data during maintenance visits on assets most at risk from surface water flooding. | Risk management | yes | yes | yes | yes | yes | Yes | Yes | Yes | Short term, high priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Tidal flooding | Contribute to Thames Estuary 2100 plan updates including risk assessments and benefits assessments to support upgrading of flood defences. | Capital and operational delivery | yes | yes | yes | yes | yes | Yes | Yes | Yes | Short term, high priority | FRM assets, Power network – substations and cables, Civil structures |
| General – applicable to all climate hazards | Contribute to reporting for all sectors currently undertaking their own interdependencies study. Prioritise engagement where there are knowledge gaps (e.g. telecoms sector). | Collaboration, communication and reporting | yes | yes | yes |  | yes | Yes | No | Yes | Medium term, high priority | All |
| General – applicable to all climate hazards | Join up adaptation investment across sectors to avoid unnecessary redundancy. | Leadership and governance | yes | yes |  |  |  | No | No | Yes | Medium term, high priority | All |
| General – applicable to all climate hazards | Open access tools for making the business case for investing in green infrastructure and nature-based solutions. | Leadership and governance | yes | yes | yes | yes | yes | No | Yes | No | Medium term, high priority | All |
| General – applicable to all climate hazards | Understand existing and future adaptation of the assets LBTS rely on. | Risk management | yes | yes | yes | yes | yes | No | Yes | Yes | Medium term, high priority | All |
| High temperatures and heatwaves | Lobby for changes to building regulations to manage risk from high temperatures. | Leadership and governance | yes | yes | yes |  | yes | No | Yes | No | Medium term, medium - high priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Ensure planning assumptions for extreme heat are aligned across power, rail and road organisations. | Risk management | yes | yes | yes | yes | yes | No | No | Yes | Medium term, high priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High winds and storms | Developing of best practice for management of vegetation and green infrastructure e.g. building on existing conversations with the RSSB and the Forestry Commission and sharing across sectors. | Information management | yes | yes | yes | yes | yes | Yes | No | Yes | Medium-term, high priority | Power network – substations and cables, Telecoms, and Vegetation and green infrastructure. |
| Landslides | Training for trackside maintenance colleagues to understand the benefits (as well as risks) of green infrastructure management to reduce landslide risk. | Organisation and people | yes | yes | yes | yes | yes | Yes | No | Yes | Medium-term, high priority | Banksides and slopes |
| General – applicable to all climate hazards | Create shared risk registers to identify joint risks and co-create/co-fund risk reduction where a single solution can deliver benefits for wider interfaces. | Information management | yes | yes | yes | yes | yes | No | No | No | High priority, long-term | All |
| General – applicable to all climate hazards | Invest in co-funding models for asset adaptation which have shared risks. | Risk management | yes | yes | yes | yes |  | No | No | No | Medium-high priority, long-term | All |
| High temperatures and heatwaves | Establish urban greening initiatives to adapt to temperature fluctuations. TfL's Green Infrastructure and Biodiversity Plan could support this. | Leadership and governance | yes | yes |  | yes | yes | No | No | No | Medium-high priority, long-term | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Develop understanding of the design/operation and performance of non-traditional solutions e.g. implementation issues and business case opportunities. | Organisation and people | yes | yes | yes | yes |  | No | No | No | Medium-high priority, long-term | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| Drought and wildfires | Investigate co-funding opportunities for vegetation management to adapt to shared risks to assets. | Risk management | yes | yes |  |  | yes | No | No | No | Medium-high priority, long-term | Vegetation and green infrastructure, Urban drainage, and Power network – substations and cables. |

Table H.15: Medium to low priority actions. Note timing of options not included.

| Risk type | Recommendation action | ARP3 category | No regret | Low regret | Win-win | Flexible or adaptive | Multiple benefits | Outcome | Organisational interface |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| General – applicable to all climate hazards | Invest in growing self-generation capacity and/or backup-power arrangements at critical sites. | Capital and operational delivery | yes | yes |  |  | yes | Medium priority | All |
| General – applicable to all climate hazards | Share details of risks with the designers of future projects to ensure designs cater for the future climate. | Collaboration, communication and reporting | yes | yes |  | yes |  | Medium priority | All |
| General – applicable to all climate hazards | Support NIC recommendations around statutory adaptation duty for regulators. | Leadership and governance | yes | yes |  | yes |  | Medium priority | All |
| General – applicable to all climate hazards | Produce adaptation pathways across infrastructure assets | Leadership and governance | yes | yes |  | yes |  | Medium priority | All |
| General – applicable to all climate hazards | Training to develop understanding of SuDS performance, implementation issues and new opportunities for business case. | Organisation and people | yes | yes | yes |  |  | Medium priority | All |
| Ground movement (e.g. subsidence) | Conduct further studies using shared data and models to highlight vulnerabilities within the pipe network. | Information management | yes | yes | yes |  |  | Medium priority | Pipe bursts, Power network – substations and cables. |
| Ground movement (e.g. subsidence) | Establish governance of building site management and wastewater to improve understanding on where its redirected and how its managed. | Risk management | yes | yes |  | yes |  | Medium priority | Pipe bursts, Power network – substations and cables. |
| High temperatures and heatwaves | Ensure cooling measures (e.g. A/C) do not increase carbon emissions. | Capital and operational delivery | yes | yes |  |  | yes | Medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Inform and educate communities and organisations regarding energy use during peak times | Organisation and people | yes | yes | yes |  |  | Medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Review and update design standards for infrastructure (e.g. for power lines and cables) in line with recent climate projections. | Leadership and governance | yes | yes |  | yes |  | Medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High winds and storms | Undertake LiDAR studies and engage in data sharing on vegetation risk | Risk management | yes | yes | yes |  |  | Medium priority | Power network – substations and cables, Telecoms, and Vegetation and green infrastructure. |
| Landslides | Increase understanding of asset risk factors to landslides and then understand exposure locations. | Risk management | yes | yes |  | yes |  | Medium priority | Banksides and slopes |
| Surface water flooding | Engage with the GLA collaborative streetworks opportunity. | Capital and operational delivery | yes | yes |  |  | yes | Medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding | Use London Surface Water Flooding Strategic Group planned data sharing agreement as a facilitator for sharing data on surface water flood risk. | Information management | yes | yes |  | yes |  | Medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding | Continue to co-fund and implement actions from Surface Water Flooding Strategic Group including development of SuDS Opportunity Modelling. | Information management | yes | yes |  |  | yes | Medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| General – applicable to all climate hazards | Provision of risk maps by asset owners. | Information management | yes | yes |  |  |  | Low-medium priority | All |
| General – applicable to all climate hazards | Improve local understanding on the value of habitats and green spaces in London. | Leadership and governance | yes |  |  |  | yes | Low-medium priority | All |
| General – applicable to all climate hazards | Training requirements that include communities, STEM outreach, stewardship | Leadership and governance | yes |  |  |  | yes | Low-medium priority | All |
| Drought and wildfires, Ground movement (e.g. subsidence) | Develop a community role in delivery of urban greening to retain water moisture and reduce risk of drought and groundwater movement. | Collaboration, communication and reporting | yes | yes |  |  |  | Low-medium priority | Pipe bursts, Power network – substations and cables. Vegetation and green infrastructure, Urban drainage. |
| High temperatures and heatwaves | Share data regarding LBTS organisations current and planned embedded generation contributions to power grid through joint study with National Grid and UKPN. | Information management | yes |  | yes |  |  | Low-medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Calculate projected energy needs for LBTS and share with energy sector. | Risk management | yes |  | yes |  |  | Low-medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High temperatures and heatwaves | Aligned safety considerations and best practices for maintenance / replacement / construction programmes. Social research on expectations on transport sector during periods of extreme weather (e.g. what is the expected service level during a 40C heatwave and does it align across sectors). | Leadership and governance | yes |  | yes |  |  | Low-medium priority | Power grid resilience, Power network – substations and cables, Power network – linear infrastructure, and Telecoms |
| High winds and storms | Work with building regulations and planning to ensure wind impact is considered in new development. | Leadership and governance | yes | yes |  |  |  | Low-medium priority | Power network – substations and cables, Telecoms, and Vegetation and green infrastructure. |
| Landslides | Undertake LiDAR studies on bankside risk and landowner mapping. | Risk management | yes | yes |  |  |  | Low-medium priority | Banksides and slopes |
| Surface water flooding | Share high-level forward capital works plans across infrastructure sectors. | Capital and operational delivery | yes |  | yes |  |  | Low-medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding, Fluvial flooding | Investigate opportunities to improve resilience at the community scale. | Organisation and people | yes | yes |  |  |  | Low-medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding, Fluvial flooding | Support in CreDo Transport Use Case dependencies analysis | Collaboration, communication and reporting | yes |  |  |  | yes | Low-medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Surface water flooding, Fluvial flooding, Tidal flooding | Align flood risk and reduction strategies with outputs from CreDo. Contribute to data sharing for digital twins where possible. | Information management | yes | yes |  |  |  | Low-medium priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures, FRM assets |
| High winds and storms | Lobby for changes to planning laws and regulators on appropriate location of cables. | Leadership and governance | yes |  |  |  |  | Low priority | Power network – substations and cables, Telecoms, and Vegetation and green infrastructure. |
| Surface water flooding | Establish one lead authority to coordinate response to surface water flood risk. | Leadership and governance | yes |  |  |  |  | Low priority | Urban drainage, Telecoms, Power network – substations and cables, and Civil structures |
| Ground movement (e.g. subsidence) | Share and maintain a skills-based database to resource the response to pipe bursts. | Risk management | yes |  |  |  |  | Low priority | Pipe bursts, Power network – substations and cables. |

1. See [HM Treasury Magenta Book: Central Government guidance on evaluation (2020)](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879438/HMT_Magenta_Book.pdf) and [HM Government Environmental Improvement Plan (2023)](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1133967/environmental-improvement-plan-2023.pdf) [↑](#footnote-ref-2)
2. [London Climate Resilience Review Interim report](https://www.london.gov.uk/sites/default/files/2024-02/LCRR%20INTERIM%20REPORT%2012%2002%202024.pdf) [↑](#footnote-ref-3)
3. See [HM Treasury Magenta Book: Central Government guidance on evaluation (2020)](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879438/HMT_Magenta_Book.pdf) and [HM Government Environmental Improvement Plan (2023)](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1133967/environmental-improvement-plan-2023.pdf) for example (accessed 16/06/2023). [↑](#footnote-ref-4)
4. Defra recommend using PSM for creating a shared understanding of environmental issues. See Defra: [Integrating a systems approach into Defra (2022), Section 2.2.3](https://www.bing.com/ck/a?!&&p=1b4e5e583c75e4d1JmltdHM9MTY4Njg3MzYwMCZpZ3VpZD0xMGJjYmUwMC00NjFhLTY0NDgtMzRiYy1hZDJlNDdkMTY1ODAmaW5zaWQ9NTI2NA&ptn=3&hsh=3&fclid=10bcbe00-461a-6448-34bc-ad2e47d16580&psq=Defra+Systems+Analysis+for+Water+Resources&u=a1aHR0cHM6Ly93d3cuZ292LnVrL2dvdmVybm1lbnQvcHVibGljYXRpb25zL2ludGVncmF0aW5nLWEtc3lzdGVtcy1hcHByb2FjaC1pbnRvLWRlZnJhL2ludGVncmF0aW5nLWEtc3lzdGVtcy1hcHByb2FjaC1pbnRvLWRlZnJh&ntb=1) (last accessed 16/06/2023). [↑](#footnote-ref-5)
5. https://www.ukclimaterisk.org/publications/type/briefings/ [↑](#footnote-ref-6)
6. [Network Rail Third Adaption Report December 2021](https://www.networkrail.co.uk/wp-content/uploads/2022/01/Network-Rail-Third-Adaptation-Report-December-2021.pdf) [↑](#footnote-ref-7)
7. Financial consequence scores were determined from a professional judgement about the relative cost to TfL of a pathway occurring rather than a quantitative assessment based on cost calculations. [↑](#footnote-ref-8)
8. [ukcp18-fact-sheet-wind\_march21.pdf (metoffice.gov.uk)](https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-fact-sheet-wind_march21.pdf) [↑](#footnote-ref-9)
9. [SPF City Pack\_editable\_template (metoffice.gov.uk)](https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/spf/london-city-pack_august-2022.pdf) [↑](#footnote-ref-10)
10. [Climate adapt](https://climate-adapt.eea.europa.eu/) [↑](#footnote-ref-11)
11. https://www.ukclimaterisk.org/publications/energy-sector-briefing/#i9 [↑](#footnote-ref-12)
12. https://www.ukclimaterisk.org/publications/telecoms-and-ict-sector-briefing/#section-2-key-messages [↑](#footnote-ref-13)
13. https://www.ukclimaterisk.org/publications/water-sector-briefing/#section-2-key-messages [↑](#footnote-ref-14)
14. Climate Change Committee, March 2023 <https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/> [↑](#footnote-ref-15)
15. In the short to medium term, extreme winter conditions may also exacerbate network resilience concerns as more people move to using heat pumps for winter heating. However, this has not included within the risk assessment due to higher levels of uncertainty and the expectation that risks from low temperatures will decrease over time. [↑](#footnote-ref-16)
16. [Transport chaos across England and Wales after major power cuts | Energy industry | The Guardian](https://www.theguardian.com/business/2019/aug/09/power-cut-hits-london-and-south-east-england) [↑](#footnote-ref-17)
17. [Report following railway power disruption on 9 August 2019 | Office of Rail and Road (orr.gov.uk)](https://www.orr.gov.uk/media/10752#:~:text=On%20Friday%209%20August%202019,are%20detailed%20in%20this%20report.) [↑](#footnote-ref-18)
18. [GB power system disruption on 9 August 2019: Final report (publishing.service.gov.uk)](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/855767/e3c-gb-power-disruption-9-august-2019-final-report.pdf) [↑](#footnote-ref-19)
19. [Digital Railway - Telecoms Technologies for the Elizabeth Line - An Infrastructure Manager’s Perspective - Crossrail Learning Legacy](https://learninglegacy.crossrail.co.uk/documents/digital-railway-telecoms-technologies-for-the-elizabeth-line-an-infrastructure-managers-perspective/#:~:text=Other%20than%20providing%20secure%20voice,radio%20at%20RFLI%20Managed%20Stations) [↑](#footnote-ref-20)
20. [Cell on Wheels (COW) | Mobile Base Station (icsindustries.com.au)](https://www.icsindustries.com.au/products/communication-trailers/cell-on-wheels) [↑](#footnote-ref-21)
21. [ETSI - Railway Telecommunication | Rail Communications Standards | FRMCS](https://www.etsi.org/technologies/rail-communications) [↑](#footnote-ref-22)
22. https://www.thameswater.co.uk/media-library/home/about-us/investing-in-our-region/counters-creek/counters-creek-technical-appendix-resilience.pdf [↑](#footnote-ref-23)
23. Thames Water DWMP 2025-2050 [technical-summary.pdf (thameswater.co.uk)](https://www.thameswater.co.uk/media-library/home/about-us/regulation/drainage-and-wastewater/technical-summary.pdf) [↑](#footnote-ref-24)
24. [River Thames scheme - GOV.UK (www.gov.uk)](https://www.gov.uk/government/publications/river-thames-scheme/river-thames-scheme) [↑](#footnote-ref-25)
25. TfL (2018) How green infrastructure contributes to the Healthy Streets Approach. Available through: [TfL Healthy Streets Planning](https://tfl.gov.uk/corporate/about-tfl/how-we-work/planning-for-the-future/healthy-streets) [↑](#footnote-ref-26)
26. [Heathrow-Airport-Travel-Report-2019.pdf](https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/heathrow-2-0-sustainability/futher-reading/Heathrow-Airport-Travel-Report-2019.pdf) [↑](#footnote-ref-27)
27. A presentation by the Forestry Commission on climate-adapted trees at a TASG meeting in 2020 led to a Network Rail and TfL workshop on climate-adapted trackside trees in 2021. This in turn led to TfL submitting a request to the RSSB to develop a set of high-level, overarching principles for trackside green infrastructure management. Findings have shown that research and guidance for the transport sector is currently limited. [↑](#footnote-ref-28)
28. Met Office (2016) Southern England: Climate. Available at: [southern-england\_-climate---met-office.pdf (metoffice.gov.uk)](https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/southern-england_-climate---met-office.pdf) [Accessed: December 2023] [↑](#footnote-ref-29)
29. The UHI effect is a phenomenon describing the elevated temperatures felt in towns and cities compared to rural surroundings. These effects are as a result of the heat retained by artificial surfaces that is slowly released. Therefore, higher temperatures are experienced. This effect occurs in combination with other impacts, such as the reduced cooling effect of vegetation in urban areas, in addition to the compounding effect of anthropogenic heat. [↑](#footnote-ref-30)
30. Greater London Authority (2023) Heat. Available at: [Heat | London City Hall](https://www.london.gov.uk/programmes-and-strategies/environment-and-climate-change/climate-change/climate-adaptation/heat) [Accessed: December 2023] [↑](#footnote-ref-31)
31. Met Office (2023) UK Climate Averages. Available at: [Greenwich Park (Greater London) UK climate averages - Met Office](https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/u10hb54gm) [Accessed: December 2023] [↑](#footnote-ref-32)
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33. Pace, S. (2021) Urban infrastructure inundation risk from permanent sea-level rise scenarios in London (UK0, Bangkok (Thailand) and Mumbai (India): A comparative analysis. Available at: [download (lu.se)](https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=9042597&fileOId=9042598) [Accessed: December 2023] [↑](#footnote-ref-34)
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35. RCP6.0 is a pathway that describes trends in long-term global emissions of greenhouse gases (GHGs), short-lived species, and land-use/land-cover change leading to a medium stabilisation scenario of radiative forcing. It is representative of an increase in global mean surface temperature of 2.8°C by 2081-2100. [↑](#footnote-ref-36)
36. National Snow and Ice Data Center (2024) Snow. Available at: [Science of Snow | National Snow and Ice Data Center (nsidc.org)](https://nsidc.org/learn/parts-cryosphere/snow/science-snow) [Accessed: January 2024] [↑](#footnote-ref-37)