Bonneagar Iompair Éireann
Transport Infrastructure Ireland

Transport Infrastructure Ireland

Climate Adaptation – National Roads Network

Implementation Plan 2026 - 2030

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Executive Summary

What is this implementation plan and why do we need it now?

Ireland's climate is changing. Consequently, Ireland will experience more severe weather and flooding events, more intense rainfall and slope failures, and higher sea levels [1]. Much of Ireland's infrastructure, including many sections of the National Roads network, was not designed or built to perform in this new emerging climate.

In recent decades, severe weather events have impacted the National Roads network. Such weather events are anticipated to become more extreme or occur more frequently (e.g. pluvial flooding), while others are expected to emerge (e.g. sea level rise). These changes increasingly pose challenges to the National Roads network as ageing infrastructure, asset deterioration and rising demand make assets more vulnerable to climate hazards [2]. With the total annual costs from extreme weather events to road infrastructure in Europe estimated to be €1.8 billion [3] – and projected to increase by 20% by 2050 – along with adverse safety, reputational and environmental impacts, it is essential that Transport Infrastructure Ireland (TII) understands and addresses these climate-related impacts.

The *Climate Action Plan 2021* recommended that the Government of Ireland improve national climate resilience and climate change adaptation on the light rail and National Roads network [4]. In 2022, TII published a six-stage approach to adapt to climate change, the *Climate Adaptation Strategy* [5]. This Climate Adaptation Implementation Plan (hereafter the Plan) for National Roads extends that work. It outlines adaptation measures that will allow TII to reduce the risks climate change poses to the National Roads network. These measures can reduce the cost and harm of damaged or destroyed infrastructure, and contribute to keeping assets, systems and communities connected and functioning. Recognising the need for timely action, the Plan has been developed in parallel with climate change risk assessments (CCRA) for National Roads.

The Plan also responds to the findings in the Department of Transport's (DoT) second *Transport Sectoral Adaptation Plan* (*T-SAP II*). The measures outlined in this Plan align with the themes covered in the *T-SAP II* and aim to address the 'considerable' risk to national and regional roads from climate -related impacts. Similarly, the Plan supports the ambition of the *Climate Adaptation Strategy for Regional and Local Roads* (*CASRLR*), by working to strengthen the climate resilience of the road network across Ireland and will ensure alignment wherever possible.

TII cannot eliminate the risk of damage to road infrastructure from future climate change events, or the consequences for communities – however, risks can be reduced. Adaptation can make infrastructure more resilient before, during and after extreme weather events.

The importance of the National Roads network

Since its designation in 1977, the National Roads network has provided transport infrastructure across Ireland. Today, it enables millions of individual journeys and facilitates the movement of Ireland's goods, despite only representing 5% of the total road network. It is essential for all sectors of society and communities, serving public transport, freight and personal travel as well as facilitating access to a wide range of destinations including health, education, employment, tourism and services. The National Roads network is one of the largest asset classes in state ownership, with a gross replacement cost of €31 billion [2].

There are approximately 5,300 km of national roads in Ireland, as shown in Figure A [2]. The network encompasses all Motorways (light blue), National Primary Roads (dark blue) and National Secondary Roads (purple). There are approximately 3.5 million vehicle, and 82,000 heavy goods vehicle trips made daily on the National Roads network.

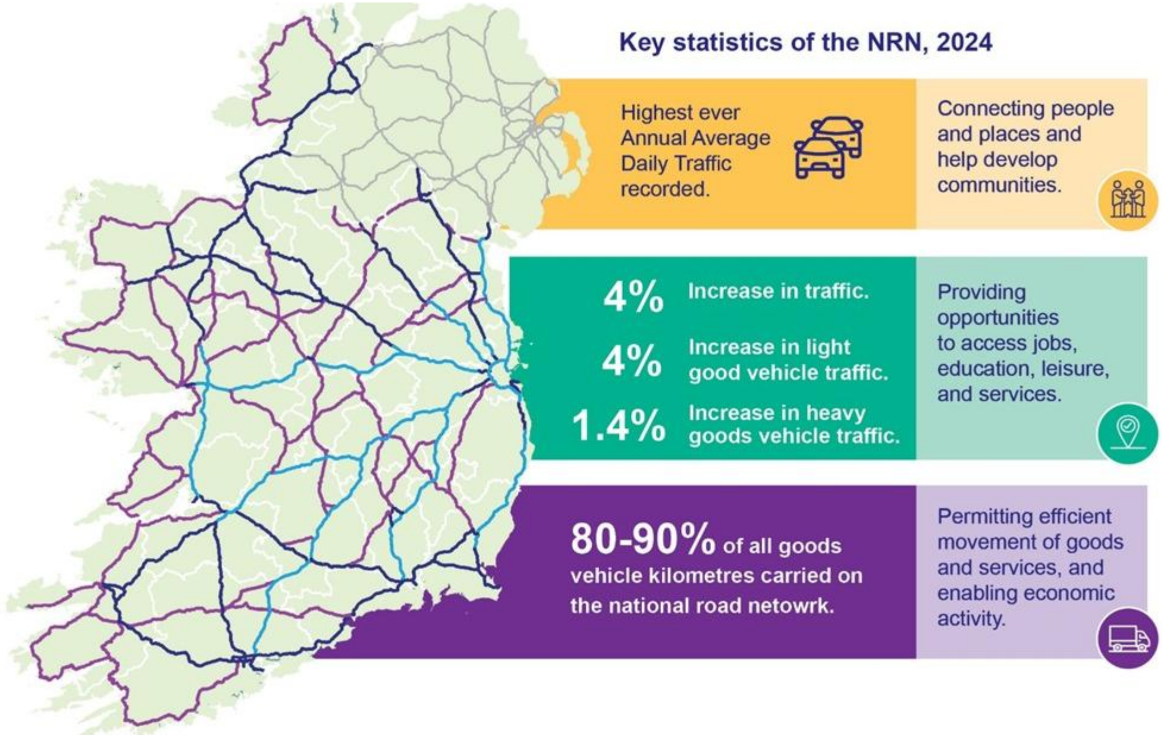

Figure A Statistics from the National Roads network

As outlined in *National Roads 2040* (also referred to as *NR2040*), the National Roads network generates economic value by reducing commuter and freight journey times to permit efficient movement of goods and services; creating links between people and businesses to aviation and maritime infrastructure; and providing opportunities to access jobs, education, leisure and services on foot, by private vehicle or public transport corridors [6]. Furthermore, it connects people and places, supports development of communities and enhances the social fabric of the country – particularly through lifeline roads that connect isolated areas and rural communities.

The National Roads network is relatively unique in comparison to other strategic road networks in many other European jurisdictions. While sections of the network, specifically the Motorways and improved sections of National Primary Roads, are designed to modern engineering standards, the National Secondary Roads consist predominantly of legacy sections of single carriageway network that predate modern standards of design and construction. From a climate adaptation perspective, this compounds the challenges of effectively adapting to climate-related hazards.

Our approach to developing this plan

The Plan aligns with the overarching six-stage approach detailed in our *Climate Adaptation Strategy* [5]. It was developed in parallel with the detailed CCRA for national roads with the intention of prioritising early-stage measures that strategically enhance TII's understanding of climate hazards, risks and vulnerabilities to support these assessments. These incremental measures also strengthen the evidence base for informed decision-making and lay the groundwork for more targeted measures in the future. This approach is outlined in Figure B below.

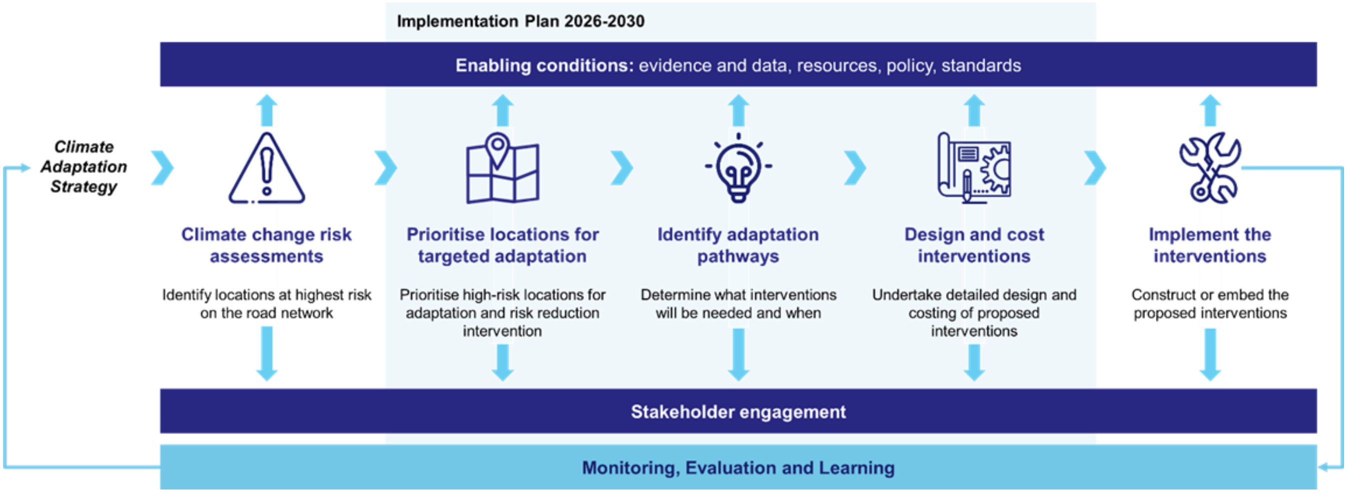

Figure B TII's approach to climate adaptation on the National Roads network

Through internal engagement, we have developed 20 individual measures for the National Roads network. These measures were then categorised by identifying the primary assets affected by each measure, and the teams responsible for their delivery. Two additional categories, overarching and motorway operations, were then established to accommodate measures that have universal application and require inputs from a wider range of personnel. The measure categories in the Plan are represented below in Figure C.

Figure C Asset groups for measures outlined within the Plan

A risk-based approach

The Plan takes a structured approach to assessing and communicating risk, in line with international best practice established by the Intergovernmental Panel on Climate Change (IPCC). Risk is the product of hazard, exposure and vulnerability.

TII completed an initial *Climate Impact Screening* in 2023 [7]. It provided a high-level understanding of the national roads asset categories that are most vulnerable to the impacts of certain climate hazards. This provided eight priority climate hazards, which were considered in this plan's development (see Figure D Shortlisted climate hazards).

Within this plan's context, increased precipitation, extreme wind, flooding and slope failures are principal hazards, as well as the cascading and compounding impacts of these hazards. The remaining hazards, which may have increased significance in the future, are of secondary importance.

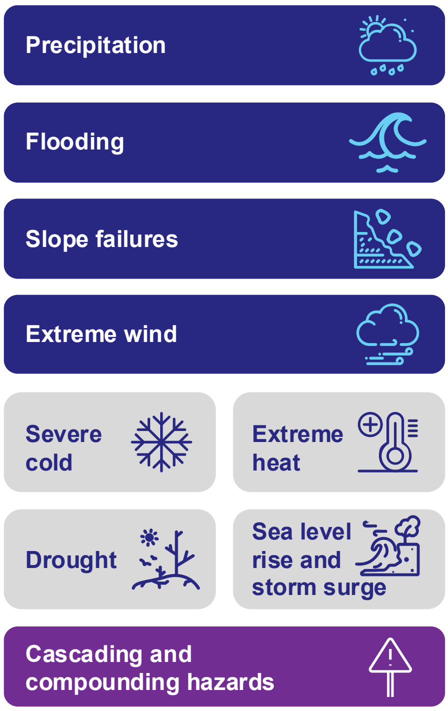

Figure D Shortlisted climate hazards

Decision making and planning under uncertainty

To create flexibility in planning for future climate change events, the Plan stages the delivery of adaptation measures as more information becomes available. This is known as the Dynamic Adaptative Policy Pathways (DAPP) approach. DAPP allows for consideration of multiple possible futures to test the likely effect of different adaptation options, providing the flexibility to adapt to changing circumstances and future uncertainties.

DAPP recognises that different adaptation measures can have complementary effects and build on each other over time. The implementation of adaptation measures can be coordinated and sequenced for greater effect in creating better resilience outcomes. Measures can be sequenced as a long-term plan, which can be adjusted and updated as new information becomes available, or as climate conditions evolve. Sequencing and potentially bundling adaptation measures can be a cost-effective way to improve baseline resilience.

By adopting this approach, TII can make best use of limited resources and simultaneously achieve a higher level of overall resilience over time. It encourages a coordinated approach to adaptation, where measures are planned and sequenced to create a more resilient and adaptive system.

Generating cost estimates under uncertainty

Costing exercises for climate adaptation measures for road infrastructure and operations are subject to significant uncertainty. Adopting a DAPP approach provides a framework for addressing this uncertainty and progressively increasing the accuracy and reliability of the cost estimates as new information emerges.

Cost estimates for measures in the Plan have been calculated used using broad data, top-down or benchmark-based approaches. Considerations include the level of staff availability, expertise and the duration required to execute the described measures as well as previous projects, contracts and expenditure figures. Higher-cost measures that respond to future climate impacts have been deferred until more information emerges.

Proposed climate adaptation measures 2026-2030

All measures in the Plan, and high-level overview of the measure type, relevant hazards, timeline and cost are captured in Table A below. The measure types referred to in the table are presented in Section 5.

Table A Adaptation measures in the Plan

Measure	Summary	Type	Hazard	Time
OVR-1 Undertake review and update of TII standards to incorporate climate adaptation and climate resilience considerations	TII will undertake a review and update of standards to incorporate considerations surrounding climate adaptation and resilience. Following the reviews, standards will be updated so that TII remains compliant with its internal and external responsibilities.			2026 - 2030
OVR-2 Development of improved/updated flood hazard data that covers the National Roads network	This measure will develop an updated and expanded national flood hazard database that is fit-for-purpose for TII's risk assessment and adaptation planning needs, while also offering wider benefits to Local Authorities and national climate resilience efforts.			2026 - 2027
OVR-3 Complete detailed climate change and natural hazard risk assessments for the National Roads network	TII will complete a detailed climate change and natural hazard risk assessment, which will provide a robust evidence base to understand how and where hazards interact with national road infrastructure, to calculate risk (as economic losses and network disruption) caused by climate change and natural hazard events, and to guide strategic investment.			2026 -2027
OVR-4 Sea level rise and storm surge study for the National Roads network	This measure will use the capabilities of TII's flood risk visualisation tool to inform a location-specific CCRA, which focuses on sea level rise and storm surge hazards. The aim is to understand how climate change may increase these hazards and associated risks along coastal National Roads network corridors (such as the N69) and to identify priority areas for adaptation.			2026 - 2027
STR-1 Asset management database expansion to include retaining walls	This measure will develop and refine modules for a retaining walls asset management database. It will also include engaging with stakeholders and reviewing existing asset data sources, conducting laser imaging detection and ranging (LiDAR) surveys of the network and populating the database.			2026 - 2028
STR-2 Capture hydraulic and hydrology data for river bridges and culverts	This measure will gather information about the existing river bridges and culvert system through desktop studies, engagement with local area engineers, and surveys. Gap analysis will inform assessment of whether these systems are fit-for-purpose. This is critical for informing catchment management and guiding design improvements for peak flows and climate impacts.			2026 - 2028
STR-3 Enhance institutional engagement with wider stakeholders responsible for watercourse management with the aim of creating improved protocols for watercourse management regarding maintenance and rehabilitation of culverts and bridges	This measure will seek to enhance the engagement and approval process for undertaking reactive maintenance and repair, as well as establish a protocol for watercourse management when necessary measures fall outside of TII's control and responsibility.			2026 - 2030
STR-4 Publish high-level technical guidance document for wind on major bridge structures/high embankments and develop operational plans for individual bridges/high embankments on the National Roads network vulnerable to severe wind events	This measure details the development of a high-level technical guidance document which outlines a protocol during severe wind conditions for all bridges and high embankments on the National Roads network, and the subsequent development of this technical guidance document into an actionable operational protocol.			2024 - 2026

Measure	Summary	Type	Hazard	Time
DNG-1 Conduct a desktop vulnerability mapping exercise on National Roads network drainage	This measure involves collating current and future climate data to assess exposure to flooding across the National Roads network, before undertaking a prioritisation exercise to identify the most exposed sections.			2025
DNG-2 Develop a Drainage Asset Management Module (DAMM) and implement programme for drainage inventory capture	This measure will develop options to capture drainage inventory data that can facilitate an efficient data collection process. In addition, it will identify a compatible DAMM that has the ability to provide real-time updates on the status of road assets and components.			2026 - 2027
DNG-3 Undertake detailed surveys of existing drainage assets to be included in the proposed drainage module in DNG-2 to facilitate planning for a long-term programme of network drainage upgrade works at locations where potential flooding and increased rainfall has been identified in DNG-1, with the initial focus on determining network catchments and location of outfalls	This measure builds on DNG-1 by undertaking detailed surveys to capture data related to network catchments and outfalls for sections of the National Roads network that are considered to have high or very high exposure to flooding.			2026 - 2028
TUN-1 Assess current and future flood hazard and risk at the Dublin, Jack Lynch, and Limerick Tunnels	These studies will identify and assess the flood hazard and risk for each tunnel including each portal area and associated staff management buildings and areas. New data will be developed where there are gaps, including for current and future climates across a range of scenarios. The primary metric for consideration in the risk assessment will be how flooding threatens the availability of the tunnel for safe use.			2026
TUN-2 Identify, assess and undertake appropriate climate-related resilience measures at Dublin, Jack Lynch, and Limerick Tunnels	This measure will be to identify and undertake appropriate measures – structural and non-structural – that are feasible for implementation and can adapt tunnel infrastructure and operations to climate hazards.			2027 - 2030
OPS-1 Implement Monitoring, Maintenance and Renewals Contracts (MMaRC) third generation contracts, including contractual enhancements for improving resilience to flood, wind, and cold spell events	This measure will review existing contract documentation and operational arrangements that MMaRCs currently have in place to respond to flood, wind and cold spell events and to identify recommendations for how resilience planning might be enhanced in the third-generation contracts.			2025 - 2026
OPS-2 Conduct climate and severe weather resilience review of operations buildings	To understand the extent of the risks facing operations buildings, this measure proposes a desktop study to determine and model future climate risks - using the results to determine capacity gaps and develop a remedial programme thereafter.			2027 - 2030
OPS-3 Undertake flood analysis for M1 (N & S) motorway service areas and design a remedial programme to address identified flood issues	This measure proposes that detailed flood hazard information be gathered for the M1 service areas via site-specific flood risk assessments, to assess risks from pluvial, coastal (including from wave overtopping), and groundwater flooding.			2026 - 2030

Measure	Summary	Type	Hazard	Time
ERW-1 Complete the detailed Geotechnical Asset Management Database (GAMD)	This measure will improve the GAMD and build on previous pilot studies through enhanced data collection and carrying out on-site validation. The GAMD will be structured to account for different data types and be maintained through regular standardised asset inspections to support long-term asset decision-making.			2026 - 2028
ERW-2 Utilise new GAMD to underpin a risk assessment programme for bog rampart sections of the National Roads network, and develop and implement a prioritised remedial programme of bog rampart rehabilitation	Utilising the GAMD developed in ERW-1, risk assessments and geotechnical surveys will be carried out on bog ramparts to identify the risk that climate change poses to them. Once at-risk locations have been identified, and prioritised based on location, risk level and road use, a remedial programme for rehabilitation will be developed and implemented subject to available funding.			2028 - 2030
ERW-3 Continue programme of reactive measures on sections of the National Roads network affected by landslip (or landslide) failures, with emphasis on the N70 & N71	This measure will develop a prioritised programme of geotechnical measures in the at-risk sections of the N70 and N71. This will include LiDAR and aerial imaging together with geotechnical surveys to inform a detailed slope stability analysis leading to a prioritised programme of appropriate remedial measures.			2026 - 2030
PAV-1 Undertake a detailed analysis of the impacts on pavement surface course materials in a changing climate	This measure comprises two studies: one to identify specific changes to pavement conditions during short duration intense rainfall (splash & spray), and another to identify pavement effects from increased rainfall (of all types) and higher temperatures (pavement material deterioration rates).			2026 - 2027

Key

Measure type			Hazard		
Technological	Operational	Policy	Multi-hazard	Flooding	Extreme Wind
					

Programme and estimated costs 2026-2030

The result of applying DAPP is a coordinated approach to adaptation, where measures are planned and sequenced to create a more resilient system. While a number of measures can be implemented independently, some are contingent upon the progress or completion of enabling measures. As such, the definitions of later-stage measures are not as yet fully understood and will rely on the results of data gathering, proposed investigations and on-site assessments before detailed cost estimation is undertaken.

Given the ongoing evaluation of measures and their anticipated expenditure, the Plan is considered a live document. Similarly, the outlined programme will extend beyond the lifetime of this Plan as later-stage measures are continually defined and programmed.

Monitoring and evaluating the Plan

The DAPP approach inherently plans for the future in a changing world, encouraging flexibility, regular reviews and updates as climate-related conditions change. A monitoring framework is therefore essential for implementing the adaptation measures, reviewing new data and information, and social, cultural and economic changes to inform the adjustments to be made to the sequencing of measures over time.

The Plan includes a monitoring, evaluation and learning (MEL) framework. It is underpinned by a Theory of Change, which articulates how the measures are expected to lead to long-term resilience outcomes. Key components of the MEL framework are the systematic collection and analysis of data (monitoring), assessing the outcomes and effectiveness of adaptation measures (evaluation), and integrating the findings to improve future planning and implementation (learning).

The MEL framework provides a clear connection between the measures set out in the Plan and TII's long-term climate adaptation goals and overall vision, as shown in Figure E, demonstrating how the short-term action contributes to broader organisational impacts and strategic vision.

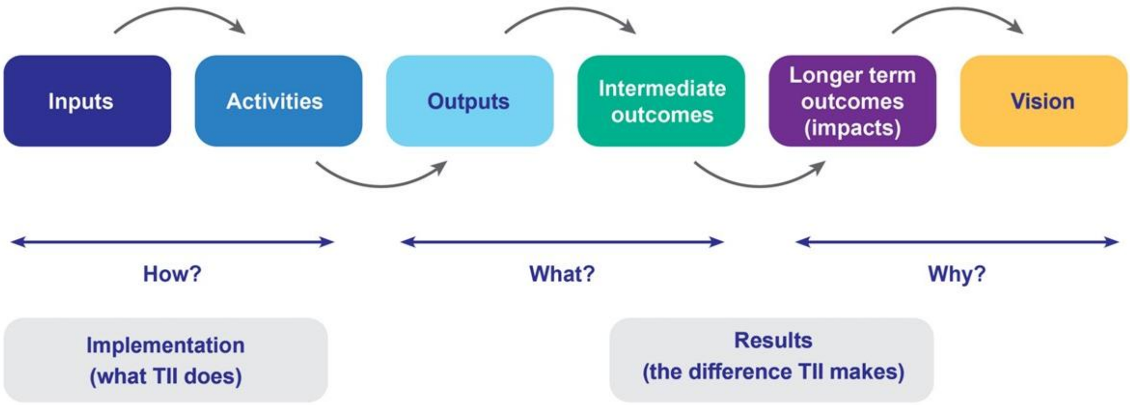

Figure E Conceptual overview of the monitoring framework

While the MEL framework underpins the delivery of the Plan, it is not a mechanism for assessment. Rather, it is a method for adaptive learning and continuous improvement, ensuring that adaptation efforts remain dynamic, effective, and responsive to both known and emerging climate risks. The key objectives of the MEL framework are captured in Figure F.

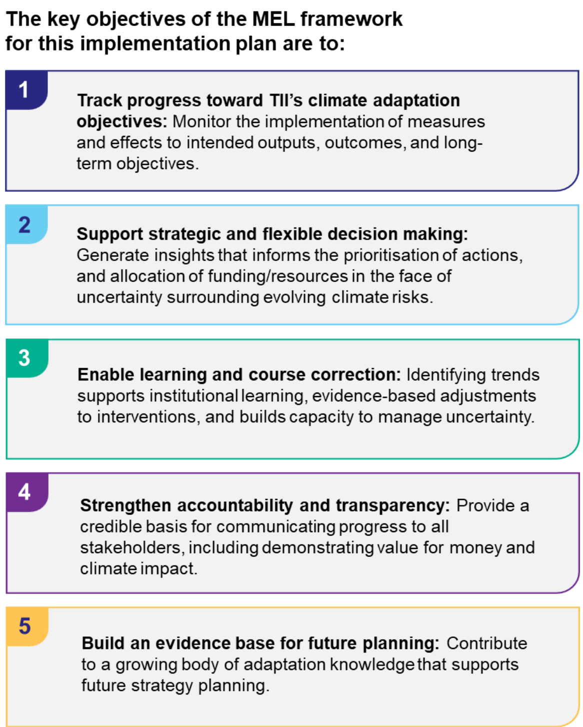

Figure F MEL framework objectives

Next steps

Investing in operational capabilities alongside infrastructure investment is critical. Effectively integrating adaptation into climate change planning and decision making will require both incremental and transformational adjustments over the short- and long-term. Additional risk reduction measures responding to RCP4.5 and RCP8.5 scenarios will be developed at the conclusion of the CCRA for national roads and will be supported by the outcomes of the incremental adaptation measures detailed in the Plan. This plan has initially identified some at risk locations for flooding and geotechnical issues which have been prioritised for further assessment and remedial measures in the short term.

Conducting the implementation plan in parallel with the CCRA will allow sufficient lead time to prepare and design the physical measures while mitigating the potential financial and social costs associated with inaction, overinvestment, or maladaptation.

Governance

The implementation of the adaptation measures within the Plan will be overseen within TII with a structured approach adopted to maintain a central coordination role to support embedded implementation, and monitoring and reporting of the adaptation measures and key performance indicators (KPIs).

Role for stakeholders

TII is committed to collaborating with stakeholders to implement the adaptation measures outlined in the Plan. Several of the adaptation measures will require engagement with government agencies, external organisations and internal stakeholders to ensure their successful delivery.

TII currently collaborates closely with Local Authorities regarding construction and management of the National Roads network, as well as contractors engaged under the MMaRC. The Office of Public Works (OPW), Inland Fisheries Ireland (IFI) and National Parks and Wildlife Services (NPWS) are also regularly engaged regarding watercourse interaction with the National Roads network. In collaboration with Local Authority's and Climate Action Regional Offices (CAROs), engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans. TII will also engage in dedicated stakeholder forums as outlined in T-SAP II actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation.

These stakeholders, as well as other government departments and external contractors, will be consulted in the implementation and development of current and future adaptation measures. This includes data collection, standards updates, and targeted investigations. Several measures also aim to support collaboration between different stakeholders with a view to create a more cohesive and unified approach to delivering climate adaptation across organisations.

TII's objectives for implementing its adaptation measures will be aligned with the statutory responsibilities of the stakeholder agencies, particularly regarding EU and national legislation. A number of such policies, strategies and initiatives have been reviewed and incorporated into the measures outlined within this plan including the Government of Ireland's *Sectoral Planning Guidelines for Climate Change Adaptation* [8], the Environmental Protection Authority's *National Climate Change Risk Assessment*, and the DoT's *Statutory Climate Change Adaptation Plan for the Transport Sector*, among others.

Under the leadership of TII, this Plan and associated adaptation measures are expected to contribute to building long-term resilience of the National Roads network to climate change.

Key Acronyms

Acronym	Definition
TII	Transport Infrastructure Ireland
ACP	An Coimisiún Pleanála
AGOL	ArcGIS Online
AR5	Fifth Assessment Report
CARO	Climate Action Regional Offices
CASRLR	Climate Adaptation Strategy for Regional and Local Roads
CCRA	Climate Change Risk Assessment
CFRAM	Catchment Flood Risk Assessment and Management
DAMM	Drainage Asset Management Module
DAP	Drainage Area Plan
DAPP	Dynamic Adaptive Policy Pathways
DoT	Department of Transport
dTIMS	Deighton Total Infrastructure Management System
EPA	Environmental Protection Agency
GAMD	Geotechnical Asset Management Database
GIS	Geographic Information System
IAPDM	Irish Analytic Pavement Design Method
IFI	Inland Fisheries Ireland
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LiDAR	Laser Imaging Detection and Ranging/Light Detection and Ranging
MEL	Monitoring, Evaluation and Learning
MMaRC	Motorway Maintenance and Renewals Contracts
MOCC	Motorway Operations Control Centre
NCCRA	National Climate Change Risk Assessment
NCFHM	National Coastal Flood Hazard Mapping
NIFM	National Indicative Fluvial Mapping
NPWS	National Parks and Wildlife Service
NR2040	National Roads 2040

Acronym	Definition
OPW	Office of Public Works
PPP	Public Private Partnership
RCP	Representative Concentration Pathway
RMO	Roads Management Office
SSFRA	Site-Specific Flood Risk Assessment
TEN-T	Trans-European Transport Network
ToC	Theory of Change
T-SAP II	Transport Sectoral Adaptation Plan

1 Introduction to the plan

1.1 Climate adaptation and the National Roads network

Ireland's climate is changing. Consequently, Ireland is experiencing, and will continue to experience, more severe weather including flooding events, more intense rainfall, higher temperatures and higher sea levels, alongside other climatic effects. **Most of Ireland's infrastructure, including the National Roads network, was not designed or built to perform in this emerging climate**.

In recent decades, severe weather events have impacted the National Roads network and its transport infrastructure assets and networks. These events have increasingly posed challenges to the National Roads network as ageing infrastructure, asset deterioration and rising demand make assets more vulnerable to climate hazards. With the total annual costs from extreme weather events to road infrastructure in Europe estimated to be €1.8 billion [3] – and projected to increase by 20% by 2050 – along with adverse safety, reputational and environmental impacts, it is essential that Transport Infrastructure Ireland (TII) understands and addresses these climate-related impacts.

Figure 1 Flooding on the M11, 2023

The *Climate Action Plan 2021* [4] recommended that the Government of Ireland improve national climate resilience, and adaptation to climate change on the light rail and National Roads network. In 2022, TII published its six-stage approach to climate change adaptation, the *Climate Adaptation Strategy* [5]. This document, the Climate Adaptation Implementation Plan for the National Roads network (hereafter referred to as 'the Plan') forms part of that approach, and outlines adaptation measures that will allow TII to reduce the risks climate change poses to the National Roads network. These measures can reduce the cost and harm of damaged or destroyed infrastructure, and contribute to keeping road assets, road networks and communities connected and functioning. Recognising the need for timely action, the Plan includes examples of incidents and anecdotal evidence of issues arising across the network that demonstrate the increasing urgency, frequency and scale of problems associated with climate-related events. In tandem with the production of the Plan, TII has commenced development of detailed climate change risk assessments (CCRA) for national roads, which will further inform future decision-making.

The Department of Transport (DoT) published the second iteration of its *Transport Sectoral Climate Adaptation Plan* (*T-SAP II*) in November 2025 [9]. This assessment found that national and regional roads are 'considerably' exposed to a variety of climate-related impacts. This Plan for National Roads responds to these key climate impacts, including projected changes in precipitation and all types of flooding. Adaptation themes covered in the *T-SAP II* are reflected in the measures outlined in this Plan, including influencing organisational behaviours and operations; delivering technical solutions; and costing adaptation actions.

This Plan will also support, build upon and strengthen the *Climate Adaptation Strategy for Regional and Local Roads* (*CASRLR*), published by the DoT in conjunction with the Climate Action Regional Offices (CARO) in 2023 [10]. Collectively, implementation of this and the *CASRLR* will ensure a wholly climate resilient road network across Ireland.

For the National Roads network, historical data and current events strongly indicate that precipitation and associated flood events are the primary climate-related hazards. In conjunction with the vulnerability of legacy earthworks and retaining structures, there is significant risk to the management and operation of the National Roads network. While the adaptation measures correspond to the four primary hazards, the measures outlined in the Plan primarily focus on addressing the consequences of precipitation and flood events.

TII cannot eliminate the risk of damage to road infrastructure from future climate change events, or the consequences for those affected, but the risks can be reduced. Appropriate adaptation can make infrastructure more resilient before, during and after extreme weather events. There is a strong economic case for investment in climate adaptation. The costs of responding to damage caused by a climate hazard are likely to be many times higher than the cost of preventative and proactive measures. The implementation of the measures and associated measures highlighted in the Plan are essential to ensure the protection of the National Roads network in a manner that enables continued service on this critical national asset.

This Plan outlines the measures and associated measures outlined for implementation between 2026 and 2030. However, without adequate and sustained funding for the ongoing maintenance of Ireland's aging road infrastructure, these adaptation efforts risk being ineffective. A significant portion of the work currently being undertaken is reactive, driven by incidents rather than controlled, proactive and planned maintenance. Climate adaptation funding must not be viewed as a substitute for essential road maintenance. A good maintenance regime is considered the first line of defence for any weather-related incident that will support climate adaptation efforts overall.

Maintaining the road network is critical to ensuring road user safety and supporting Ireland's economic resilience. As will be discussed further in Section 1.2, the National Roads network is one of the State's most valuable infrastructure asset. Its strategic importance to the Irish economy must be reflected in budget allocations that ensure its continued upkeep and resilience. Current maintenance allocations to TII have fallen dramatically since 2008, with current funding levels approximately 50% of 2008 values [11]. It is estimated that current needs for routine maintenance for national roads is a minimum of €77 million annually [12]. This decline highlights the significant pressure placed on TII's ability to adequately fund baseline road maintenance, which is a critical enabler of climate adaptation. Without sufficient and sustained maintenance funding, the effectiveness of future adaptation measures will be compromised, and risks of climate-related damage will remain elevated. With additional assets being added to the network and public private partnership (PPP) schemes returning to TII's maintenance remit in the coming years, it is imperative that maintenance funding meets a level that reflects the scale and importance of Ireland's National Roads network.

1.2 The National Roads network

Since 1977, the network classified as national roads has provided essential transport infrastructure across Ireland. There has been significant capital investment in modernising the network, most notably during the period 2000 to 2010, where €13.6 billion was invested in the development of inter-urban motorway roads within the overall network [13]. Today, the National Roads network represents an asset valued at €31 billion and enables millions of individual journeys and facilitates the movement of goods [2]. Despite only representing 5% of Ireland's total road network, the National Roads network is essential to supporting Ireland's economy and society, across all sectors. **The National Roads network is a vital, multi-generational asset which will continue to support the economy's development in the medium- and longer-term**.

National Roads 2040 [6] (also referred to as *NR2040*) is TII's long-term strategy for planning, operating, and maintaining the National Roads network, aligned with Project Ireland 2040 [14] objectives and commitments in wider Government policy including the *Climate Action Plan* and the DoT's *National Sustainable Mobility* policy. As outlined in *NR2040*, the network generates economic value by reducing commuter and freight journey times to permit efficient movement of goods and services; by creating links between people and businesses and connecting to aviation and maritime infrastructure; and by providing opportunities to access jobs, education, leisure and services. Furthermore, through public services and private vehicles, it connects people and places, supporting the development of communities and to enhance the social fabric of the country – particularly through lifeline roads connecting isolated areas and rural communities.

There are almost 5,300 km of national roads in Ireland. As shown in Figure 2, this encompasses all Motorways (995 km), National Primary Roads (1,639 km) and National Secondary Roads (2,659 km), with approximately 3.5 million vehicular trips made daily on the National Roads network and 82,000 heavy goods vehicle trips [2]. Section 2 expands further on the importance of the National Roads network and discusses the portfolio of national assets that are managed and operated by TII.

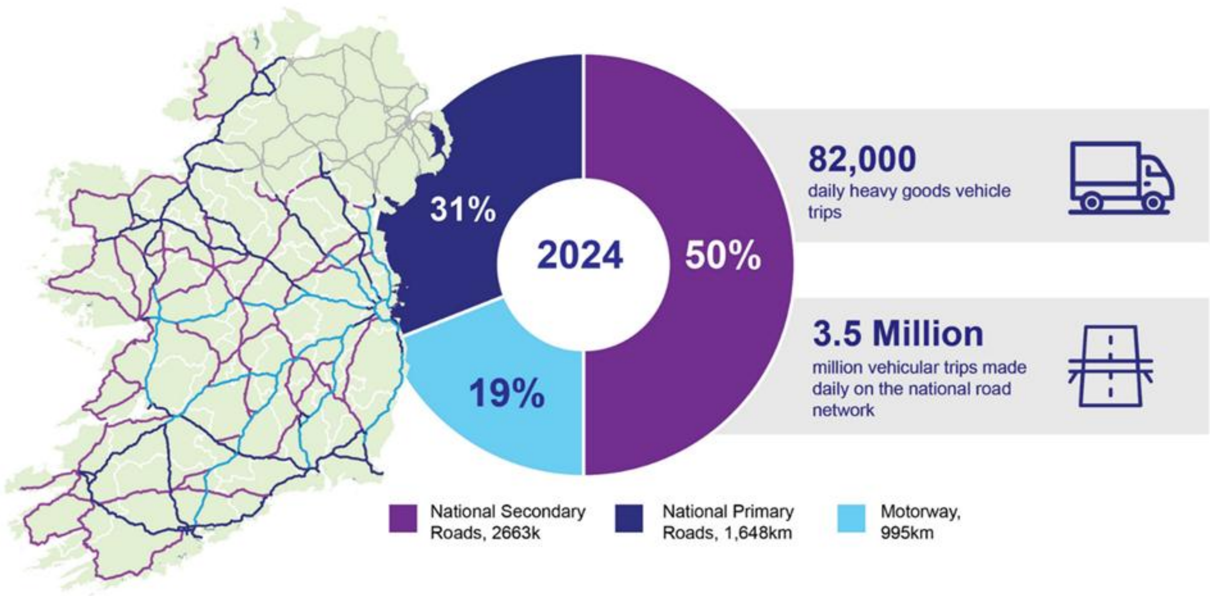

Figure 2 Summary of the National Roads network by road classification

It is important to acknowledge from the outset that climate adaptation solutions are complex, primarily due to the uncertainty surrounding future climate projections. This Plan sets out the approach TII will take to improve the National Roads network's resilience to climate change impacts. It acknowledges it is challenging to demonstrate the positive impacts of investment today without the ability to quantify its long-term benefits under uncertain future climate conditions. Additionally, all climate adaptation solutions will be developed with a focus on low-carbon solutions being at the core of all climate adaptation measures. Challenges may arise when balancing the need to implement climate adaptation solutions that conflict with our goal to reduce carbon, therefore, a cross organisational and disciplinary team will be engaged to deliver throughout this implementation plan.

1.3 Objectives of the Plan

The key objective of this Plan is to establish a basis for proceeding with the short-term measures and associated measures required to accelerate our momentum on the delivery of National Roads network climate adaptation improvements. The Plan is focused on improvements targeting the risks associated with rainfall, flooding and inundation on the network, with a particular focus on resilience of the Motorway network and lifeline roads to protect their critical functions.

A secondary objective is to **assure stakeholders that climate adaptation and resilience is being embedded into asset investment, maintenance programmes, and decision-making – ensuring the National Roads network can withstand risks associated with increasingly worsening and more frequent future climatic hazards.** This marks an important shift in how TII is approaching climate change adaptation to support a resilient National Roads network, with an emphasis on the motorway network (see Section 3 for further information).

This Plan is a snapshot in time, as TII continues to work to iterate and improve, to learn from the latest evidence and respond to the latest events, working in partnership with stakeholders to tackle the shared challenges faced by all. The Plan has been developed to align with the overarching aim and objectives set out in the *Climate Adaptation Strategy* [5], which are shown in Figure 3. These strategy objectives underpin the overall strategic direction of climate adaptation and resilience at TII and will guide how the Plan evolves over the course of its lifetime. In the context of the Plan, this focuses on the National Roads network, with an emphasis on the motorway network. Broadly, the measures set out in this plan are focused on:

- Identifying asset locations on the National Roads network that are at risk and vulnerable to climate hazards.
- Developing a programme of proposed measures that will be implemented throughout and beyond the lifetime of this implementation plan.
- Improving climate adaptation literacy within our organisation.
- Establishing and/or strengthening relationships with external stakeholders in the delivery of climate adaptation solutions.

The Plan aligns with TII's asset management policies as set out in *Strategic Asset Management Plan 2024-2028*, where climate adaptation is identified as an overarching objective.

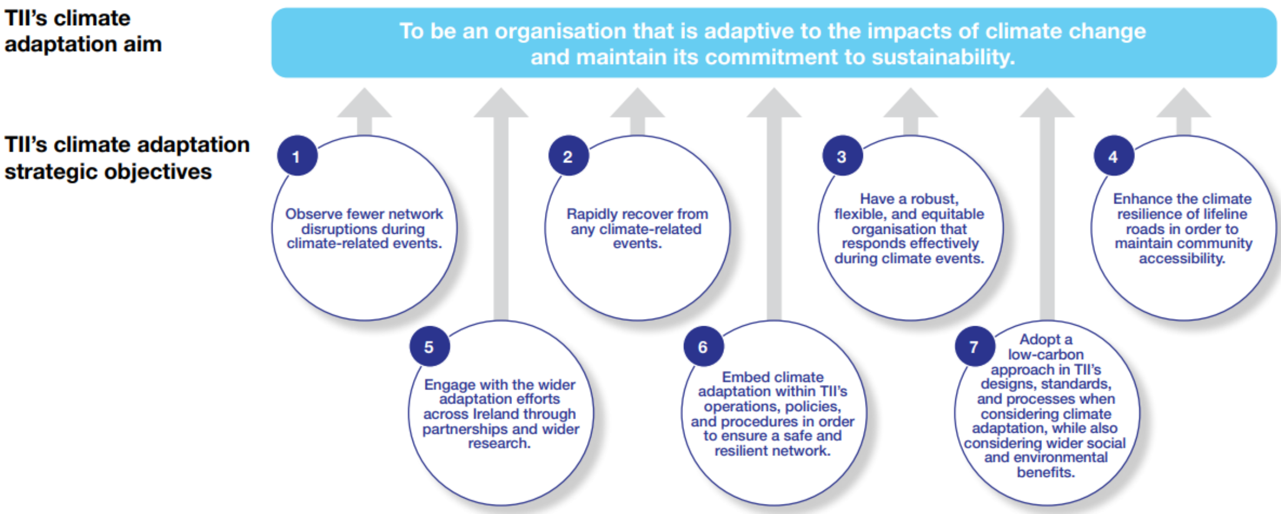

Figure 3 Aim and strategic objectives of the Climate Adaptation Strategy

1.4 Structure and navigation of the Plan

The Plan is structured as set out in Table 1 below and a list of key references cited in the Plan is available at the end of the document.

Table 1 Structure of the Plan

Section number	Section title	Description
Section 2	The National Roads network as a critical asset	Provides a summary of the National Roads network and its importance, including the assets explored within the Plan, key statistics, and case studies to exemplify its importance and diversity.
Section 3	Our approach to developing the Plan	Outlines TII's overall climate adaptation journey, risk framework and key terminology that underpins many of the proposed measures in the implementation plan. This section also outlines how network criticality has been factored into prioritisation and how uncertainty is considered in long-term adaptation planning for the national road network. It also describes work to date on the development of a flood risk visualisation tool, and how this has been used to preliminary highlight National Roads network sections at risk of fluvial flooding.
Section 4	Priority climate hazards	A summary of the primary climate hazards impacting the National Roads network. More information on secondary hazards is also available in Appendix A.
Section 5	Proposed climate adaptation measures 2026-2030	This section sets out the proposed climate adaptation measures across each asset type (defined in Section 2.5) and 'overarching' and 'operations' measures and their associated outline plan for implementation.
Section 6	Programme and estimated costs, 2026-2030	Provides a high-level programme and spend profile for implementation of the proposed measures detailed in Section 5 between 2026 and 2030. It also provides a high-level summary of historic reactive measure costs and projected costs for drainage and geotechnical measures foreseen from current understanding across the network.
Section 7	Monitoring, Evaluation and Learning	Sets out the proposed approach to monitoring and evaluation, setting out key performance objectives and the reporting framework in alignment with broader TII adaptation strategies.
Appendices	*Appendix A*	*Additional detail on secondary climate hazards.*

2 The National Roads network as a critical asset

2.1 Importance of the National Roads network to the State

The National Roads network is a central component of Ireland's national infrastructure, and a cornerstone of the social and economic fabric of the country. National Roads have an estimated gross replacement cost of €31 billion, making them one of the largest asset classes in state ownership [2]. Essential and wide-ranging benefits derive from the availability of a safe and efficient National Roads network for people and goods, include the range of overarching benefits outlined below in Figure 4.

Economic

Forms part of European TEN-T network.

Major freight/commerce link both nationally and internationally.

Enables commuters, goods and services to move across Ireland.

Safety

Management of the entire national road network by a single operator ensures a consistent, top-quality approach to the management and operation of key national infrastructure.

Social

Vital connection between cities, towns and villages.

Enables movement to social/cultural/ sporting events.

Important tourism asset (e.g. Wild Atlantic Way).

Figure 4 Overarching benefits of Ireland's National Roads network

2.2 Characteristics of the National Roads network

Transport Infrastructure Ireland (TII) is responsible for the planning, development, operation, and maintenance of the National Roads network, comprising nearly 5,300 km of National Roads, including Motorways. Although it represents only around 5% of the total road network in Ireland, it carries over 50% of the country's total road traffic and facilitates most movements of goods across the country (80-90%) [2]. The network encompasses all National Primary Roads, including Motorways, and National Secondary Roads.

The inter-urban motorway network radiating from Dublin City is the spine of the National Roads network, enabling essential economic and social functions of the state. For context, the M50 (shown in Figure 5) is Ireland's busiest motorway, with certain sections carrying more than 160,000 vehicles per day [2]. More than 450,000 individual journeys take place each day on the entire route. Constructed over multiple phases between 1983 and 2010, the M50, including the Dublin Tunnel, is the single most economically significant section of road infrastructure in Ireland, being a vital artery for the movement of people, goods and services around the capital and its hinterland. The M50 connects Dublin City and the wider eastern region with Dublin Airport and Dublin Port – the major international gateways to and from Ireland for people and commerce. Dublin Airport saw 33.3 million passengers travel through the airport in 2024 [15], representing approximately 85% of all passenger traffic through Irish airports, and 35.2 million tonnes of freight passed through Dublin Port, including over 80% of all unitised freight through Irish ports [16].

Recognising its economic significance, **much of the motorway network forms part of the Trans-European Transport Network (TEN-T)** specifically the North Sea-Rhine-Mediterranean Corridor. TEN-T is a landmark policy within the EU to enable consistent, high-quality transport infrastructure across multiple nations, for the purpose of moving goods and services internationally. Inclusion within this major international trade instrument affirms its economic and political significance for Ireland and reinforces the role of the National Roads network providing national and international connectivity.

Figure 5 Annual average daily traffic and percentage of heavy goods vehicles on the M50 in 2024

Ireland's National Roads network is relatively different in character compared to strategic road networks in other European jurisdictions. For example, the trunk road network in England, and in countries such as Germany, the Netherlands, and France are predominantly motorway and designed to modern engineering standards. The National Roads network in Ireland consists of sections designed to modern engineering standards alongside legacy sections of single carriageway network that predate modern standards of design and construction. Therefore, most stretches of the legacy network have limited, if any, drainage. From a climate adaptation perspective, this compounds the challenges of developing a comprehensive climate adaptation implementation plan. In effect, there are two distinct sub-networks of the national road network, each requiring a significantly different approach to frame a coherent plan.

The improved National Primary Roads and Motorways, are typically of high quality, designed and constructed to modern standards and include associated elements such as substations, lighting, maintenance depots, and other infrastructure and technology (e.g. variable messaging signs). These roads support the large-scale movement of people and strategically important goods, underpinning the economy. The consequence of significant climatic effects that severely disrupt services on these sections of the network can be far reaching beyond their immediate loci, with potential for regional or even national impacts depending on the scale of the event.

The National Roads network also includes significant sections of unimproved roads, not designed to modern standards, either in terms of alignment, pavement construction or drainage provision, particularly on the national secondary network. The National Secondary network fulfils an important economic and social function in linking smaller towns and villages, particularly along the western seaboard, with larger towns and settlements. A subsection of the National Secondary network is characterised as 'lifeline roads', roads that provide key connections for smaller population centres, including public transport connections, providing essential links for the population in more remote areas with essential public services such as education and health. This is especially important in the case of health and emergency response, given the trend towards concentration of acute services in fewer major centres. The consequence of significant climatic effects that severely disrupt services on these sections of the network will be more localised but would be profound for those communities and businesses impacted.

2.3 Examples of critical issues for this Plan

The scale – and in many cases, the sheer variance – of the National Roads network emphasises the need for TII to fully understand the climate-related hazards that can potentially impact the network. It is also important to understand how these hazards will evolve with future climate change projections, and how TII can manage these changes and potential impacts to optimise the accessibility and operability of the National Roads network.

To demonstrate the urgent need for improvements targeting the risks associated with rainfall, flooding and inundation on the network, two case studies are considered in Sections 2.3.1 and 2.3.2 below as examples of critical issues on the National Roads network. Examples of historical events and critical links are presented across both the improved National Primary Roads with key economic risks, and unimproved roads, including the National Secondary Roads, with key social risks, respectively. These examples also highlight the social and economic significance of the National Roads network, while demonstrating the diversity of infrastructure assets managed by TII. The case studies emphasise the importance of ensuring the National Roads network is adaptable and resilient to climate change and hazardous events.

2.3.1 Case Study 1: Examples with improved National Primary Roads, including Motorways

Ireland's improved National Primary Roads already experience the impacts of extreme weather with these events becoming more frequent and severe. For example, in 2017, sustained heavy rainfall overwhelmed drainage culverts on the M4 in County Kildare, leading to flooding and repeated road closures across the course of the day to allow flood waters – which pose a significant safety risk to road users – to subside (see Figure 6). Alongside the disruptive effects on road users who were diverted off the M4, this flood event caused damage to adjacent agricultural fields and residential properties.

Figure 6 M4 Flooding, 2017

On a national scale, Storm Emma in 2018 saw red weather warnings issued across the country, with extreme cold temperatures and significant snowfall causing extensive closures and disruption along the National Roads network – with reports of blue light services required to assist stranded motorists. Following the event, Met Éireann's *Storm Emma: An Analysis* [17] noted that the increasing frequency and velocity of storm events could be 'attributed to climate change and is linked to human activity'.

From a risk perspective and considering the potential for future more intense and frequent climatic events, the M50 motorway is a useful example as the most critical link on the network. Operating at or close to capacity along much of its length, the M50 is highly susceptible to disruption in the events of incidents, both traffic and weather-related. Considerable operational resources are devoted to dealing efficiently with traffic incidents and ensuring that traffic flows can return to normal as quickly as possible, and economic loss caused to freight and other economic movements can be minimised. To-date, TII has avoided significant weather related and climatic disruption on the M50. During Storm Emma in 2018, the M50 continually remained open despite heavy snowfall over a five-day period. Gritting and snow plough resources deployed proved capable of maintaining 24-hour treatment of the route. However, it is not certain whether significant disruption could occur on the route in the event of a more powerful storm. As yet, TII has not seen major flooding on the M50, but there is uncertainty in whether future climate scenarios (e.g. RCP4.5 or RCP8.5; see Section 4.1) could increase the risk of disruptive flooding on this critical section. While not known for certain, it is unlikely that TII's current maintenance measures will be sufficient to address rainfall and flood impacts under future climate.

2.3.2 Case Study 2: Examples with unimproved national roads, including lifeline roads

Coastal routes along the western seaboard such as the N56 in Donegal, the N59 in Galway and Mayo and the N71 and N86 in Kerry are examples of 'lifeline roads' (see Figure 7 for their spatial distribution). Given their remoteness and the lack of alternative routes, the closure of such routes for a period will likely result in considerable additional journey length and time for road users. Ireland's lifeline roads are in regions with the most rainfall and largest projected increases, making them more vulnerable to disruption from flooding, bridge or culvert washouts, and landslips. It is important that sufficient priority is given to our lifeline roads to ensure that appropriate adaptation programmes are put in place to reduce climate change risks.

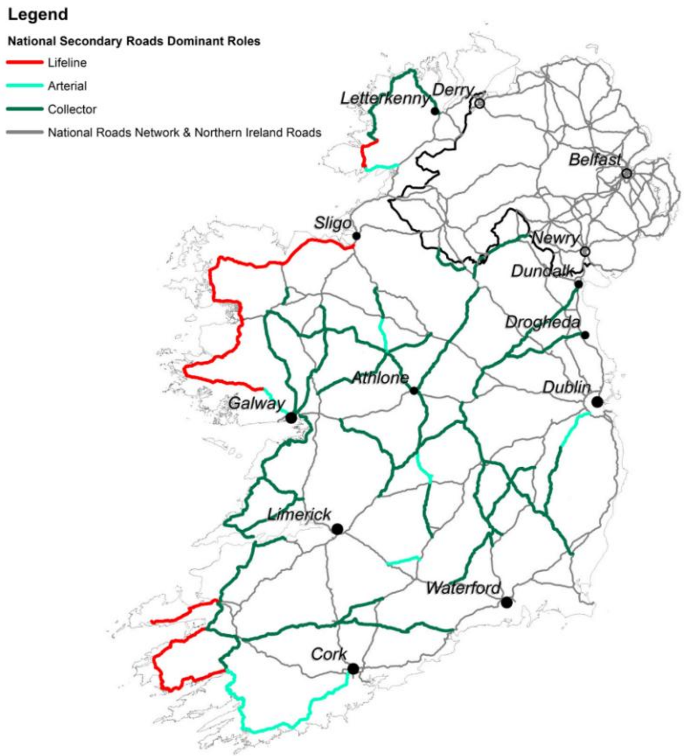

Figure 7 National Secondary Road network classification map showing lifeline roads [6]

2.4 Stakeholders relevant to the Plan

A wide range of Local Authorities, private organisations and other state agencies have a role in managing the National Roads network. Many of the measures and measures considered in the Plan will require communication and engagement with these stakeholders to ensure their effective delivery. **TII is committed to the stakeholder collaboration necessary for success**.

While TII has overall responsibility for the construction and management of the National Roads network, apart from Motorway roads, the delivery of this function has been transferred to Local Authorities under the Roads Act 1993 [18]. TII has a leading role in setting the standards, guidance and direction for the management of the network, working in partnership with the Local Authorities to ensure oversight of funding and prioritisation of their work. Local Authorities will be critical in implementing climate change adaptation measures for road networks within their boundaries. For example, flooding issues on the National Roads network caused by incidences of overland flow across adjacent lands, will mean countermeasures involving temporary attenuation of peak flows within adjacent agricultural lands are likely to be required. Such measures can only be developed and implemented in a partnership between landowners, the relevant Local Authority and TII. Other supporting organisations such as the Road Management Office (RMO) and the Climate Action Regional Offices (CAROs) will also be an important stakeholder.

Arrangements for the operation and maintenance of motorway roads are handled through direct contracts with private organisations in the form of Public Private Partnerships (PPP), Motorway Maintenance and Renewals Contracts (MMaRC) or direct outsources contracts (e.g. for tunnel operations). The contract mechanisms and associated operational procedures ensure a collaborative approach is taken to key operational and maintenance management of these network sections.

TII also interfaces with several other state agencies in its work. For the climate adaptation measures and associated measures set out in this Plan, key interfaces relate to watercourses crossing national roads and other receiving waters for drainage outfalls.

The state agency stakeholders for these interfaces include the Office of Public Works (OPW), Inland Fisheries Ireland (IFI) and the National Parks and Wildlife Service (NPWS). TII has strong working relationships across these statutory bodies, and the development of adaptation schemes involving river crossings, culvert design and flood relief scheme design will require close interaction and coordination with them. There are challenges for TII in ensuring that implementation of effective adaptation measures for the National Roads network can be aligned with the statutory responsibilities of the listed agencies, particularly regarding EU and national legislation. Several policies, strategies and initiatives have been reviewed and incorporated into the measures outlined within this Plan including the Government of Ireland's *Sectoral Planning Guidelines for Climate Change Adaptation*, the Environmental Protection Authority's (EPA) *National Climate Change Risk Assessment*, and the Department of Transport's (DoT) *Statutory Climate Change Adaptation Plan for the Transport Sector*, among others. Experience to-date indicates a need for early and close engagement to deliver the required alignment of objectives, policies and statutory obligations. TII will also engage in dedicated stakeholder forums, as outlined in T-SAP II actions. It is understood that these forums will likely provide TII with an ability to engage with wider transport infrastructure stakeholders and other government agencies to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation.**TII will engage these stakeholders, as well as other government departments and external contractors as part of the ongoing development and delivery of climate adaptation measures.** This includes data collection; standards updates and targeted investigations. Several specific measures in the Plan support collaboration between different stakeholders, creating a more cohesive and unified approach to delivering climate adaptation across organisations. Under the leadership of TII, the Plan and associated adaptation measures are expected to contribute to building long-term resilience of the National Roads network to climate change.

2.5 National Roads network asset groups

For a more detailed examination of the National Roads network, this Plan will assess the associated assets by dividing them into several smaller groups, which for the purposes of this Plan include:

- **Tunnels:** Dublin, Jack Lynch and Limerick Tunnels.
- **Bridges and Other Structures:** underbridges, overbridges, footbridges, retaining walls, sign gantries, high masts, and culverts above 2.0m in dimension.
- **Drainage systems:** culverts below 2.0m in dimension, longitudinal drains, pipes, outfalls, inlets, manholes, filter drains, transverse drainage items less than two metres in dimension and attenuation areas.
- **Pavement:** the driving surface of the National Roads network. Pavement is characterised as 'engineered' (including but not limited to Motorways) and 'non-engineered' (including but not limited to legacy routes).
- **Geotechnical:** includes the foundations to the pavement and structures, together with the surrounding land, through which the route is formed, (including but not limited to cuttings, embankments, pavement subgrade and a diverse range of natural geological strata and man-made materials).
- **Buildings:** Motorway service areas, MMaRC maintenance depots, toll plazas and the Motorway Operations Control Centre (MOCC).

The organisation of these groups has been informed by TII's existing asset management procedures, which are outlined in TII's asset management documentation suite. The *TII Strategic Asset Management Plan for Managed and Concession Roads* is a key document in this suite, the objectives of which have been informed by both the TII *Sustainability Implementation Plan* and the TII *Climate Adaptation Strategy*, demonstrated in Figure 8 below.

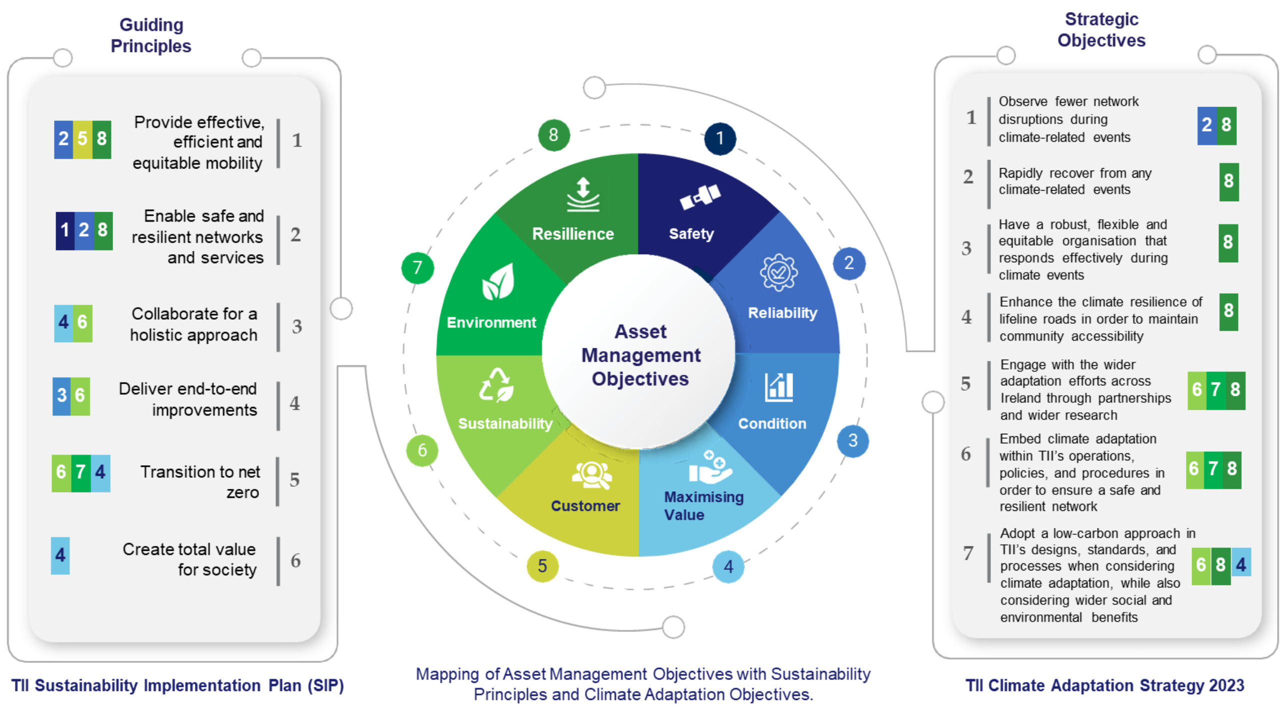

Figure 8 Objectives of the Strategic Asset Management Plan

Furthermore, the TII *Asset Management Strategy* enables asset lifecycle management, aiming to maximise the longevity of an asset whilst optimising its performance. Asset lifecycle management requires coordinated planning and communication across the development and lifespan of an asset, thereby ensuring that an asset, once created, can benefit from a high level of operation, maintenance, and eventual renewal or replacement.

Section 5 of this Plan organises the proposed adaptation measures into seven categories. Five of these correspond to the asset groups listed above: i.e. ***Tunnels, Bridges and Other Structures, Drainage, Pavements***, and ***Geotechnical***. The measures have been developed based on vulnerabilities specific to these assets. Buildings are not included as a group in the Plan, although some building-related measures, such as those concerning the MOCC, are found within other groups. The two additional groups, ***Overarching*** and ***Operations***, contain measures that address broader, cross-asset activities.

3 Our approach to developing the Plan

Building resilience to climate change across the National Roads network requires an integrated approach. Transport Infrastructure Ireland (TII) must strengthen the foundations of a resilient National Roads network by investing in data, evidence, standards, processes and institutional capacity – the enabling conditions that allow climate risk to be understood, managed, and integrated into decision-making. TII must also deliver targeted adaptation and risk reduction measures at specific locations where the National Roads network is most exposed and vulnerable climate hazards. This section sets out TII's overall approach to developing this plan.

3.1 TII's climate adaptation journey

TII is following national and international best practice approaches regarding climate adaptation planning, and specifically the process outlined in Ireland's *Sectoral Planning Guidelines for Climate Change Adaptation*. For the purposes of this Plan, this process is set out Figure 9 below. The specific focus and role of this iteration of the Plan within this process is **investing in the enabling conditions that underpin a resilience transport system, while commissioning targeted investigations at known problem sites to prepare for future measures.** This iteration of the Plan includes targeted studies at locations where flooding impacts are already being experienced and are likely to increase under climate change (see Section 3.5). These studies are an essential precursor to measure, ensuring that any adaptation measures are designed and implemented based on robust evidence.

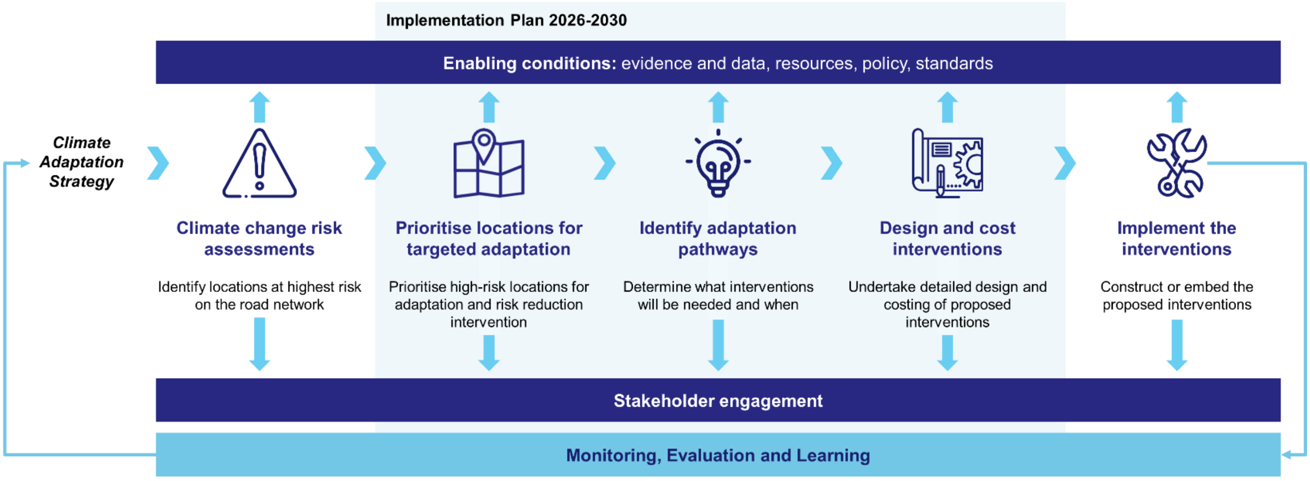

Figure 9 TII's approach to climate adaptation on the National Roads network

In parallel to this plan, comprehensive Climate Change Risk Assessments (CCRA) for the National Roads network are already underway. These will provide a nationally consistent, evidence-based basis for prioritising future investment, while the measures in this implementation plan focus on enabling conditions and targeted studies that strengthen preparedness now. The measures set out in Section 5 of this Plan emphasise:

- Strengthening the evidence base.
- Enhancing asset management systems.
- Updating standards, tools, and guidance.
- Institutional and operational strengthening.
- Targeted investigations to improve understanding at known challenge locations.

The impacts of climate change are characterised by deep uncertainty. While extreme weather events are becoming more frequent and severe, the exact timing, severity, and spatial distribution of future hazards remain unpredictable. For long-lived infrastructure such as the National Roads network, this uncertainty presents a significant challenge: **how can responsible and cost-effective adaptation decisions be made today without knowing exactly the impacts of future climate scenarios and events?**

The approach set out in Figure 9 above is designed to be adaptative, responding to the uncertainties represented by the potential impacts of climate change. The principles of Dynamic Adaptative Policy Pathways (DAPP) have been integrated into the overall process, ensuring that investments can be sequenced over time, adjusted as conditions change, and supported by continuous monitoring, evaluation, and learning (MEL, see Chapter 7). DAPP provides a structured way to sequence short- and long-term measures and measures based on how future conditions unfold. It includes considerations beyond adaptation, such as an asset's lifespan, acknowledging that the end of lifecycle may be an opportune time to introduce a new adaptation measure or measure. This staged approach to planning allows for cost-effective investment by prioritising low-regret measures in the near term and deferring higher-cost or transformative measures until there is a higher level of certainty on future conditions.

A key feature of this approach is the use of adaptation tipping points – the points at which existing measures no longer meet their objectives [19]. These tipping points trigger a shift to alternative strategies and are used to time measures and measures based on monitored changes in environmental, socio-economic, asset performance, or risk conditions. This cycle enables responsive adaptation to changing conditions and new information, in an ongoing, flexible process.

3.2 Risk framework

To understand the potential impact of climate change on infrastructure and to prioritise adaptation effectively, it is essential to take a structured approach to assessing and communicating risk. CCRAs enable the assessment of potential consequences of climate impacts, and to identify and prioritise the most effective points of climate adaptation and investment, whether through reducing asset vulnerability or exposure to hazards, or by ensuring there are appropriate response and recovery protocols in effect.

In its *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [20] and since the *Fifth Assessment Report (AR5)* [21], the Intergovernmental Panel on Climate Change (IPCC) has shifted its focus to a risk-centred assessment framework, in which risk is expressed as a function of **hazard, exposure, and vulnerability,** as shown in the equation below and in Figure 10.

Risk = Hazard x Exposure x Vulnerability

By focusing on risk, the IPCC recognises that a significant proportion of interrelated impacts are triggered by hazardous events, and thus these impacts should be appropriately addressed by the risk concept. The IPCC encourages more investigative studies in risk management to determine the potential consequences of hazardous events. This approach to risk has also been adopted in Ireland's *National Climate Change Risk Assessment* (NCCRA). The definitions used here are adapted from the IPCC and tailored to the specific context of this plan, as shown in Table 2.

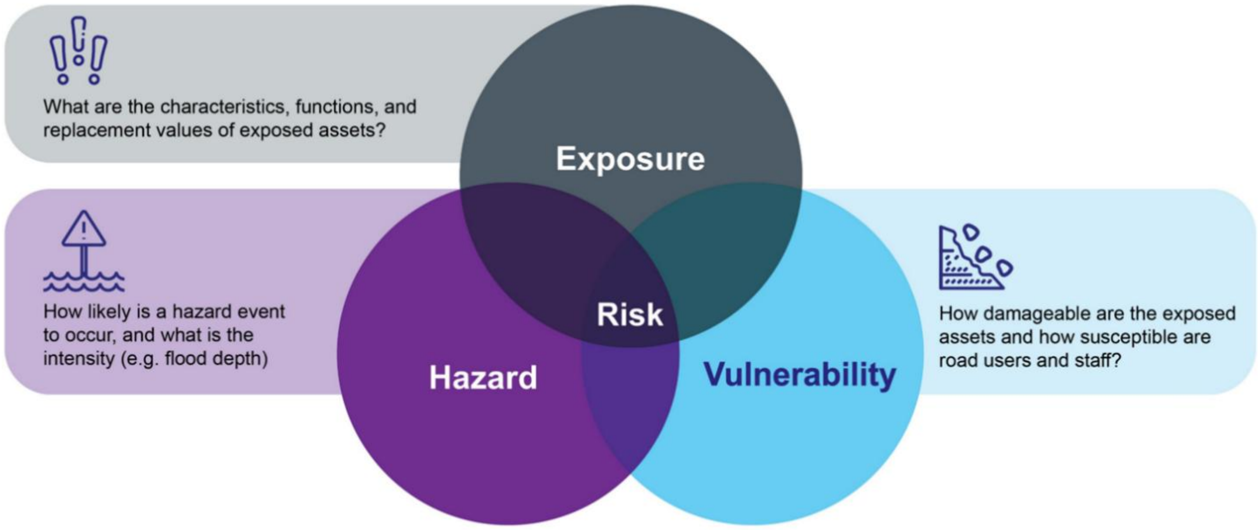

Figure 10 Risk Venn diagram

Table 2 Risk framework definitions

Term	Definition
Hazard	The potential occurrence of a natural 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.
Exposure	Exposure describes the presence of transport infrastructure, for example roads, rail, seaports, airports; and related economic and social aspects of this infrastructure that could be adversely affected by a natural hazard.
Vulnerability	Vulnerability is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
Risk	Risk results from dynamic interactions between hazards with the exposure and vulnerability of the affected system to the hazard. It is the combination of the probability of hazard and its negative consequences.

The risk framework is used to build an understanding of where climate risk arises, for example, from the intensity or frequency of hazards, the location of assets in high-hazard areas, or the vulnerability of those assets to hazard exposure. This language and risk framework are applied consistently throughout the Plan to support the assessment of climate and natural hazard impacts, prioritisation of actions, and planning for a more resilient national transport network.

3.3 Integrating criticality

In addition to risk, this Plan incorporates the concept of criticality to support prioritisation. Not all sections of the network contribute equally to network functionality, economic performance, or community access. Criticality describes how important an infrastructure element is to the overall functioning of the transport network and society. For example, a road segment may be exposed and vulnerable to hazards, but if it is not critical, the consequences of its failure may be limited.

Conversely, disruption to a highly critical link, regardless of its exposure and vulnerability, can cause disproportionate economic, operational, or social consequences. A criticality assessment by TII has provided the foundation for this element of prioritisation. It is detailed in the technical note *National Roads Criticality Assessment* [22] (see Figure 11). This assessment evaluates the relative importance of different segments of the National Roads network using two primary dimensions:

- Physical: the direct economic consequences of losing or damaging an element of the network.
- Functional: the impact on connectivity or mobility.

The integration of risk and criticality ensures that adaptation measures are prioritised not only where hazard is highest, but where damage and disruption would have the most significant social, economic, and operational impacts.

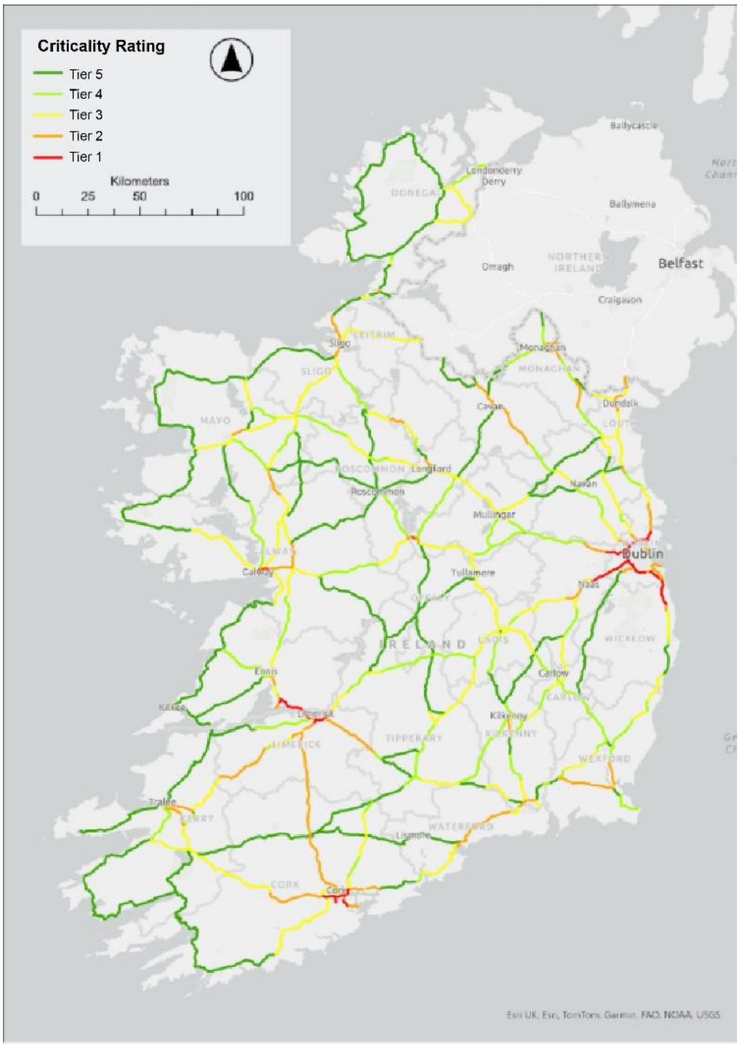

Figure 11 Map of the National Roads network showing assigned Tier 1 to Tier 5 criticality levels

3.4 Identification to site selection

Risk provides a robust foundation for understanding where adaptation measures may be required. However, moving from risk assessment to implementation requires a practical route for prioritising sites for investment in the short-, medium- and long-term. To translate risk into action, this Plan combines risk (Section 3.2) with criticality (Section 3.3) and other relevant criteria to support the prioritisation of high-risk locations or assets for adaptation investment. This ensures that adaptation measures are targeted not only where climate risks are highest, but also where disruption would have the most significant social, economic, and operational impacts.

In the short-term (i.e. next 12 months), while comprehensive CCRAs for the National Roads network are still underway, there is an immediate need to act where risks are already apparent and impacting the network. Therefore, it is proposed to select sites for early investment using the best available information and decision-making tools such as multi-criteria assessments. This approach enables the identification of “low-regret” sites — locations where climate hazards are already evident, where the best available data highlights that future climate change will likely exacerbate these challenges, and where the sites are critical to the National Roads network.

This temporary but necessary measure allows urgent risks to be addressed now, while the longer-term systematic prioritisation process is being established, as shown in Figure 12. Section 3.5 discusses TII's approach for identification of locations across the National Roads network, that based on currently available information, require short-term action to ensure their resilience to flooding events.

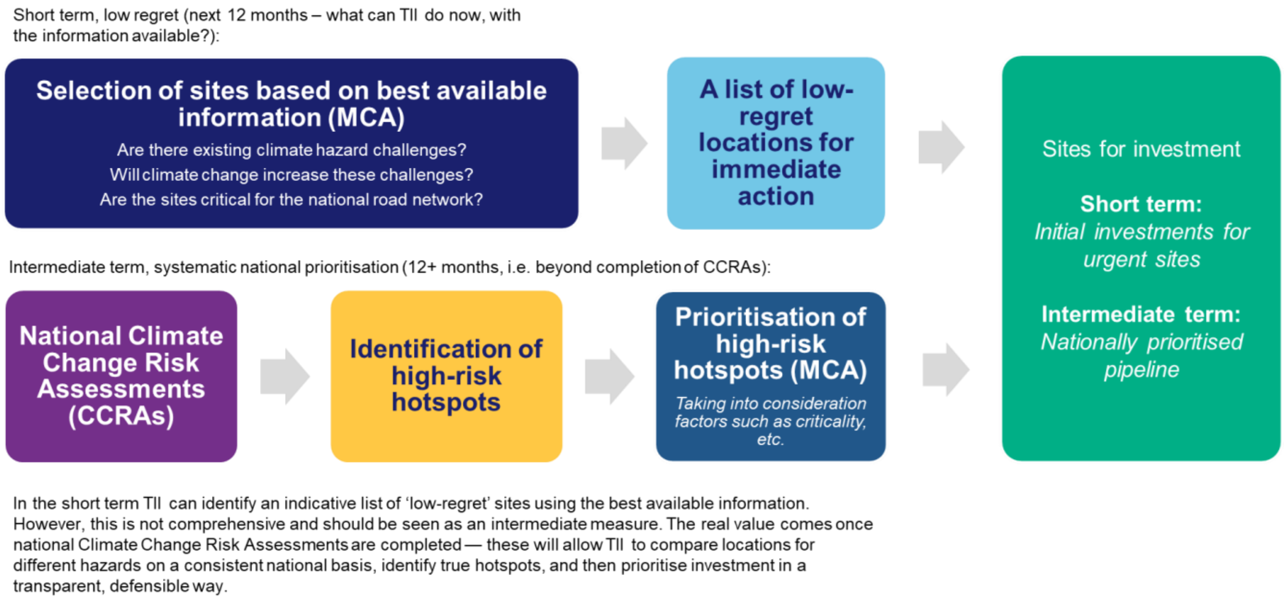

Figure 12 Short-term and long-term routes for prioritising sites for adaptation investment

In the intermediate to long-term (i.e. 12+ months), prioritisation will be guided by the outcomes of the CCRAs for the National Roads network, which are being undertaken in parallel with this Plan. These assessments will enable a consistent, evidence-based comparison of hazard, exposure, and vulnerability across the network, supporting the identification of high-risk hotspots and careful prioritisation of investment. The outcomes of these CCRAs will form the basis for the next iteration of the Climate Adaptation Implementation Plan in 2031, providing a robust national framework to steer long-term adaptation investments.

Importantly, the CCRAs will:

- Support the careful prioritisation of limited resources, ensuring funds are directed to where they deliver the greatest adaptation and resilience benefits.
- Enable anticipation of both frequent and rare high-impact climate events, providing insights into the most effective ways to avoid major losses and allowing decision-makers to understand the potential consequences of low-probability but catastrophic hazards, alongside more frequent, chronic events.
- Provide a foundation for long-term planning, ensuring that today's investments align with national adaptation pathways.
- These hotspots are then prioritised using multi-criteria analysis, with criticality as a key criterion, resulting in a nationally prioritised pipeline of investments. These will then be taken forward through a DAPP approach, supported by MEL (see Section 7).

For hazards expected to reach adaptation tipping points at later dates (for example, sea level rise or increased frequency of extreme heat days projected around 2050), the DAPP approach guides incremental early-stage measures such as enhanced monitoring and comprehensive risk assessments.

These incremental measures provide early signals of changing conditions, allowing TII sufficient lead time to prepare for and implement transformational measures – such as asset relocation or redesigning vulnerable coastal roads – should incremental measures be projected as insufficient to maintain infrastructure performance and safety. Adaptation planning must therefore accommodate a range of possible futures and retain flexibility to adjust decisions over time. This proactive flexibility is essential to effectively manage physical risks and mitigate the potential financial and social costs associated with inaction, overinvestment, or maladaptation.

Figure 13 Examples of recent flooding and landslide events which occurred on the National Roads network

This approach links risk assessments to implementable solutions and adaptation pathways, with MEL incorporated to ensure investments remain effective under changing climate conditions. It provides a clear, defensible process for investing in the resilience and adaptation of the National Roads network. At the same time, it creates an avenue for identifying urgent sites for investment where problems are already evident, enabling action to begin now while the data and information needed for a robust, nationally consistent method continue to be developed.

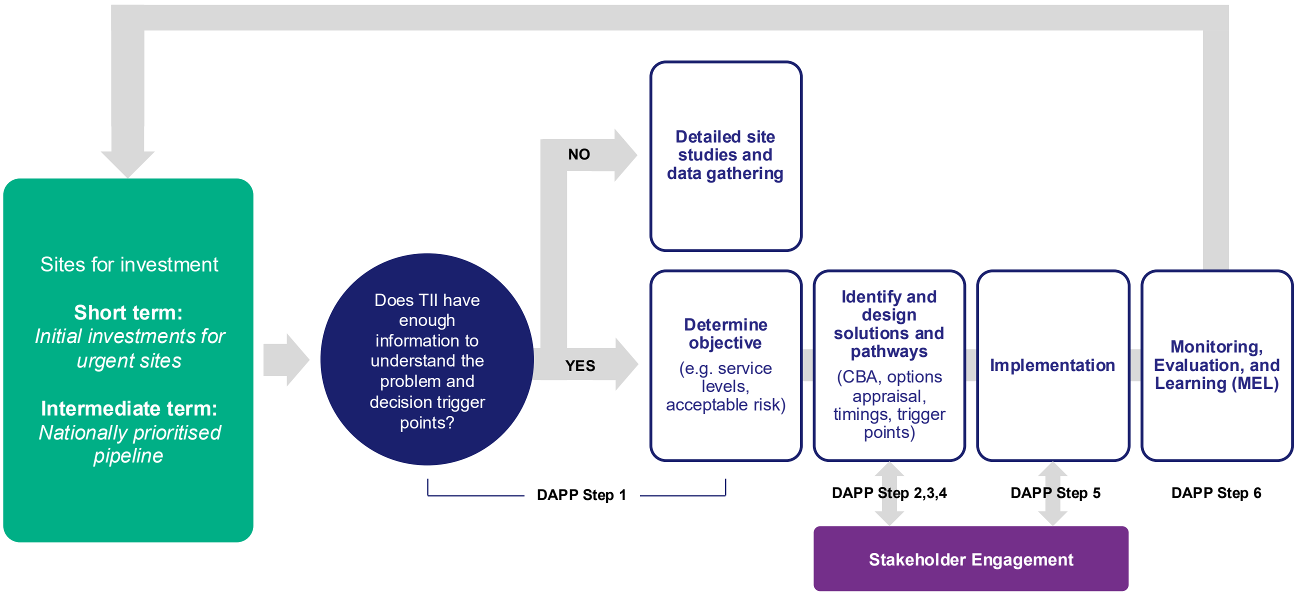

Figure 14 Linking prioritised sites to dynamic adaptive policy pathways and the monitoring, evaluation and learning framework to support resilient investment decisions

3.5 National Roads network flood risk visualisation

Based on historical data, TII has a strong evidence base to support early action on precipitation and flood risk. Through the Motorway Management and Renewal Contracts (MMaRC), a comprehensive database of flood events across the Motorway network has been compiled. Additionally, records of flooding events on the single carriageway network have been collated since 2000, as well as records of landslip and geotechnical failures on exposed areas of the network, including the N70 and N71 in Kerry. Examples of recent flood and landslide events across the network are included in Figure 13.

These historical records, combined with flood hazard and precipitation data from Met Éireann and the *National Road Network Criticality Assessment* provide a foundation to identify sites for immediate action and commence a programme of measures across the network. The datasets used in this process are detailed in Table 3.

Table 3 Key datasets supporting future flood hazard assessment

Hazard Type	Name	Use	Scenario	Return Period
Fluvial Flooding	Catchment Flood Risk Assessment and Management (CFRAM) mapping	Identifies river-based flood zones under future climate conditions	Mid-Range and High-End Future Scenario	10-Year and 100-Year Return Periods
	National Indicative Fluvial Mapping (NIFM)	Supplements CFRAM data with additional fluvial flood extents	Mid-Range and High-End Future Scenario	20-Year and 100-Year Return Periods
Coastal Flooding	CFRAM mapping	Maps coastal flood risk under future sea level rise projections	Mid-Range and High-End Future Scenario	10-Year and 200-Year Return Periods
	National Coastal Flood Hazard Mapping (NCFHM)	Supplements CFRAM data with additional present-day coastal flood extents (2022)	Current Scenario (2022)	10-Year and 200-Year Return Periods

The seven-step process used in assessing flood hazard exposure and subsequent vulnerability of the network is:

1. Define objectives and scope.
2. Assemble and integrate.
3. Assess exposure.
4. Assess system sensitivity.
5. Characterise adaptive capacity.
6. Determine vulnerability.
7. Prioritise assets and identify adaptation options.

This integrated process ensures that:

- Urgent sites can be addressed quickly, using best available information.
- A robust and defendable nationally consistent, prioritisation pipeline is developed in the intermediate term.
- Investments remain adaptable, flexible, and aligned with evolving climate science, infrastructure needs, and community priorities.

Furthermore, the process aligns with international best practice and integrates with the conceptual risk framework discussed in Section 3.2. It provides a pathway for TII to incorporate climate-adjusted hazard projections with asset-specific condition and vulnerability assessments, ensuring that prioritisation of adaptation strategies and measures reduces risk and enhances resilience.

A flood risk visualisation tool was used as part of this approach to process large volumes of hazard and asset data, as well as identify exposed sections of the National Roads network using geographic information systems (GIS). The integration of these data sources facilitates longlisting of candidate locations that are at higher exposure to flood hazard and associated adverse impacts. These locations will then be prioritised for more detailed surveys and assessments for example, asset condition surveys and targeted drainage assessments, to verify on-the-ground conditions and implement necessary physical adaptation measures (see Section 5.4 for further details).

3.5.1 Flood risk visualisation output

The flood risk visualisation tool was used to identify precipitation and flood hazard exposure and identify at-risk sections of the National Roads network based on best available information. Figure 15 provides an overview of the sections of the National Roads network at risk to flooding with an estimated 301.3 kilometre of the network exposed (under a mid-range scenario with 10–20-year return period).

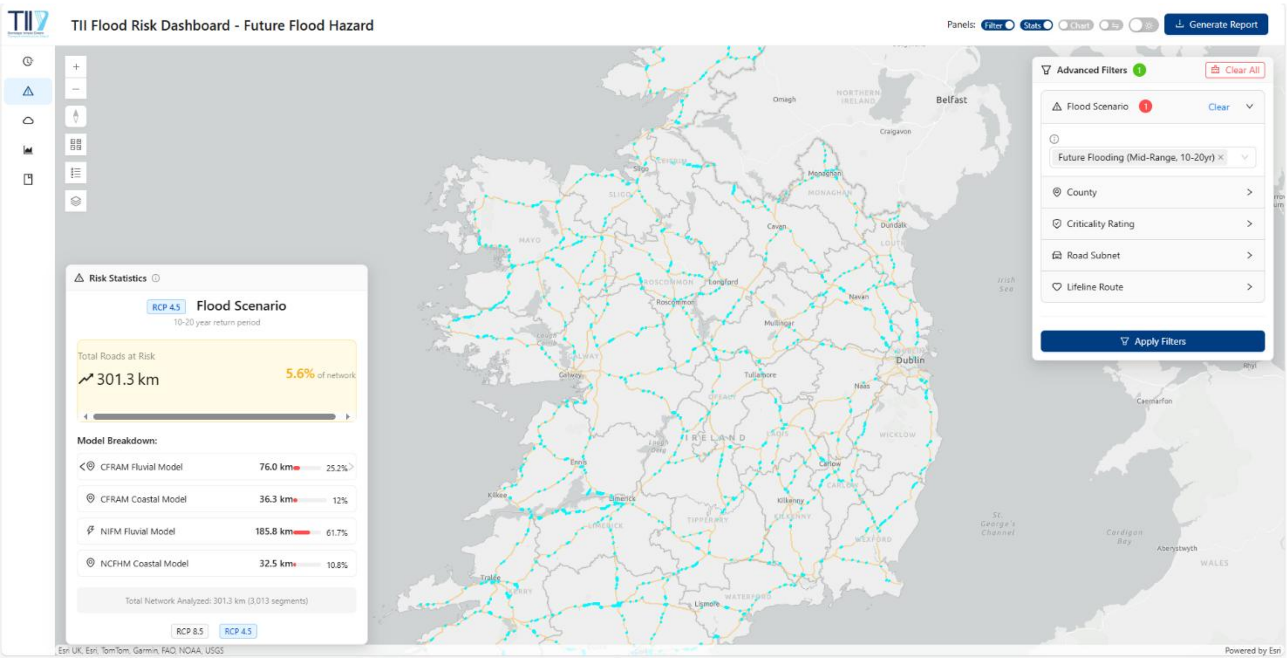

Figure 15 National Roads network segments affected by future flooding

Figure 16 presents an example output of the tool applied to a site-specific use case. It demonstrates its functionality to analyse asset data (purple), road criticality (red), historic flood data (orange and black) and modelled flood extent data (blue) for an integrated assessment of flood risk.

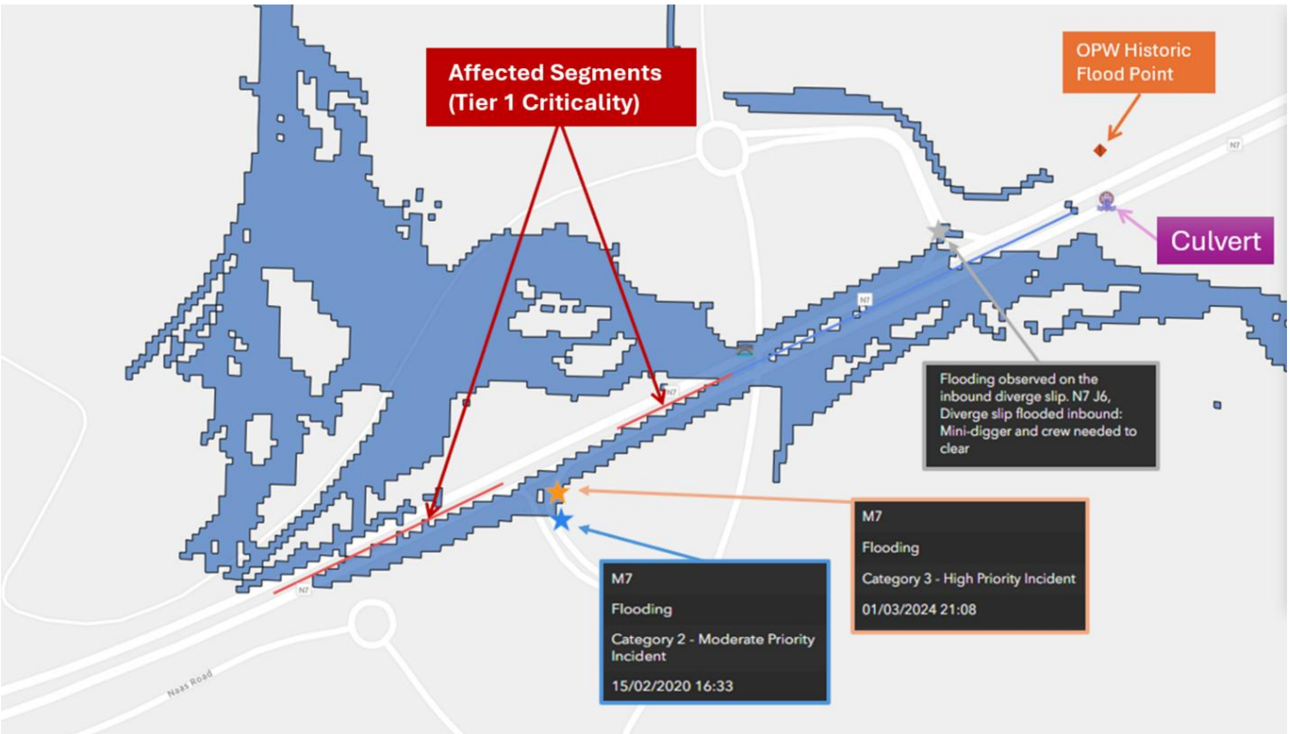

Figure 16 Strategic assessment output and application to site-specific use

3.5.2 National Roads network sections exposed to flooding

The processing of asset and hazard data and subsequent evaluation of precipitation and flood exposure shows a significant proportion of the National Roads network is exposed to flooding under RCP4.5 and RCP8.5 (see Section 4.1 for an explanation of climate projections). Of the 5,314km of National Roads and Motorways managed and operated by TII, approximately 301km and 406km have projected exposure under the mid and high-range scenarios, respectively. Further prioritisation shows that, of the 301km exposed under RCP4.5, 45km are classified as Tier 1 or 2 criticality. Additional prioritisation can also be undertaken by assessing for historical flooding, as shown in Table 4.

Table 4 National Roads network flood exposure statistics

	RCP4.5	RCP8.5	RCP4.5 and historic flood events	RCP8.5 and historic flood events
Exposure to future flood events	301km	406km	53km	69km
Exposure to future flood events on Tier 1 and Tier 2 criticality segments	45km	67km	10km	15km
Exposure to future flood events on Tier 1 criticality segments	12km	18km	2km	3km
Exposure to future flood events on lifeline routes	46km	59km	8km	10km
Exposure to future flood events on lifeline routes with Tier 3 criticality	2km	3km	0.5km	0.6km
Exposure to future flood events on lifeline routes with Tier 1 and Tier 2 criticality	0km	0km	0km	0km

This flood risk visualisation tool enables TII to strategically identify locations for assessment, design measures, and implement climate adaptation measures across the National Roads network. It has also been used to determine the number of bridges and other structures located within the exposed areas, as shown in Table 5. This will support further prioritisation of assets to undergo comprehensive risk assessments upon completion of the national roads CCRA.

Table 5 Number of bridges and other structures exposed to future flooding events

	Bridge	Underpass (scour prone)	Culvert	Gantry
Number of structures within the 301km exposed to flooding under RCP4.5	688	8	128	4
Number of structures within the 406km exposed to flooding under RCP8.5	769	9	153	4

3.5.3 Next steps

The flood risk visualisation tool will continue to evolve throughout the lifetime of this implementation plan. It will be further informed by the completion of CCRAs and the availability of new hazard and asset data. TII will continually review the current methodology used to prioritise locations, with a view to incorporating further weighting criteria to refine network exposure and vulnerability where applicable.

3.6 Generating cost estimates under uncertainty

Adopting a DAPP approach provides a structured framework for managing uncertainty in climate adaptation planning. Over time, this approach enables greater confidence in cost estimates by allowing decisions to be staged and adjusted as new information becomes available.

At present, the overall costs associated with implementing climate adaptation measures for national road infrastructure and operations remain subject to significant uncertainty. This is due to several interrelated factors, including:

- The variability and unpredictability of future climate impacts.
- Site-specific conditions across the National Roads network.
- The range of potential adaptation measures and policy choices.
- The limited precedent and guidance available in the emerging field of climate adaptation costing.
- Selection of the appropriate physical measure and then the associated design, procurement and construction costs.

The cost estimates presented in this Plan are primarily representative of enabling actions, designed to lay the groundwork for future measures across all asset categories. These cost estimates (see Section 6) are based on assumptions regarding staff availability, expertise, and the duration required to execute each measure.

4 Priority climate hazards

Ireland's first *National Climate Change Risk Assessment* (*NCCRA*) conducted by the Environmental Protection Agency (EPA) in 2025, states that the primary hazards facing the built environment across Ireland are flooding, extreme winds, and coastal erosion. These hazards are projected to have catastrophic late-century impacts on Ireland's built environment and require the most immediate urgency amongst policymakers to mitigate or adapt as necessary.

While it is probable that the primary threats facing the National Roads network will generally mirror those outlined in the *NCCRA*, they do diverge in the immediate future. Namely, coastal erosion is unlikely to pose an immediate threat to the National Roads network due to the relatively small length of network within proximity of the coastline.

TII undertook an initial *Climate Impact Screening* in 2023 [7], which provided a high-level understanding of the National Roads network's key asset typologies that are most vulnerable to the impacts of certain climate hazards. As shown in Figure 17, this process generated a shortlist of four principal hazards (dark blue) and four secondary hazards (grey) as well as cascading and compounding impacts (purple).

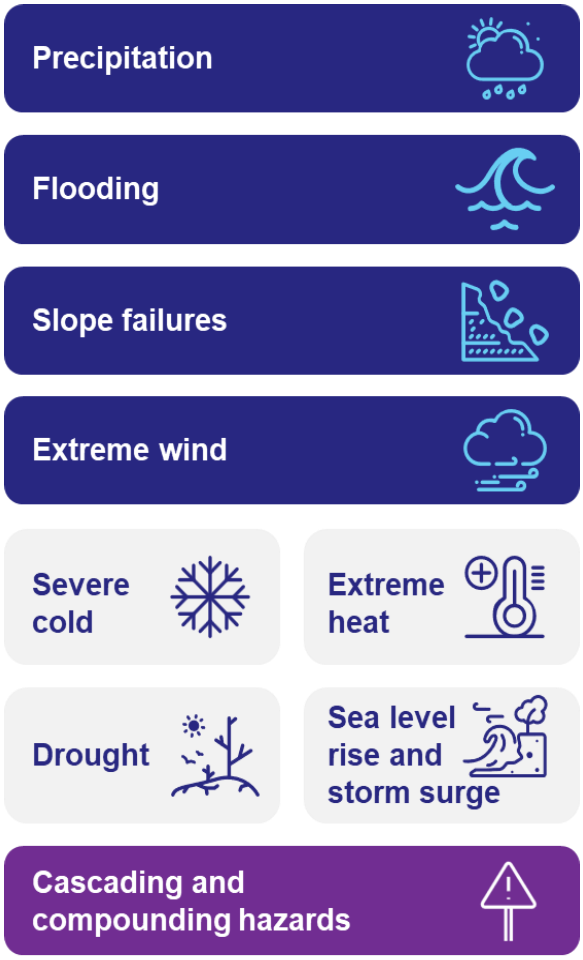

Figure 17 Climate action hazards linked to measures within 2026-2030 implementation plan

Currently, major threats to the National Roads network include extreme winds, precipitation, flooding and slope failure. These hazards can and will affect different asset types in distinct ways, depending on their location, design, condition, and operational role within the network. To fully understand potential risks (as defined in Section 3.2), the completion of a Climate Change Risk Assessment (CCRA) for the National Roads network is underway to enable the development and implementation of appropriate adaptation measures. However, it must be recognised that TII has already developed a broad understanding of National Roads network sections exposed to flooding (see Section 3.5).

Details of each primary hazard (i.e. precipitation, flooding, slope failures and extreme wind) and its potential implications for the National Roads network are provided in the following subsections, while further details for secondary hazards are in Appendix A. This acknowledges that while extreme heat, drought, severe cold and coastal erosion are considered unlikely to pose immediate hazards to the National Roads network, projected changes for each hazard is non-linear, and the risks posed by each may fluctuate over time and become more significant in the future.

It is essential to recognise the growing threat of climate change and its hazards and consider these risks within current and future organisational planning and asset management. Table 6 contains the asset groups explored within the Plan and whether climate hazards identified may impact them.

Table 6 Climate hazard exposure to the National Roads network asset groups between 2026-2030

Hazard	Overarching	Bridges & Other Structures	Drainage	Tunnels	Motorway Operations	Geotechnical Risk including Landslide Risk	Pavement
Increased precipitation	●	●	●		●	●	●
Flooding	●	●	●	●	●	●	
Slope failures	●	●					
Extreme wind	●	●			●		
Sea level rise & storm surge	●						
Severe cold	●		●		●	●	
Extreme heat	●						●
Drought	●		●			●	

4.1 Climate projections

Climate projections have been used to determine whether National Roads network assets are exposed to a hazard and how they may be impacted in future scenarios and time periods. To model and predict future climate it is necessary to make assumptions about the economic, social and physical changes to our environment that will influence climate change. Representative Concentration Pathways (RCPs) are a method for capturing those assumptions within a set of scenarios.

Representative Concentration Pathways

Representative Concentration Pathways, or RCPs, is the term used by the Intergovernmental Panel on Climate Change (IPCC) to describe the various scenarios that project future temperature changes worldwide. RCP 8.5 refers to the 'worst case' scenario, in which global efforts to reduce emissions are minimal and temperatures rise by approximately 4.3°C by 2100. RCP 4.5 projects a rise of approximately 2.4°C, due to moderate efforts to reduce emissions and manage global warming. RCP2.6 projects a global temperature rise of 1.6°C by 2100, due to significant and successful efforts to reduce greenhouse gas emissions. RCP1.9 is the aspiration of the 2015 Paris Agreement, curtailing global temperature increases to below 1.5°C due to comprehensive, global decarbonisation measures.

RCPs were defined by the Intergovernmental Panel on Climate Change (IPCC) in their Fifth Assessment Report and are globally recognised, standardised projections. It is international best practice to align with IPCC methodologies – including the use of RCPs – to ensure consistency in risk assessments and policy development. While RCPs are not codified in EU legislation, they are embedded in their climate modelling tools and databases, used to inform strategic planning and are foundational to EU-supported climate risk assessments. Nationally, RCPs are actively used in climate modelling and adaptation planning, particularly by the EPA. RCPs also underpin the scientific bases for several climate policies, including the *Climate Action and Low Carbon Development (Amendment) Act 2021*, the *National Adaptation Framework* and the *Transport Sectoral Adaptation Plan* (*T-SAP II*).

In the context of infrastructure and road asset management, the most used RCPs are:

- RCP4.5 (a 'best estimate' scenario) reflecting a moderate global effort to reduce emissions.
- RCP8.5 (a 'business-as-usual' scenario) is used as a stress-test scenario for resilience planning and is seen as a worst-case scenario.

Across the EU and other advanced jurisdictions, it is considered best practice to carry out risk assessments using multiple RCPs, most typically RCP4.5 and RCP8.5. This ensures that adaptation plans are robust, flexible, and resilient under a range of future climate outcomes.

While the use of RCPs promotes awareness of potential ramifications of climate change on transport infrastructure and network assets, TII acknowledges that it is not likely that all National Roads network assets and infrastructure will be adapted to accommodate these scenarios in the immediate term. Planning under RCP8.5 and RCP4.5 will involve prioritising measures and measures based on climate trends, as well as the criticality of the assets. This prioritisation will require further analysis, and a clearer understanding of how future hazards may affect specific asset types and locations on the National Roads network.

TII intends for this document to be a 'live' plan, reserving the right to amend adaptive measures and priorities depending on the context of the specific project, or in response to the evolution of engineering approaches/technological solutions.

4.2 Precipitation

Heavy and/or prolonged precipitation, which includes snow, sleet, and hail, is a key hazard to the National Roads network. In Ireland, a 5% increase in average annual precipitation has already been observed for the period 1981-2010 relative to the period 1961-1990 [23]. Furthermore, by mid-century (2050), average annual rainfall in Ireland is projected to increase by 14% under RCP8.5, with most of this rainfall projected to occur during the winter. Intense rainfall events (≥20mm/day) are also projected to increase by 20% and are expected to occur during winter and autumn [24].

Changes in the frequency of heavy rainfall are evident in the increased frequency and volatility of storms across Ireland. In 2015, Met Éireann, alongside the meteorological offices of the UK and the Netherlands, began the practice of naming storms to improve communication surrounding severe weather events. Between 2020 and 2024, there were 34 named storms that directly affected Ireland, with a low of three storms in 2021 [25] and a high of 11 storms in 2023 [26], demonstrating the fluctuation and unpredictability of these events

Heavy and/or prolonged precipitation can heighten risks for the operation of the National Roads network and the overall safety of its users. For example, the increased likelihood of flooding where excess water cannot drain effectively. Additionally, heavy and/or prolonged precipitation can result in earthwork slope and road foundation destabilisation, as well as scouring on structures such as bridges. On pavement, heavy rainfall can lead to excess surface water causing reduced friction and possible aquaplaning, as well as increasing the rate of deterioration in surface course functionality. Heavy rainfall can also lead to increased splash and spray, reduced visibility and potentially increased risk of accidents for users.

4.3 Flooding

Historically, flooding is the most significant and destructive climate-related hazard to impact Ireland's built environment. Understanding the sources of flooding is essential for designing, maintaining and adapting the National Roads network to withstand current and future flood risk. There are four different sources of flood hazard, summarised in Figure 18 and described in the following subsections.

Source	Description
Fluvial (river)	When watercourses exceed the capacity of a channel and overflow.
Pluvial (surface water)	When intense rainfall cannot drain away quickly enough, either due to blocked or full drainage systems, or ground that cannot absorb more water. Includes flash flooding when heavy rainfall exceeds the rate of drainage/saturation.
Coastal	Caused by storm surges, high tides, wave overtopping, sea level rise or a combination of these.
Groundwater	When the water table rises and reaches the surface.

Figure 18 Sources of flooding

Importantly, while different flood sources are discussed separately in the Plan, these events can overlap or compound, resulting in multiple sources contributing to a single flood event. For example, fluvial flooding may coincide with coastal storm surges, blocking river outlets and worsening upstream flooding. Further details regarding cascading and compounding hazards are provided in Section 4.6.

4.3.1 Fluvial flooding

Fluvial flooding occurs when watercourses exceed the capacity of the channel and overflow, causing inundation to surrounding areas. Fluvial flooding can result in the following impacts to the national road infrastructure and operation:

- Drainage system capacities can be exceeded by inundation of floodwater, which will severely reduce performance of drainage assets, with cascading impacts to road surface safety and overall pavement integrity.
- Submersion/inundation of bridges, culverts, low-lying road sections and tunnels which are particularly exposed to the impacts of fluvial flooding.
- Destabilise geotechnical assets through erosion or scour, which undermines foundations and causes structural damage. This impact has the potential to affect other assets with sensitivity depending on factors such as asset age and condition.

4.3.2 Pluvial flooding

Pluvial flooding occurs when intense and/or prolonged rainfall cannot drain away either due to blocked or full drainage systems, or ground that cannot absorb more water. Pluvial flooding poses a risk to the National Roads network, particularly in built-up and poorly draining areas. Common impacts from pluvial flooding on national road infrastructure and operation include:

- Cascading impacts on geotechnical assets if drainage rates are exceeded by rainfall intensity, causing premature deterioration of the assets.
- Increased intensity of rainfall in climate change projections increases drainage surcharging and increases water film thicknesses on pavement surfaces. Both of these impacts contribute to the secondary hazard of aquaplaning, which carries significant risks to road users by adversely affecting road visibility, stopping distances and their overall level of control over their vehicles.
- Similarly, premature deterioration of pavement can occur if drainage rates are exceeded by rainfall intensity, leading to structural degradation and ultimately potholes from water infiltration.
- Flash flooding has the potential to cause tunnel entrances to become inaccessible.

The impacts of pluvial flooding described above affect not only the physical condition of National Roads network assets, but also the safe and efficient operation of the National Roads network.

4.3.3 Coastal flooding

Coastal flooding is caused by storm surges, high tides, wave overtopping, sea level rise, or a combination of these factors. It can cause impacts such as inundation or erosion of coastal assets and blocked outfalls increasing upstream flooding. Other impacts of coastal flooding on National Roads network infrastructure include:

- Groundwater changes driven by sea level rise and coastal flooding can cause premature failure of pavement, if drainage is insufficient to remove floodwater.
- Exceedance of drainage system capacities presents a risk to road surface safety and could also lead to surcharging and erosion of soil material through pipe joints with the risk of hydraulic jacking.
- Flood levels could exceed tunnel or building entrances and cause water ingress, potentially causing damage to equipment and structures.

4.3.4 Groundwater flooding

Groundwater is water stored underground in the fractures and pore spaces of bedrock and unconsolidated materials. Groundwater flooding occurs when this water rises above the ground surface, typically after prolonged or exceptional rainfall. Unlike pluvial and fluvial flooding, it develops slowly, often over weeks or months, and can persist for extended periods.

In Ireland, groundwater flooding is most common in areas underlain by karstified limestone or sand and gravel aquifers, where extensive underground drainage networks (of fractures and conduits created because of the dissolution of the limestone bedrock) limit the presence of surface water features such as rivers. An example is the presence of turloughs, which are seasonal, groundwater-fed lakes that flood low-lying depressions in winter and recede in summer. In Ireland, these are mainly found west of the River Shannon in counties Roscommon, Galway, Mayo, and Clare. Groundwater flooding has become more frequent in recent years and can pose significant risks to communities and infrastructure, including:

- Instability and potential failure to embankments and pavements driven by uplift pressure, internal seepage/erosion or reduced soil cohesion associated with groundwater flooding/Submersion of low-lying roads such as the M18, N67, N63 and N5, which are subject to seasonal groundwater flooding.

4.4 Slope failures

Though slope failures are geophysical hazards arising from the physical processes of the Earth's geology, these failures are heavily influenced by weather events. Incidences of slope failure on both engineered and natural slopes are influenced by several climatic variables, including increased precipitation, rainfall intensity, increased temperature, heatwaves and prolonged drought. The most common impacts from slope failure on the National Roads network include:

- Washouts or earth slips leading to debris on roads or blocking of tunnel portals, which are hazardous for drivers.
- Requirements to install structures to remediate natural slopes that have failed. Retaining walls in steep slopes can often be the preferred solution to reprofiling due to space constraints.
- Damage to adjacent pavement, structures, drainage, or other assets if they abut the landslide/failed embankment.

Recently, the National Roads network has had several slope failures on the N70 and N71 in County Kerry. As many sections of these roads are hewn from steep mountainsides, the geotechnical and geological characteristics of the terrain and the high levels of rainfall in the region make these roads particularly susceptible to landslip failures.

4.5 Extreme wind

Wind remains one of the most difficult climate variables to predict, as wind speed and storm tracks are highly sensitive to small changes in atmospheric conditions. While there is no evidence of a sustained long-term trend in wind speed or direction, evidence exists of an increase in the number and intensity of storms over the North Atlantic, which are associated with high wind speeds. Since 1950, the number of North Atlantic storms has increased by three storms per decade [23].

By mid-century, projections indicate an overall decrease in wind speeds, but an increase in extreme wind speeds, particularly during winter. These changes correlate with the projected increase in the number of very intense storms over the North Atlantic region during the winter months.

Extreme wind can cause significant impacts to transport infrastructure, including:

- Structural damage to bridges – particularly long-span bridges – and gantries, high masts, and signage due to sustained wind loading or gusts.
- Disruption to road operations and usage – particularly on bridges – due to high wind speeds causing unsafe driving conditions.
- Obstruction of carriageways from fallen trees, branches, or wind-blown debris, leading to hazardous driving conditions.

A major challenge relating to extreme wind is its impact on major bridges and high embankments. Through the Motorway programme a number of long-span bridges have been constructed including the M50 Westlink bridges, the M1 Boyne Bridge and the N25 Rose Fitzgerald Kennedy Bridge. Long-span high bridges are most susceptible to the impacts of extreme wind.

4.6 Cascading and compounding hazards

Natural hazards often occur simultaneously or successively, rather than as singular events, resulting in impacts that interact and often amplify their effects. Ireland is increasingly impacted by the effects of cascading impacts where one hazard causes another hazard to occur, and the convergence of compounding events where multiple hazards or events strike simultaneously or in rapid succession. For example, extreme wind and heavy rainfall often occur at the same time (compound hazards) and can trigger secondary hazards, such as coastal flooding (cascading hazards), as shown in Figure 19.

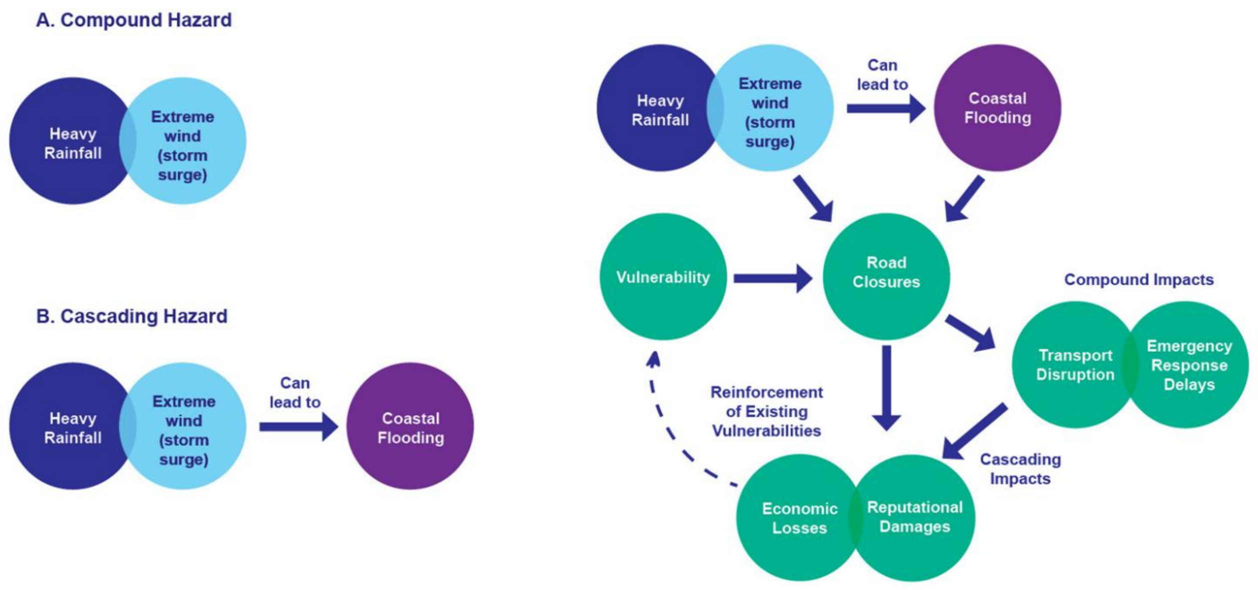

Figure 19 Graphical representation of compound hazards (A), cascading hazards (B) and their impacts (C)

Recent examples of compounding and cascading hazards across Ireland include:

- Compounding: the extreme cold spell experienced in Ireland during the winter of 2009/10. Although total rainfall was below-average, episodes of rain were followed by sudden and significant drops in air temperature [27], causing surface water to freeze rapidly. The occurrence of these two hazards in immediate succession led to the deterioration of pavement surface dressing materials.

- Cascading: the storm surge and subsequent flooding which occurred in Clarinbridge, County Galway, in 2023. Storm Debi made landfall in the Clarinbridge area, bringing intense rainfall and extreme winds. These two hazards combined as a storm surge event which caused significant coastal flooding and extensive damage to Clarinbridge [28].

If compound and cascading risks are not identified and planned for, hazard events may be significantly underestimated, posing a risk to the operability and safety of Ireland's transport assets. Furthermore, it is not just hazards that are interrelated. The exposure and vulnerability elements of risk also have complex interactions, as illustrated in Figure 19 above. For example, if a high wind event destabilises trees, causing them to block roadways, road authorities may divert traffic onto alternative routes, causing more rapid deterioration or damage to other roads that may not be designed to tolerate that amount of traffic. An understanding of the full spectrum of impacts is important as two or more single hazards may not result in a linear relationship with risk, allowing proper consideration and preparedness for complex, multi-hazard scenarios.

An assessment of the interactions between hazard, exposure and vulnerability, with respect to compounding and cascading hazards will be undertaken as part of the CCRA for national roads.

5 Proposed climate adaptation measures 2026-2030

The following section explores climate adaptation measures for the National Roads network proposed for implementation between 2026-2030. There are 20 individual measures, which are categorised into seven groups. This categorisation was conducted by identifying the primary assets associated with each measure.

Most measures can be applied in isolation without restriction, but some are either informed by or entirely dependent on the delivery of other measures. These links shall be identified throughout the process, as they may influence the overall potential success of a specific measure as well as the timeframe of delivery. The details of each measure are presented through an overview describing its context and method of delivery. The measures are also presented with anticipated outcomes, proposed engagement and links to ongoing works where relevant.

The measures include classifications for each measure type – operational, technological, and policy. Operational measures directly relate to the operation of Transport Infrastructure Ireland (TII) assets and processes, and which may influence operations in the future, such as the collection of new asset management data for use in decision-making. Technological measures will require the provision of specific technical and technological processes, such as to record hydraulic/hydrology data for culverts. Policy measures directly influence the internal policies adhered to at TII, or measures which will affect the operational policies of TII assets, such as guidance on the operation of bridges during high wind speeds. These measure types are displayed below.

Figure 20 Measure types

5.1 The measures within this Climate Adaptation Implementation Plan

Table 7 contains a list and summary of all 20 measures included within this Plan. The measures have been tagged using a three-letter system, based on the name of the most relevant asset group. Where possible, these tags are based on existing TII documents for consistency. For example, standards and publications relating to national road structural infrastructure are marked as ‘STR’, which is the same tag utilised within this plan. Where this has not been possible such as for the ‘overarching’ measures, these tags have been created for the purposes of this plan whilst utilising the same approach.

Table 7 Adaptation measures within this Climate Adaptation Implementation Plan

Measure	Summary	Type	Hazard	Time
OVR-1 Undertake review and update of TII standards to incorporate climate adaptation and climate resilience considerations	TII will undertake a review and update of standards to incorporate considerations surrounding climate adaptation and resilience. Following the reviews, standards will be updated as necessary.			2026 - 2030
OVR-2 Development of improved/updated flood hazard data that covers the National Roads network	This measure will develop an updated and expanded national flood hazard database that is fit-for-purpose for TII's risk assessment and adaptation planning needs, while also offering wider benefits to Local Authorities and national climate resilience efforts.			2026 - 2027
OVR-3 Complete detailed climate change and natural hazard risk assessments for the National Roads network	TII will complete a detailed climate change and natural hazard risk assessment, which will provide a robust evidence base to understand how and where hazards interact with national road infrastructure, to calculate risk (as economic losses and network disruption) caused by climate change and natural hazard events, and to guide strategic investment.			2026 -2027
OVR-4 Sea level rise and storm surge study for the National Roads network	This measure will use the capabilities of TII's Flood Risk Visualisation Tool to inform a location-specific climate change risk assessment (CCRA), which focuses on sea level rise and storm surge hazards. The aim is to understand how climate change may increase these hazards and associated risks along coastal National Roads network corridors (such as the N69) and to identify priority areas for adaptation.			2026 - 2027
STR-1 Asset management database expansion to include retaining walls	This measure will develop and refine modules for a retaining walls asset management database. It will also include engaging with stakeholders and reviewing existing asset data sources, conducting laser imaging detection and ranging (LiDAR) surveys of the network and populating the database.			2026 - 2028
STR-2 Capture hydraulic and hydrology data for river bridges and culverts	This measure will gather information about the existing river bridges and culvert system through desktop studies, engagement with local area engineers, and surveys. Gap analysis will inform assessment of whether these systems are fit-for-purpose. This is critical for informing catchment management and guiding design improvements for peak flows and climate impacts.			2026 - 2028
STR-3 Enhance institutional engagement with wider stakeholders responsible for watercourse management with the aim of creating improved protocols for watercourse management regarding maintenance and rehabilitation of culverts and bridges	This measure will seek to enhance the engagement and approval process for undertaking reactive maintenance and repair, as well as establish a protocol for watercourse management when necessary, measures fall outside of TII's control and responsibility.			2026 - 2030
STR-4 Publish high-level technical guidance document for wind on major bridge structures/high embankments and develop operational plans for individual bridges/high embankments on the National Roads network vulnerable to severe wind events	This measure details the development of a high-level technical guidance document which outlines a protocol during severe wind conditions for all bridges and high embankments on the National Roads network, and the subsequent development of this guidance document into an actionable operational protocol.			2024 - 2026

Measure	Summary	Type	Hazard	Time
DNG-1 Conduct a desktop vulnerability mapping exercise on National Roads network drainage	This measure involves collating current and future climate data to assess exposure to flooding across the National Roads network, before undertaking a prioritisation exercise to identify the most exposed sections.			2025
DNG-2 Develop a Drainage Asset Management Module (DAMM) and implement programme for drainage inventory capture	This measure will develop options to capture drainage inventory data that can facilitate an efficient data collection process. In addition, it will identify a compatible DAMM that has the ability to provide real-time updates on the status of road assets and components.			2026 - 2027
DNG-3 Undertake detailed surveys of existing drainage assets to be included in the proposed drainage module in DNG-2 to facilitate planning for a long-term programme of network drainage upgrade works at locations where potential flooding and increased rainfall has been identified in DNG-1, with the initial focus on determining network catchments and location of outfalls	This measure builds on DNG-1 by undertaking detailed surveys to capture data related to network catchments and outfalls for sections of the National Roads network that are considered to have high or very high exposure to flooding.			2026 - 2028
TUN-1 Assess current and future flood hazard and risk at the Dublin, Jack Lynch and Limerick Tunnels	These studies will identify and assess the flood hazard and risk for each tunnel including each portal area and associated staff management buildings and areas. New data will be developed where there are gaps, including for current and future climates across a range of scenarios. The primary metric for consideration in the risk assessment will be how flooding threatens the availability of the tunnel for safe use.			2026
TUN-2 Identify, assess and undertake appropriate climate-related resilience measures at Dublin, Jack Lynch and Limerick Tunnels	This measure will identify and undertake appropriate structural and non-structural measures that are feasible for implementation and can adapt tunnel infrastructure and operations to climate hazards.			2027 - 2030
OPS-1 Implement MMaRC third generation contracts, including contractual enhancements for improving resilience to flood, wind, and cold spell events	This measure will undertake a review of existing contract documentation and operational arrangements that MMaRCs currently have in place to respond to flood, wind and cold spells events for evaluation and to identify recommendations for how resilience planning might be enhanced in the third-generation contracts.			2025 - 2026
OPS-2 Conduct climate and severe weather resilience review of operations buildings	To understand the extent of the risks facing operations buildings, this measure proposes a desktop study to determine and model future climate risks - using the results to determine capacity gaps and develop a remedial programme thereafter.			2027 - 2030
OPS-3 Undertake flood analysis for M1 (N & S) motorway service areas and design a remedial programme to address identified flood issues	This measure proposes that detailed flood hazard information will be gathered for the M1 service areas via site-specific flood risk assessments, to assess risks from pluvial, coastal (including from wave overtopping), and groundwater flooding.			2026 - 2030

Measure	Summary	Type	Hazard	Time
ERW-1 Complete the detailed Geotechnical Asset Management Database (GAMD)	This measure will improve the GAMD and build on previous pilot studies through enhanced data collection and carrying out on-site validation. The GAMD will be structured to account for different data types and be maintained through regular standardised asset inspections to support long-term asset decision-making.			2026 - 2028
ERW-2 Utilise new GAMD to underpin a risk assessment programme for bog rampart sections of the National Roads network, and develop and implement a prioritised remedial programme of bog rampart rehabilitation	Utilising the GAMD developed in ERW-1, risk assessments and geotechnical surveys will be carried out on bog ramparts to identify the risk that climate change poses to them. Once at-risk locations have been identified, and prioritised based on location, risk level and road use, a remedial programme for rehabilitation will be developed and implemented subject to available funding.			2028 - 2030
ERW-3 Continue programme of reactive measures on sections of the National Roads network affected by landslip (or landslide) failures, with emphasis on the N70 & N71	This measure will develop a prioritised programme of geotechnical measures in the at-risk sections of the N70 and N71. This will include LiDAR and aerial imaging together with geotechnical surveys to inform a detailed slope stability analysis leading to a prioritised programme of appropriate remedial measures.			2026 - 2030
PAV-1 Undertake a detailed analysis of the impacts on pavement surface course materials in a changing climate	This measure comprises two studies: one to identify specific changes to pavement conditions during short duration intense rainfall (splash & spray), and another to identify pavement effects from increased rainfall (of all types) and higher temperatures (pavement material deterioration rates).			2026 - 2027

Key

Measure type			Hazard		
Technological	Operational	Policy	Multi-hazard	Flooding	Extreme Wind

5.2 Overarching

OVR-1 Undertake review and update of TII standards to incorporate climate adaptation and climate resilience considerations

Overview

When assessing TII's preparedness for climate change, there is a need to reflect on the current standards and technical documents within TII Publications and recognise that there is likely to be scope for updating and adapting these standards in the face of increasingly hazardous climatic conditions. From a National Roads perspective, a specific standard and overarching technical document already exist to address climate with *PE-ENV-01105 Climate Assessment of Proposed National Roads* [29] and *PE-ENV-01104 Climate Guidance for National Roads, Light Rails and Rural Cycleways (Offline and Greenways)* [30], however, it is anticipated that additional guidelines and standards will be necessary in order to address TII's approach to dealing with identified climate and severe weather hazards. As part of this Plan, TII will undertake a review of relevant standards to incorporate considerations connected to climate adaptation and resilience, across the infrastructure lifecycle from planning and design through construction, operation and end of life.

A particular focus will fall on developing a robust suite of operational standards and guidance documents. A targeted assessment will be undertaken to determine whether existing standards sufficiently address the operational impacts of climate change and extreme weather events, or if new standards and supplementary guidance are required. While some standards are in place or are being developed, such as emerging guidance on wind impacts for large bridges, the footprint of these documents must broaden to encompass other critical areas such as culvert performance and upgrade criteria, Motorway flood response protocols, and enhancements to winter maintenance procedures under changing climatic conditions. Any new or revised standards must align with existing and developing *Strategic Asset Management Plans*, where climate adaptation will be a core component. This body of work will be foundational to embedding climate resilience into the operational lifecycle of national road assets.

The review will focus on the most critical TII asset groups including pavement, bridges and other structures, drainage assets, and earthworks. Following review, it is intended that relevant standards will be updated on a prioritised basis. Where deemed necessary, additional standards to guide climate adaptation actions on the National Roads network will be progressed to capture the benefits of the updates.

Among a wider study of climate change impacts on standards, considerations for key standards relating to pavement, bridges and structures, drainage assets and earthworks will be made in line with international best practice, including risk-based approaches, and these include:

Table 8 Considerations for undertaking a standards review and update across key asset groups

Asset group	Considerations for standards review
Pavement	Review of pavement bituminous materials subject to increased temperatures under two Representative Concentration Pathways (RCP) – RCP4.5 and RCP8.5 (for further information, refer to Section 4). Anomalous instances of exceptionally cold temperatures, which can result in the stripping of surface-dressed pavement, exposing the pavement to the risk of premature structural deterioration. Other changing climate parameters including combination of changes to precipitation with changes to temperature conditions. Review of specific pavement standards relevant to climate adaptation, including: *DN-PAV-03023, -03024* and *-03074*, which refer to the design and choice of pavement materials.
Bridges and Other Structures	Exploration of the second-generation Eurocodes where they relate to climate change, including development of the National Annexes and Nationally Determined Parameters that may introduce scaling factors for climate change. This will be completed as part of the wider assessment of the impact of second-generation Eurocodes on the design of structures. Update of assessment standards suite to account for changes in deterioration of assets and impacts of climate change, for example, in *AM-STR-06002 The Assessment of Road Bridges and Structures*. Update of the structural review process to account for changes in deterioration of assets and impacts of climate change, for example, in *AM-STR-06042 Structural Review and Assessment of Road Structures*. Any new standards that are required, for example, on adaptability of road bridges to climate change. Additional attention will be given to addressing bridge scour. 78 bridges on Ireland's National Roads network are susceptible to scour, which may become more prevalent as a risk due to increased erosion caused by coastal and fluvial flooding. Standards will be considered which can improve the resilience of bridges, embankments, culverts and retaining walls to scouring.

Asset group	Considerations for standards review
Earthworks	Update to Materials Management standard *CC-CMG-04001 Preparation and Delivery Requirements for As-Built Records* to incorporate earthworks data frameworks within the proportion of the overall work package and deliverable. The collection of this data, along with the use of digital tools, will facilitate the integration of sustainable working practices within engineering and construction. Development of new standards and technical guidance documents, such as a new geohazard mapping manual which can outline the process for developing and managing susceptibility mapping. Additional new standards and technical guidance documents may also relate to data collection, which can provide a structured approach to collecting inventory data (see ERW-1). New documents relating to the maintenance and management of geotechnical assets can provide frameworks for using deterioration modelling and network criticality outputs to determine and prioritise maintenance measures.
Drainage	Update to key drainage documents such as *DN-DNG-03022-06 Drainage Systems for National Roads*, which includes the provision of a 20% climate uplift so drainage systems can accommodate increased quantities of rainfall in the future. *DN-DNG-03022-06* notes the research which has led to the promotion of sustainable drainage systems, which are critical components for reducing climate hazards. Additional documents such as *DN-DNG-03061-02 Design of Outlets for Surface Water Channels* and *DN-DNG-03067-02 Spacing of Road Gullies* must also be updated in line with climate change projections and the probable impact on the frequency and intensity of rainfall events. For *DN-DNG-03067-02 Spacing of Road Gullies*, this update will relate to the rainfall intensity formula used to determine gully capacities and therefore, the quantity and placement of gullies across the National Roads network. Further exploration of the use of vegetation within sustainable drainage systems, as outlined in *DN-DNG-03063-02 Vegetated Drainage Systems for Road Runoff*. Vegetated drainage systems reduce maintenance requirements, and support carbon sequestration and biodiversity.

TII has extensive asset information requirements. Work is currently underway to consolidate existing practice for bridge asset information requirements into a single source of truth, a single data specification published in a structured format (it is intended to expand this to include all assets). This taxonomy will provide a flexible means of capturing and maintaining data standards and will provide TII with a master data dictionary for each asset class, with various sections within TII having sub-set data dictionaries for that same asset, relevant only to their information needs while at the same time ensuring consistency of terminology across teams and contracts. The data captured to support asset management and climate adaptation assessment and measures in the future will be aligned with this taxonomy, enabling a comprehensive view of each asset’s lifecycle and its climate resilience status. The taxonomy must be considered during the review and update/development of standards and guidance as part of this broader climate adaptation measure.

Anticipated outcomes

Ongoing updates to pavement standards within the last decade means reviewing these standards to incorporate climate adaptation and climate resilience considerations will be less time and resource intensive than other assets resulting in a more efficient process. Therefore, it is anticipated that a wider benefit of OVR-1 is the ultimate reduction in time required to carry out reviews and updates of other assets in the future.

This benefit is most evident when comparing the probable timeframes in reviewing and updating standards for pavement – which have been recently updated – and structures – which have not. The work on pavement standards is estimated to take several months, whereas reviewing structural standards is expected to be a multi-year process due to the scale and complexity of the task.

This is to account for the comprehensive technical innovations which have occurred since the previous review. Undertaking a review and update of all standards between 2026-30 is a major workstream in the short-term but will reduce the intensity of work needed for the same task in the long-term.

As updated standards are applicable to new infrastructure, an additional wider benefit from updating standards is the reduced life cycle costs within maintenance in the long-term. Reviewing and updating design requirements, material specifications and inspection regularity can reduce the cost of maintenance across an asset's lifespan. These improvements can be achieved by improving the minimum standards of design that infrastructure must attain. Developments to reduce the intensity of maintenance required, while also extending lifespan, will reduce disruption to road users by limiting the need for diversions or traffic control measures. Reduced life cycle costs can also lead to a long-term reduction in emissions, due to a longer lifespan reducing the potential need to construct replacements or renewals.

Another wider benefit of updating standards in consideration of future climate conditions is the improved safety of road users while travelling. Reinforcing safety requirements on new infrastructure through standards updates will reduce the likelihood of accidents caused by increasingly volatile inclement and severe weather conditions.

Engagement with stakeholders

It is anticipated that external engagement will be required as part of the review and update, for example, with the Met Éireann TRANSLATE project, supply chain partners on the qualities of procured materials, or relevant academics on a given topic. Additional stakeholders include government departments, local authorities and national agencies such as Office of Public Works (OPW), National Parks and Wildlife Services (NPWS), and Inland Fisheries Ireland (IFI).

Effective climate adaptation across Ireland's National Roads network requires strong collaboration in the development of standards and the delivery of rehabilitation and remedial measures. Early and ongoing engagement with statutory bodies and Local Authorities is critical, as these stakeholders bring essential expertise, regulatory oversight, and local knowledge to the process. Local Authorities, in particular, will serve as the primary conduit for implementing many of the physical measures required on the ground. Their involvement ensures that measures are context-sensitive, feasible, and aligned with broader regional considerations. Collaborative development of standards will also ensure consistency, transparency, and alignment with national strategies such as *Strategic Asset Management Plans*, where climate adaptation is a key pillar. This coordinated approach will be vital to building a resilient, future-proof road network capable of withstanding the increasing impacts of climate change and extreme weather events.

TII will also engage in dedicated stakeholder forums as outlined in the Transport Sectoral Adaptation Plan (*T-SAP II*) actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and Climate Action Regional Offices (CARO), engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

OVR-2 Develop improved/updated flood hazard data that covers the National Roads network

Overview

Flooding is a significant risk for the National Roads network. As described in Section 2, the network comprises new Motorway and single carriageway sections, designed and constructed to modern engineering standards (approximately 50% of the network) and legacy sections of the network which are not subject to engineering design and which are substandard in relation to overall pavement design and drainage provision. The challenge for TII is to effectively deal with the range of diverse flooding challenges presented by both new and legacy sections of the network.

As climate change increases the frequency and severity of extreme weather events, and exposure to flooding will inevitably grow. To effectively assess and manage flood risk, access to accurate and up-to-date, high-resolution, and climate change informed flood hazard data is essential.

Existing datasets, such as those developed through the Catchment Flood Risk Assessment and Management (CFRAM) and National Coastal Flood Hazard Mapping (NCFHM) studies, provide a strong foundation however they require supplementing with additional infrastructure-focused risk assessments as they present several limitations for infrastructure-focused risk assessments.

The OPW's National Indicative Fluvial Mapping (NIFM) is also relevant, but due to its use of coarse topographic data, it lacks effective representation of the road or embankment profile, particularly on single carriageway roads. The OPW caveats that this dataset provides only an indication of potential flooding [31]. Other relevant datasets do exist, such as flood event records and maintenance records (e.g. internal drainage works records), which can provide a good indication of where previous issues have arisen. However, they are inherently backward-looking and therefore do not account for a changing climate.

The following steps will be undertaken as part of OVR-2:

- Define the purpose, scope, and intended applications of the updated national flood hazard database. For example, determine whether the database is being developed specifically to support climate change and natural hazard risk assessments for the national road infrastructure, or whether it will have broader applications such as supporting planning, emergency response, or climate adaptation by local authorities and other stakeholders. Establish intended spatial resolution, hazard types, and time horizons, for example, present-day, 2050s, 2080s.
- Building on available flood hazard studies and data, conduct a comprehensive review of existing national and local studies and datasets – such as the CFRAM studies, the NCFHM project, the *Assessment and Management of Flood Risks at a Structural Level on the National Road Network* study, and any relevant Local Authority or academic work. Assess the fitness of these datasets for climate risk assessment purposes and identify any key gaps or limitations, for example, lack of pluvial flood modelling, outdated climate scenarios, low spatial resolution, absence of infrastructure representation.
- Collaborate with key data custodians and stakeholders including the OPW, Local Authorities, the Environmental Protection Authority (EPA), Met Éireann, and academic partners, to gain access to the most recent and detailed datasets, modelling inputs, and local knowledge. This engagement will also enable alignment with national climate adaptation goals and avoids duplication of efforts.
- Where available, update and expand existing hydrologic and hydraulic models to enhance them using the best available data and methods. This includes incorporating:
  - Consistent and robust climate change scenarios, for example, rainfall projections and sea level rise scenarios.
  - A broader set of flood mechanisms, including fluvial, pluvial, coastal, and groundwater flooding.
  - Joint probability analysis to assess compound flood events, for example, tidal and fluvial flooding. As described in Section 4.6, compound flood events are increasing in

frequency in Ireland, highlighting the need to better understand these complex interactions.

  – Representation of hydraulic control structures such as culverts, bridges, embankments, and urban drainage networks.
  – Current topographic and land-use information.
  – Consideration of blockage scenarios where relevant.

- Develop new hydrologic and hydraulic models where existing models are not available or are unsuitable for the intended purpose. These models shall reflect current land-use, topography, and infrastructure conditions and include simulations under current and future climate conditions for a range of events.
- Calibrate and validate models using available historical rainfall and flood records. This is essential for improving the reliability of the outputs and increasing stakeholder confidence in the results. Insights gained from the measures described in STR-1 and DNG-1 can be used to further validate the models.
- Produce updated flood hazard data, including key outputs such as flood depth, velocity, water level, duration of inundation, and depth-velocity products in flood modelling. Outputs will be formatted for integration with existing data platforms such as the OPW's FloodInfo.ie and TII's internal geospatial systems, with access to appropriate metadata and documentation.

This approach excludes undertaking location-based validation and topographic surveys as the magnitude of the investigations is currently indeterminable.

Anticipated outcomes

Improved national flood hazard data will play a role in growing TII's understanding of the exposure of existing assets to both current and future flooding. This information is essential for identifying at-risk assets and prioritising maintenance and adaptation measures. It also provides flood hazard information to inform the planning and design of new infrastructure, ensuring that future developments are located and constructed with climate resilience in mind, ultimately reducing long-term costs and avoiding maladaptation. In addition to supporting internal planning, the improved flood hazard database will offer broader value across the transport and public sectors. It will provide an updated source of consistent, high-quality flood hazard information for Local Authorities, emergency services, and infrastructure owners to better assess and manage risks. This will support more coordinated planning, investment, and emergency preparedness, while reducing duplication of efforts. The updated database will also strengthen compliance with national legislation and evolving EU climate resilience regulations, such as the EU Floods Directive. By facilitating the quantification of exposure and risk to flooding for network infrastructure, the database will enhance the robustness of business cases for investment, support applications for funding, and enable prioritisation of measures.

Engagement with stakeholders

The OPW will be a key technical partner, alongside Met Éireann and the EPA. Local Authorities will contribute valuable local data and use the outputs for planning and emergency management. Specialist technical advisors will likely be required to undertake the technical flood modelling and database development, working in close collaboration with TII and relevant stakeholders to enable a consistent and fit-for-purpose approach.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and

CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

OVR-3 Complete detailed climate change and natural hazard risk assessments for the National Roads network

Overview

The National Roads network supports economic activity, connectivity, and public safety across Ireland. To promote long-term resilience in the face of a changing climate, it is essential that TII undertakes detailed climate change and natural hazard risk assessments across the network, using a consistent and comparable methodology. These assessments will provide a robust evidence base to understand how and where hazards interact with national road infrastructure, to calculate risk as economic losses and network disruption caused by climate change and natural hazard events, and to guide strategic investment, maintenance, and adaptation planning.

The following steps are recommended as part of OVR-3 (external technical advisors to TII will deliver this scope):

- Undertake a comprehensive review and collation of the best available and relevant hazard datasets. This includes national flood hazard data, for example, CFRAM, NCFHM, as well as datasets on coastal erosion, extreme heat, wind, and other relevant hazards. Newly developed flood hazard data (refer to OVR-2) shall be incorporated. Climate change scenarios shall be included for future time horizons, using appropriate RCPs. Review national road asset databases to confirm availability and quality of spatial and attribute data for road infrastructure. Where possible, integrate asset-level vulnerability characteristics such as material type, and age. This step may include engagement with asset specialists to refine or supplement available vulnerability data.
- Using the best available hazard, exposure, and vulnerability information, conduct a detailed risk assessment for the National Roads network. Where adequate data is available, adopt a quantitative risk assessment methodology to estimate direct damage and direct disruption such as road closures. Where data and modelling capacity allow, extend the assessment to estimate indirect impacts, such as wider network disruption, economic losses, or effects on emergency access. Risk assessments will be carried out for current conditions and project future scenarios to inform short and long-term planning.
- Analyse risk results to quantify high-risk locations, corridors or hotspots with the highest risk to infrastructure under current or future conditions. Use this information to guide the prioritisation of resilience measures, such as drainage upgrades, pavement upgrades, or operational strategies. Risk outputs will also support cost-benefit analysis and business case development for adaptation and resilience investments. Ensure that the risk assessment findings are incorporated into national road asset management systems, investment planning tools, and decision-making processes. This includes linking to maintenance schedules, capital works planning, and performance monitoring frameworks. Where possible, establish processes for updating the risk assessment over time as new data or climate projections become available, or changes to the network occur.

Anticipated outcomes

Completing detailed climate change and natural hazard risk assessments for national roads will provide clear and defensible evidence to support the prioritisation of resilience investment, contribute to the reduction of long-term maintenance costs, minimise service disruptions, and avoid costly reactive emergency repairs.

OVR-3 will also promote data-driven decision-making and improve understanding of how climate change and natural hazards interact with critical infrastructure. The results can support coordination with local authorities, emergency services, and other transport operators, particularly in areas with shared risk or interdependencies. The findings will also contribute to national adaptation reporting and policy development, aligning with national *Sectoral Planning Guidelines for Climate Change Adaptation*.

Engagement with stakeholders

Key partners such as the OPW, Met Éireann, and the EPA will support the measure by providing access to relevant hazard and climate data. Local Authorities may contribute local datasets and assist TII in validating risk hotspots.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

Pilot studies for the detailed climate change risk assessments have been conducted as part of TII's *Climate Adaptation Strategy*. These pilot studies lay the groundwork for OVR-3, including a thorough review of existing asset and hazard datasets, and testing of the methodology, that can be used to expedite some of the steps outlined above.

In addition, the measure described in DNG-1 provides valuable input for this study. While the work focuses on exposure to heavy rainfall and flooding, relevant data can inform the hazard and exposure components of the national roads CCRA and be utilised to validate findings. There is also an opportunity to align terminology and methodologies between the measures, particularly in distinguishing between exposure and vulnerability, and to coordinate data-sharing efforts to maximise efficiency and consistency across the programme of climate resilience work.

As described above, the risk assessments will incorporate the best available hazard, exposure, and vulnerability information. Updated flood hazard data will be developed as part of OVR-2, and where possible, OVR-3 will incorporate this data.

OVR-4 Sea level rise and storm surge study for the National Roads network

Overview

OVR-4 focuses on assessing hazard exposure, vulnerability, and risk for the N69 route, a 97.5 km National Road connecting Limerick and Tralee. This serves as a pilot for assessing sea level rise and storm surge at critical locations. It will use the improved flood hazard database described in OVR-2 and form a location-specific application of the detailed CCRA described in OVR-3, focusing specifically on sea level rise and storm surge scenarios. OVR-4 will build on earlier measures, ensuring a coherent and replicable approach for other routes in future. The aim of this pilot is to understand how climate change may increase risks along a specific corridor and to identify priority areas for adaptation or protection.

The following steps are recommended as part of OVR-4:

1. Confirm the scope and objectives of the study for the N69. For example, identify sections of the N69 estimated to have the highest average annual losses because of damage from, disruption to operations due to flooding and coastal erosion.

2. Gather available hazard data for current and future climate scenarios (e.g. CFRAM, NCFHM, and data developed under OVR-1), and any available supplementary local studies. Obtain detailed topography, road infrastructure data, and records of past events. This information can be extracted from measures that have already been undertaken (e.g. DNG-1, OVR-1 and OVR-3). It is known that there is limited coastal erosion data available for future climate scenarios.
3. Review the available hazard data to determine if additional localised studies are required. Ensure appropriate sea level rise, storm surge, wave action, and shoreline retreat conditions are accounted for under both current and future climate scenarios. Consult technical specialists to determine if coincident flood-erosion interactions require modelling.
4. Extract the exposure and vulnerability information collated under the earlier measure described in OVR-3 and determine if any additional local information can be used to enhance the exposure and vulnerability model for the N69.
5. Combine the hazard, exposure, and vulnerability data to quantify expected damage and/or disruption (risk) under current and future climate scenarios for the N69. Identify and map high-risk "hotspots" to visualise spatial variation. Collaborate with local authorities and review findings of other relevant studies (e.g. JBA's *Assessment and Management of Flood Risks at a Structural Level on the National Roads Network* [32]) to validate findings of the risk assessment.
6. Use the outputs of this study to identify potential adaptation and resilience measures and rank measures based on factors such as risk reduction potential, feasibility, and cost-effectiveness. Continue collaboration with Local Authorities and other relevant stakeholders so local conditions and plans are considered (e.g. *National Coastal Change Management Strategy* [33]). Incorporate prioritised measures into TII's asset management plan and investment planning frameworks.
7. Evaluate the pilot and extract insights for application to other at-risk locations across the National Roads network once risk assessments have been completed.

Anticipated outcomes

OVR-4 supports national climate adaptation objectives while improving the resilience of a critical coastal corridor. It demonstrates how inputs and outputs from national-scale risk assessments can be used to undertake location-specific assessments by applying consistent methods. Findings can inform broader national resilience planning and serve as a pilot for developing coastal road management strategies that consider climate change.

Engagement with stakeholders

The OPW will be a key partner in providing access to existing hazard data, while Met Éireann will support integration of climate projections. Regional bodies such as the CAROs and Local Authorities may contribute local knowledge, site-specific data, and insight into ongoing or planned adaptation works, supporting the validation of findings and coordinating responses in shared-risk areas.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

This study is closely aligned with the broader measures to development of improved/updated flood hazard data and complete detailed CCRAs for national roads (refer OVR-2 and OVR-3). While these measures provide a national-level framework for assessing risk to a broader range of hazards across the entire National Roads network, the N69 coastal erosion and flooding study serves as a targeted, location-specific application of that methodology. It builds on the same principles: using best available hazard and exposure data, and vulnerability relationships, and incorporating future climate scenarios, but applies them in greater detail to a critical coastal corridor.

The ongoing measure described in DNG-1 captures the N69 and therefore can also add value to OVR-4. Refer to OVR-3 for further description.

5.3 Bridges and other structures

Overview

The National Roads network has many watercourse crossings, either involving bridge structures or smaller culverts.

Inspections and routine maintenance and rehabilitation of these structures are the core activities underpinning TII's bridge asset management programme. All bridge and culvert structures are inspected to a planned programme of routine, principal and special inspections coordinated through the EIRSPAN Bridge Management System (hereafter referred to as 'EIRSPAN').

In particular, in the aftermath of major flooding events TII undertakes special inspection programmes for scour, focusing on at-risk bridge and culvert structures to determine if the flooding has in any way undermined bridge foundations. In addition, TII undertakes programmes of routine maintenance under its regional maintenance contracts along with annual programmes of capital rehabilitation works, essential to ensuring the integrity and resilience of these bridges and the broader reliability of the National Roads network.

However, in general, the emphasis in the EIRSPAN system is on the bridge and culverts and their structural and load carrying capacity, rather than on the flood resilience of watercourses at these structures. As part of this Plan, an objective is to broaden the focus of TII's bridge and culvert management activities to include the collection of watercourse flood and catchment characteristics and related inventory data.

A second climate hazard related to bridges is the impact of high winds on major river and estuarine crossings, such as the M50 Westlink, the M1 Mary McAleese Boyne Bridge, and the N25 Rose Fitzgerald Barrow River Crossing. Such bridges are particularly susceptible to the effect of high winds, particularly those that do not include wind-shielding. High winds represent a potentially significant safety hazard for high-sided vehicles in particular, especially unladen heavy goods vehicles. In circumstances where the risk of extreme high winds may increase in the future, it is important that TII has appropriate protocols in place to deal with such circumstances and that these protocols are implemented in a consistent manner across the network.

STR-1 Asset management database expansion to include retaining walls

Overview

Currently, the EIRSPAN system does not include data on retaining walls, other than those associated with bridge abutments. Accordingly, TII intends to expand the scope of EIRSPAN to incorporate data pertaining to retaining walls.

EIRSPAN is currently in the process of being updated to operate on the Deighton Total Infrastructure Management System (dTIMS), providing an opportunity to include a new module for retaining walls. The purpose of STR-1 is to scope the expansion of a new retaining walls module on EIRSPAN. It is intended that the scope of the new module will prescribe necessary data capture and inspection standards to be included in the dTIMS module.

Implementing the updated module will require appropriate data collation and processing. Some data for retaining walls will be accessible from design and construction records held by TII, Public-Private Partnership (PPP) concessions, and Tailte Éireann (formerly Ordnance Survey Ireland). The need for additional data gathering and processing will be assessed in the scope of the new module update.

The key steps for delivering STR-1 include:

- Review the extent of existing retaining wall asset data, specifically the metrics recorded, for example, location, length, height, material, condition rating, maintenance history, and load type.
- Collaborate with the dTIMS system developers to develop and refine the module for retaining walls during development.
- Engage with MMaRCs, PPPs, Local Authorities, and Tailte Éireann, to gather sources of retaining wall data.
- Where appropriate, undertake LiDAR surveys of the network.
- On completion of the retaining wall inventory capture, undertake a screening exercise to identify and evaluate locations where retaining walls are exposed to climate hazards.
- Identify gaps in retaining wall data to inform future data collection and inspection standards.

Anticipated outcomes

At present, TII undertakes retaining wall maintenance primarily with a reactive approach when issues arise, which requires approval from various stakeholders for example An Coimisiún Pleanála (ACP), Uisce Eireann, and Local Authorities. Such approval can result in delays, meaning the overall degree of maintenance required is likely to have increased by the time all stakeholders have approved of TII's proposed measure. Inclusion in EIRSPAN enables proactive inspection and maintenance of retaining walls, reducing the likelihood of long-term damage and the necessity of major, disruptive unplanned maintenance, improving the longevity of these assets and minimising the impact to road users as a result of unplanned route closures and detours.

Engagement with stakeholders

Local knowledge held by Local Authorities, MMaRCs, PPPs, and Tailte Éireann will be leveraged to identify available data on retaining walls along the National Roads network.

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

STR-2 Capture hydraulic and hydrology data for river bridges and culverts

Overview

The EIRSPAN System defines a culvert as a structure accommodating a watercourse having a clear span or internal diameter greater than 2.0m. Anything less than this is considered a drainage asset (see Section 5.4). On the National Roads network, the most common culverts used through road embankments are buried concrete box structures, although corrugated steel structures are also used.

On the legacy network, most particularly on the National Secondary network, there are many old masonry culvert structures.

As outlined above, the primary focus of the EIRSPAN system has been on the capture of data related to the structural condition of bridges and culverts crossing rivers, streams and other watercourses. Hydraulic capacity refers to the maximum volume of water that can physically flow through a system without overflows, spillage, or damage to culvert infrastructure [34]. The objective of STR-2 is to expand inventory data capture for all such structures to include hydraulic data and other associated data relating to the watercourses in question, so as to allow future effective management of the watercourse structure interface, assess risks arising from increased future precipitation and associated future flood hazard.

While existing studies like the *Assessment and Management of Flood Risks at a Structural Level on the National Roads Network* [32] provide an overview of flood susceptibility across the network, further understanding is necessary for a comprehensive and up-to-date assessment of flow conditions and culvert parameters. This will involve:

- Scoping a data collection and mapping exercise to better understand the effectiveness and suitability of the existing culverts with regard to flood management on the National Roads network. As the OPW are the governing body in respect to culvert hydraulic capacity, and the body that stipulates compliance with specific flood probabilities for culverts, they will be consulted in the first instance to understand existing datasets and plans for future data gathering. This scoping will also include engagement with other key stakeholders, for example, Met Éireann and Local Authorities, prior to data gathering. It is anticipated that Local Authorities – through the development of local flood risk management strategies and surface water management plans – have access to historic hydrological and hydraulic data that could be utilised by TII for planning and decision-making. However, the extent, format, access rights and preservation details of this data is unknown and therefore will require engagement with Local Authorities.
- Undertaking the desktop data collection exercise with a focus on several key inputs. This includes rainfall data – specifically intensity, duration and frequency – to inform water volume calculations. Historical data on streamflow shall also be gathered to understand peak flow patterns. Culvert geometry is essential, including length, width, height/diameter, invert levels, gradient, alignment, and material deposited within the culvert bed. These characteristics influence culvert capacity and flow behaviour.
- In addition, watershed data shall be collected, including catchment size, shape, land use and soil type, all of which affect runoff rates and volumes. Finally, capture the condition and characteristics of the channel leading to and from the culvert crossing, including slope, roughness and cross-sectional shape.
- Undertake a data collection exercise to understand historic flood events at culverts across the National Roads network, via the OPW Past Flood Event database and engagement with local area engineer. Examine data gaps for assets across the network and engage surveyors to collect data in the field to address these gaps. It is anticipated that this would be for an estimated 150 assets/locations. Analyse compiled data including hydraulic capacity, flow regime and peak flow calculations and modelling as well as identification of hotspots in the network with very low hydraulic capacity compared to demand for review by TII. These results will then be integrated into the existing system, EIRSPAN (see STR-1 for further details). Identify undersized culverts across the National Roads network based on analysis from the previous step and develop a remediation and replacement schedule for addressing capacity under future climate scenarios. Any upstream and downstream impacts of replacing and/or resizing a culvert will be taken into consideration as part of the replacement schedule development.

- STR-2 will inform catchment management and flood studies at the network level, rather than evaluating individual culverts within the system.

Anticipated outcomes

There are a number of benefits to increasing TII's understanding of culvert hydraulics and catchment hydrology. With climate change projected to result in higher intensity storms and more frequent rainfall events, the mapping exercise will enable TII to understand the existing catchment hydrology and identify where specific drainage infrastructure is exposed to climate hazards, for current and future climate scenarios. This will inform proactive maintenance and data-driven upgrade and replacement decisions, which was evident in the context of the *M4 Flooding: Flood Risk Scoping and Options Review* [35]. The review showed that increasing culvert capacity would have diverted floodwaters towards a nearby residential development. It is therefore essential that the capacity and demand of culverts are understood within the context of the wider catchment and applied to decision-making in future infrastructure development.

By identifying and replacing undersized culverts, TII can improve the long-term effectiveness of culverts in the National Roads network. Considering the impact of climate change on watercourse hydrology will inform TII's understanding about future peak flows and ability to flag assets that cannot manage increased rainfall. Proactively remediating and replacing these culverts assists with building long-term resilience against flooding, as well as improving the longevity of assets. replacement schedule demonstrates the importance that TII places on effectively managing current and future flooding events.

Engagement with stakeholders

The OPW is a key stakeholder in the progression of this measure. Other stakeholders include Met Éireann, Local Authority engineering staff, NPWS and IFI.TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

TII's *Strategic Asset Management Plan 2024-2028* for managed and concession roads also includes mapping and classification of existing drainage assets as a key action from 2024 to 2028. It outlines mapping the location of gullies, channels, chambers, drains and associated pipework, as well as examining culvert capacity against rainfall predictions for future climate. Depending on the progress of this measure, it could serve as a useful source for data collation.

Extensive data collation is being completed for DNG-1. This data could support the rainfall, watershed and historical data required for STR-2.

STR-3 Enhance institutional engagement with wider stakeholders responsible for watercourse management with the aim of creating improved protocols for watercourse management regarding maintenance and rehabilitation of culverts and bridges

Overview

As part of its bridge management processes, TII undertakes annual and multi-annual programmes of bridge and culvert inspections, maintenance activities and larger scale rehabilitation projects. At present, bridge management activities focus on determining the structural condition of the bridges and culverts, and based on the condition ratings thus obtained, implement programmes of annual maintenance and more substantial rehabilitation programmes to ensure the long-term condition of the bridge infrastructure.

In undertaking such programmes of work, TII is required to engage with key statutory stakeholders charged with responsibility for ensuring that obligations in respect of both EU and national regulations are complied with.

The key stakeholders responsible for regulatory oversight of rivers and water courses are:

- OPW, who manage and maintain watercourses and are responsible for flood risk management and arterial drainage schemes.
- NPWS, who conserve and manage watercourses in relation to biodiversity and habitat protection.
- IFI, who are responsible for protection, conservation and management of inland fisheries and watercourses.

TII has undertaken successful interaction with the bodies above in the delivery of a number of river bridge and culvert replacement projects to date. A challenge has been aligning the programme management of these projects with the statutory obligations for compliance with relevant EU and national regulations, including the Habitats Directive and Environmental Impact Assessment Directive. The requirement and/or scope of these assessments will depend on the scale of the project and the sensitivity of the location of the project. Environmental screenings may need to be undertaken to determine the requirement of the assessments.

Initial screening analyses indicate that there in the region of 60 culvert and smaller river bridges that are at risk of causing significant flooding or suffering structural damage in the event of the flooding models at RCP4.5 and RCP8.5. More detailed analysis will determine whether measures to upgrade or replace these structures will be necessary.

Many of these structures are located on sections of lifeline roads, as shown on Figure 7. As noted earlier in the document, lifeline roads provide critical connectivity between smaller towns and more isolated communities along the west coast with larger towns and cities. Serious damage or washout of one or more culverts in an extreme flood event poses the risk of isolation or the imposition of extensive detours and delays to reach essential medical, educational and retail services. Thus, it is intended that a long-term multi-annual programme of culvert replacements will be developed to obviate the risk of such climate change disruption to local communities along lifeline roads.

Such a programme can only be delivered though an effective collaboration with the statutory bodies listed above, and TII hopes through STR-3 to develop appropriate protocols for the development of culvert replacement and flood remediation projects with each of the statutory bodies listed.

Anticipated outcomes

The primary benefit of STR-3 will come from effective interaction with relevant bodies responsible for Ireland's rivers and watercourses and the development of effective protocols for the implementation of essential engineering measures to the adaptation of bridge and culvert structures in the face of increasing flood risk. Collaborative development of protocols between TII and key stakeholders will support mitigation of risks by facilitating the implementation of essential bridge works and the avoidance of future disruption to key national roads. Engaging with stakeholders will also mean the interests of each party can be established and respected.

Engagement with stakeholders

External stakeholders, including those listed above as well as representatives from the Department of Transport (DoT) and the Department of Climate, Energy and the Environment will be engaged, given their responsibility for shaping and delivering national policies relevant to STR-3.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

STR-4 Publish high-level technical guidance document for wind on major bridge structures/high embankments and develop operational plans for individual bridges/high embankments on the National Roads network vulnerable to severe wind events

Overview

Ireland's motorway network includes a number of long span and exposed bridges, predominantly located in or close to coastal locations. Included in this list of bridges are the N25 Rose Fitzgerald-Kennedy Bridge, the N25 Thomas Francis Meagher Bridge, the M8 Blackwater Viaduct, the M1 Mary McAleese Boyne Bridge, and the M50 Westlink Bridge. The operation of these bridges is the responsibility of different PPP concessionaires, all of whom must comply with the general provisions of the specific PPP contracts. However, there is no standard protocol for the management of severe wind events across the various concessions. Moreover, the bridges are located in different Garda Síochána divisions, where local procedures and thresholds apply for closure of the bridges in the event of severe winds. Ongoing developments in monitoring technology offer the prospect of being able to instrument the bridges to measure wind speeds and direction and relay this information to decision makers in real-time so that appropriate and consistent decisions can be made at all of these bridge sites.

In spite of recent severe windstorms, there have been few incidences of high-sided vehicles overturing at these bridge locations. Although isolated incidents have occurred, no road users have been seriously injured. However, with an increasing severity of storms projected in future, it is important for TII to undertake appropriate measures to mitigate the consequences and risk to road user safety of such events.

While there is a high level of uncertainty regarding the impact of climate change on wind patterns, there is general consensus that the incidence of storms with high wind speeds is likely to increase in Ireland [36], increasing the necessity to ensure that there is a consistent and effective approach to managing vehicle movements, especially high sided vehicles across vulnerable bridges during severe storms.

To address this, TII will publish a high-level technical guidance document which outlines the need for separate operational plans tailored to the site-specific conditions at all bridges and high embankments on the National Roads network [37]. The technical guidance document includes:

- An overview of the current approach to managing operational risks associated with severe wind events.
- Directions to collate data on historical severe wind events and their impacts on National Roads network operations.

- Identification of vulnerable locations and development of site-specific wind thresholds for these locations.
- Example mitigation measures, including interactive wind warning signs, advisory speed reductions and diversion routes.
- Recommendations for future data monitoring and collection, including the potential installation of wind anemometers.
- Continued data/information analysis to maintain up-to-date knowledge of vulnerable locations.
- Recommendations for the development of operational plans for severe wind events at vulnerable locations by road operators in consultation with TII.

Application of the technical guidance document will enable preparation of operational plans for specific bridges or high embankments throughout the country. Doing so will provide tailored requirements for managing bridges and high embankments during inclement weather conditions based on site-specific data and pilot studies, in comparison to the existing blanket restrictions. The development of these plans will involve:

- Collecting information pertaining to historical severe wind events and their impacts on national roads users and operations at specific locations.
- Investigating the cause of severe wind-related incidents and disruptions.
- Analysing historical data/information to identify locations that are vulnerable to severe wind events.
- Using the technical guidance document to develop site-specific operational plans for bridges and high embankments situated in vulnerable locations in collaboration with the relevant network operators.

Anticipated outcomes

The primary benefit of STR-4 will be the improved safety of road users, coupled with a reduction in disruption to the motorway network at long span bridge locations.

Two long-span bridges, the M50 Westlink and the M1 Boyne Bridge, are wind-shielded. This has meant that no disruption occurs at these locations during severe winds. TII will assess the history of closures at each of the impacted bridge locations during severe winds to assess whether there is a case for retrofitting wind shielding on these structures. A previous incident of vehicle rollover on a bridge in Fermoy, County Cork, illustrates the need to implement a variety of adaptation measures so that risk mitigation is not solely reliant on behavioural change.

Developing operational plans that are tailored to site-specific conditions will minimise periods of closure and provide evidence-based information for restricting vehicle speeds or implementing bridge closures during severe wind events. Operational plans will outline requirements for managing the closure of infrastructure based on the specific location and conditions, minimising the closure periods based on the evidence incorporated from the technical guidance document. Furthermore, given that the operational plans will minimise unnecessary closure, they should promote public compliance when road closures are essential during periods of very high winds, increasing the safety of road users.

Engagement with stakeholders

As successful management of severe wind events depends on the cooperation of a number of organisations, external consultation is essential before preparing and implementing the national policy. Key stakeholders include An Garda Síochána, Local Authorities, road operators (PPPs and MMaRCs), Met Éireann, and the Road Safety Authority.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

As outlined in OVR-1, a review and update of TII standards has been proposed as a key measure.

A relevant study that can inform the development of the site-specific operational plans was conducted for the proposed Shannon River crossing on the N4 Carrick-on-Shannon Bypass. The study evaluated the potential risk of vehicles overturning based on wind climate data and the lack of wind protection barriers. The *N59 Dawros Bridge: Technical Services* [38] not only outlines potential physical mitigation measures to reduce vehicle overturning risk, but also the shortcomings of blanket restrictions on traffic during windy conditions and the need for tailored restrictions depending on the direction of traffic, for example, a westerly or easternly approach. The outcomes of this study will be utilised by TII in the implementation of STR-4.

5.4 Drainage

Overview

Drainage systems consist of specific culverts, drains, pipes (those that are less than two metres in diameter), and any other structures relevant to these networks. Examples include (but are not limited to) ancillary items, catch pits, ditches, channels, outfalls, inlets, manholes, filter drains, filter control devices, kerbs, balancing ponds, and attenuation basins. There are over 1,950 km of linear drainage systems with more than 69,000 drainage point items and 520 attenuation areas on the managed and concession road network.

There are numerous climate hazards which pose a significant risk to the operation of these drainage systems, the most significant of which – by occurrence and by impact – are increased rainfall, flooding, and storm events. Storms, which are categorised by intensive rainfall and high winds, can overwhelm the drainage system by exceeding its capacity and causing localised flooding.

Intense rainfall events also lead to excess surface water runoff, which, when combined with the drainage capacity issues, can contribute to significant danger and disruption to road users from pluvial flooding. Additionally, high wind speeds can displace debris from trees and other structures, which can then block drains, pipes and culverts, increasing pluvial flooding. The measures discussed in this section represent TII's priorities for addressing climate change impacts on drainage systems. TII has already initiated steps to address these climate change impacts on the network, including commencing a desktop exposure mapping exercise across the National Roads network. This exercise aims to identify areas that are particularly exposed to the impacts of climate change, as well as areas of insufficient drainage data.

This work will be undertaken as part of a phased approach across the National Roads network, which will then guide and inform the subsequent measures discussed further in this section. This mapping will enable TII to identify and prioritise areas that need further analysis through field studies, and will ultimately feed into a comprehensive, centralised DAMM which will assist TII in maintaining and extending the life of its drainage assets.

DNG-1 Conduct a desktop vulnerability mapping exercise on National Roads network drainage

Overview

TII has commenced initial desktop vulnerability mapping of motorway, dual carriageway and designed single carriage sections of the National Roads network (referred to as Subnetwork 0 and Subnetwork 1). DNG-1 will further develop the desktop vulnerability exercise underway, continuing initially on the subnetworks with the highest traffic volumes and economic value, Subnetworks 0 and 1, and then expanding to include the full National Roads network. An overview of the subnetwork classifications can be found in Figure 27 in Section 5.8.

DNG-1 will initially involve the collation and analysis of current and predicted climate data to assess exposure to flooding across the National Roads network. This will be followed by a prioritisation exercise to identify the highest risk sections of the network with respect to flooding at RCP4.5 and RCP8.5. A number of data sources have been identified to support DNG-1, including:

- *Assessment and Management of Flood Risks at a Structural Level on the National Roads Network* [32].
- OPW flood models, including CFRAM and NIFM [31].
- *National Roads Criticality Assessment* [22].
- Flood event records, collated in the OPW's Past Flood Events Database [31], Flood Risk Warning Sign records (from the Asset & Fault Management System) and in TII's flood event register issued to MMaRCs in all areas.
- Internal drainage works records in TII's drainage defects database (2015-2024) and the Incident Manage System hosted by the Motorway Operations and Control Centre (MOCC), which is a record of all types of reported incidents across the Motorway/Dual carriageway network, including flooding. For the legacy network, records on drainage works are held within local authorities and TII's Drainage Management System.
- TRANSLATE, a Met Éireann-funded data collection project. TRANSLATE data includes projections for precipitation rates within future climate scenarios RCP4.5 and RCP8.5 [39].

This data will be utilised to create a geo-referenced database of flood exposure, which, combined with the road asset data, will identify of the specific network areas most susceptible to flooding hazard and most in need of flood remedial measures.

DNG-1 will provide essential insights into the sections of the National Roads network that are most at risk of flooding. The work reflects a practical approach to identifying areas of potential flood exposure using currently available data and contributes to building an evidence base for future measures. While DNG-1 does not represent a full risk assessment as per the framework adopted in this Plan (refer Section 3.5) and instead focuses on flood exposure and susceptibility, it supports the overall objective of improving flood resilience.

Anticipated outcomes

The primary benefit of DNG-1 will be a more comprehensive understanding of the sections of the National Roads network that are most susceptible to flooding. This will permit the development of detailed adaptation programmes as well as providing clearer focus on the management of flooding risks through TII's asset management, maintenance and operational activities. DNG-1 will draw on the recent collation of flooding data across the motorway network, the development of increasingly refined climate modelling data by Met Éireann, under the TRANSLATE project, and increasingly sophisticated Geographic Information System (GIS) modelling and visualisation tools. It will address gaps whilst also incorporating future climate data, to enable greater understanding of how flooding varies across the network under different climate change scenarios and time periods. This will enhance short-term maintenance and long-term asset management for the most susceptible locations.

Engagement with stakeholders

External stakeholders that will be consulted as part of the data gathering and collation include Local Authorities, the technical advisors that prepared the *National Roads Criticality Assessment*, the OPW, Met Éireann, and other national agencies with information on climate change in Ireland, such as the EPA.

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

Several measures within this implementation plan depend on the collation and analysis of historic flooding and future projected climate data. Data collected under DNG-1 will support similar data gathering exercises in measures OVR-3 and STR-2, and vice versa.

In addition, Uisce Éireann is in the process of creating a library of hydraulic wastewater models under its programme of Drainage Area Plans (DAPs). Their intention is to determine and prioritise risk associated with the urban drainage network, with a focus on wastewater [40]. The risks will incorporate current and future development scenarios and address project drivers such as flooding and catchment growth. While not completely aligned with the vulnerability mapping exercise, already completed DAPs have identified flooding locations in combined networks and could be a useful consideration to DNG-1.

Similarly, flood registers have been complied across the motorway network by TII appointed MMaRC contractors. These flood registers capture tacit knowledge on historic flood events, the measures required at the time of the flooding, recommendations for long-term mitigation measures, and any residual issues that may remain. This is an ongoing operational exercise, which will be significantly strengthened through DNG-1.

Furthermore, TII has commenced work on a detailed CCRA for national roads, which will assess the impact of climate hazards on national road infrastructure and service delivery for current and future climate scenarios (RCP4.5 and RCP8.5) – as set out in measure OVR-3. Relevant opportunities for data sharing between these two projects will be pursued.

DNG-2 Develop a Drainage Asset Management Module and implement programme for drainage inventory capture

Overview

A comprehensive, centralised asset management database is essential for TII to maintain the performance, efficiency and lifespan of all assets in the National Roads network. Currently, most datasets pertaining to drainage assets outside of the MMaRC/PPP areas are not digitised. Additionally, large sections of the legacy network have only rudimentary drainage infrastructure discharging to adjoining lands.

Feasibility studies have been conducted to assess the viability of developing a DAMM within the existing TII asset management system. The feasibility studies proposed a risk-based approach to managing drainage assets by evaluating the vulnerability of all locations on the National Roads network to a particular climate hazard(s). This vulnerability rating would inform the creation of a prioritised list of road sections for drainage asset inventory capture, collection of condition data for existing drainage assets, and optimisation of multi-annual drainage asset inspection, maintenance, rehabilitation and upgrade programmes.

The DAMM developed as part of DNG-2 will facilitate an efficient data collection process, with strong data manipulation and querying capabilities. It is intended that it be capable of interacting with data exported from a wide range of other systems, for example, from specialist programmes/systems used across departments at TII or by MMaRCs/PPPs, and should be capable of exporting data for presentation to a wide audience and providing data to other relevant systems such as ArcGIS Online (AGOL) and PowerBI.

In addition to a DAMM, there is also a need to capture drainage inventory data. There are several platforms that could be used and will be investigated as part of DNG-2 including, but not limited to:

- MapRoad, a pavement management system designed to improve management and monitoring practices for local road networks. In Ireland, it is owned and managed by the Road Management Office (RMO), who oversee the development and implementation of the system within Local Authorities.
- The suite of ESRI tools within the AGOL platform, for example, Survey123. These tools are designed for creating, sharing, and analysing surveys. These surveys can be used to collect field data which can be integrated within AGOL, allowing access to data from any location.
- An expansion of the Operation and Maintenance module which is utilised within the existing asset management system.

The platforms identified above are not a comprehensive list of alternative management or inventory capture systems, and additional platforms should be explored within the investigation. There are multiple providers of Road Management and Maintenance Systems, which are specialised tools for managing and maintaining road infrastructure. The chosen DAMM must have the ability to provide real-time updates on the status of road assets and components.

Anticipated outcomes

The primary benefit of DNG-2 is to centralise all asset information pertaining to other drainage assets, and in turn, improve the reliability of these assets through regular monitoring and maintenance. At present, the lack of an asset management module, coupled with the number of drainage assets managed by TII, means maintenance is focused on locations known to maintenance teams. This can lead to necessary maintenance required in other, less visible problematic areas being undertaken reactively, sometimes when extensive damage or asset failure has already occurred. This limits opportunities to repair the asset in lieu of replacement, thereby potentially avoiding a more costly measure. Such monitoring and maintenance require a comprehensive asset management module to capture up to date information and facilitate informed decision-making to improve asset longevity and reduce lifecycle costs. Furthermore, the proposed analysis and classification of drainage asset vulnerability will provide an overview of the systems' susceptibility to climate change, further informing infrastructure planning.

Engagement with stakeholders

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

Given that the desktop vulnerability mapping outlined in DNG-1 is already underway, the outcomes of this data collation and review may be relevant in determining the most appropriate features of the DAMM and should be accounted for when selecting the most appropriate platform.

DNG-3 Undertake detailed surveys of existing drainage assets to be included in the proposed drainage module in DNG-2 to facilitate planning for a long-term programme of network drainage upgrade works at locations where potential flooding and increased rainfall has been identified in DNG-1, with the initial focus on determining network catchments and location of outfalls

Overview

In the context of road infrastructure, a 'network catchment' refers to the area of land draining towards/into the road drainage system. These catchments can be within or outside the road corridor and are referred to as road and overland catchments respectively [41]. 'Outfall' is the term applied to the point where the road drainage system discharges into a different type of drainage system, like purpose-made drainage channels or watercourses [42]. An understanding of network catchments and outfalls is a key component of designing effective drainage systems that minimise impacts on road infrastructure and mimic natural catchment processes.

DNG-3 builds on DNG-1, which aims to map flood susceptibility for motorways and designed single carriageways as well as identify the most exposed road sections. Sections of the National Roads network considered to have high or very high exposure to flooding shall then undergo detailed surveys focusing on collecting data related to network catchments and outfalls. Additional information on the condition and capacity of the assets within these exposed sections of the National Roads network will also be required to assess their respective adaptive capacities. It is recommended that a desktop study is carried out first, to identify potential sources of network catchment and drainage data. This data may include:

- Replacement, upgrade, or installation of new transverse drainage structures (< 2.0m), which are the pipes and culverts that manage fluvial and pluvial flows across road infrastructure.
- Replacement, upgrade, or installation of new motorway and engineered single carriageway longitudinal drainage systems, which are drainage systems that typically run parallel to the roadway collecting runoff from the roadway itself. These drainage systems include road edge collection systems, such as channels and carrier and filter drainpipes.
- Upgrade of motorway attenuation and receiving waters adaptation, which refers to attenuation ponds and natural water bodies that receive runoff from the drainage system.

Anticipated outcomes

Supplementing the vulnerability mapping exercise with network catchment and outfall data will support TII in improving the long-term effectiveness of drainage assets in the National Roads network. Collating additional topographical, asset and environmental data will inform TII's understanding about natural catchment processes in areas considered to have high or very high susceptibility to flooding. Not only does this allow anticipation of flooding events, but it also assists TII with building the long-term resilience of its assets. Designing drainage systems to minimise impacts on road infrastructure and mimic natural catchment processes improves the longevity of assets and reduces the need for reactive maintenance or measure. Furthermore, developing a programme for network drainage upgrades demonstrates to stakeholders the importance that TII places on effectively managing current and future flooding events, and that TII is taking a proactive approach to protecting its assets by scheduling necessary improvements.

Where possible, the programme for network drainage upgrades will be considered for prioritising nature-based solutions where appropriate, to reduce the exposure of the assets to climate hazards whilst simultaneously reducing their ecological footprint.

Engagement with stakeholders

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

In parallel to this Plan, TII is completing a CCRA for national roads. This assessment aims to identify critical components of the road system that are susceptible to damage or disruption; evaluate the potential impacts of extreme weather events and long-term climate changes on road infrastructure; and develop strategies to enhance the resilience of transportation systems. Given the potential synergies between this Plan and the risk assessment, the progress of both projects will be monitored to minimise duplication and take advantage of opportunities for knowledge sharing.

As outlined in DNG-1, Uisce Éireann are in the process of developing DAPs that aim to determine and prioritise risk in the urban drainage network. The DAPs also identify flooding locations in combined networks and the outfall locations for storm drainage that combined sewer overflows spill into. While this scope of work does not directly overlap with DNG-3, Uisce Éireann could serve as a useful source for data collation.

Similarly, DNG-1 also requires extensive data collation. Whilst this work has already commenced, the data gathered in that exercise may include outfall data to support DNG-3. TII's *Strategic Asset Management Plan 2024-2028* [11] for managed and concession roads also includes mapping and classification of existing drainage assets as a key measure from 2024 to 2028. It outlines mapping the location of gullies, channels, chambers, drains and associated pipework as well examining existing culvert capacity against rainfall predictions for future climate. Depending on the progress of this measure, it could serve as a useful data source.

5.5 Tunnels

Overview

The three tunnels on the National Roads network, the Dublin, Jack Lynch and Limerick Tunnels, represent three of the most critical elements of Ireland's national road infrastructure. The tunnels are vital transport links, utilised by millions of users every year, and facilitate the movement of goods and services throughout their immediate region and more generally across the country.

Dublin Tunnel provides a crucial link between Dublin Port and the Motorway network, facilitating the movement of goods across the Eastern region and beyond. Dublin Port handles approximately 80% of all unitised freight movements into and out of Ireland and as such is the dominant port in the country. In 2024, 35.2m tonnes of freight passed through the port [16]. When incidents occur necessitating closure of the tunnel to traffic for anything more a short period of time, it results in severe congestion on the approaches to the tunnel, which progressively extends across the city if the closure becomes prolonged during the day. Thus, any event, including a future climate event that might result in the closure of the tunnel for days, or even weeks or months, would result in significant disruption and economic loss to the city and nationally. In 2023, transactions through the toll gates increased by 12.5% to 9.6 million [43], underlining its criticality within the National Roads network as a key route for the movement of goods, services, and people. The Dublin Tunnel is also a key route for road users to and from Northern Ireland, due to its connection between Dublin City Centre and the M50. Additionally, as noted within Section 2.2, the Dublin Tunnel provides a direct link between the city centre and Dublin Airport. Dublin Airport handles approximately 85% of all airport passengers in Ireland, is Europe's thirteenth busiest airport and accommodated 34.6m passengers in 2024 [15].

The Jack Lynch tunnel in Cork accommodated the movement of approximately 22.1 million vehicle movements in 2023 [44] including all commercial traffic travelling from points east and north seeking to access Cork Airport or the Port of Cork at Ringaskiddy. Similar to Dublin, incidents that necessitate the closure of the tunnel lead to significant traffic delay and disruption across the city. In the case of the Limerick Tunnel, the tunnel is located at the lowest downstream crossing of the River Shannon, and any disruption to service in the tunnel at peak times results in significant traffic disruption in Limerick City. Thus, a severe future weather event resulting in a flooding incident in any of the three tunnels could have prolonged and costly consequences for businesses and the broader economy in the three regions. It is therefore important that TII understands the climate risks to the tunnels and implements appropriate adaptation countermeasures to mitigate the risks. The locations of these tunnels are shown in Figure 21 below.

The events associated with Hurricane Sandy in the United States in 2013 showed the risk due to compounding climate and severe weather hazards. Higher than normal tides, in tandem with the hurricane's approach from the east and its associated severe winds and low pressure led to a storm surge of more than 7 metres. This resulted in the well documented widespread inundation of coastal and low-lying areas of New York City and its environs. In particular, the New York subway and road tunnels suffered severe flooding. The challenge for TII is to establish the level of risk that exists of a similar type of event occurring at any of TIIs three tunnels, and if necessary to implement appropriate adaptation remedial measures.

Figure 21 Map showing the location of tunnels on the National Roads network

TUN-1 Assess current and future flood hazard and risk at the Dublin, Jack Lynch and Limerick Tunnels

Overview

As outlined above, rising sea levels in tandem with a severe storm event with winds coming from an adverse direction has the potential to result in significant storm surge events impacting low lying coastal areas and estuaries. While these climate hazard scenarios will provide a shared ground for the flood hazard assessment for each tunnel, it should be acknowledged that each tunnel has its own particular locational characteristics and hazards. It may be the case that the Limerick Tunnel for example has an added risk as compared with Dublin and Jack Lynch Tunnels because of potential fluvial flooding risks associated with the River Shannon.

TUN-1 will involve undertaking a detailed site-specific study of each location, including consideration of the sea / riverbed characteristics. In addition to the tunnels themselves consideration will be given to all ancillary buildings and facilities, such as tolling infrastructure and in the case of the Dublin Tunnel, the vulnerability of the tunnel control and MOCC building (refer OPS-2). A broad overview of the elements of TUN-1 are set out below:

- Building on the existing flood hazard information presented in Appendix A, conduct a comprehensive review of existing national and local studies and datasets such as the CFRAM studies, the NCFHM project, and any relevant Local Authority or academic work (such as the Dunkettle Interchange upgrade). Identify any key gaps or limitations (for example, lack of pluvial flood modelling or hydrographic data).
- Collaborate with key data custodians and stakeholders including the OPW, Local Authorities, the EPA, Met Éireann, and academic partners, to gain access to the most recent and detailed datasets, modelling inputs, and local knowledge. This engagement will also enable alignment with national climate adaptation goals and avoid duplication of effort. Identify historical flood events in the vicinity of the tunnel assets using OPW's National Flood Data Archive and any other relevant databases. Use TII's flood event database and drainage defect database to supplement the understanding of local conditions.
- Update, expand and enhance existing hydrologic and hydraulic models using the best available data and methods. This includes incorporating:
  - Consistent and robust climate change scenarios (for example, rainfall projections and sea level rise scenarios).
  - A broader set of flood mechanisms, including fluvial, pluvial coastal, and groundwater flooding.
  - Joint probability analysis to assess compound flood events (for example, storm surge tidal and fluvial flooding). As described in Section 4.6 above, compound flood events are increasing in frequency in Ireland, highlighting the need to better understand these complex interactions.
  - Current topographic, hydrographic and land use information.
  - Consideration of defence failure and blockage scenarios where relevant.
- Develop new hydrologic and hydraulic models where existing models are not available or are unsuitable for the intended purpose. These models will reflect current land use, topography,

and infrastructure conditions and include simulations under current and future climate conditions for a range of events.

- Calibrate and validate models using available historical rainfall and flood records. This is essential for improving the reliability of the outputs and increasing stakeholder confidence in the results. Insights gained from the measure described in OVR-2, STR-1, and DNG-1 can be used to further validate the models. Produce updated flood hazard data including key outputs such as flood depth, velocity, water level, duration of inundation, and depth-velocity product. Ensure that outputs are formatted for integration with existing data platforms such as OPW's FloodInfo.ie and TII's internal geospatial systems and provide access to appropriate metadata and documentation.
- Determining the flood hazard at the Dublin, Jack Lynch and Limerick Tunnels largely depends on the available data and opportunity to utilise existing hydrologic and hydraulic models.

Following completion of hazard identification assessment of the flood risk for each tunnel (including each portal area and associated staff management buildings and areas) shall be undertaken. Assessments will focus on how flood hazard exposure translates into direct economic losses and disruption impacts. The risk assessment will follow the approach outlined in Section 3.2. This understanding of risk will enable TII to prioritise further measures and measures and allocate resources effectively for climate resilience (TUN-2).

Anticipated outcomes

The assessment of current and future flood hazard and risk will provide a consistent, climate-informed foundation for understanding flooding in Ireland's three tunnels. It will identify the levels of risk and inform decision making in regard to countermeasures required to deal with the identified levels of risk.

Engagement with stakeholders

Relevant stakeholders include Local Authorities, transport and utility owners, academic institutions, and emergency planning bodies.

Links with ongoing work

As well as TII's internal flood event database, the OPW undertook a data collection programme between 2004-2006 to collate information about flooding across Ireland. Information was collected from a variety of sources, including photographs of flood events, technical advisors' reports, press articles, gauging stations recordings, eyewitness accounts from emergency response staff, letters from members of the public, and minutes of meetings with key officials. This information was used to create the National Flood Data Archive, from which 'Flood Event' records have been created. Since 2006, as flood events occur or as information is submitted to the OPW, new records are added to this dataset on an ongoing basis. This dataset is available to view at www.floodinfo.ie.

OPW's *Flood Risk Management: Climate Change Sectoral Adaptation Plan* [45], will be considered in any measure linked to flood risk assessment and management. That plan was first published in 2015, with the latest revision published in 2019, and another revision due to be published in autumn 2025. That plan sets out a long-term goal for OPW for adaptation in flood risk management, along with a set of objectives and actions aimed at achieving effective management of the potential impacts of climate change on flooding and flood risk. The synergies with the work included within this Plan are clear, and there will be ongoing reference or coordination with the OPW on any flood risk management goals to coordinate a coherent approach to climate resilience.

TUN-2 Identify, assess and undertake appropriate climate-related resilience measures at Dublin, Jack Lynch and Limerick Tunnels

Overview

Following the completion of the flood hazard and risk assessments, it is anticipated that a number of measure measures may be required to strengthen the resilience of aspects of the tunnels' infrastructure – particularly drainage. Previous experience at the Jack Lynch Tunnel has shown that intense precipitation coinciding with the occurrence of an unusually high tide can lead to a heightened risk of flooding on the immediate approaches to the tunnel. TII has already undertaken a series of measures to strengthen the resilience of the surface water drainage systems at Jack Lynch Tunnel. As part of TUN-1, analysis at RCP4.5 and RCP8.5 will determine the levels of risk applying under severe future scenarios and the extent of further adaptation that may be required at the tunnel. Similarly, in the case of the Dublin and Limerick Tunnels, analysis at RCP4.5 and RCP8.5 scenarios will allow the preparation of a set of future measures that will be required to protect the tunnels in the most severe eventuality. Increased capacity of drainage systems may be required to improve the flood resilience of the tunnels against groundwater flooding.

A characteristic of tunnel management is the constrained timescale for undertaking any works within the tunnel bores. Essential maintenance can only be undertaken during night-time possessions, and the number of possessions are limited to the greatest extents possible in order to avoid undue disruption to tunnel users who are obliged to find alternative routes while the tunnel is closed. The intention will be to implement climate adaptation measures insofar as is possible during existing planned tunnel closures for maintenance purposes. Synergies and economies may be achieved through undertaking drainage system adaptation measures in tandem with routine maintenance, or other non-climate adaptation related activities.

Anticipated outcomes

The primary outcome of TUN-2 will be an enhanced climate resilience of the three National Roads network tunnels. Other outcomes include the potential reduced lifecycle cost of maintaining the tunnels, and the improved maintenance and longevity to the infrastructure. Implementing climate-related resilience measures for inclusion in a long-term asset management programme will, insofar as is possible, eliminate the risks to the long-term operation of the tunnels and avoid any disruption or closure caused by a future extreme weather event.

Links with ongoing work

The delivery of TUN-2 is intrinsically linked to the successful completion of TUN-1. It is intended that TUN-1 will draw upon the most up-to-date available historical data and future predicted climate data, thereby ensuring that designs of all measures undertaken under TUN-2 will address any identified vulnerabilities as completely as is feasible.

5.6 Motorway operations

OPS-1 Implement MMaRC third generation contracts, including contractual enhancements for improving resilience to flood, wind, and cold spell events

Overview

Approximately 900 kilometres of the motorway network is operated and maintained by contractors appointed by TII under MMaRC contracts. In total there are three networks – Region East (A), Region West (B) and Region South (C), as shown in Figure 22 below.

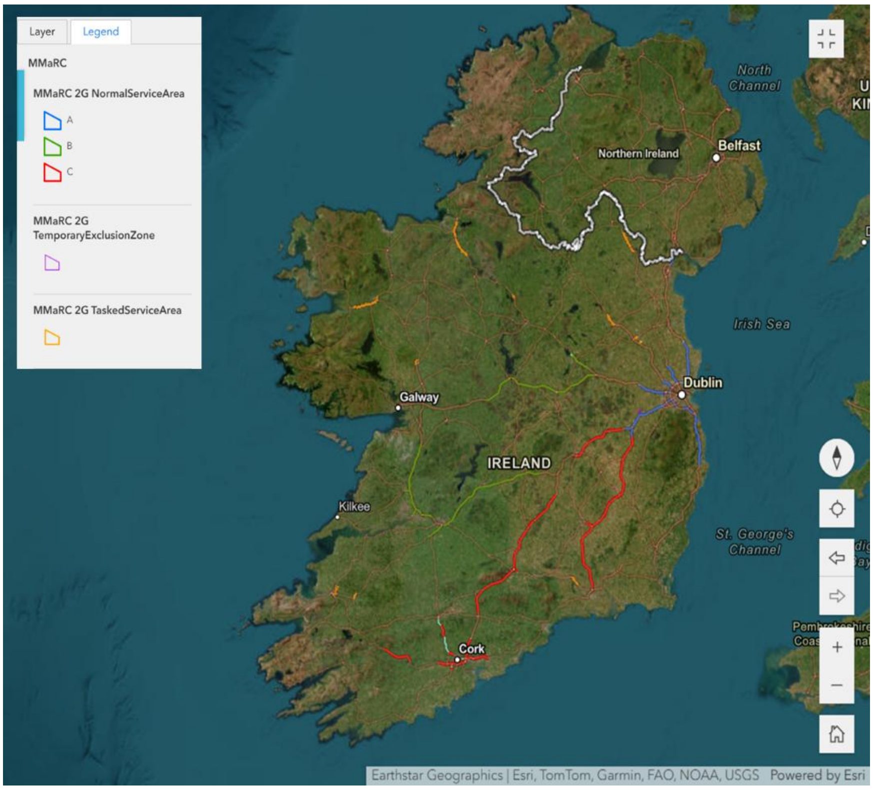

Figure 22 National Roads MMaRC network

Currently, TII is in the process of developing its contract requirements for the third generation MMaRC, which are due to be awarded in 2027. The third generation of the contracts will allow TII to include greater levels of severe weather and climate change response within the maintenance and operation provisions of the contract, and the opportunity for proactive planning and new measures to avoid climate-related network interruptions.

MMaRC contractors have successfully dealt with major recent storm events. Contractor responses in the case of Storm Babet in 2023 and in flood events arising as a consequence of other un-named storms has been positive, with rapid response to flooding scenes. In general, over-pumping to an outfall located outside motorway lands has been sufficient to ensure that flooding subsided in a relatively short period of time.

MMaRC and PPP contractors successfully dealt with severe wind events such as Storm Ophelia in 2017. In general, extreme wind events tend to be short-lived in nature. For occupational health and safety reasons, contractors must withdraw their staff from the network during the phase of most severe winds, returning to operations as soon as winds have abated sufficiently. Overall, MMaRC and PPP crews have been adequately resourced to deal with the aftermath of severe winds in an expeditious manner, ensuring that minor hazards such as fallen branches and dislodged sign panels are quickly removed from trafficked carriageways.

As set out in STR-4, the major adaptation measure as part of this Plan in relation to severe wind hazard is the development and publication of policy and operational plans in respect of long-span bridge structures, which are the most vulnerable locations on the network to the effects of severe winds.

MMaRC operators have also very successfully dealt with severe winter weather events such as Storm Emma in 2018 and the unnamed snowstorm in early 2025. MMaRC contract requirements ensure that the contractors have sufficient plant and reserve driver capacity to plough and treat routes for extended periods of time during snowfall.

Enhancements proposed to contract requirements

The following enhancements to contract requirements to enhance the resilience of motorway operations to severe weather events will be implemented:

- TII will fund the purchase of additional high-powered pumps to be located at the various MMaRC maintenance compounds across the motorway network. These can be deployed as required to alleviate flooding events that arise on the network faster.
- TII will purchase temporary bridge kits which can be used to replace any bridge washed out or damaged in a severe river flood. Although rare occurrences, river bridges have been washed destroyed during extreme flooding in the past e.g. in 2007, in Leenane, County Galway. The intention is that these bridge kits will be stored at a number of MMaRC compounds, that a cohort of MMaRC operatives will be trained in the assembly and installation of these bridge kits. The bridge kits can then be deployed at any location required across the National Roads network.
- TII will purchase snow blowing equipment to allow for easier and quicker removal of snow drifts on the National Roads network. Equipment will be stored in MMaRC depots, but available as required for deployment across the National Roads network.

Contract requirements will provide for MMaRC contractors to operate outside of the MMaRC contract boundaries and to be appropriately paid for their services in supporting severe weather response beyond their direct contract requirements.

In addition, TII will engage with the Department of Transport with a view to agreeing a framework whereby MMaRC contractors can be deployed to support local authorities to deal with severe weather consequences on the regional and local road network.

Anticipated outcomes

By further integrating climate resilience into the third generation MMaRCs, TII will endeavour to deliver enhanced response in the face of increased severity storm and severe weather events. Moreover, the use of motorway contract resources to provide for back-up support to Local Authorities in dealing with extreme weather events on the regional and local road network will assist in enhancing Ireland's overall response to the impacts of climate change on the National Roads network.

OPS-2 Conduct climate and severe weather resilience review of operations buildings

Overview

As well as maintaining Ireland's national transportation infrastructure, TII owns and/or operates buildings throughout the country to fulfil a variety of functions. The buildings asset group includes various facilities relating to the maintenance and management of roads, including:

- Service areas.
- MMaRC compounds.
- Maintenance depots.
- Strategic salt stores.

- Toll plazas.
- MOCC.

TII buildings are exposed to a wide range of climate hazards, which threaten the structures themselves and also interfere with their functions and operations. Storms are among the most significant climate hazards facing TII properties, bringing intensive rainfall and high velocity winds, both of which can significantly damage buildings by causing flooding and debris. Extreme heat also threatens TII buildings by causing cracking and weakening of construction materials, as well as increasing the internal energy consumption to power air conditioning without which the excessive heat may lead to increased health issues for building occupants.

The MOCC was constructed as part of an upgrade and extension to the existing Dublin Tunnel Control Building and is critical for keeping the network open and operational. It is a state-of-the-art facility, essential for real-time monitoring of the Motorway network, incident management and coordinating response to major incidents. The MOCC oversees over 65 million vehicle journeys annually [46], and is also designed to accommodate any operational upgrades or changes across the entire road network. The MOCC is located in East Wall, an area of inner-city Dublin that was first built on reclaimed land in the 19th century. East Wall is located in close proximity to the Dublin Port and therefore, the Irish Sea, but is also bound on either side by the River Liffey and Tolka River as shown in Figure 23. The MOCC is based on East Wall Road which is currently defended by a sea wall and flood gate designed to contain 200-year tide levels. To date they have contained the highest recorded tidal levels. However, the *Dublin City Development Plan 2022-2028: Strategic Flood Risk Assessment* [47] by Dublin City Council categorised the area as under ‘significant’ risk to rising sea levels. Due to this context, it is critical to the oversight of the National Roads network that TII is fully aware of the hazards and impacts that threaten the MOCC and can act accordingly.

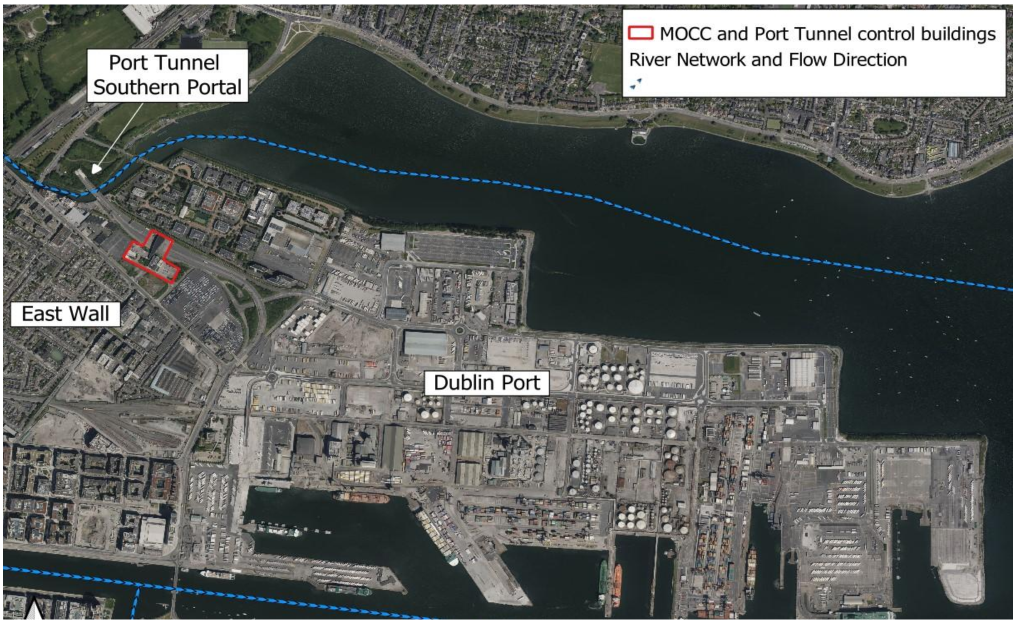

Figure 23 Location of MOCC and Port Tunnel control building, showing southern portal of Port Tunnel and Tolka River, River Liffey, East Wall and Dublin Port

The substation at the Jack Lynch Tunnel is a crucial part of the tunnel's electrical system, providing power to various essential functions, including lighting, ventilation, the supervisory control and data acquisition system and is part of a larger system that includes CCTV and other tunnel management systems. The MOCC and the substation building at the Jack Lynch Tunnel are both vital elements of keeping the road network open and operational.

Disruption to these assets would have significant collateral impacts along the network. As such, OPS-2 aims to improve the resilience of these assets to climate and severe weather, crucial for protecting lives and the critical operations of the National Roads network from the increasing impacts of climate change and severe weather. Flood hazard and risk assessments for the Dublin Tunnel and Jack Lynch Tunnel, including the portal areas and control buildings, are addressed by TUN-1. These measures outline the steps to be taken to complete a climate and severe weather resilience review of these assets outside of the flood hazard and risk assessments already being completed as part of TUN-1.

A climate and severe weather resilience review of these assets will broadly comprise the following activities:

1. A desktop study to assess the severe weather and climate scenario responses including collation of best practice and lessons learned (national and international for similar mission critical assets), documents from previous weather events on the National Roads network and example response plans.
2. Interviews with existing operations staff managing and maintaining the asset facilities to ascertain the existing capabilities and gaps to responding to severe weather and climate events.
3. For each asset, a summary of the key severe weather and climate hazards, existing capability to respond, and identified gaps.
4. Based on the gaps identified, develop required remedial measures.
5. Create a plan to implement the remedial measures.

Example remedial measures might include, but are not limited to, developing severe weather response plans for each asset for the different severe weather scenarios (for example, severe ice, snow, flooding, heat) similar to the *Winter Service Plan* required from Local Authorities by TII. These will be reviewed annually and updated based on lessons learned and the condition of the asset.

Anticipated outcomes

The primary benefit of OPS-2 is in understanding the level of exposure facing infrastructure that is key to the operation of Ireland's transport network, and identifying ways to increase their resilience, such as avoiding delayed journeys and closure of parts of the network. For example, the M1 connects two major cities – Dublin and Belfast. The two-hour drive passes Dublin Airport and Dublin Port, the two major international gateways for the island. Any long-term failure to the MOCC due to extreme weather events would inevitably disrupt TII's ability to manage and maintain the motorway, potentially leading to greater traffic and longer delays at significant national financial ramifications. The traffic may also limit the effective range of blue light services (ambulance, police, fire) by increasing their time spent idle in traffic. It is therefore essential for TII to understand the effects of climate and severe weather on key logistical infrastructure and utilise the results of the resilience review to improve future asset management strategies. The findings of the severe weather and climate review on these assets will be shared with other relevant stakeholders, including the private companies and Local Authorities that manage other parts of the network.

Links with ongoing work

There will be concurrent flood-related hazard studies ongoing for the Dublin Tunnel and Jack Lynch Tunnel (TUN-1), which can inform the approaches used for OPS-2 on several buildings in close proximity to or within the tunnels. Similarly, insights from the review and updating of TII standards (OVR-1) can be applied to decision-making within the resilience review, such as when identifying the potential adaptation measures for the various buildings.

OPS-3 Undertake flood analysis for M1 (N & S) motorway service areas and design a remedial programme to address identified flood issues

Overview

Figure 24 Route of M1 and location of N & S service areas

Stretching 80 km, the M1 corridor connects Dublin and Belfast and links to major towns such as Dundalk and Drogheda. The M1 also connects to Dublin Airport at its southern end and is a key freight route for heavy commercial vehicles travelling between the northern half of the island and Dublin Port, Ireland's largest port based on its approximately 80% share of the total volume of unitised freight passing through Irish ports [16]. The M1 has two double sided motorway service areas at Lusk and Castlebellingham, serving the needs of professional heavy goods vehicle drivers, drivers of light commercial vehicles and private motorists alike. Both service areas have been operational since 2010 and are managed by the Superstop Ltd Consortium as part of a 25-year PPP contract. Both Lusk and Castlebellingham sites are situated in low flat terrain that is subject to flooding after major rainfall events. The OPW's 'Flood Maps' GIS tool [31] provides relevant fluvial and coastal flood hazard information through a number of flood mapping studies conducted by the OPW. The CFRAM study involved hydraulic modelling of fluvial and coastal flood hazards for a suite of design storm events and future climate scenarios. In River Basin Districts not captured by CFRAM studies, indicative fluvial flood hazard mapping has been completed as part of the NIFM project. The methodologies for these studies included several assumptions suitable for a national level assessment and therefore provide only an indication of flood hazard.

Existing flood hazard information indicates that both service areas are exposed to pluvial flooding, requiring further investigation to better understand localised flood behaviour and exposure of site assets. In addition, more detailed flood hazard information will be gathered for each site via comprehensive, site-specific flood risk assessments, to assess risks from pluvial, coastal (including from wave overtopping), and groundwater flooding.

The following actions will be undertaken as part of OPS-3:

- Conduct a scoping study for each service area to identify and assess the flood hazards, where the service area includes all buildings, fuel areas and parking areas. Using the findings from the scoping study, develop detailed flood-hazard datasets for the site. Hydraulic modelling will be required to fully understand and capture the local flood behaviour and flood risks at the sites.
- Using the localised flood hazard information, review the exposure of building assets and operations for each site to conduct a Site-Specific Flood Risk Assessment (SSFRA) that captures the criticality and vulnerability of each site's assets. Outputs from the SSFRA could be used to rank risks and prioritise remedial measures.
- Identify remedial measures that can adapt the service areas' infrastructure and operations to flood hazards. The remedial measures will need to be assessed for feasibility and subsequently integrated into a remedial programme for implementation. Possible flood-related resilience measures include structural and non-structural measures, such as provision of flood relief embankments, increasing drainage maintenance regimes, and increased liaison with the operations staff at the service areas.

Anticipated outcome

The primary output of OPS-3 will be to develop detailed vulnerability and flood hazard assessment for the two service area locations. Thereafter, it is intended to develop a flood remedial scheme to address the hazards identified and to ensure the resilience of the service areas in the face of future rainfall events. Subject to funding and compliance with all planning requirements it is envisaged that a flood remedial scheme will be implemented in the period 2031-2035. Ensuring the continued availability and quality of these services areas is therefore the primary benefit of OPS-3, given their vital role in supporting and encouraging safe, satisfactory vehicle journeys.

Figure 25 Aerial imagery of 2008 flood event in proximity of Lusk Services [31]

5.7 Geotechnical including landslide

Overview

Earthworks assets are formed from or within the existing ground, making them particularly sensitive to changes in hydrogeological and intense precipitation events. Heavy rainfall can affect the stability and longevity of earthworks assets, especially older legacy assets that were not designed to cater for increased extreme weather events and climatic changes. In Ireland, the performance of earthworks assets is influenced by the country's temperate maritime climate, experiencing frequent rainfall and variable weather conditions, and, increasingly, occurrences of extreme weather events due to climate change.

The vulnerability of earthworks to climate hazards varies significantly depending on the angle of construction, the materials used, the different underlying soil types, and rock cuttings, all of which may respond differently to precipitation and temperature patterns. The geological and hydrogeological variability across Ireland means that the likelihood and severity of deterioration can vary significantly across the National Roads network. While most of the National Roads network is underlain by, and constructed from, glacial till soils, in the west and midlands there are significant sections constructed over bog and peat embankments. Many of these "*bog rampart*"[1] structures require continuous maintenance and rehabilitation, due to the extent to which they are subject to ongoing settlement. With increasing annual precipitation, in tandem with the projected increased occurrence of extended dry spells as part of a warmer climate, it is anticipated that the challenges of maintaining bog ramparts and their pavements in a safe and operable condition will increase significantly over time.

[1] Low to medium height embankment structures to carry roads across sections of bog.

It will be necessary to undertake a network-wide analysis of bog rampart assets and develop a long-term remediation and strengthening programme for these geotechnical assets. In the more mountainous sections of the west coast, from County Donegal to Counties Cork and Kerry, the coastal National Secondary routes include sections of road cut into mountainous terrain, both bog and rock. Although not as challenging as the kind of terrain traversed by trunk roads in the west of Scotland, there are sections of the network – particularly along the N71 and N70 in Cork and Kerry – where embankments and cuttings through the terrain were constructed using Victorian engineering techniques, which are particularly susceptible to the impacts of increased precipitation intensities brought on by climate change.

Recently, TII has increasingly dealt with incidences of landslips and slope failures on the section of the N71 between Glengarriff and Kenmare, in the area around Moll's Gap, and at separate locations around the Ring of Kerry. Due to the interplay of ad-hoc construction methods, inadequate drainage systems, and complex geological conditions, it is anticipated that these sections of the network will present further operational and management challenges of increasing sophistication.

TII has dealt with earthworks failures in a reactive manner, responding to failure by undertaking remedial works at the location once a failure has occurred. It is clear with increasing precipitation rates, that TII will have to proactively address more geotechnical failures along the listed sections of the N70 and N71. Into the future, it will not be tenable to maintain a reactive approach. Rather, a proactive programme of remediation and strengthening – based on a comprehensive study and geotechnical analysis of affected National Roads – will need to be implemented.

ERW-1 Complete the detailed Geotechnical Asset Management Database

Overview

In 2020, TII commissioned an investigation into methods of mapping geotechnical assets on the National Roads network and developed a GAMD. The pilot study [48] focused on a section of the National Roads network in County Kerry and two methodologies were developed: a ModelBuilder tool and a Python application. Topographical data from LiDAR was used to automatically map the extents of geotechnical assets and extract geotechnical information to store in the GAMD.

A review of the asset inventory report in 2021 [49] identified that there was limited geotechnical information available on the majority of the National Roads network's earthworks and other geotechnical assets, with only polygon extents and topographical information available. TII completed further work to use the 2019 pilot study as the basis for the GAMD and to expand the approach to the full extent of the National Roads network.

As it requires appropriate on-site validation, LiDAR should not be relied upon solely to inform the geometrical characteristics of the GAMD. Similarly, while geological properties can and have been estimated through linking to the Geological Survey of Ireland Database, these datasets are often coarse and may not accurately reflect the geology of the earthworks. Ground investigation data will be used to inform more localised ground models, better informing potential failure mechanisms. Structures such as reinforced earth structures (soil nails, reinforced earth layers, and soil columns) and rock netting should also be included within the database, and it will not be possible to identify these from remote sources alone. Recognising that field validation is a time and work intensive process and given the time and budget constraints of undertaking such a large data collection and validation activity, it is necessary to explore and understand the various options – including remote sensing – available to collate and validate the data required to populate the geotechnical asset management database.

The approach would therefore involve:

- Generation of an up-to-date GAMD database from LiDAR surveys recording the unvalidated geometric properties of the earthworks.
- Where possible, on-site validation of visual characteristics, earthwork heights, slope angles, geology, the location of peat ramparts, the presence of engineered structures, and geotechnical hazards.
- Collation of publicly available and internal GIS information, requiring an innovative approach to mass processing.
- Exploring in-situ conditions using remote sensing techniques.

The database will need to be structured to account for different data types (including digital, manual, as-built data entry) and be maintained through regular standardised asset inspections. This will enable the database to be used in the development of proactive measures and long-term asset management plans. Standards detailing the requirements of the data structure, requirements, structure of the database and inspections will need to be developed concurrently (see OVR-1).

This approach assumes undertaking location-based validation and LiDAR surveys across 26 locations, one in each county.

Anticipated outcomes

A detailed geotechnical database is a valuable tool for managing and maintaining the National Roads network. It offers many benefits, including:

- Informed decision-making: with comprehensive data, more informed decisions can be made about asset measure and maintenance programmes leading to a more coordinated and proactive asset management approach (for example, with structures and drainage).
- Financial: a systematically managed database enables prioritisation of asset measures and provide opportunities to plan more coordinated works, reducing the number of reactive measures – saving time, cost and resources.
- Risk management: up-to-date data enables identification of any high-risk assets, allowing works to be planned in advance. This reduces the likelihood of failure and promotes safety.
- Regulatory compliance: a structured and standardised way of data collection and maintenance aids data quality.

Engagement with stakeholders

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

ERW-2 Utilise new GAMD to underpin a risk assessment programme for bog rampart sections of the National Roads network, and develop and implement a prioritised remedial programme of bog rampart rehabilitation

Overview

Once ERW-1 is completed, the GAMD will be used to identify at-risk locations for geotechnical assets. TII's objective is to develop a prioritised adaptation and measure programme across the National Roads network.

In Section 2, the diverse nature of the National Roads network was highlighted, including the major differences between the modern network designed and constructed in accordance with modern engineering standards, and the largely unimproved legacy network comprising the majority of national routes. Approximately 21% of Ireland's land surface is covered by peat bogs [50], predominantly located in the midlands and along the western seaboard. This is reflected in the prevalence of lengths of bog ramparts.

Consistent with the general disposition of peat bogs in the country, sections of National Secondary roads along the western seaboard from Donegal to Kerry, and across midland counties such as Offaly, Westmeath, and Longford contain significant lengths of bog rampart.

These embankment structures were built with rudimentary foundations of tree branches to spread the loads across the peat sub-stratum and have worked effectively in circumstances of modest overall traffic volumes and loads. However, given the very low bearing capacity of the underlying peat stratum, such embankments continuously settle, causing continuing distortion, cracking, and failure of the pavement layers above. This means that bog rampart sections of the National Roads network require much more frequent maintenance and pavement rehabilitation compared to other network sections. Moreover, increasing volumes of heavy goods vehicles and ever-increasing vehicle weights mean that the challenges of maintaining the condition of bog rampart pavements is becoming increasingly challenging and costly.

Into the future, the challenges presented by bog rampart embankments may significantly increase. As outlined in Section 4.1, climate change projections for Ireland indicate higher overall levels of precipitation, with longer dry spells and higher temperatures also predicted. The two factors of increased and more intense precipitation, together with longer dry spells, has the potential to significantly impact on bog rampart structures.

For the most part, the fill material used in the construction of bog rampart sections of road by 19th and early 20th century road builders was not engineered material equivalent to that specified in modern road building standards. Therefore, it is generally more susceptible to the effects of long dry spells, which tend to cause cracking and desiccation in all road embankment structures, old and modern. Intense precipitation following a long dry spell is likely to result in enhanced damage to the embankment fill material, compounded by the existence of cracking and the variable quality of the material used.

TII will adopt the following steps to address the increasing vulnerability of bog rampart embankment structures under climate change scenarios RCP4.5 and RCP8.5:

- Using the GAMD data compiled under ERW-1, TII will compile a full register of all bog rampart embankment structures on the National Roads network.
- TII will procure detailed geotechnical surveys and analysis, enabling a comprehensive risk and vulnerability risk assessment and a prioritisation exercise of the most at-risk sections of the network and sections most susceptible to further impacts of climate change to be undertaken.
- Subject to funding, TII will then commence a programme of remedial measures across the network. Depending on the depth of peat sub-stratum, the measures may involve the full excavation of the existing embankment replaced by a new embankment supported on foundations through the peat. Given the wide occurrence of bog rampart structures across the National Secondary network, it is envisaged that such a programme of remediation may involve a timeline extending to 20 years.

Anticipated outcomes

The prioritised programme, of bog rampart remediation for at-risk bog rampart sections, will deliver the following benefits:

- The programme will deliver long-term value for money through a series of measures that will eliminate the cycle of ongoing costly remedial measures to repair pavements that are currently prone to failure every few years, due to continuous settlement of the embankment.
- The replacement of sub-standard legacy bog-rampart embankments with modern engineered embankments will ensure the future climate resilience of these at-risk sections of the network.

Engagement with stakeholders

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

ERW-3 Continue programme of reactive measures on sections of the National Roads network affected by landslip (or landslide) failures, with emphasis on the N70 & N71

Overview

As discussed in Section 5.7, parts of the National Secondary network, particularly along the N71 and N70 in Kerry and Cork are located in areas prone to geotechnical risk, where sections of the routes are founded on embankments and cuttings through mountainous terrain in the Caha and Iveragh peninsulas. The road engineering construction were of their time and therefore limited in scope and sophistication. Consequently, these routes have always been vulnerable to landslips, rockfalls and other incidents. The local authorities over decades have been required to devote significant resources to continuously address the engineering challenges arising.

Over the past decade, TII has undertaken several reactive measures to address significant challenges at various locations between Glengarriff and Kenmare, the area around Moll's Gap, and at different locations around the Ring of Kerry. TII managed to undertake the works through lane closures, without having to completely close any of these lifeline roads during the works; this limited the degree of disruption to associated communities. Recently, important works have taken place near Moll's Gap and at the Caha retaining walls near the Cork and Kerry County boundary – see Figure 26 below. However, it is inevitable that TII will continue to undertake remedial measures in response to slope stability problems, and in the long-term a more proactive approach will be necessary. It is likely that with increased intensity of rainfall in these mountainous areas of the south-west under future climate change scenarios, the frequency and the severity of such landslips is likely to increase. The combination of ad-hoc construction, poor drainage and complicated geology means that additional and increasingly complex challenges in the operation and management of these sections of the network are expected. In such circumstances, there is a heightened risk of more severe slips occurring potentially leading to the blockage of a section of road for an extended period and leading to considerable inconvenience and disturbance to local communities involving extended diversions disrupting daily activities.

TII will develop a prioritised programme of geotechnical measures in the at-risk sections of the N70 and N71. A programme of LiDAR and aerial imaging together with geotechnical surveys will inform a detailed slope stability analysis leading to a prioritised programme of measures.

The completion of ERW-1, involving the development of a comprehensive geotechnical asset management database for the National Roads network, will provide a strong foundation for undertaking the necessary surveys, analysis and prioritisation works. Subject to funding, it is envisaged that TII will be in a position to commence a programme of geotechnical resilience remedial works on the N70 and N71, improving the resilience of this segment of the National Roads network to the impacts of climate change and geotechnical failure which it faces disproportionately.

Figure 26 Retaining wall works at Caha (left) and Moll's Gap (right)

Anticipated outcomes

While reactive measures in response to unpredictable landslides and other geotechnical events will continue in the foreseeable future, in the longer term, a proactive management approach is essential in dealing with the growing climate change risks that arise on the affected sections of the N70 and N71. It is TII's intention that, subject to the availability of the necessary funding, a transition approach is planned, from one that is currently entirely reactive to one which will be predominantly pro-active, with measures undertaken in a prioritised sequence across a multi-annual programme to minimise the risk of disruption to communities in the locality.

Engagement with stakeholders

TII will also engage in dedicated stakeholder forums as outlined in *T-SAP II* actions to share knowledge and processes, highlight potential shared climate risks, and approaches and lessons learnt with regards to climate adaptation. Additionally, in collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

5.8 Pavements

Overview

Road pavement refers to a multi-layer structure typically formed by combining layers of bound materials on top of a foundation, which is formed by combining layers of unbound materials on earthworks. Road pavement on the National Roads network is characterised as 'engineered' (Motorways, dual and selected single carriageways) and 'non-engineered' (including selected single carriageways, older National Secondary Roads, and coastal/rural legacy routes).

Pavement assets are an essential part of road transport infrastructure, providing users with a comfortable and safe surface to drive on. In 2019, the gross replacement cost of the National Roads network was valued at approximately €31 billion, with over €14 billion associated with carriageway and earthworks alone. Pavement assets are therefore a critical and valuable component of Ireland's transport network [49].

Refer to (c2.4) *DN-PAV-03021 Analytic Pavement & Foundation Design* [51] and (c13) *CC-SPW-00600 Earthworks Specification for National* Roads for details on pavement construction.

The majority of the National Roads network consists of fully flexible pavement structures, bituminous bound on unbound granular materials. There is a limited length of flexible composite pavement structures, bituminous bound on hydraulically bound materials, and very limited rigid pavement structures concrete on hydraulically bound materials, mostly found at toll plazas.

In TII, the pavement asset group is characterised and divided into five subnetworks for asset management purposes. The five subnetworks are based around the characteristics and functions of a specific pavement. These subnetwork classifications are presented in Figure 27.

	Subnetwork	Detail	% of Network
0	Motorway and dual carriageway	High-speed, high-volume pavement.	23%
1	Engineered single carriageway	Moderate-to-high speed, high-volume pavement.	22%
2	Urban roads	Low-to-medium speed, high volume pavement within towns and cities.	13%
3	Legacy network – high traffic	High-volume road built without formal geometric or pavement design.	24%
4	Legacy network – low traffic	Low-volume road built without formal geometric or pavement design.	18%

Figure 27 Subnetwork classifications for the National Roads network

There are numerous climate-related hazards which pose heightened threats to the characteristics and functionality of pavement. It is possible to look at how one or a combination of hazards may impact the pavement deterioration or focus on one or a combination of deterioration mechanisms and assess how different hazards may impact them. A summary of some example impacts on pavement are included within Table 9.

Table 9 Examples of climate impacts on pavements

Change	Example of impact on pavements
Higher air temperatures	Softer mastic in the bituminous mixtures potentially leading to rutting and accelerated deterioration. On specific subgrades like peat, prolonged periods of heat may lead to significant loss of bearing capacity due to shrinkage.
Increase in UV radiation	Accelerated ageing of the mastic in the surface bituminous mixtures.
Increase in operating temperature range across the year (for example, higher extreme temperatures in the summer and lower extreme temperatures in the winter)	Changed range of stiffnesses and fatigue resistance the bituminous mixtures are operating at, potentially leading to accelerated surface and structural deterioration. Changed functional characteristics of surface-dressed surfaces subnetwork 3 and 4. Higher rate of thermal expansion and shrinkage of hydraulically bound mixtures and concrete, leading to increased likelihood of reflective cracking for flexible composite pavement type; increased likelihood of buckling for rigid pavement type.

More intense rain events	Increased number of days when the pavement surface macrotexture is water saturated and more prone to aquaplaning for road users. Heightened risk of accelerated surface/structural deterioration of roads with under capacity or non-existent surface drainage systems. Heightened risk of accelerated surface/structural deterioration of roads with under capacity or non-existent sub-surface/foundation drainage. Accelerated deterioration of already aged, cracked or micro-cracked pavement surfaces and structure due to debonding of the bitumen from the aggregate. This can be exacerbated by the freezing of pavement foundations and the formation of ice on the surface under sub-zero temperatures.
Note that pavement structures are subject to several deterioration mechanisms occurring simultaneously and that one type of failure may lead to another one.	

Given the vital role of the National Roads network in connecting Ireland's communities and enabling economic activity, it is essential to better understand the potential impacts that climate hazards will have on pavement. The study described below is intended to spotlight the current vulnerability of pavement to climate change. Using insights gained from this study, TII will be in a stronger position to mitigate any potential impacts and adapt practices to limit the impacts altogether.

PAV-1 Undertake a detailed analysis of the impacts on pavement surface course materials in a changing climate

Overview

As highlighted in Table 9, there are numerous ways in which a changing climate can impact pavement surface course materials. This study focuses on two specific changes, short duration intense rainfall, and the combination of increased rainfall (of all types) with increased temperatures. Given that winter temperatures are projected to increase by more than 2ºC, PAV-1 focuses on temperature increases. TII remain cognisant of cold weather events and maintain a comprehensive Winter Maintenance Programme that provides a roadmap for steps to be implemented in the event of a cold weather event.

According to Climate Ireland [52], future climate projections for precipitation show an increase in the occurrence of extreme rainfall events, and more rainfall overall. RCP8.5 projections underline an approximately 14% increase in the average annual rate of precipitation by 2050 [24]. Additionally, rainfall is expected to become much more seasonal. Met Éireann's TRANSLATE report [39] suggests that the rate of rainfall in winter could increase by up to 38%, whereas the rate of rainfall in the summer is expected to decline. These projections not only account for climate change scenarios but also reflect the recent historical trends in precipitation. 2006 – 2015 was the wettest decade recorded in Ireland, based on data stretching back to 1711. The period 1991 – 2020 saw a 7% increase in precipitation from the previous period, 1961 – 1990 [52]. Overall, there is a clear trend of increasingly frequent rainfall in Ireland, and all climate projections show this trend continuing into the future.

Short duration rainfall is defined as a localised rainfall event that lasts up to three hours and can occur at multiple intervals throughout the day [53]. Exploring the consequences of these rainfall events requires granular, location-specific datasets. This analysis will be crucial for TII to consider when considering the performance of the pavement surface in the face of increasingly volatile and unpredictable rainfall events. Heavier rainfall could potentially reduce the functional characteristics of the surface course, which is a critical layer for providing safe driving conditions for road users. Without action, it is possible that short-duration, intense rainfall events could lead to the surface macro-texture being overwhelmed more quickly and frequently, reducing the pavement functionality. A previous study investigated the impacts that splash and spray caused by intensive rainfall can have on the overall 'nuisance level' and useability of a pavement surface. The study utilised eight parameters, including factors such as the speed of the road user and the gradient of the pavement surface. These findings, when combined with the calculation of 'water film thickness', were used to determine the safety hazards that can arise from splash and spray and provide appropriate mitigation measures accordingly. Scoping has been completed on follow-up studies which will use GIS overlays of the National Roads network so the calculations and mitigation measures are specific to Ireland. Additionally, future studies could account for numerous degrees of rainfall intensity, allowing further insights into the influence that different pavement parameters such as the texture depth and durability will have on splash and spray occurring at a different rate or velocity.

Due to the hazard that aquaplaning can pose, understanding how the projected increased intensity of precipitation will impact pavement functionality through splash and spray is critical to measuring the long-term functionality of the National Roads network.

It is also critical to recognise the potential impacts that climate change such as higher temperatures and increased rainfall combined will have on pavement material deterioration rates. Moisture can damage pavement by infiltrating into and stripping the base and subgrade layers, which can lead to accelerated layer failure through significant cracking and deformation over time. Additionally, warmer moisture can accelerate the oxidation and ageing process within pavement binding materials, which causes the softening and instability within the asphalt and can lead to cracking. The study of pavement material deterioration rates will be composed of four distinct processes:

- Conduct a **sensitivity analysis** on the environmental and climate parameters within the Irish Analytical Pavement Design Method (IAPDM). The IAPDM contains a model that identifies pavement material deterioration rates using fixed parameters (the country, system, average temperature) and variable parameters (determined by the specific project, such as its design or location). Sensitivity analyses identify the quantum of change within the model in the event of the fixed parameters (such as the climate) changing. Previous design models used in measuring pavement material performance have been based on historic weather conditions, underlining the value of aligning the analysis with future climate projections. A sensitivity analysis will enable deeper understanding of pavement material deterioration rates, as well as how these rates are potentially affected by other climatic changes. For example, greater moisture due to precipitation will degrade the pavement base and subgrade layers. The sensitivity analysis will allow for the consideration of how increasing average temperatures and associated warmer moisture will further exacerbate this degradation through material softening and cracking.
- Undertake a **literature review**, specifically focusing on literature which explores the impacts of climatic conditions and climate change on pavement materials or explores the performance of pavement materials in countries with similar climate conditions expected to affect Ireland in the future. The literature review shall also consider climate change projections, both in Ireland and the wider world.
- Complete a series of **laboratory tests**, which will simulate the occurrence of climate change hazards in an enclosed environment. Laboratory testing allows for the further examination of pavement material deterioration rates prior to field scenario testing. Laboratory testing requires the provision of appropriate sample materials (such as aggregate and bitumen) to be sent to appropriate laboratories. Where possible, promote collaboration with domestic academic institutions and industry partners, which has historically been restricted due to specific technological requirements not being available in Ireland.
- Develop a **comprehensive report**, including key assumptions, methodologies and findings from across the three steps. The report can be utilised to develop potential mitigation measures, influence current maintenance and procurement decisions, and inform future pavement material deterioration rate studies.

Key parameters for consideration within the sensitivity analysis and wider pavement material deterioration rate studies will include:

- The existing rate of pavement material deterioration.
- Existing weather data (which can be sourced from TII's weather stations, operated by Vaisala).
- Historic environmental modelling results within the IAPDM.
- Future climate data (from Met Éireann's TRANSLATE project).
- Pavement condition data from TII.

The condition parameters used within existing pavement deterioration models, several of which are outlined in Table 10.

Table 10 Examples of existing pavement condition parameters [54]

Parameter	Description
International Roughness Index	The variation in surface elevation on a pavement, inducing vibration in moving vehicles. Measured using laser profilometer systems, which surveys wheel paths over 10 metre intervals.
Longitudinal Profile Variance	The 'bumpiness' of a road. Calculated to account for short wavelength (3m) features. Measured using road surface profiler lasers to identify longitudinal profile of pavement surfaces – the level of variance in the readings correlates to the bumpiness of the road.
Rut Depth	Rutting is a deformation on the pavement, typically creating channels in the path of wheels. It is caused by the consolidation or lateral movement of material due to inadequate layering during construction, inadequate pavement layer thickness, or repeated traffic loading. It is measured using road surface profiler lasers.
Laser Crack Measuring System	Profiling system for surface defects, such as cracking and ravelling. Cracking is the formation of visible fractures/splits in the pavement material, and ravelling is the progressive disintegration of layers within a pavement, caused by pavement distress. The laser crack measuring system uses laser projectors and advanced optics to capture 3D images of the surface.

Anticipated outcomes

The primary benefit of PAV-1 will be an improved understanding of the effects that intense rainfall events have on pavement surfaces, with this information greatly shaping the development of management strategies in the face of increasingly frequent volatile weather events. Although there have been previous studies into the impacts of rainfall on visibility for road users, the development of a specialised analysis will enable greater understanding of the impact on pavement, enhancing short-term maintenance and long-term asset management. Solutions to reduce the impact of rainfall on pavement will require a range of approaches, including integrating steeper pavement crossfalls into future earthworks, the introduction of more capacity in drainage systems, variable speed limits and live information boards for road users. PAV-1 will enable these approaches to be optimised, which will improve the cost effectiveness of maintenance for TII.

Engagement with stakeholders

Engagement will be required with external stakeholders, including bodies within the pavement material industry, academic institutions, technical experts and Met Éireann.

In collaboration with Local Authorities and CAROs, engagement will also be undertaken, at TII's discretion, to ensure implementation of the measure aligns with local and regional climate adaptation and resilience strategies and plans.

Links with ongoing work

There are several ongoing and recently completed projects which can influence and enhance PAV-1. As mentioned above, there was a recent study exploring and measuring the impact of 'splash and spray' on pavement visibility and useability. This study provides valuable datasets, approaches and insights that can be of future use during PAV-1. There is also an opportunity to utilise the insights from previous studies to support the development of the national CCRA outlined in OVR-3. The findings from the splash and spray study can be used as an input for the level of vulnerability facing the National Roads network, and the findings from the pavement material deterioration study can be used as exposure inputs for the national risk assessment based on the potential danger and disruption along the National Roads network.

Externally, the collection and publication of TRANSLATE data is ongoing work by Met Éireann and will be a critical resource for the analysis of intensive rainfall. This data, however, is currently only available in 24-hour intervals, and will therefore require refinement prior to application within a 'short duration' analysis.

6 Programme and estimated costs, 2026-2030.

6.1 Programme

The programme of adaptation measures set out in this Plan includes both assessments and a range of physical risk reduction measures, some of which will commence during the lifetime of the current Plan. The programme of physical measures will continue beyond the current Plan (i.e. beyond 2030) into subsequent Climate Adaptation Implementation Plans for National Roads. Progress on developing the programme of physical measures will depend on the envelope of available funding throughout the duration of the Plan.

Should works on physical measures not be undertaken in the lifetime of this Plan, this will add to the programme of works and associated costs of future Implementation Plans. It is anticipated that the initial programme of network physical measures will be developed in detail during the early years of this Plan through 2026 and 2027 with a ramp-up in works from 2028, subject to the availability of funding.

6.2 Overview of estimated costs

Costs presented in this section represent initial preliminary estimates for the network physical risk reduction measures currently proposed. Estimates will be refined during the analysis and design phases during 2026 and 2027.

The Dynamic Adaptative Policy Pathway (DAPP) approach (see Section 3) supports decision-making under uncertainty by prioritising early-stage, lower-cost measures while deferring more substantial investments until trigger points are met. As performance monitoring and risk assessments enhance Transport Infrastructure Ireland's (TII) understanding of climate hazards, vulnerabilities, and asset performance, future physical risk reduction measures can be more clearly defined with greater cost certainty.

6.2.1 Historic reactive physical costs

Reactive physical measures, which are undertaken in response to climate-related damage or failures, are known to carry significant costs. For example, reactive construction costs for geotechnical failures are estimated at approximately €1 million annually. The scale of costs involved can be further understood in the context of a single reactive physical measure in 2023 on the N70 near Gleensk, County Kerry. These works involved the installation of a 40-metre length of retaining wall and the stabilisation of an embankment that was slipping, which incurred a construction cost of €1.7 million.

While this Plan focuses on enabling measures that will lead to physical risk reduction measures, the importance of sufficiently funding routine maintenance and operations cannot be overstated. An appropriately funded maintenance regime will support climate adaptation resilience. Maintaining National Roads assets so that they can perform as designed is the first step in mitigating network disruption from severe climatic events (e.g. flooding). Current road maintenance budget allocations to TII have fallen significantly since 2008 – current funding levels are approximately 50% of 2008 values. It is estimated that current needs for routine maintenance for National Roads is a minimum of €77 million annually. This decline significantly impacts TII's ability to adequately provide for baseline road maintenance, which is a critical enabler of climate adaptation and resilience. Without sufficient and sustained maintenance funding, the effectiveness of future adaptation physical measures will be compromised, and risks of climate-related damage will remain elevated.

6.2.2 Estimated climate adaptation costs 2026 - 2030

As outlined above, the level of expenditure that TII can devote to measures outlined in this plan will depend on the funding envelope available under the *National Development Plan*.

To cover the two climate change scenarios assessed (i.e. RCP4.5 and RCP8.5) and in recognition of the inherent uncertainty associated with climate adaptation planning, the cost of network physical measures to be undertaken in the Plan have been estimated for a lower bound and an upper bound. In the lower bound, the total cost of the Plan with physical measures is estimated to be circa €82 million between 2026 and 2030. In the upper bound, the total grows to circa €265 million between 2026 and 2030. Cost estimates will be refined and updated as part of the enabling actions set out in this plan including, risk and vulnerability analysis, planning and design that will commence in 2026 and 2027.

While the methodologies for cost estimation of the physical measures across a number of asset groups will be established through the progression of the Plan, initial estimates for drainage, culverts, slope stability and structural interventions, based on the sections of road network exposed to flooding, are presented in Table 11 below. These figures are based on the exposure data obtained from TII's flood risk visualisation tool Flood Analysis Tool as presented in Table 4 from Section 3.5. It is acknowledged that data on some climate hazards are further developed than others. Resultantly, some costs submitted as part of the *National Development Plan 2025* are not included in the below table, as they will be further refined once more data and information becomes available. The figures are based on broad-scale data and benchmark driven, top-down assessment methods, reflecting the current absence of detailed condition surveys and specific physical measure designs. These preliminary estimates are intended to provide an initial indication of the scale of potential physical measure needs in the absence of detailed climate change risk assessments (CCRA). They will be refined and validated through subsequent, bottom-up analyses and site-specific studies during the planning and design phases. The costs outlined in Table 11 provide a cost envelope for Tier 1 and Tier 2 criticality locations. This plan prioritises these locations for development and implementation due to their critical nature within the National Roads network. Tier 3 to Tier 5 locations identified in Section 3.5 will be assessed and scoped as part of this Plan for potential physical measures based on learnings from the cost build-up at Tier 1 & 2 critical locations.

Figure 28 and Figure 29 below set out the anticipated form/shape of the expenditure profile over the five years of this plan. The profile is based on the requirement to undertake the appropriate CCRAs followed by design and planning of the adaptation schemes. Expenditure is therefore projected to be modest through 2026 and 2027 but is proposed to increase substantially in the following years of the programme as construction commences on site. The programme of works is thereafter expected to continue through the following Implementation Plan 2031 to 2036 and subsequent plans, subject to the availability of the necessary levels of funding.

Table 11 Preliminary cost estimates for physical road network measures

Category		Lower bound (cost per km)	Upper bound (cost per km)	Amount	Total costs est. lower bound	Total costs est. upper bound	Amount	Total costs est. lower bound	Total costs est. upper bound
				RCP4.5			RCP8.5		
Drainage	***Segment of road exposed to future flood events*** (in Tier 1 and 2 criticality locations only)			45km			67km		
	Based on 80% of the drainage system needing to be upgraded			36km			54km		
	Based on 50% requiring light to medium upgrade	€700,000	€1,100,000	23km	€15,750,000	€24,750,000	34km	€23,450,000	€36,850,000
	Based on 30% heavy upgrade	€1,500,000	€3,000,000	14km	€20,250,000	€40,500,000	20km	€30,150,000	€60,300,000
	Subtotal				**€36,000,000**	**€65,250,000**		**€53,600,000**	**€97,150,000**
Culverts	Number of culverts exposed to future flood events (in Tier 1 and 2 criticality locations only)			32 no.			42 no.		
	Based on 30% of culverts in Tier 1 and 2 needing to be upgraded	€750,000	€1,000,000	10 no.			13 no.		
	Subtotal				**€7,500,000**	**€10,000,000**		**€9,750,000**	**€13,000,000**
Slope stability	Segment of road exposed to future flood events (in Tier 1 and 2 criticality locations only)			45km			67km		
	Based on 10% of network has exposed embankments in Tier 1 and 2 locations	€1,500,000	€10,000,000	4.5km			6.7km		
	Subtotal				**€6,750,000**	**€45,000,000**		**€10,050,000**	**€67,000,000**

Category		Lower bound (cost per km)	Upper bound (cost per km)	Amount	Total costs est. lower bound	Total costs est. upper bound	Amount	Total costs est. lower bound	Total costs est. upper bound
Bridges	Number of bridges exposed to the impacts of scour on the whole network			8 no.			9 no.		
	Based on all bridges requiring physical climate adaptation works over the next 5 years	€1,000,000	€2,000,000	8 no.			9 no.		
	Subtotal				**€8,000,000**	**€16,000,000**		**€9,000,000**	**€18,000,000**
Bog ramparts	Protection and renewal of bog rampart routes				€2,000,000	€11,000,000		€11,000,000	€35,000,000
	Subtotal				**€2,000,000**	**€11,000,000**		**€11,000,000**	**€35,000,000**
Costs of physical interventions					**€60,250,000**	**€147,250,000**		**€93,400,000**	**€230,150,000**
Costs of measures outlined in this Plan					**€22,000,000**	**€34,000,000**		**€22,000,000**	**€34,000,000**
Total costs					**€82,250,000**	**€181,250,000**		**€115,400,000**	**€264,150,000**

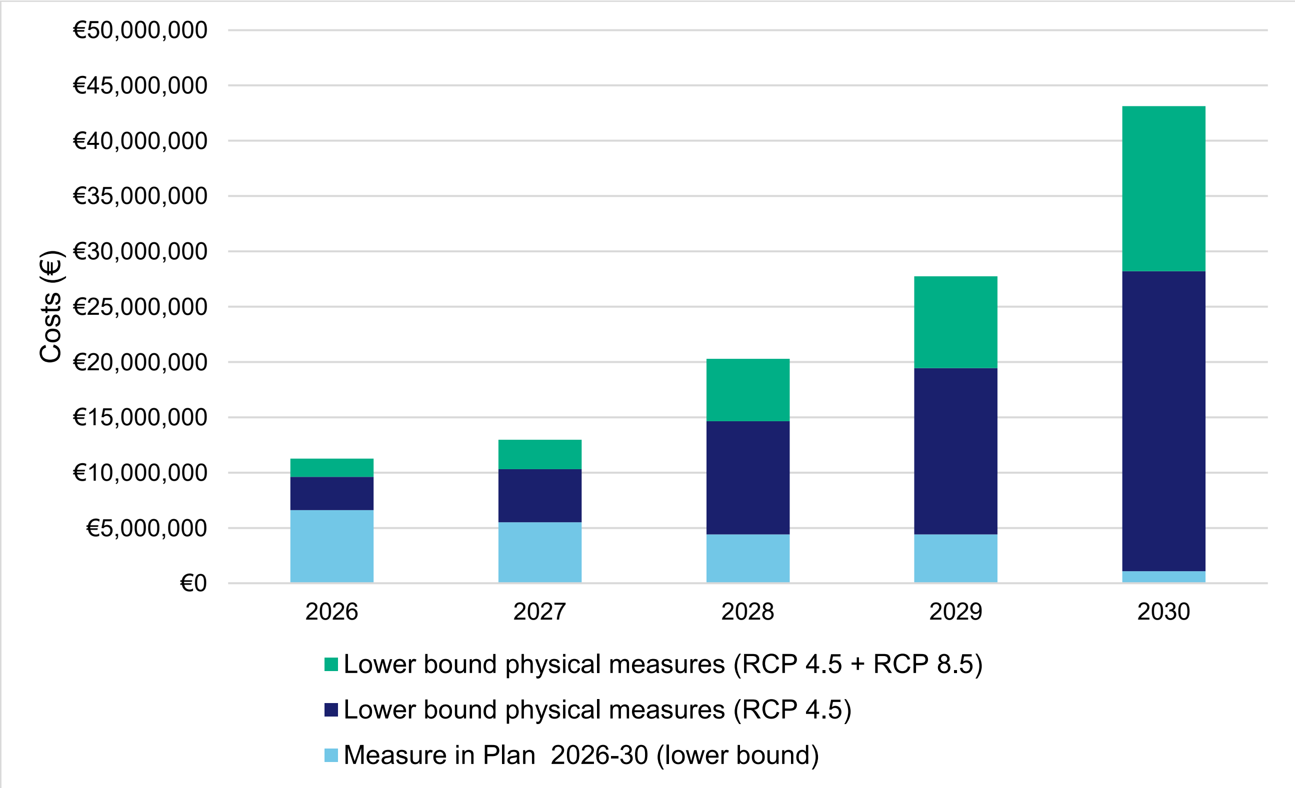

Figure 28 ***Anticipated cost profile – lower bound****: Profile of the anticipated cost profile for the measures as set out in this Plan and estimated lower bound costs for physical measures in climate scenarios*

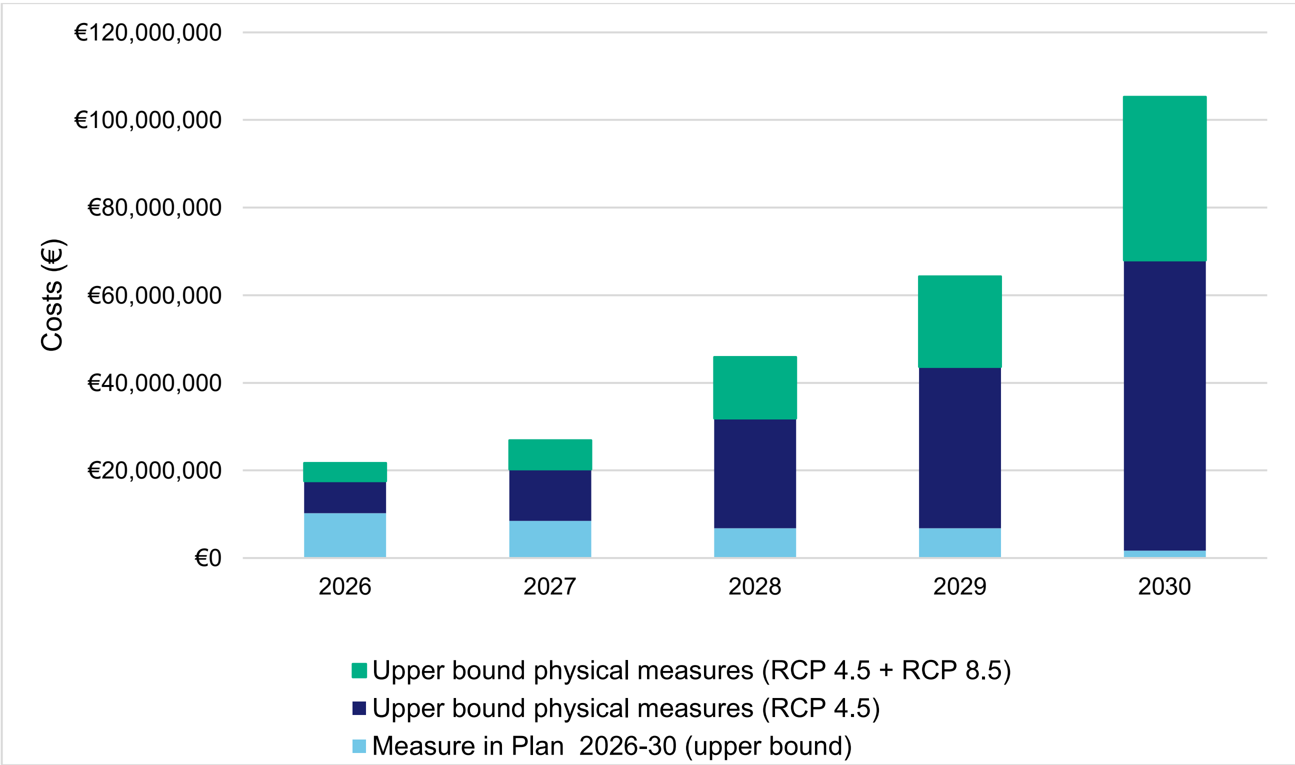

Figure 29 ***Anticipated cost profile – upper bound:*** *Profile of the anticipated costs of the measures as set out in this Plan and estimated upper bound costs for physical measures in climate scenarios*

7 Monitoring, Evaluation, and Learning

7.1 Introduction

Transport Infrastructure Ireland's (TII) progress on climate adaptation is complex, iterative, and inherently long-term. In this context, it is proposed to apply a Monitoring, Evaluation, and Learning (MEL) framework which will support effective, accountable, and adaptive implementation of climate and resilience strategies. This aligns with the Dynamic Adaptative Policy Pathways (DAPP) approach, which emphasises the ongoing monitoring of key indicators to inform reassessment and timely adjustments.

The MEL framework will be based on the Theory of Change (ToC) principles of planning and evaluation, which articulate how the measures outlined in the Plan are expected to lead to long-term resilience outcomes. It maps the logical pathway from planned inputs and measures to outputs and ultimately to the desired outcomes and impacts such as climate resilient assets and a network that continues to deliver safe, reliable services despite a changing climate. The ToC also provides the foundation for prioritising actions, tracking progress, and evaluating whether adaptation efforts are delivering meaningful change.

Key components of the MEL framework include:

- **Monitoring:** refers to the systematic collection and analysis of data to track the progress of adaptation measures and their impact over time. Monitoring will enable TII to identify trends in performance, track changes relative to baseline conditions, and understand how external drivers, such as climate variability, are influencing the network. It will provide timely insights into whether adaptation efforts are proceeding as planned and flag where adjustments may be needed.
- **Evaluation:** focuses on assessing the outcomes and effectiveness of adaptation measures. Evaluation will draw upon monitoring data and other sources of internal and external evidence to allow TII to assess performance across dimensions such as efficiency, equity, and impact. It will provide an opportunity to reflect on what has worked, what has failed to deliver expected outcomes and why, and to build a robust evidence base for learning.
- **Learning:** integrates the findings and insights from monitoring and evaluation processes to improve future planning and implementation. Learning will include embedding new or improved knowledge, behaviours, and institutional practices. In the climate adaptation space, learning is especially important given uncertainties about future hazards and risks, the long timescales involved, and the need to remain flexible and responsive to evolving circumstances.

MEL plans must acknowledge that climate change presents a challenge characterised by deep uncertainty. While the direction of change (such as more frequent and intense extreme weather events) is increasingly clear, the timing, severity, and location of future climate impacts remain unpredictable. For long-lived infrastructure and systems, this uncertainty presents significant challenges, such as understanding how responsible and cost-effective decisions can be made today without knowing exactly what the future holds. As discussed in greater detail in Section 3, adaptation planning must accommodate a range of possible futures and retain the flexibility to adjust over time. MEL provides the structure to support this adaptive approach, enabling evidence-based learning and responsive decision-making.

7.2 Purpose and objectives

The MEL framework underpins the delivery of the Plan; providing a structured approach to assess progress, guide implementation, and inform ongoing decision-making. The MEL framework is not a mechanism for assessment, but a method for adaptive learning and continuous improvement, ensuring that adaptation efforts remain dynamic, effective, and responsive to both known and emerging climate risks.

The key objectives of applying the MEL framework to this Plan are to:

1. Track progress toward TII's climate adaptation strategic objectives: Systematically monitor the implementation of adaptation measures and measures and assess whether they are achieving the intended outputs, outcomes, and impacts. TII's climate adaptation strategic objectives – and the objectives of the Plan – are described in Section 1.3.
2. Support strategic and flexible decision making: Generate timely insights that inform prioritisation and sequencing of measures and measures, investment decisions, and resource allocation. This is particularly important in the face of deep uncertainty and evolving climate risks.
3. Enable learning and course correction: Identify what is working, what is not, and why. This supports evidence-based adjustments to measures, fosters institutional learning, and builds organisational capacity to manage uncertainty and change.
4. Strengthen accountability and transparency: Provide a credible basis for communicating progress to internal and external stakeholders, including governance bodies, delivery partners, and the public. This includes demonstrating value for money and climate impact.
5. Build an evidence base for future planning: Contribute to a growing body of knowledge that supports the design of more effective adaptation strategies in the future.

7.3 Ownership and responsibilities

The measures set out within the Plan will require ownership and accountability from across TII. On a day-to-day basis, responsibility for the oversight and delivery of the Plan will lie with TII's Climate Adaptation Manager and their team. Specific responsibilities will include the implementation of the MEL framework outlined below, development of key performance indicators (see Table 12), and communication across the relevant parts of TII to assist in ensuring that the objectives and measures of the implementation plan are embedded into daily operations.

7.4 Developing a MEL framework

The development of the MEL framework requires the relationship between inputs, measures, outputs, outcomes and impacts to be clearly mapped (Figure 30) and relationships understood for the successful delivery of TII's vision. The MEL framework has been developed based on the guidance provided in the HM Treasury's *Magenta Book: Central Government guidance on evaluation* [55] and the *Theory of Change Toolkit* developed by the UK Department for Environment, Food and Rural Affairs [56]. As described in Table 13, this MEL framework provides a clear connection between the measures set out in this implementation plan and TII's long-term climate adaptation strategic objectives and aim, demonstrating how short-term action contributes to broader organisational goals and strategic vision.

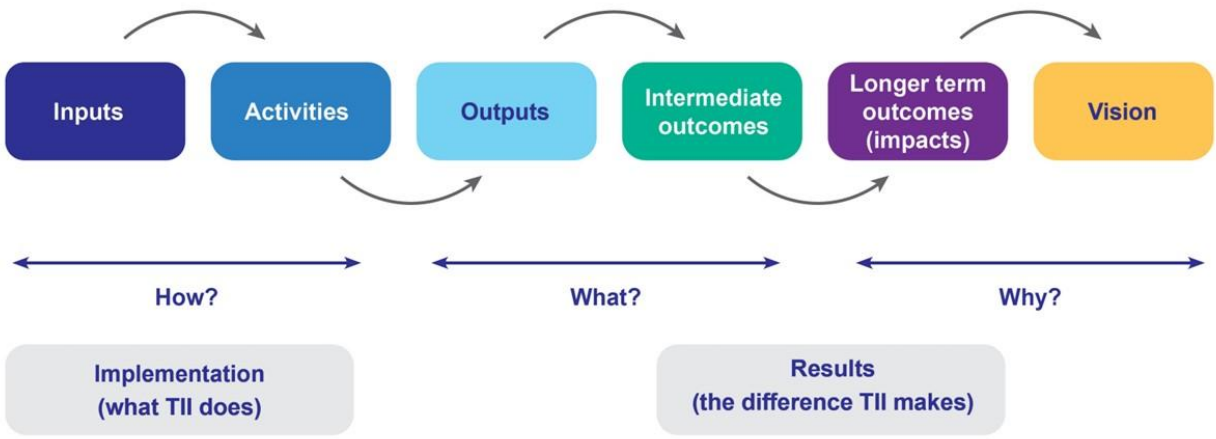

Figure 30 Conceptual overview of the monitoring framework

Table 12 sets out further definitions for each of the MEL framework building blocks included in Figure 30.

Table 12 Definition of the MEL framework building blocks

Building blocks	Definition	Source
Vision	The long-term purpose and direction for TII is to provide safe, resilient, and sustainable transport networks. Within the context of climate adaptation, this vision is expressed as TII's aim to be an organisation that is adaptive to the impacts of climate change while maintaining its commitment to sustainability.	*Statement of Strategy 2021-2025* *Climate Adaptation Strategy*
Longer term outcomes (impacts)	These are the strategic objectives and aim of TII's *Climate Adaptation Strategy* and the Plan. The aim and objectives are listed in Section 1.2 and are shown in Figure 30.	*Climate Adaptation Strategy*
Intermediate outcomes	Achieving the main outputs of the plan will result in direct outcomes. It can also unlock, drive, catalyse, and support a range of potential indirect and wider benefits. *For example, an intermediate outcome of measure "STR-1 Asset management database expansion to include retaining walls" is the integration of existing data into the updated asset management database to centralise TII's information and resources.*	To be developed as MEL framework is implemented
Outputs	The products of the measures within the implementation plan. *For example, an output of measure "STR-1 Asset management database expansion to include retaining walls" is the updated asset management database for use by TII.*	Developed specifically for the Plan
Activities	Any actions, analysis, modelling, data gathering, development of information, or physical works that can be used by TII to implement or inform climate adaptation. *For example, "STR-1 Asset management database expansion to include retaining walls" is a measure.*	Developed specifically for the Plan
Inputs	The necessary actions and support that TII will require for a successful implementation of this plan. This includes the key financial and non-financial inputs to support the development and implementation of the implementation plan.	Developed specifically for the Plan

7.5 Measuring impact

Key Performance Indicators (KPIs) are the primary tool for measuring progress toward impact and achieving TIIs strategic vision. In line with the MEL framework described in Section 7.4, an initial long list of preliminary KPIs has been proposed, building on the Environmental Protection Agency's (EPA) *Implementation of Climate Adaptation Indicators: Lessons Learned from the Transport Sector* [57]. While the Plan will evolve, with new measures and shifting priorities, the proposed KPIs are designed to remain relevant across multiple planning cycles, thereby supporting TII to monitor both short-term implementation and long-term progress toward a more resilient National Roads network.

This KPI initial long list should be considered as a starting point and will be further refined and prioritised over time. KPIs will continue to evolve as TII's programme develops in line with emerging priorities, improved data availability, and lessons learned through this implementation process. The development of KPIs will require an assessment of data currently available to TII, the setting of appropriate targets, and ultimately, the selection of an achievable shortlist. It is important to note, not all KPIs in the long list will be taken forward.

Setting targets will involve review of TII's goals and strategic objectives. In the context of climate change, which will have greater impacts over the coming years, an assessment will be required on whether the network shall *improve*, *standstill*, or even *disimprove*. This involves a decision on the provision of the same level of service as at present, or an acceptance that some disruption from adverse weather events will occur, despite the implementation of this Plan. This decision will depend on several factors including the global trajectory of greenhouse gas emissions and resulting climate change impacts, the amount of funding available to TII, and the success of cross-sector collaboration.

To support interpretation and a clear understanding of how each indicator contributes to the overall monitoring framework, Figure 31 sets out the categories that are used.

Input indicators reflect the resources committed to adaptation measures, such as funding

Process Indicators (or measure/intervention) capture the specific activities, such as the number of assessments completed

Output indicators measure the immediate, tangible products of implementation, such as updated standards

Outcome indicators assess the effects of adaptation measures, such as reduced disruption, improved safety, or increased resilience

Figure 31 MEL framework categories

While input, process, and output indicators are generally measurable immediately using existing systems, outcome indicators may require further investment in data systems or methodologies and may only become measurable later in the Plan's cycle. Many outcome indicators also require the establishment of baselines before meaningful progress can be monitored. These baselines are an understanding of the current level of performance or condition.

Wherever possible, baseline conditions will be defined using a combination of historical data and early implementation data collected prior to the first measures/measures. Although climate change (and other external influences) presents a moving target, baselining remains a useful tool for understanding relative improvements and supporting evidence-based decision making. To support meaningful interpretation of outcome indicators, it will also be necessary to track relevant climate and environmental indicators in parallel (for example, the number of adverse heat/rainfall events). Monitoring these external factors allows distinguishing the effects of adaptation measures from broader climatic changes and supports a more robust evaluation of resilience outcomes.

Table 13 shows an initial long list of KPIs for each climate adaptation strategic objective to track progress towards long-term climate adaptation goals. These indicators are classified as either 'present' or 'future'. The 'present' classification applies where TII is already in a position to begin measurement or implementation based on existing data or processes. The 'future' classification applies where additional development (such as new data collection, systems, or methodologies) is required before regular tracking can begin. This classification reflects TII's current capabilities while planning for enhanced measurement and learning over time.

Table 13 Initial long list of key performance indicators for TII's monitoring framework

Key performance indicators		Indicator type	Implementation
Objective 1 | Observe fewer network disruptions during climate-related events			
1.1	Number of adverse weather events* (for example, flooding) compared to baseline years	Outcome	Future
1.2	Average duration of disruptions due to adverse weather events	Outcome	Future
1.3	Length of National Roads network with incident reporting systems that capture disruption (due to adverse weather events*) data	Output	Present
1.4	Funding allocated to climate adaptation measures	Input	Present
Objective 2 | Rapidly recover from any climate-related events			
2.1	Average time taken to restore full network operation following an adverse weather event* (target by road class or criticality)	Outcome	Future
2.2	Length of network with climate incident response and recovery plans in place	Output	Present
Objective 3 | Have a robust, flexible, and equitable organisation that responds effectively during climate events			
3.1	Number of Motorway Operator business continuity or emergency plans that address flood risk mitigation	Output	Future
Objective 4 | Enhance the climate resilience of lifeline roads to maintain community accessibility			
4.1	Number of closures on lifeline roads caused by adverse weather events*	Outcome	Future
4.2	Damages and associated costs on lifeline roads attributed to adverse weather events*	Outcome	Future
Objective 5 | Engage with the wider adaptation efforts across Ireland through partnerships and wider research			
5.1	Number of collaborative projects or partnerships established for example, with local authorities, academia or agencies focused on adaptation/resilience	Output	Present
5.2	Annual reporting of shared lessons or contributions to national adaptation networks	Output	Present

Key performance indicators		Indicator type	Implementation
Objective 6 | Embed climate adaptation within TII's operations, policies, and procedures to ensure a safe and resilient network			
6.1	Number of policies, standards and procedures reviewed and updated to reflect climate risk and resilience practices	Process	Present
6.2	% of new projects incorporating climate risk assessments in planning/design	Output	Future
Objective 7 | Adopt a low-carbon approach in TII's designs, standards, and processes when considering climate adaptation, while also considering wider social and environmental benefits			
7.1	% of new capital projects incorporating nature-based solutions or green infrastructure	Output	Future

**Adverse weather events must be clearly defined for each relevant hazard type, likely in coordination with the Climate Change Risk Assessments (CCRAs). Definitions should be based on thresholds that reflect meaningful operational or safety risks. For example, an adverse heat event might be defined as temperatures exceeding a specified degree threshold (for example >30°C), while an adverse rainfall event might relate to hourly or precipitation above critical levels known to affect road safety. These definitions will promote consistent and meaningful tracking of climate-related impacts on network performance and user safety.*

Vision

In fulfilling our purpose we strive towards three over-arching aims which, taken together, represent our vision:

- To ensure that Ireland's national road and light rail infrastructure is safe and resilient, delivering better accessibility and sustainable mobility for people and goods;
- To ensure that Ireland's national road and light rail infrastructure is safe and resilient, delivering better accessibility and sustainable mobility for people and goods;
- To be recognised as an organisation that values its people, customers, partners and the environment.

Mission/ Purpose

Provide sustainable transport infrastructure and services, delivering a better quality of life, supporting economic growth and respecting the environment.

TII's climate adaptation aim

To be an organisation that is adaptive to the impacts of climate change and maintain its commitment to sustainability.

Impact

TII strategic goals and objectives

Organisational Excellence	Existing Infrastructure	New Infrastructure	Services	Safety	People	Engagement and Collaboration
Implement best practice in governance and how we conduct our business in TII, achieving a high standard of professionalism, compliance, assurance and securing value for money in all we do.	Operate, maintain and extend the life of national roads and light railway infrastructure to ensure the safety and efficiency of our transport networks, ensure appropriate management of environmental resources and contribute to the transition to a low-carbon and climate-resilient society.	Deliver national road, light railway, metro and Active Travel infrastructure, contributing to compact growth, sustainable mobility, enhanced regional accessibility and the transition to a low-carbon future.	Operate TII's light rail, tolling and traffic control systems and contribute to the electrification and digitalisation of transport, benefiting our customers and contributing to sustainable mobility and decarbonisation of transport.	Reduce the risk and number of collisions, injuries and deaths on our light rail and road infrastructure.	Maintain, enhance and harness the capability of our people, while promoting TII's values, to ensure the delivery of our goals.	Engage and collaborate, partnering effectively with external parties, both nationally and internationally, to support the achievement of our strategy.

TII's climate adaptation strategic objectives (the objectives of this Implementation Plan)

Observe fewer network disruptions during climate-related events	Rapidly recover from any climate-related events.	Have a robust, flexible, and equitable organisation that responds effectively during climate events.	Enhance the climate resilience of lifeline roads in order to maintain community accessibility.	Engage with the wider adaptation efforts across Ireland through partnerships and wider research.	Embed climate adaptation within TII's operations, policies, and procedures in order to ensure a safe and resilient network.	Adopt a low-carbon approach in TII's designs, standards, and processes when considering climate adaptation, while also considering wider social and environmental benefits.

Key Performance Indicators (KPIs)

Number of adverse weather events* (for example, flooding) compared to baseline years Average duration of disruptions due to adverse weather events Length of national road network with incident reporting systems that capture disruption (due to adverse weather events*) data Funding allocated to climate adaptation measures	Average time taken to restore full network operation following an adverse weather event* (target by road class or criticality) Length of network with climate incident response and recovery plans in place	Number of Motorway Operator business continuity or emergency plans that address flood risk mitigation	Number of closures on lifeline roads caused by adverse weather events* Damages and associated costs on lifeline roads attributed to adverse weather events*	Number of collaborative projects or partnerships established for example, with local authorities, academia or agencies focused on adaptation/resilience Annual reporting of shared lessons or contributions to national adaptation networks	Number of policies, standards and procedures reviewed and updated to reflect climate risk and resilience practices % of new projects incorporating climate risk assessments in planning/ design	% of new capital projects incorporating nature-based solutions or green infrastructure

Outcomes

Wider benefits (defined for each measure in this Implementation Plan in the "anticipated outcomes" sections).

Outputs

The direct products of the measures recommended in this Implementation Plan.

Actions

Measures delivered as part of this Implementation Plan.

Inputs

Financial and non-financial inputs to support the development and implementation of the plan.

Figure 32 Application of the Theory of Change in the Plan

7.6 Reporting impact

Effective impact reporting is a crucial part of the MEL process to ensure transparency, support accountability, and inform adaptive decision-making by clearly communicating the outcomes of adaptation measures. Impact reporting will:

- Align with the MEL framework and its KPIs.
- Combine quantitative metrics and qualitative insights.
- Be tailored to different audiences.
- Acknowledge uncertainties and limitations.

Impact will be reported at least annually, with more frequent updates aligned to key planning and decision cycles. This could be incorporated into the annual *National Road & Greenway Network Indicators* publication or alternatively into the *Annual Report and Financial Statements*.

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Appendix A | Secondary climate hazards

This appendix summarises the potential climate change impacts associated with the secondary climate hazards.

Severe cold

There has already been an observed decrease in the number of cold days (days below 0ºC) and annual frost days over the period 1890-2012 [58]. This trend is projected to continue by mid-century, with the average number of frost days in Ireland projected to further decrease by 50%. Despite these changes within climate change projections, severe cold is still a material hazard for the National Roads network and will be subject to annual fluctuations. Severe cold can result in the following impacts on infrastructure:

- Freezing can cause blockages to the drainage system, and result in water expansion that may impact drainage condition.
- Greater use of salt to improve vehicle traction and road safety can increase pavement wear. Where severe cold events occur, the intensity of salt consumption increases can lead to a heightened risk of pavement wear. Salt can also cause corrosive damage to road user vehicles, with chemical reactions between salt and metal car components potentially accelerating the formation of rust [59].
- Freeze-thaw can cause further degradation of the integrity and functionality of the pavement when snowmelt or rainwater enters any existing cracks and expands them.

Frozen/frosted surfaces are difficult to drive on due to the lack of friction, causing potentially unsafe driving conditions and heightened risk to road users. Similarly, melted ice can form a slush-like surface which can also be difficult to drive on, and melted ice itself can cause localised flooding where drainage systems get overwhelmed [60].

Extreme heat

Rising temperatures and prolonged heat present a growing concern for national road infrastructure and operations. While Ireland has a temperate oceanic climate, mean annual surface air temperatures have increased by 0.8ºC over the period 1890-2012, which equates to an average rise of 0.07ºC per decade. The number of warm days (days over 20ºC) has also increased, while the number of cold days (days below 0ºC) and annual frost days has decreased [58]. These changes are projected to intensify under the RCP4.5 scenario by 2050, with mean annual temperatures projected to rise by 1-1.6ºC compared to the 1961-1990 average. Extreme warm temperatures are also projected to increase, with summer maximums increasing by 2.6ºC and winter maximums increasing by 3.1ºC under a high emissions scenario (RCP8.5) for 2050.

The projected increases in temperature and periods of prolonged heat are, in the long-term, a potentially significant hazard to the National Roads network. While a number of assets adopt design standards which consider temperature, there may be greater risk for historic infrastructure which has not been designed with climate change uplifts. Extreme heat can result in the following impacts to national road infrastructure and operations:

- Soil is prone to shrinkage and cracking during hot, dry weather, which can destabilise earthworks or drainage assets. Rising temperatures and heatwaves can threaten the integrity of binding materials used within pavement, causing surfaces to become soft and can lead to cracks forming within the weakened pavement.
- Expansion joint and bridge bearing durability can be affected if extreme temperatures exceed material safety standards, albeit on a small scale.

Drought

In addition to the observed changes in temperature, the likelihood of an extreme dry summer has doubled over the last century in Ireland. For both RCP4.5 and RCP8.5 scenarios, there is a projected 12-40% increase in dry periods by 2050, as well as longer average duration of dry periods (5 days with <1mm of rain) [23].

Drought can result in the following impacts to National Roads network assets and operations:

- Lack of water can lead to a build-up of debris or sedimentation in drainage ducts.
- Tunnels, which rely on water for the removal of pollutants to ensure sufficiently good air quality, may also be impacted by reduced water availability.
- Reduced soil moisture due to prolonged dry periods can lead to soil shrinkage and cracking, as well as subsidence which may damage drainage assets and destabilise embankments and pavements.

Sea level rise and storm surge

In general, the National Roads network is exposed at relatively few locations to the effects of sea level rise and associated flooding. Short sections of the N67 in County Clare, the N69 along the Shannon Estuary and sections of the N70 Ring of Kerry are the principal points of interaction in the case of legacy national roads. Generally, our motorway and modern two-lane sections of network do not interact closely with the coast, and as such sea level rise and associated storm surge is not a hazard for the vast majority of the modern National Roads network.

However, an obvious exception are the National Roads network's three tunnels, all of which are located at estuarine crossings (Jack Lynch Tunnel and Limerick Tunnel) or adjacent to the coast (Dublin Tunnel). All three tunnels were designed to ensure that the tunnel bores would be protected from inundation under well-established design flood thresholds. However historical design parameters may no longer be appropriate in the face of the kind of extreme weather events that we are increasingly witnessing.

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