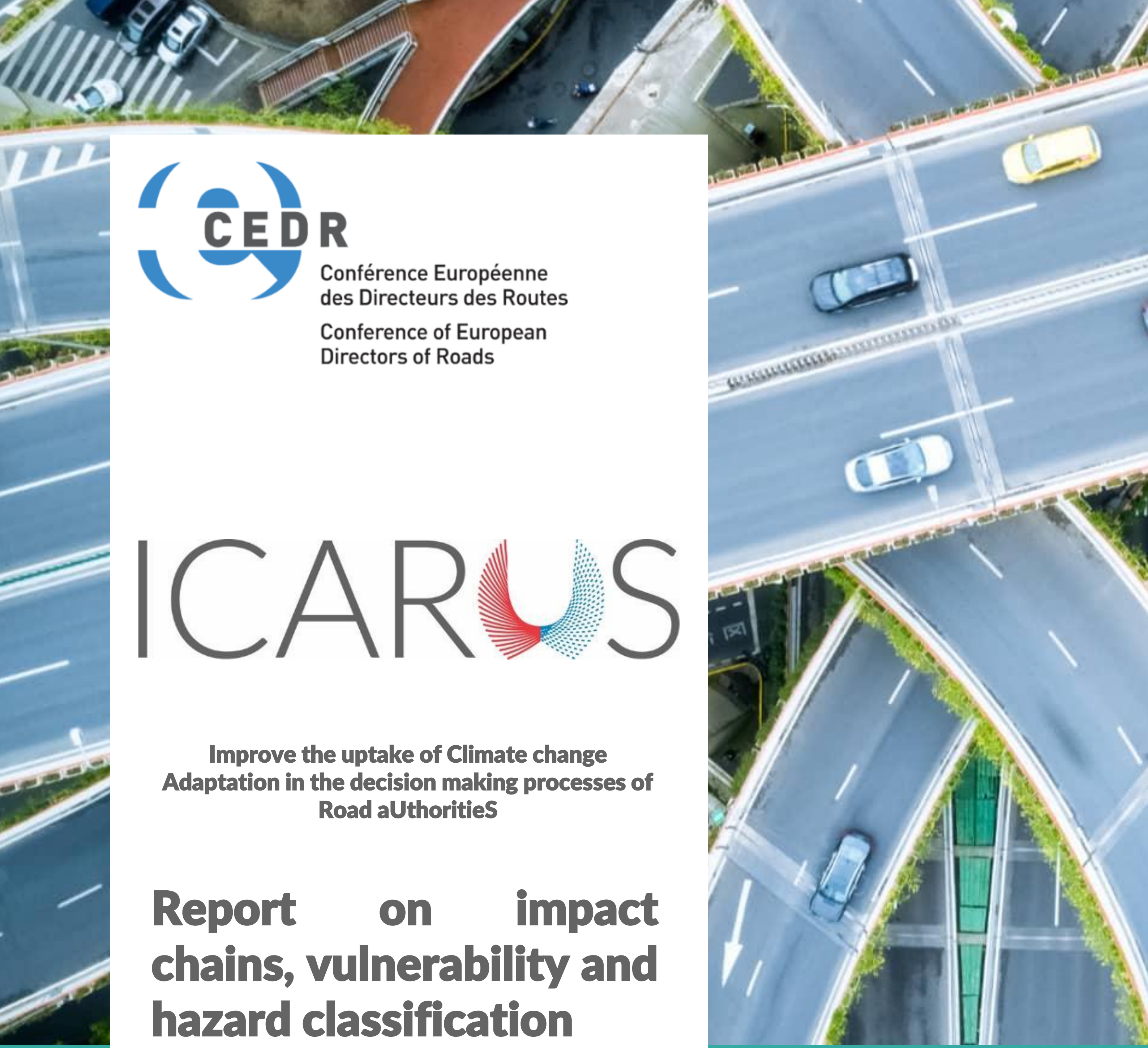

CEDR
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ICARUS

Improve the uptake of Climate change
Adaptation in the decision making processes of
Road aUthoritieS

Report on impact chains, vulnerability and hazard classification

Deliverable D1.2 Version 2.0

July 14th 2023

ICARUS

Improve the uptake of Climate change Adaptation in the decision making processes of Road aUthoritieS

CEDR
Conférence Européenne des Directeurs des Routes
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CEDR call 2022: Climate Change Resilience

Deliverable D1.2 Version 1.0

Report on impact chains, vulnerability and hazard classification

14-07-2023

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Summary

Work Package 1 focusses on impacts and risks due to climate change. In particular, this report starts establishing causal relationships (asset/component/sub-component level) with Climate Impact-Drivers (CID) defined in D1.1. Implications in terms of variation in magnitude and geography are described in Annex 1.

Secondly, this deliverable 1.2 includes the concept and the methodology of impact chains. These impact chains consider the overall performance and function of the road stretch and systemic impacts at network level in different European contexts that take account the latest projected changes in climate.

The last part of this D1.2 includes a new classification of hazards according to their effect on road resilience taking into account their impact before (e.g., forecast and preparation time), during (e.g. hazard duration, intensity, scale and physical impact) and after (e.g. recovery time) an event using multicriteria analysis.

This classification will provide key input for evaluating adaptation measures in WP2 and 3 including grey and green solutions.

This report is linked also to the report D2.2: Guidelines on how to define and use minimum viable service levels for evaluating resilience and adaptation options based on quantification and valuation of associated costs and wider benefits.

The ICARUS project, framed within the CEDR Transnational Road Research Programme, aims at developing knowledge products for the integration of climate resilience into decision-making processes, as well as implementing existing resilience thinking and research into practice within the NRAs.

The key recommendations of the report are outlined below.

- Key recommendations for risk assessment in an holistic approach based on graphic cocreation.
- Key recommendations for CID projection interpretation according to geographic location and potential impact in transport infrastructure.
- Key recommendations for including climate change in Infra Manager Route Asset plans.
- Key recommendations in terms of hazard prioritisation based on a resilience perspective versus the traditional damage-based perspective.

Table of Contents

1 INTRODUCTION

1.1 Background and key challenges

In today's rapidly changing world, there is a growing recognition of the need to assess risk and resilience for gaining insight in climate change adaptation options. The assessment of risk and vulnerability, as first step, is crucial in addressing the challenges posed by climate change.

While the significance of resilience and climate change adaptation is well understood, practical cause-effect-relationship among elements with a systemic ambition is still pending.

Moreover, establishing a connection between risk and vulnerability, and the various stakeholders and steering mechanisms at different management levels of National Road Authorities is crucial. By aligning risk and resilience strategies with existing governance structures, policies, and regulations, decision-makers can ensure that climate change adaptation are not treated as standalone concept but as an integral part of sustainable development for road transport infrastructures.

A key challenge in promoting the identification and assessment of expected impacts according to climate predictions agreed by scientific committees (e.g., IPCC, 2021).

This is what this ICARUS guideline is about. By effectively understanding the causal relationship explained before decision-makers at the NRA's can optimize their efforts to build resilience and foster a more sustainable and resilient future.

1.2 Objective of this guideline

Main objective of this guideline is to provide recommendations on how to effectively build the impact chain case for risk assessment and hazard classification according to NRA specificities. Key in this regard is the link that is established between assets (e.g., asset/component/ subcomponent), Climate Impact Drivers (CID), and variation in magnitude and geography under different scenarios according to scientific evidence.

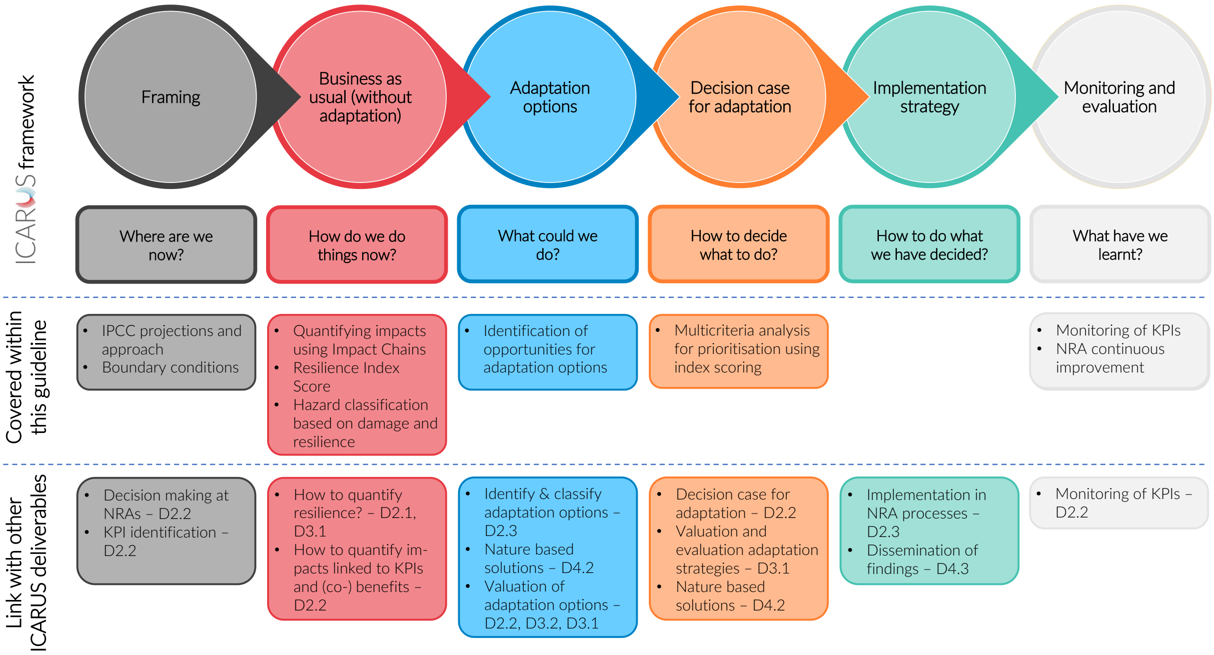
Sub objectives are:

- To consider the impact chains at NRAs and how this should be used and informed regarding risk and vulnerability assessment.
- To provide recommendations for approaches to build the impact-chain case.
- To rank the potential impacts of different CID on road assets according to NRA specifications in terms of asset and geography under different climate change scenarios.
- To provide a methodology to systemise CID priorisation from a resilience perspective.

1.3 Reading guide

In Section ¡Error! No se encuentra el origen de la referencia. the context within which this guideline s hould be used is described. This links to the general framework for risk and vulnerability assessment at NRAs. Section ¡Error! No se encuentra el origen de la referencia. describes the causal effect relationship to be understood, which is important to fully rank the potential impact of each CID. Section **¡Error! No se encuentra el origen de la referencia.** provides a description of ten impact-chain examples for roads. In Section 5 a new approach for CID classification is provided based on the expected impact on the resilience road. Finally, everything is being integrated in Section **¡Error! No se encuentra el origen de la referencia.**, as a integral methodology summary with practical recommendations.

This guideline should be read in conjunction with the other reports of the ICARUS project. An overview of these reports and how they relate to the underlying guideline is provided in the next point.



ICARUS framework	Framing	Business as usual (without adaptation)	Adaptation options	Decision case for adaptation	Implementation strategy	Monitoring and evaluation
	Where are we now?	How do we do things now?	What could we do?	How to decide what to do?	How to do what we have decided?	What have we learnt?
Covered within this guideline	• IPCC projections and approach • Boundary conditions	• Quantifying impacts using Impact Chains • Resilience Index Score • Hazard classification based on damage and resilience	• Identification of opportunities for adaptation options	• Multicriteria analysis for prioritisation using index scoring		• Monitoring of KPIs • NRA continuous improvement
Link with other ICARUS deliverables	• Decision making at NRAs – D2.2 • KPI identification – D2.2	• How to quantify resilience? – D2.1, D3.1 • How to quantify impacts linked to KPIs and (co-) benefits – D2.2	• Identify & classify adaptation options – D2.3 • Nature based solutions – D4.2 • Valuation of adaptation options – D2.2, D3.2, D3.1	• Decision case for adaptation – D2.2 • Valuation and evaluation adaptation strategies – D3.1 • Nature based solutions – D4.2	• Implementation in NRA processes – D2.3 • Dissemination of findings – D4.3	• Monitoring of KPIs – D2.2

Figure 1.1 Integration of deliverable in the entire framework and other deliverable interactions.

2 CAUSAL-EFFECT RELATIONSHIPS BETWEEN ASSETS AND CIDs

As presented in deliverable D1.1 (ICARUS, 2022a) the existing framework for risk management of roads (PIARC. 2016a, PIARC. 2016 b) can learn from the IPCC approach and some of the methodologies and tools that are being implemented by the climate change adaptation community.

In a first approach, as seen in D1.1, IPCC classifies Climate Impact Drivers (CIDs) in extreme and slow-onset processes and trends. It is important to keep in mind that extreme events can have stronger impact on the operation and exploitation of transport infrastructures than slow-onset processes and trends. For this reason, managing this type of events should be prioritized and, more specifically, those extreme events affecting road transport infrastructures in Europe.

In order to establish the causality-effect relationships between IDCs and assets, it is mandatory to clarify the following concepts:

- Target area and road strategy: target area is the zone containing an asset that will be affected by a hazard of a predefined severity. ICARUS considers three target areas according to the three levels: asset level, connection level and network level. Network levels comes to be defined by the road strategy. This approach is important because the improvement of the service provided by transport infrastructure and its resilience needs starting by clearly define the parts of the transport system to be considered. It is noted that the classification of items within a transport system is situation dependent, e.g., something that is in one category for one transport system may be in another category in another transport system. For example, if a bridge is controlled by the responsible organisation, it may be considered to belong to the infrastructure part of the transport system. However, if a bridge is not controlled by the responsible organisation, it may be considered to belong to the environment and, in that case, NRA would not be responsible for managing its potential hazards e.g., vegetation fires, fuelled by poor brush maintenance in forests and other green areas, may be a hazard for road surrounding while NRA are not responsible for its management.

- Direct damages: Damages affecting infrastructure asset condition after an extreme event. These damages trigger intervention actions by infrastructure manager to recover previous infrastructure asset condition. These interventions are the ones required to ensure that the infrastructure once again provides an adequate service. It is important to make the difference between maintenance associated with the costs of intervention if no event occurs (preventive maintenance) and the costs of interventions if an event occurs (corrective maintenance, response, repair). For example, intervention costs CEN-CENELEC, (2021) rise due to the placing of sandbags and the evacuation of people during the flood event, and then continue to increase due to the cleaning up immediately following the event and the reconstruction of damaged infrastructure until a maximum yearly expenditure is reached. This maximum yearly expenditure then continues until the infrastructure is almost restored and then tapers off as the last work is completed.

- Indirect damages: these are typically related to the cost of transportation experienced by users and shippers and loss due to traffic detour. Indirect damages are based on measures look at transportation’s contribution to the general economy and are expressed in measures such as economic output (e.g., gross state product), employment (e.g., jobs supported or created), and income. Various proxy measures are often used to gauge economic development impacts, including traffic at border crossings, manufacturers/ shippers/employers who have relocated for transportation purposes, volume of freight originating or terminating in region, number or percent of employers that cite difficulty in accessing the needed labour supply because of transportation, and measures of truck travel per unit of regional economic activity.

These concepts are applied in the definition of impact chains presented in the next chapter, which are based on four pillars: hazard, exposure, vulnerability, and impact. On the one hand, target area and road strategy should be clear when vulnerability and exposure is assessed. On the other hand, it is important to distinguish between direct and indirect damages for impact assessment.

3 IMPACT CHAINS FOR ROAD ASSETS

Impact chain is an analytical concept to better understand, systemise and prioritise the climate factors as well as environmental and socio-economic factors that drive climate related threats, vulnerabilities, and risks in a specific system. Impact chains serve as the backbone for an operational climate vulnerability assessment with indicators based on quantitative approaches (data, models) combined with expert assessments (Zebisch, 2021).

ICARUS proposes the use of impact chains as a methodology to understand how the various climate hazards can impact the roads including, also, the opportunity for adaptive responses (grey and green solutions). In this regard, its necessary to be aware that adaptive response to the impact chains may well have impacts of their own, for instance responses may drive up the carbon impact of the road. While this is not going to be recognised in the impact chains, ICARUS introduce this discussion in point 4 of this deliverable.

Finally, to validate the impact chain methodology 10 representative cases are presented.

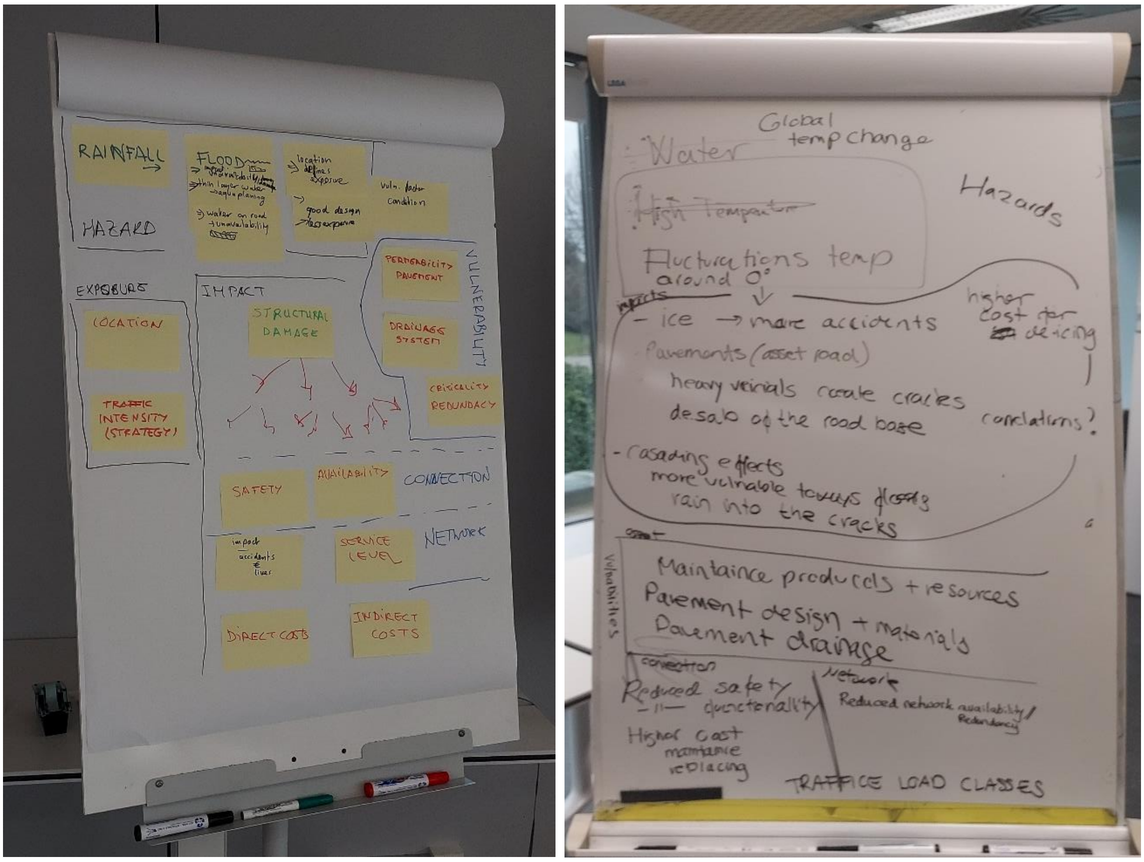


Figure 3.1 Impact chain examples based on participative development during Workshop in Bilbao 2022.

3.1 Impact chains conceptualisation

The relation of climate change impacts and the assets may adopt very different pathways. The most evident relation is direct and short-term. This is the case of extreme events highlighted in point 4.2.1.

On the other hand, accumulative impacts and with an indirect effect may create important impacts that are not always evident[1].

The concept of impact chain is defined as an analytical tool that helps to better understand, systemise, and prioritise the factors that drive vulnerability in the system under review (GIZ & EURAC, 2017). It is a representation of how potential climate change risks can affect a system via direct and indirect impacts, including cause-and-effect relationships.

The four pillars on which it is built are: hazard, exposure, vulnerability and impact and definitions can be found in the following points (Commission Notice, 2021).

3.1.1 Hazard

The potential occurrence of natural and human-induced event and 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 (Commission Notice, 2021).

Hazard is the starting point of the impact chain: the **first step**. Sometimes the hazard is caused by a combination of events on a smaller scale that need to be known to understand how the threat is triggered. The understanding of the confidence of occurrence gives the NRA the importance of each specific hazard in the future.

3.1.2 Exposure

The exposure concept refers to the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. In the road system environment, this exposure component refers to the presence of transport and assets like part of the road that could be subject to potential adverse impacts; it therefore depends on its location and not on the type of the transport asset (Commission Notice, 2021).

Exposure is the **second step** to consider for the impact chain development because it will help in the definition of the area to be prioritized according to different aspects as explained before.

In particular, the location of an area for assessment will play a large part in determining the climatic variables that should be considered as risks for a target area. That is why this is the second step to bear in mind for the impact chain development. Consequently, road authorities must consider their geographical location at both the global and local scale and identify associated climatic variables in line with this.

Geographical factors to consider when identifying future climate change risk types include but are not limited according to PIARC (PIARC, 2015):

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[1] As an example, in some countries the reduction of precipitations may lower the ground water level, and that may affect the stability of structures as bridges that are built on wooden poles, especially on clay soil.

- The presence of water bodies: For instance, coastal areas are more likely to consider sea-level rise than inland areas.

- Altitude: Areas at higher altitudes may be more concerned with extreme weather events such as high wind speeds and increased precipitation levels associated with an increased frequency and magnitude of storms associated with climate change.

- Land-use: Areas which are heavily urbanised may be focused on damage to highway drainage systems and road and pavement fabrics whereas more rural areas may be concerned with access and over-reliance on road structures because of a lack of redundancy.

- Topography: Topography is likely to be a major consideration for national road authorities especially regarding excess surface water runoff associated with flood events exacerbated by climate change.

- Soil and geology: This will be a consideration for authorities who have previously experienced landslides and will be a factor in flood risk.

- Accessibility: Some geographical locations may have poor access and/or transportation links that may be further affected and limited by climatic variables such as extreme weather events including flooding.

3.1.3 Vulnerability

Propensity or predisposition of the exposed to be adversely affected by the hazard and encompasses the combination of sensitivity and adaptive capacity. It depends on the hazard, as well as on the intrinsic factors of the infrastructure itself (design and current state of the asset), varying its ability to withstand the impacts derived from climate change (Commission Notice, 2021).

Vulnerability is the **third step** to analyse in the impact chain after hazard and exposure assessment. Once potential hazards are identified and the presence of natural and human systems, services etc. is confirmed it is time to specify the level of intrinsicity/extrinsicity to be analysed: asset/component/subcomponent and asset/connection/network.

3.1.4 Impact

Impact means the consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. That is why impact is the **fourth step** to be considered.

Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social, and cultural assets, services (including ecosystem services), and infrastructure[2]. The impacts will refer to the intrinsic vulnerability at different levels (network, connection, and asset-component/subcomponent).

Impacts may be referred to as consequences or outcomes and can be adverse or beneficial (Commission Notice, 2021).

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[2] Service Level States (SLS) and Ultimate Level States (ULS) can be useful for the assessment of the different impacts as seen in point 4.2.1 and NRA can take use of it acceptance and agreement from the design to the operation and maintenance phase of the infrastructure life cycle.

It is likely that a road authority will have a reasonable idea of the climate change effects and impacts their assessment will consider because of direct knowledge about historic events, present conditions, and future projected trends. An indicative list of potential impacts is provided below. The potential impacts are split into five broad effect categories PIARC. (2015):

- Impacts associated with changing temperatures and lack of precipitation (drought).
- Impacts associated with prolonged and/or heavy precipitation and storms.
- Impacts associated with sea level rise and heightened storm surge.
- Impacts associated with changes to snowfall, permafrost, and ice coverage; and,
- Impacts associated with other climatic effects.

Whilst the impacts of climate change and extreme weather may predominantly be negative in nature, there are also a range of opportunities and benefits, which should also be considered in any assessment or strategy. These can include at Operation and Maintenance phases:

- Operation:
    - Increase in mean temperature would lead to less salt needing to be spread on the network during winter months.
    - Changes in weather conditions that reduce the incidence and/or severity of incidents would place less demands on traffic management, including the traffic officer service.
    - For short distance journeys, warmer summers could attract some road users away from private cars. This has potential benefits of reducing the levels of localised congestion and air pollution.
- Maintenance:
    - A reduction in the frequency of freeze-thaw events would benefit the integrity of the pavement surface. We can expect less degradation with a reduction in surface cracking/potholes.
    - Customer satisfaction: reduction in summer rainfall could create safer, more reliable driving conditions. On the other hand, for example in the Netherlands, more extreme rainfall events are expected which causes problems like congestion and loss of safety.
    - A reduction in the number of fog days during the winter months is likely to have a beneficial effect. This is also a consequence of better air quality.
    - Impact in reducing the number of serious incidents.
    - A reduction in the number of icy days during the winter months is likely to have a beneficial impact in reducing the number of serious incidents and less frost damage.

- Fewer days with salt on the road would mean less corroded vehicles and highways assets.

- A longer growing season would mean that the soft estate (verges) could look greener for longer, enhancing the aesthetic of the network. The other side to this, it requires more maintenance of the vegetation.

- Secondary benefits include potential health gains of a shift from private motorised transport to walking, cycling and rapid transit/public transport.

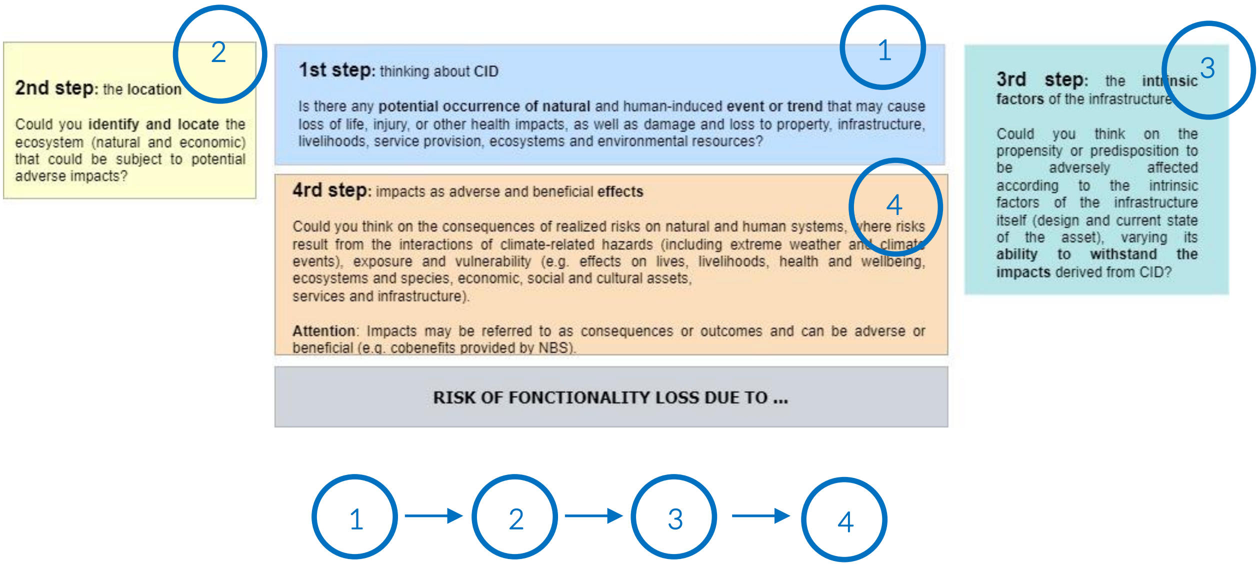
3.1.5 ICARUS Impact chain Flowchart

Graph below shows the structure followed to define ICARUS impact chains, where hazard, exposure, vulnerability, and impact are represented as explained in previous sub-chapters.

The methodology consists of answering the questions posed in each of the steps (from 1 to 4) in a structured way.

It is a flexible methodology and, as will be seen in the examples given in the next section, it should be adapted to the needs of each NRA.

Although in ICARUS only the conceptual part is developed, the impact chains are the basis for the development of more sophisticated quantitative studies (e.g. Bayesian networks).



2nd step: the location

Could you **identify** and **locate** the ecosystem (natural and economic) that could be subject to potential adverse impacts?

1st step: thinking about CID

Is there any **potential occurrence of natural** and human-induced **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?

3rd step: the **intrinsic factors** of the infrastructure

Could you think on the propensity or predisposition to be adversely affected according to the intrinsic factors of the infrastructure itself (design and current state of the asset), varying its **ability to withstand the impacts** derived from CID?

4rd step: impacts as adverse and beneficial **effects**

Could you think on the consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure and vulnerability (e.g. effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services and infrastructure).

Attention: Impacts may be referred to as consequences or outcomes and can be adverse or beneficial (e.g. cobenefits provided by NBS).

RISK OF FONCTIONALITY LOSS DUE TO ...

Figure 3.2 Impact chain graph for hazards and transport infrastructures

3.2 Making the impact chain examples

This chapter builds upon the previous chapters and describes how NRAs can make the impact chains. Ten approaches are included as examples, to inspire NRA in the process.

3.2.1 Hazard selection for impact chain validation

As explained in D1.1 Concise baseline report on determining impacts and risk due to climate change, hazard identification is one of the most important steps in climate risk assessment, as not all CIDs will affect all countries and regions in the same way.

In that deliverable 23 climate-related hazard indices not only applicable for adaptation planning at the European and national level, but also relevant to road sector, are described. These indices are available in the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S) and are also available through the European Environment Agency's interactive climate hazards report (EEA, 2021).

The framework in which these indexes are presented adopts the six main categories (IPCC, 2021a) entitled Climatic Impact-Drivers (CID) ("Heat and cold", "Wet and dry", "Wind", "Snow and ice", "Oceanic" and others) and links to the already existing classification in the Implementing regulation 2020/1208 (European Commission, 2020), which splits climate related hazards into:

- Extreme events (acute) are extreme deviations that vary from minutes to seasons and can be described by their duration, magnitude, and frequency as they have a start and an end. Extreme events are typically those, which occur suddenly, sometimes with limited warning, typically over a period of hours, days or weeks. These events include heavy and/or prolonged precipitation events leading to surface water flooding, storm surges and landslides, heat waves, single very hot or cold days, and prolonged periods of drought.
- Slow-onset processes or trends (chronic) are long-lasting monotonic changes and can be described by their change rate. Gradual changes related to climatic variables are those experienced over a period of time such as months, years, decades and/or centuries. Such impacts include sea-level rise, changing seasonal precipitation levels, and gradual climatic warming.

Some CID such as Exteme heat/Heat Wave (acute) can be considered of paneuropean interest in favour of mean air temperature (chronic) according to NRA understanding.

The table below presents the CID and indices applicable to road and transport system for both types of climate related hazards.

Table 3.1 CID for impact chain validation based on IPCC 2021,a.

	Climatic Impact-Driver (CID)					
	Heat and cold	Wet and dry	Wind	Snow and Ice	Coastal and oceanic	Others: radiation & subsidence
Extreme events	Extreme heat/Heat wave	River flood	Severe wind speed[3]	Heavy snowfall and ice storm	Coastal flood	
	Cold spell	Heavy precipitation and pluvial flood	Tropical cyclone	Hail	Coastal erosion	

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[3] For example in thunder storms combined with extreme precipitation.

	Frost	**Landslide**	Sand and dust storm	Snow avalanche		
		Hydrological **drought**				
		Fire weather				
Slow-onset processes and trends	Mean air temperature	Mean precipitation[4]	Mean[5] wind speed	Decreasing glaciers, ice sheet, permafrost, **Freeze-thaw cycle changes**	Sea level rise	Radiation at surface
					Ocean and lake acidity	Subsidence

For impact chain validation ICARUS dedicates special attention to the remarked CID according to the following criteria selection:

- Becoming more common/severe in the future
- Of interest for many countries/NRA in Europe (from south to north)
- Costly already in the present climate
- Both extreme events and more gradual/slow-onset (or annual) “events”
- Being a good model in development for impact chains for hazards not included.
- Opportunity for NbS and co-benefits.

It is well-known for Infrastructure managers that intense or prolonged **heat-wave** or **cold spell** events cause accelerated deterioration on asset such as road pavements.

Regarding **pluvial flooding** ICARUS considers that it may result from not just heavy precipitation, but also prolonged rainfall or higher rainfall intensity too. Although these kind of rainfall could cause flooding there is also important to consider the specificities of **river flooding**.

No doubt, that **landslides** will have significant impacts, but also impact chains should recognise that there are causal chains that need to be recognised prior to a landslide taking place, for instance rainfall, causing groundwater flooding[6] and surface flooding, causing slope instability and landslide.

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[4] For example, leading to rising groundwater levels may impact electrical systems and Steel bridges. On the other hand, longer and more periods of drought may lead to more soil subsidence.

[5] Note in Holland wind speeds are not expected to change

[6] Groundwater flooding is the emergence of groundwater at the ground surface. It happens in response to a combination of already high groundwater levels (usually during mid or late winter) and intense or unusually lengthy storm events. Groundwater flooding often lasts much longer than flooding caused by a river overflowing its banks. It may last many months and can cause significant social and economic disruption to the affected areas.

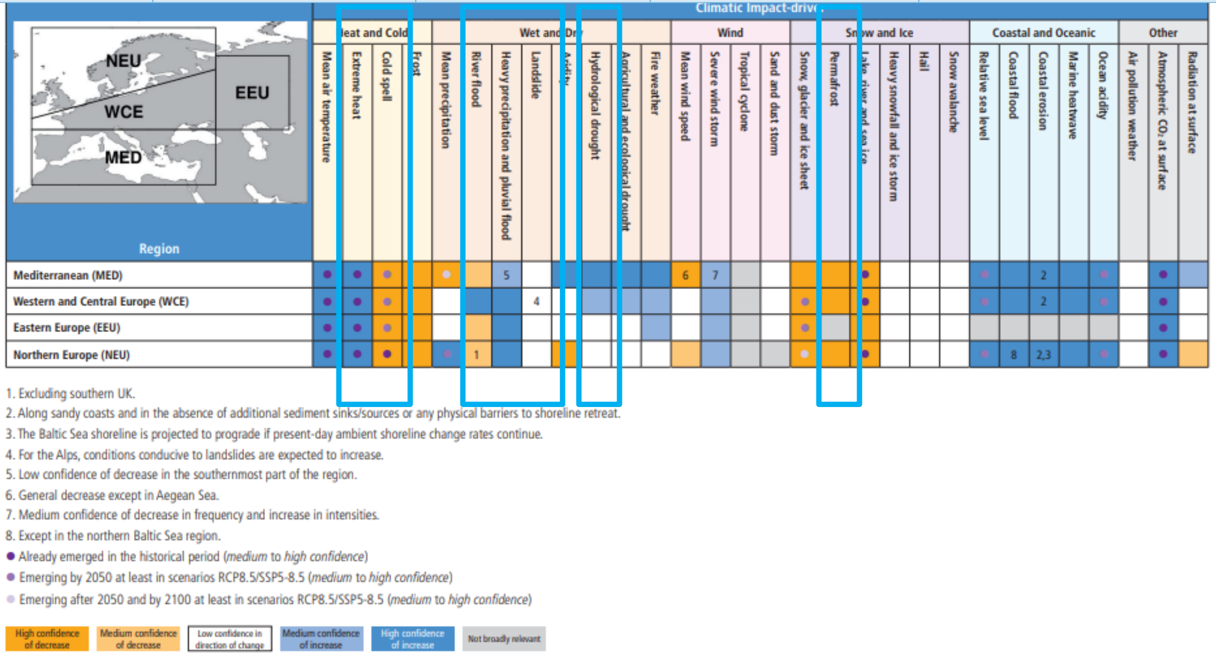
An other extreme event selected is **drought**. It may occur due to a number of reasons, such as extended lack of rainfall and / or prolonged high temperatures. Impacts may be felt for example on the verges alongside the road, on the surface of the road (e.g. build up of polluting residues) etc.

As slow-onset process and trend **freeze-thaw cycle change** has been selected for particular impact chain analysis. This is rather than decreasing glaciers, icesheet and permafrost as freeze thaw cycles impact a wider geography. However, this should include not just the impact on hard pavements but also the impact of ground frosts on gravel roads, which is a particular problem in the spring and autumn e.g. in Scandinavia.

There should also be recognition that some climate impact drivers interact, for example, extreme heat and drought could, together, amplify fire risk on road verges, freeze thaw may induce landslides etc. or subsidence related to drought and freeze-thaw cycles.

Based on IPCC reports, seven CID were found more relevant for road sector in Europe and were prioritized for ICARUS impact chains definition. The matrix below summarizes projected changes for each one.

	Heatwave	Cold spell	Drought	River flood	Pluvial flood	Landslide	Freeze-thaw cycle changes
Asset/ Location/ Emerging/ Confidence	**Bridge**/MED-WCE-EEU-NEU/High confidence to increase/Already merged in the historical period (also pavement)	**Road**/MED-WCE-EEU-NEU/High confidence to decrease/Emerging by 2050 for MED-WCE-EEU & Already merged in the historical period for NEU	**Bridge**/MED-WCE/ MED-High confidence to increase &WCE-Medium confidence to increase (roadbed impacts and fires)	**Road**/ MED-WCE-EEU-NEU/Medium confidence to decrease for MED-EEU-NEU (excluding UK &WCE high confidence to increase	**Road**/ MED-WCE-EEU-NEU/High confidence of increase for WCE-EEU-NEU&Medium confidence of increase for MED (low confidence of decrease in the southernmost part of the region)	**Road**/WCE/ For the Alps conditions conducive for landslides are expected to increase	**Road**/MED-WCE-NEU/High confidence of decrease



1. Excluding southern UK.
2. Along sandy coasts and in the absence of additional sediment sinks/sources or any physical barriers to shoreline retreat.
3. The Baltic Sea shoreline is projected to prograde if present-day ambient shoreline change rates continue.
4. For the Alps, conditions conducive to landslides are expected to increase.
5. Low confidence of decrease in the southernmost part of the region.
6. General decrease except in Aegean Sea.
7. Medium confidence of decrease in frequency and increase in intensities.
8. Except in the northern Baltic Sea region.

- ● Already emerged in the historical period (*medium to high confidence*)
- ● Emerging by 2050 at least in scenarios RCP8.5/SSP5-8.5 (*medium to high confidence*)
- ● Emerging after 2050 and by 2100 at least in scenarios RCP8.5/SSP5-8.5 (*medium to high confidence*)

High confidence of decrease | Medium confidence of decrease | Low confidence in direction of change | Medium confidence of increase | High confidence of increase | Not broadly relevant

Figure 3.3 Summary of confidence in direction of projected change in climatic impact-drivers in Europe (IPCC, 2021)

3.2.2 Asset selection for impact chain validation

The impact chains developed by ICARUS consider different increasing levels of complexity and aggregate impact starting from the highway asset-level impact. The definition of the asset, the component and the sub-component are crucial for the more complex analysis at connexion and network level.

As explained in deliverable D1.1 Concise baseline report on determining impacts and risk due to climate change, considering CoDEC[7]'s classification of road entities, highway asset types can be categorized as the table below.

Table 3.2. Asset types according to CoDEC's classification of road entities. Selected assets and components for impact chain examples in bold letters.

Entity Class (CODEC)	Asset (ICARUS)	Component
Road Entities	**Road Section**	Kerb and traffic separation
		Lanes
		Pavement Layer
		Pavements
		Road studs
		Soft shoulders
		Traffic signage and marking
Structures	**Bridge**	**Substructure**
		Bridge deck system
		Mechanical connections
		Pylon
		Reinforcement and Pre-stressing
		Maintenance Access
		Retaining wall systems
		Drainage and wastewater collection
	Tunnel	Tunnel
		Supporting structures
		Reinforcement and Pre-stressing
		Electromechanical

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[7] **CoDEC** is a project funded by the CEDR (Conference of European Directors of Roads) Transnational Research Programme Call 2018 aiming to understand, in a very practical way, the key means for successful implementation of Building Information Modelling (BIM) principles within the European highways industry, with regards to freeing and enriching data flow to and from Asset Management Systems (AMS).

		Fire-fighting system
	Earthworks Embankments Cuttings Reinforced earth retaining wall	Earthworks Embankments Cuttings Reinforced earth retaining wall
	Culverts	Pipe culvert, pipe arch culvert, box culvert, arch culvert, bridge culvert
Electrical power and lighting functions	Roadway lighting systems	Streetlights Column Lantern housing Lamp Interface cabinet Drainage Pipe Open drain Manhole Catch pits Outfalls
Drainage and wastewater collection	Drainage and wastewater collection	Drainage Pipe Open drain Manhole Catch pits Outfalls
NBSs- Green infrastructure	SuDS	

All assets may be subject to different risks across their lifecycle, and the response to risk may also need to address different life cycle stages and it is clear the main asset when managing road transport infrastructure is the **road entity**, itself.

Tunnels and **bridges** can be considered as subterrain road entities and aerial road entities and nodes at the same time because of their criticality at network level. Lighting and drainage (longitudinal or/ and transversal) system could be considered as equipment of the road.

For ICARUS, bridges are structures that, by their nature, can show higher exposure levels to extreme weather events (these events will appear most frequently with climate change), but this exposure is, however, inevitable and inherent in the definition of the function of the structure. Nevertheless, it is possible to reduce exposure level by working on others factors which lead, for example, to location of the bridge in a place that is less exposed to natural events (possible landslides or flooding), or providing, for example, **auxiliary structures** that can protect the main structure; the purpose of which is to be sacrificed in the case the event happens (such **adaptation measures** should be carefully considered, because structures that provide an immediate protection from an event may generate a mechanism that increases future risk. This can happen, for example, with dike systems, where flood exposure is reduced by offering immediate protection, but where settlement patterns are encouraged that may increase risk in the long term) PIARC. (2016b).

The rehabilitation of bridge structures so that they may resist extreme climatic events usually has important economic implications and at the same time leads to a significant impact on society due to the fact that a climate disaster may lead to the interruption of the infrastructure system. In case of a non-destructive event and analysing only the changes related to a high probability value, for maintenance operations, several factors that influence both the security and the type of the operations should be taken into consideration. For example, the rising temperatures could produce a reduction of the service life of the asphalt, structural joints and sealants, impose stresses in steel bridges, etc. All these factors show that we will have to follow a new maintenance scheduling, in terms of type and frequency of actions. Similarly, working on structures exposed to considerable rainfall, flooding and possible landslides, will lead to an increase of the safety provisions needed, and which will have to be defined for each maintenance phase PIARC (2016b).

That is why ICARUS will validate impact chains from point 4.2.4 to 4.2.13 for these two kinds of assets: **road** and **bridge**.

3.2.3 Bridge and heatwave impact chain

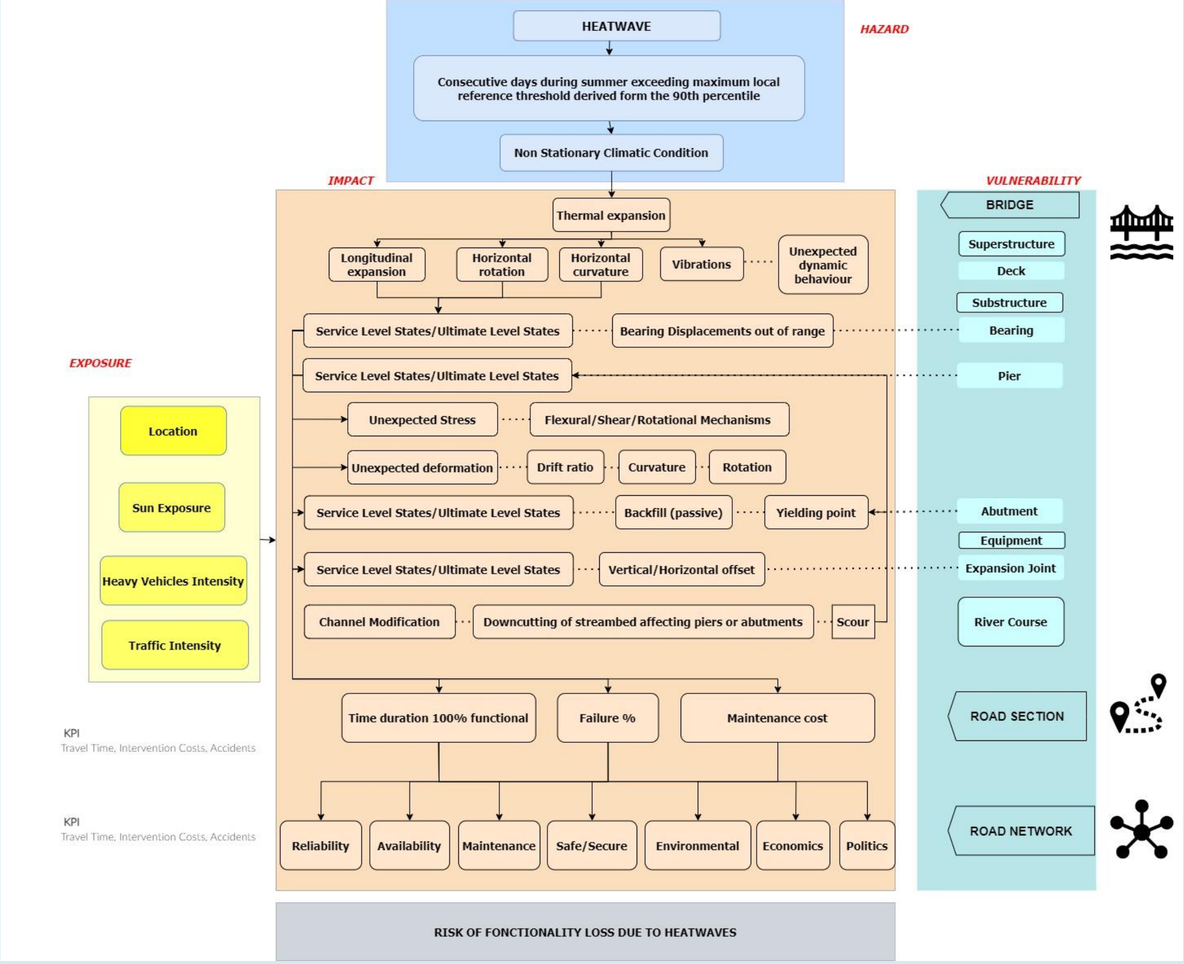
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of HEATWAVE as a CID to be considered and with the HEATWAVE concept review to find agreement among all stakeholders. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In case of a BRIDGE, sun exposure can be an important condition to be considered. Step 3: VULNERABILITY. Definition of asset/component/sub-component (e.g., bridge/superstructure/bearing) and asset/connection/network (e.g., bridge/section/network). Internal conditions and characteristics. This step defines the level of detail of the impact to be analysed in Step 4. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. NBS opportunities can be detected at this level.

Figure 3.4 Impact chain for bridge and heatwave.

3.2.4 Bridge and hydrological drought impact chain

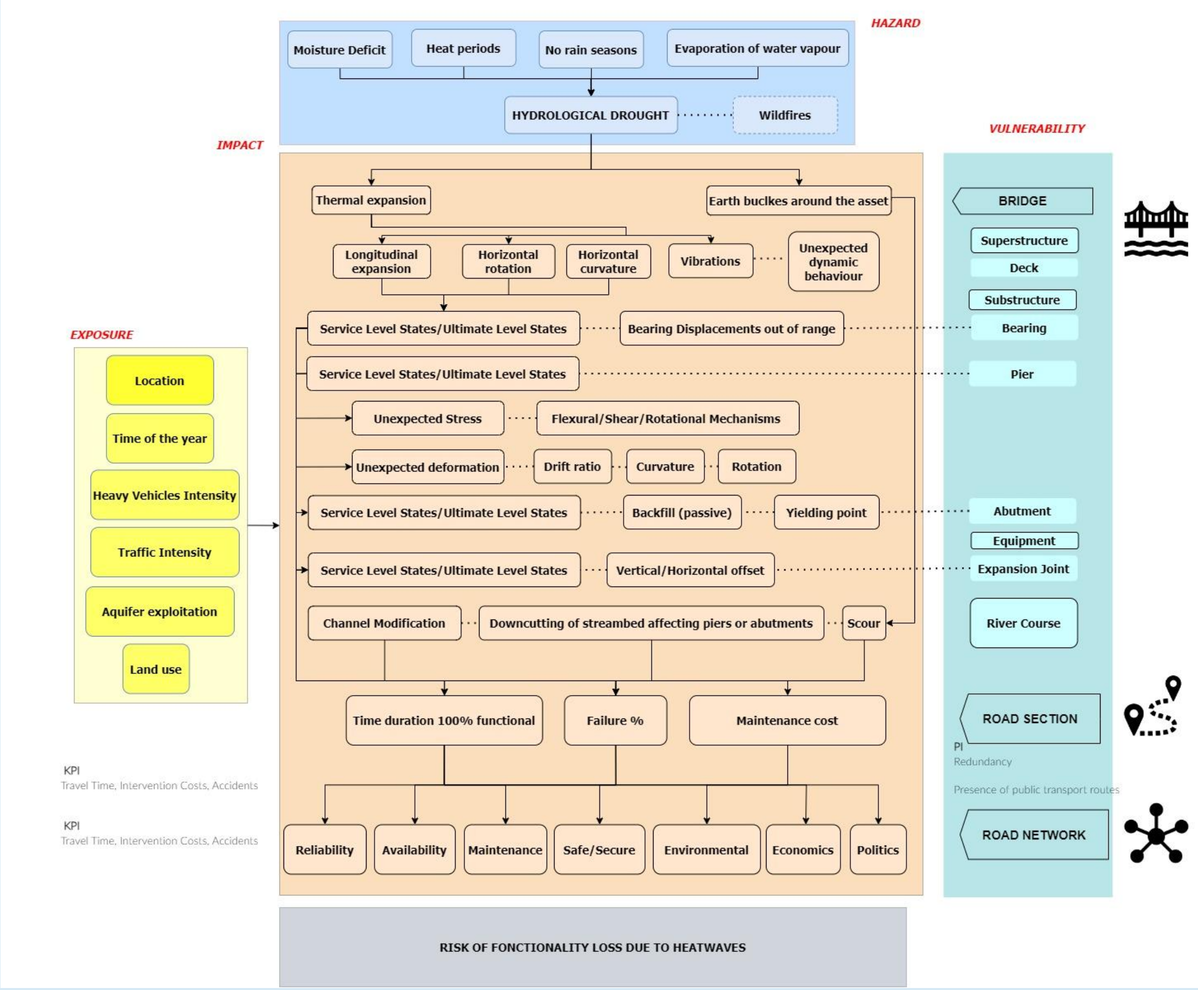
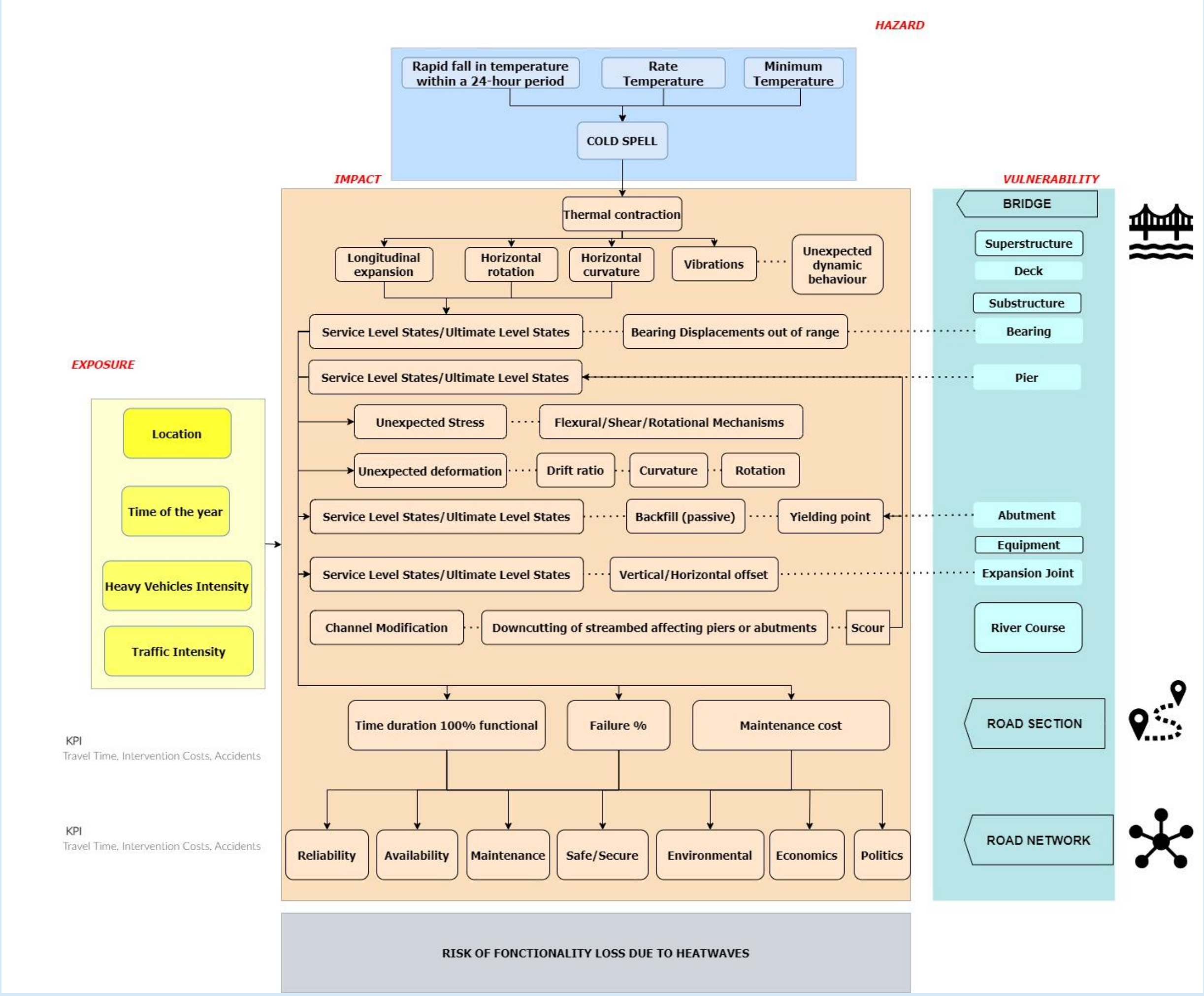
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of the HYDROLOGICAL DROUGHT as a CID to be considered and with some subsequent hazards for different stakeholders (e.g., wildfires). Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In this case, the aquifer exploitation and the land use can be an important condition to be considered. Step 3: VULNERABILITY. Definition of asset/component/sub-component (e.g., bridge/superstructure/bearing) and asset/connection/network (e.g., bridge/section/network). Internal conditions and characteristics. This step defines the level of detail of the impact to be analysed in Step 4. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. NBS opportunities can be detected at this level.

Figure 3.5 Impact chain for bridge and hydrological drought.

3.2.5 Bridge and cold spell Impact chain

Impact chain



Explanation

Step 1: HAZARD. This impact chain starts with the identification of COLD SPELL as a CID to be considered and with the COLD SPELL concept review to find agreement among all stakeholders.

Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In case of a bridge, sun exposure can be an important condition to be considered.

Step 3: VULNERABILITY. Definition of asset/component/sub-component (e.g., bridge/superstructure/bearing) and asset/connection/network (e.g., bridge/section/network). Internal conditions and characteristics. This step defines the level of detail of the impact to be analysed in Step 4.

Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. NBS opportunities can be detected at this level.

Figure 3.6 Impact chain for bridge and cold spell.

3.2.6 Bridge and pluvial flood

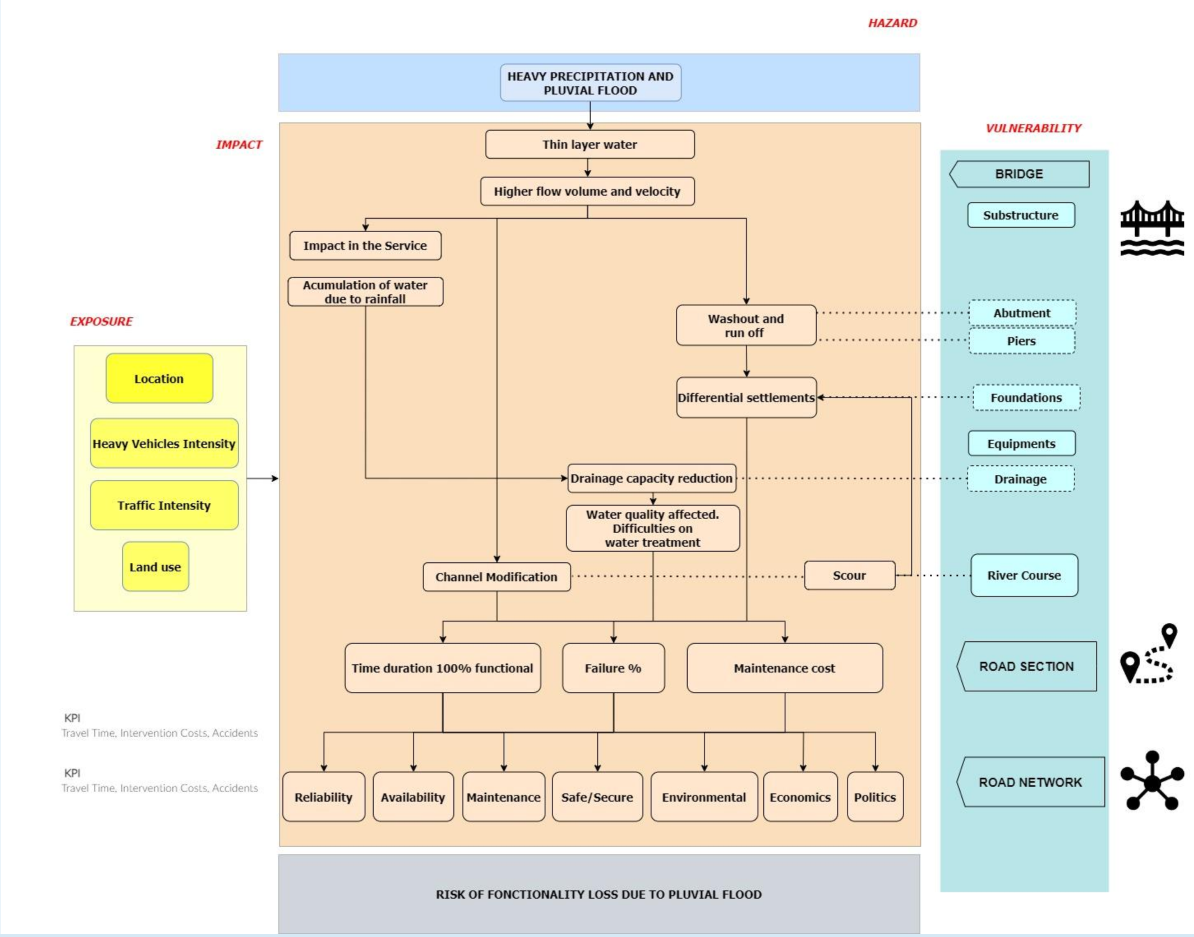
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of the PLUVIAL FLOOD as a CID to be considered. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In this case, the aquifer exploitation and the land use can be an important condition to be considered. Step 3: VULNERABILITY. Definition of asset/component/sub-component (e.g., bridge/superstructure/bearing) and asset/connection/network (e.g., bridge/section/network). Internal conditions and characteristics. This step defines the level of detail of the impact to be analysed in Step 4. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. NBS opportunities can be detected at this level (e.g., rainwater harvesting). In this impact chain the river course has been included as another element of the bridge because some NRA considered river course as a point to be considered in bridge inspection.

Figure 3.7 Impact chain for bridge and pluvial flood.

3.2.7 Bridge and River flood

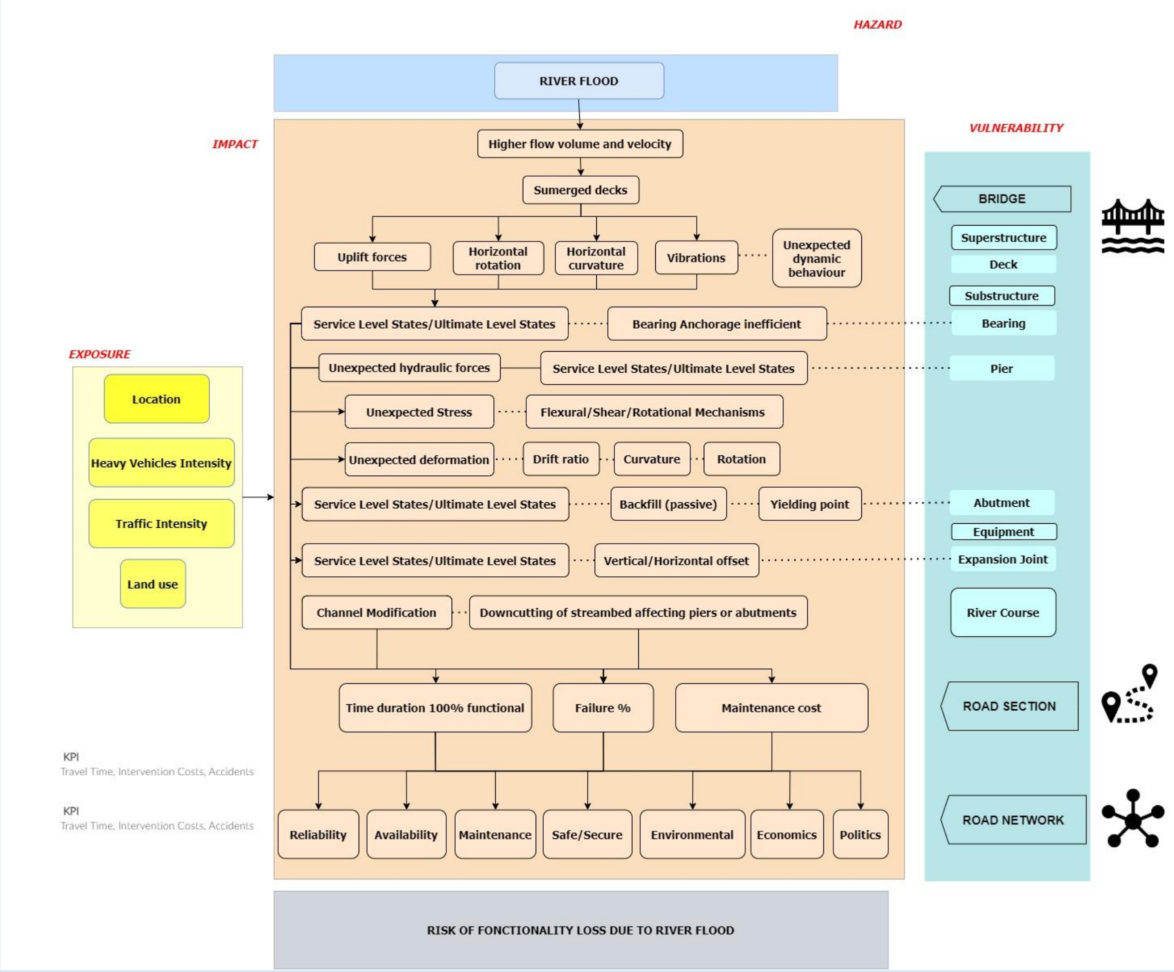
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of the RIVER FLOOD as a CID to be considered. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In this case, the land use can be an important condition to be considered. Step 3: VULNERABILITY. Definition of asset/component/sub-component (e.g., bridge/superstructure/bearing) and asset/connection/network (e.g., bridge/section/network). Internal conditions and characteristics. This step defines the level of detail of the impact to be analysed in Step 4. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. NBS opportunities can be detected at this level (e.g., floodable areas for temporary storage of storm water during extreme events). In this impact chain the river course has been included as another element of the bridge because some NRA considered river course as a point to be considered in bridge inspection.

Figure 3.8 Impact chain for bridge and river flood.

3.2.8 Road and cold spell impact chain

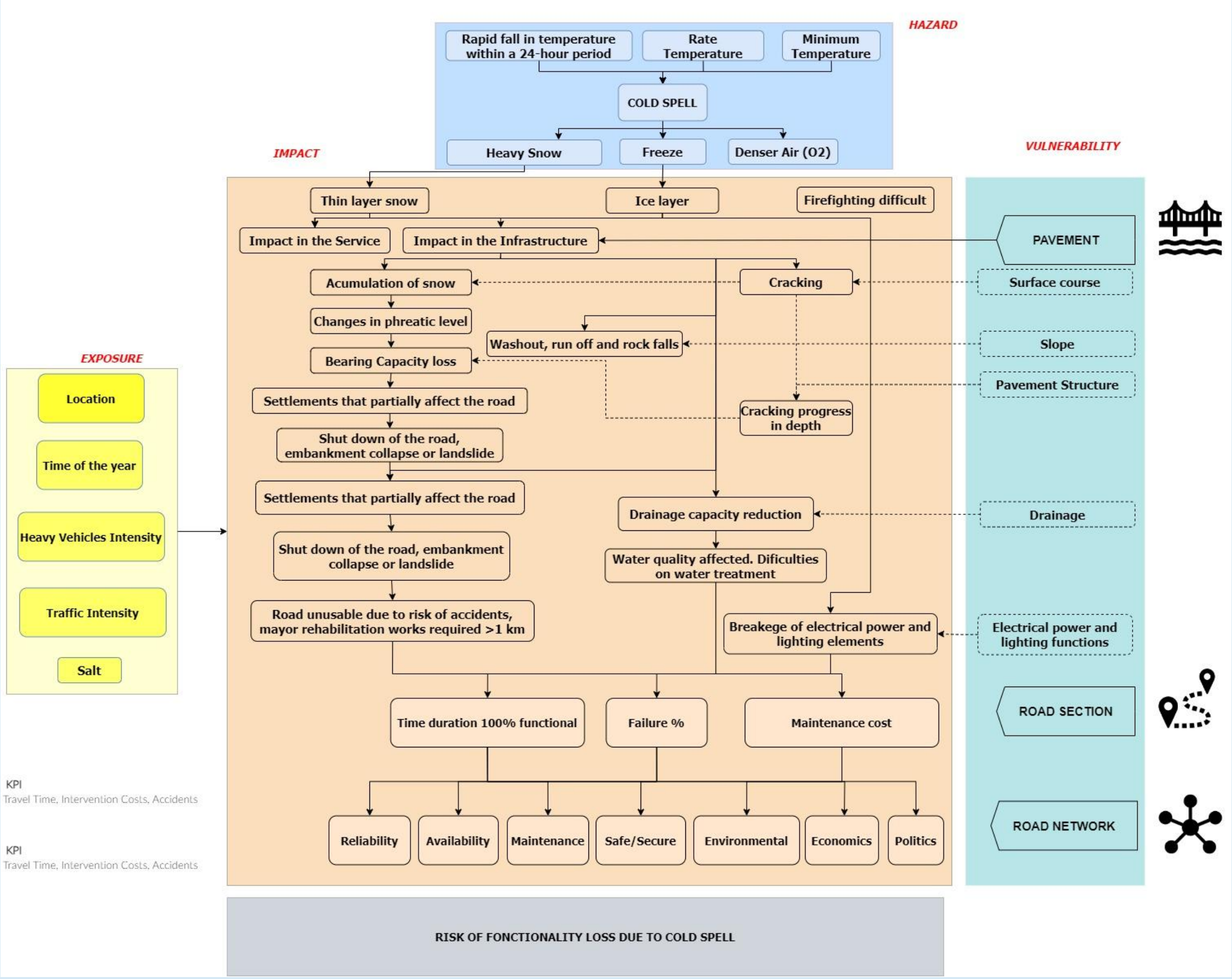
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of COLD SPELL as a CID to be considered and with some subsequent hazards for different stakeholders (e.g., dense air is relevant for firefighting in a tunnel). Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. In this case the use of salt is considered as an external action to be considered. Step 3: VULNERABILITY. Definition of asset/component/sub-component and asset/connection/network. Internal conditions and characteristics. In this impact chain drainage and electrical power and lighting have been included as equipment of the road Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. Drainage and electrical power and lighting impacts are also associated to dotted lines. In this example NBS opportunities can be detected at this level.

Figure 3.9 Impact chain for road and cold spell.

3.2.9 Road and river flood impact chain

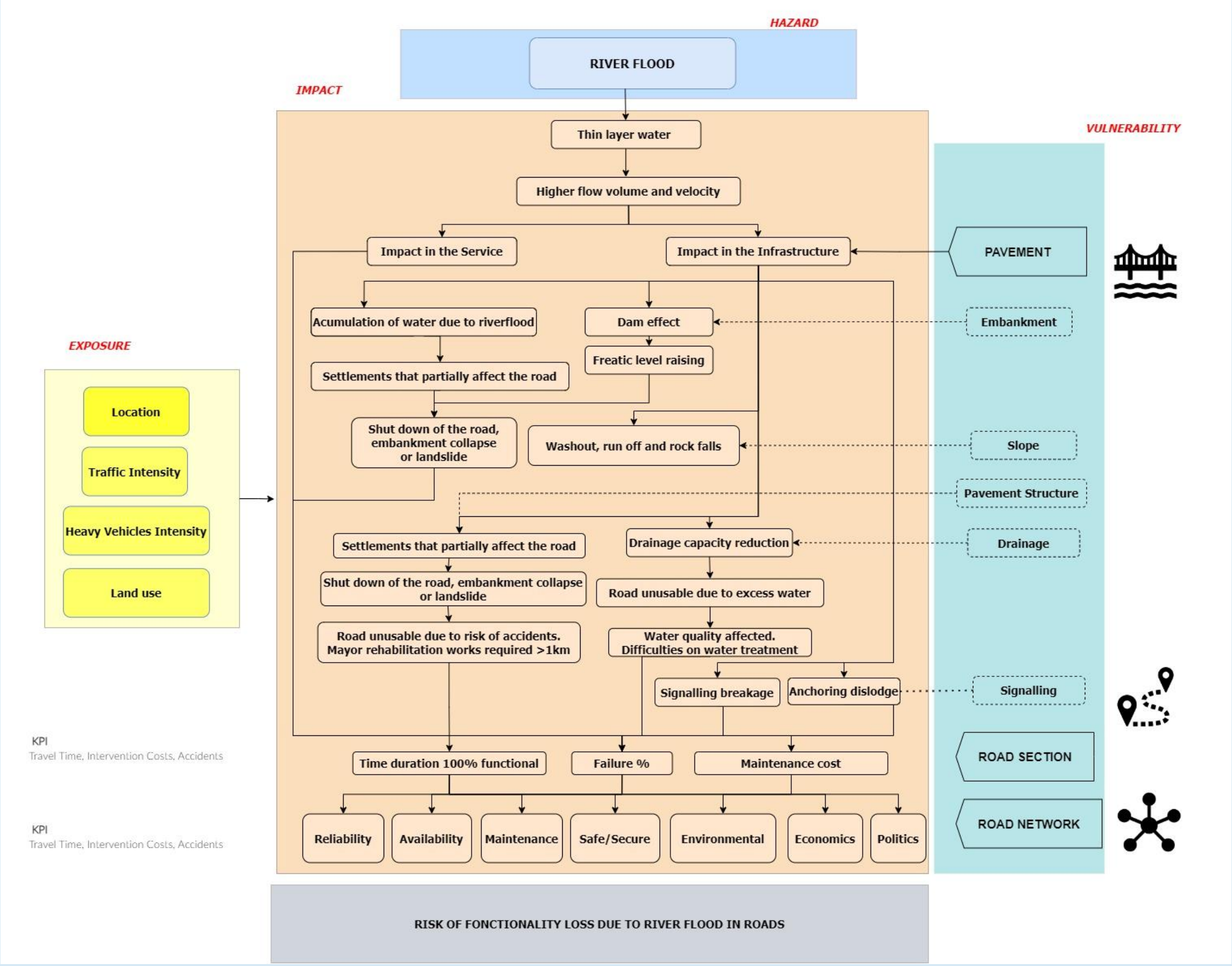
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of RIVER FLOOD as a CID to be considered. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. Step 3: VULNERABILITY. Definition of asset/component/sub-component and asset/connection/network. Internal conditions and characteristics. In this example NBS opportunities can be detected at this level. In this impact chain drainage and signalling have been included as equipment of the road. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. Drainage and signalling impacts are associated to dotted lines.

Figure 3.10 Impact chain for road and river flood.

3.2.10 Road and pluvial flood impact chain

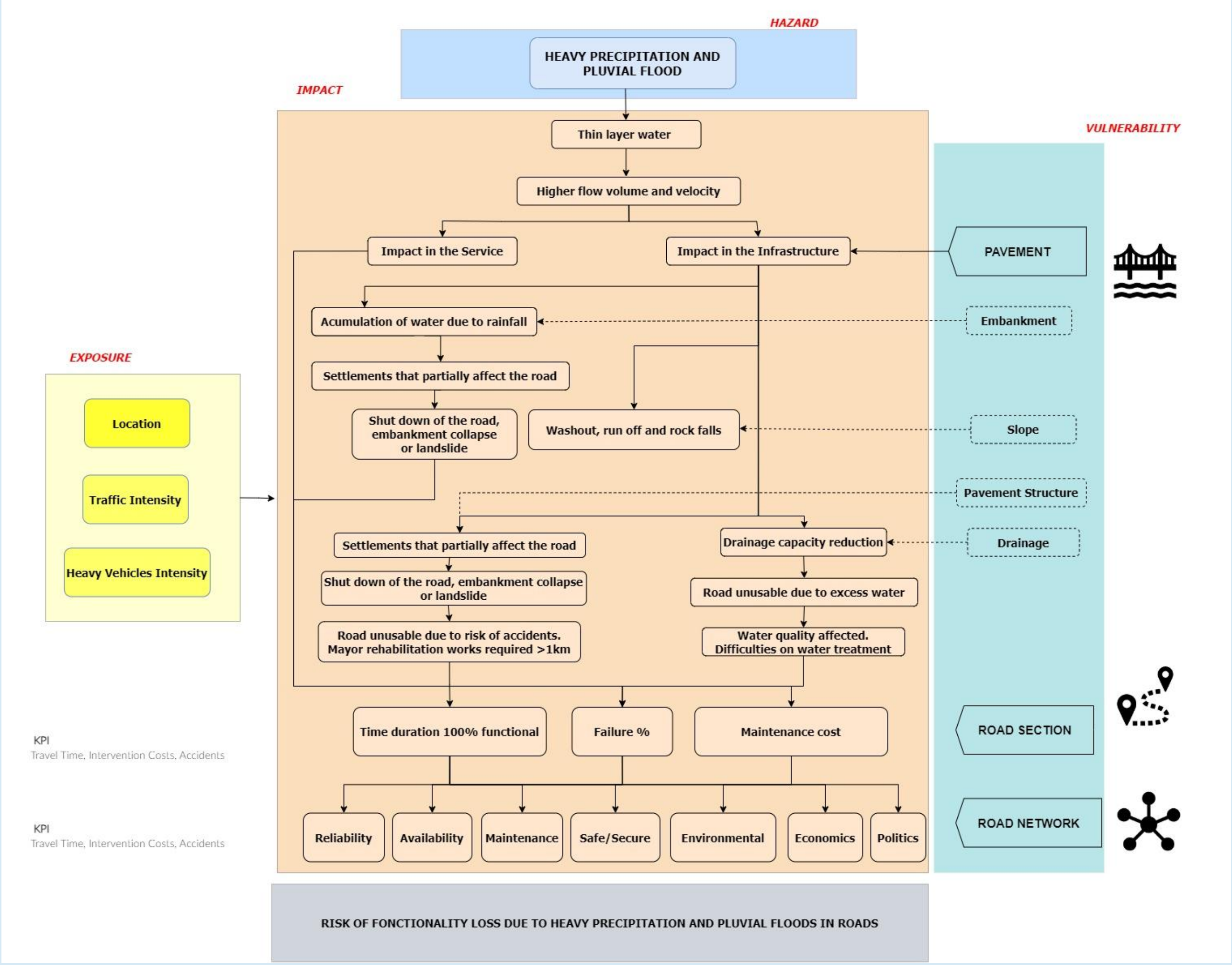
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of HEAVY PRECIPITATION AND PLUVIAL FLOOD as a CID to be considered. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. Step 3: VULNERABILITY. Definition of asset/component/sub-component and asset/connection/network. Internal conditions and characteristics. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. Drainage impacts are associated to dotted lines. In this example NBS opportunities can be detected at this level. In this impact chain drainage has been included as equipment of the road.

Figure 3.11 Impact chain for road and pluvial flood.

3.2.11 Road and landslide impact chain

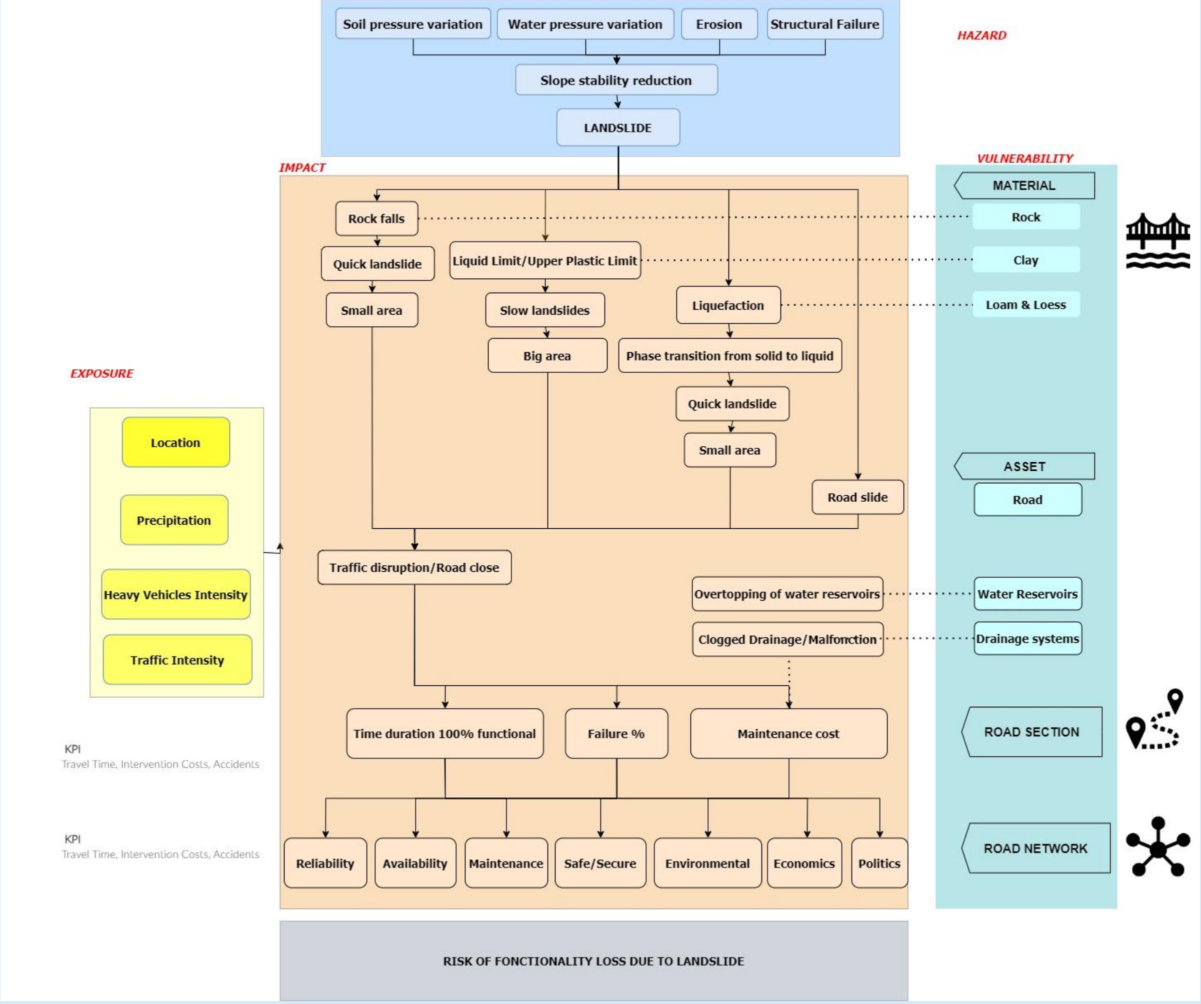
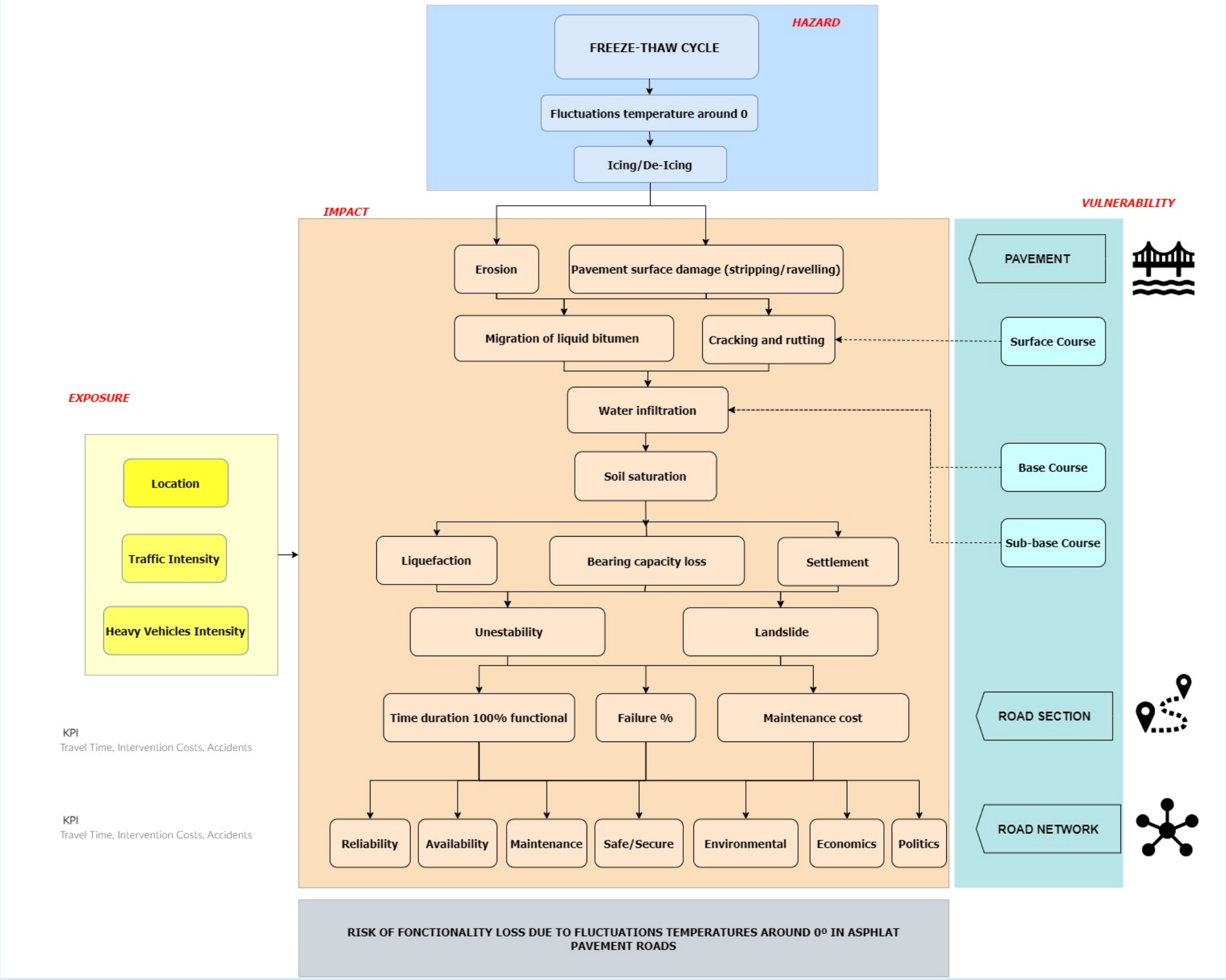
Impact chain	Explanation
	Step 1: HAZARD. This impact chain starts with the identification of LANSLIDE as a CID to be considered and the different conditions that can trigger the process. Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways. Step 3: VULNERABILITY. This is a particular case where the composition and materials will activate different mechanisms and different landslides. There is an equivalence in this case between component and material. Internal conditions and characteristics. In this example NBS opportunities can be detected at this level (e.g. planted embankment mat, mangrove restoration, living fascine, etc.). In this impact chain water reservoirs and drainage systems have been included. Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts for each material are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation. Water reservoirs and drainage impacts are associated to dotted lines.

Figure 3.12 Impact chain for road and landslide flood.

3.2.12 Road and freeze-thaw cycle changes impact chain

<table>
<tr><th>Impact chain</th><th>Explanation</th></tr>
<tr><td>



</td><td>

Step 1: HAZARD. This impact chain starts with the identification of FREEZE-THAW CYCLE as a CID to be considered. This CID refers to a temperature pattern of reaching above freezing, dipping below freezing, then returning to above freezing.

Step 2: EXPOSURE. Characterisation of transport area to be prioritised according to external conditions. The prioritisation can be done in different ways.

Step 3: VULNERABILITY. Definition of surface/base and sub-base of the road, and asset/connection/network. Internal conditions and characteristics.

Step 4: IMPACT. Direct and Indirect damages at different levels. The impacts at component and subcomponent level are associated with dotted lines to mark the difference with the impacts at the higher level: section and network. Although a cluster of KPI are proposed in this example D2.2 of ICARUS is available for consultation.

</td></tr>
</table>

Figure 3.13 Impact chain for road and freeze-thaw cycle changes.

4 NEW APPROACH TO CLASSIFY THE EFFECT OF HAZARDS/IMPACTS ON THE RESILIENCE OF ROADS

The concept of impact chains has been used to better understand and systemise the climate factors as well as environmental and socio-economic factors that drive climate related threats, vulnerabilities, and risks at asset (road/bridge), connection and network level.

In this chapter 4 a new prioritisation methodology for CID classification is proposed considering a resilience perspective which will be useful for the NRA for quick assessment to answer the question "how resilient is our transport system against CID?" or "how to prioritise hazards according to their impact on asset resilience?". These questions are essential if we want to anticipate, and to be able to respond to the unexpected, so that highway infrastructure continues to provide the essential services on which society depends.

As mentioned before, a new classification methodology has been developed and is presented in this section. As demonstrated by the impact chains in the previous chapter, many aspects of a road's performance may be impacted by a single CID. Road service levels provided may be monitored and assessed using KPIs and combined with the methodology demonstrated in this section, critical hazards may be identified for an object, connection, or network.

A methodology to quantify resilience is presented in this chapter, and the subsequent impact on resilience of each of the CID shown in Table 3.1, Chapter 3¡Error! No se encuentra el origen de la referencia. is assessed. Finally, these are classified according to the impact on resilience of a road object, connection, or network.

4.1 Infrastructure Resilience

Resilience is a commonly-used term and has been applied to many different sectors to describe behaviour of both physical and societal systems. Many definitions of resilience were presented in baseline reports D1.1 and D2.1 (ICARUS, 2022a, 2022b). Following the review of these, the definition to be used for ICARUS, is the IPCC definition where resilience is defined as *"the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation"*. Going one step further, and pertaining specifically to transport systems, the CEN-CENELEC Workshop Agreement (European Committee for Standardization, 2021) from the project FORESEE has defined resilience as the *"ability to continue to provide service if a disruptive event occurs"*.

As described in Deliverable 2.1 (ICARUS, 2022b), resilience assessment goes beyond that of risk, toalso include the system's ability to plan for, recover from and adapt to external events over time, and so the temporal component must also be considered. See Figure 4.1 (Linkov et al., 2014). From this figure, we can say that resilience is a function of the performance of the system with respect to time, and the level of service maintained during an event provides a measure of the resilience of the system.

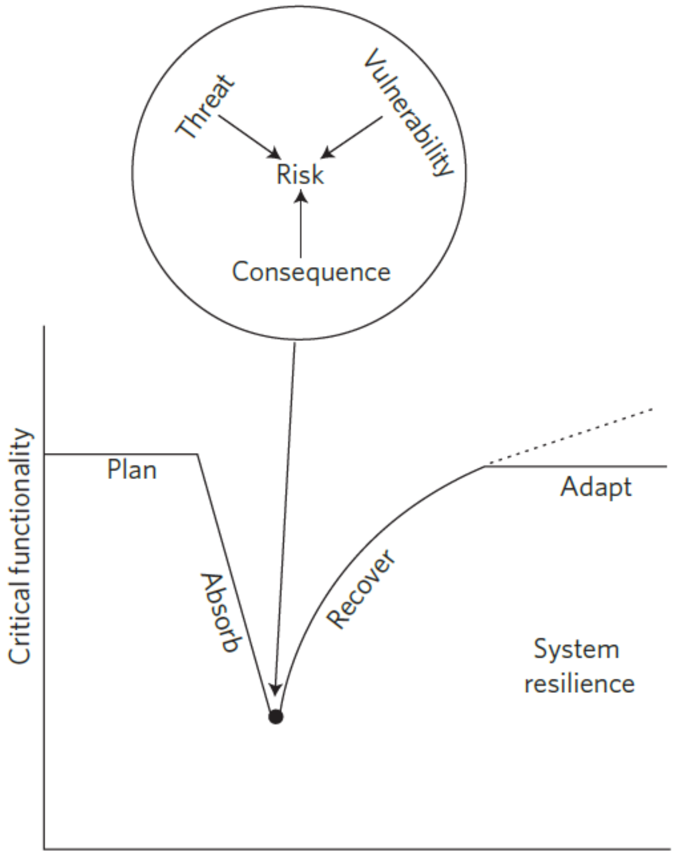
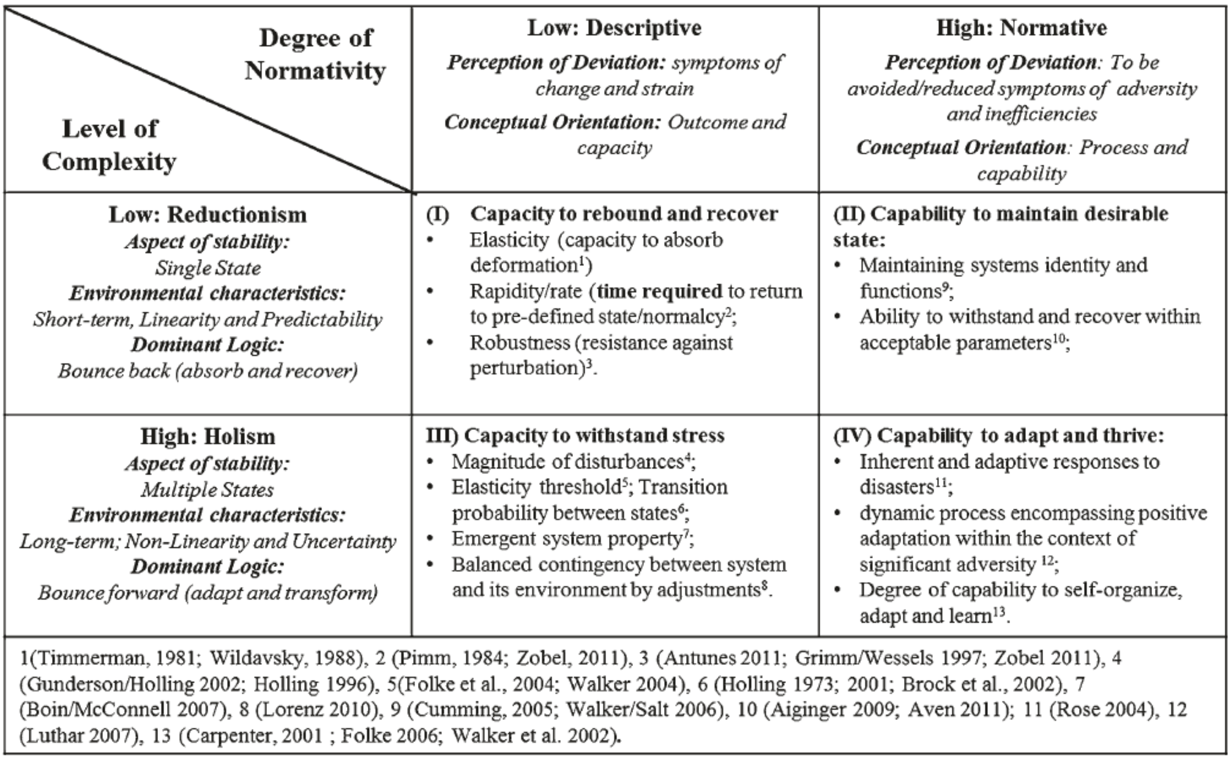


Figure 4.1 A resilience management framework including risk analysis as a central component (Linkov et al., 2014)

Also discussed in Deliverable 2.1 was the proposal of a multidisciplinary framework classifying the different definitions of resilience as proposed by Koslowski & Longstaff (Koslowski & Longstaff, 2015). Four categories are distinguished with a high or low degree of normativity and complexity as shown in Figure 4.2. Normativity describes the resilience as a coping capacity and a desired outcome. That is, a system with low normativity indicates the ability of the system to cope with a hazard and "bounce back", whereas high normativity indicates the ability to adapt and "bounce forward". Complexity refers to the type of system; single or multi-state, linear or non-linear.

Following review of these four categories, it is deemed that the category that best applies to road infrastructure is Category 1: The capacity to rebound and recover, which has both a low degree of normativity focusing on capacity to cope with a hazard and desired ability to "bounce back", and a low level of complexity (linear, single state system).

The classification of the hazards, or climate impact drivers in this case, will be developed based on this categorisation, as shown in Section 4.4.



Degree of Normativity **Level of Complexity**	**Low: Descriptive** ***Perception of Deviation:*** *symptoms of change and strain* ***Conceptual Orientation:*** *Outcome and capacity*	**High: Normative** ***Perception of Deviation****: To be avoided/reduced symptoms of adversity and inefficiencies* ***Conceptual Orientation****: Process and capability*
Low: Reductionism ***Aspect of stability:*** *Single State* ***Environmental characteristics:*** *Short-term, Linearity and Predictability* ***Dominant Logic:*** *Bounce back (absorb and recover)*	**(I) Capacity to rebound and recover** • Elasticity (capacity to absorb deformation[1]) • Rapidity/rate (**time required** to return to pre-defined state/normalcy[2]; • Robustness (resistance against perturbation)[3].	**(II) Capability to maintain desirable state:** • Maintaining systems identity and functions[9]; • Ability to withstand and recover within acceptable parameters[10];
High: Holism ***Aspect of stability:*** *Multiple States* ***Environmental characteristics:*** *Long-term; Non-Linearity and Uncertainty* ***Dominant Logic:*** *Bounce forward (adapt and transform)*	**III) Capacity to withstand stress** • Magnitude of disturbances[4]; • Elasticity threshold[5]; Transition probability between states[6]; • Emergent system property[7]; • Balanced contingency between system and its environment by adjustments[8].	**(IV) Capability to adapt and thrive:** • Inherent and adaptive responses to disasters[11]; • dynamic process encompassing positive adaptation within the context of significant adversity [12]; • Degree of capability to self-organize, adapt and learn[13].
1(Timmerman, 1981; Wildavsky, 1988), 2 (Pimm, 1984; Zobel, 2011), 3 (Antunes 2011; Grimm/Wessels 1997; Zobel 2011), 4 (Gunderson/Holling 2002; Holling 1996), 5(Folke et al., 2004; Walker 2004), 6 (Holling 1973; 2001; Brock et al., 2002), 7 (Boin/McConnell 2007), 8 (Lorenz 2010), 9 (Cumming, 2005; Walker/Salt 2006), 10 (Aiginger 2009; Aven 2011); 11 (Rose 2004), 12 (Luthar 2007), 13 (Carpenter, 2001 ; Folke 2006; Walker et al. 2002).		

Figure 4.2 Multidisciplinary resilience framework from (Koslowski & Longstaff, 2015)

4.2 Quantifying Resilience

Using these definitions for resilience of road infrastructure presented in Section 4.1, a methodology for quantifying resilience is developed. Several methods of quantification were presented previously in Deliverables 1.1 and 2.1, and for this application, to demonstrate how the hazard classification may be calculated, the concept of the Resilience Triangle is used.

The Resilience Triangle was presented by Tierney & Bruneau (Tierney & Bruneau, 2007), to quantify the loss of service due to a hazard or event as well as the recovery from that event. In Figure 4.3, the x-axis represents time and the y-axis represents Quality of Infrastructure. In this case, Quality of Infrastructure may represent service level provided, or functionality of the infrastructure. For normal operations, we would expect that this would be operating at 100%, but may not be due to works closures for instance, or the system may be recovering from a previous event. At time t_0, an event occurs which causes a loss of service or functionality from 100% to say 50%. The time it takes for the system to recover to full service at time t_1 will depend on how much damage was caused, and to what extent the system is affected. These in turn will depend on factors such as redundancy in the system to cope with an event, or how quickly resources can be put in place to aid the system recovery.

FIGURE 1 The Resilience Triangle

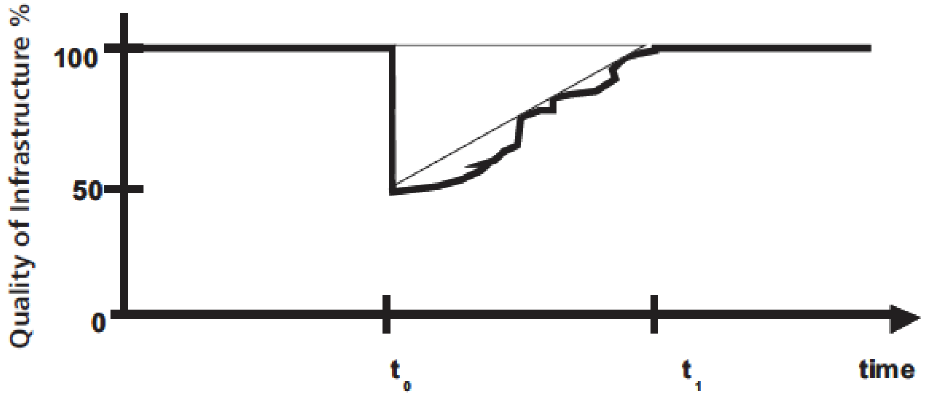


Figure 4.3 The Resilience Triangle (Tierney & Bruneau, 2007)

The *loss of service* may then be determined by calculating the area of the resilience triangle:

$$Loss\ of\ Service\ =\ \frac{1}{2}(t_1 - t_0) \cdot (\Delta Q)$$

Equation 4.1

Where:

- t_0 is the time of the event,
- t_1 is the time at which the system returns to normal functionality (this may also include the duration of the event), and thus (t_1 – t_0) is the recovery time;
- ΔQ is the reduction in system functionality from 100% functionality pre-event, and reduced functionality following the event.

4.3 Resilience Impact Score

Based on this concept of quantifying resilience in terms of service loss, and subsequent recovery, a method of classification of climate impact events with respect to road infrastructure resilience has been developed. This method requires that an object, connection or network is specified so that the impact on resilience may be calculated. The impact of the climate impact event on the object, connection or network, hereby referred to as *system*, may be scored in a number of categories. These categories are then combined to provide a Resilience Impact Score. It is important to note that the resilience impact score gives an indication of the impact of the hazard on the resilience of the infrastructure. The higher the score, the greater the loss of service, whilst the lower the score, the lower the loss of service or impact on the system.

Shown in Figure 4.4, these categories are:

1. Event duration, $t_E = t_1 - t_0$: simply the time the event lasts;
2. Recovery time, $t_R = t_2 - t_1$: the time it takes for the system to resume normal service;
3. Impact on service due to damage, Q_d: the amount of damage to the system;
4. Scale of impact, I: how widespread the damage is. Is it confined to asset level or has it spread to network level?

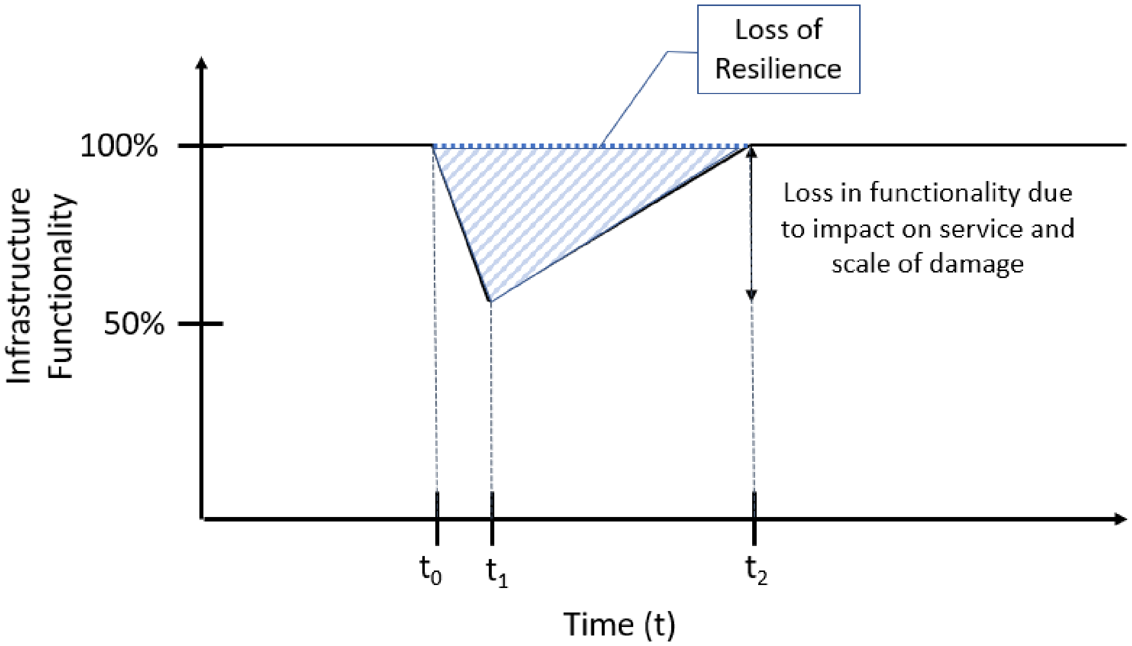


Figure 4.4 ICARUS Resilience representation based on (Tierney & Bruneau, 2007)

Based on the resilience triangle shown in Figure 4.4, the resilience impact score may be calculated by:

$$Resilience\ Impact\ Score = 0.5 * (t_E + t_R) * (Q_D * I)$$

Equation 4.2

Where the loss of service or functionality of the system is represented by the damage and scale of impact of the hazard. Note, that in this case, the loss in service due to physical damage and scale of impact have been multiplied to consider the scaling up effect of shifting from an object to connection, to network level.

It is important to note that other factors such as preparation or warning time of the climate event, redundancy in the network, or hazard intensity (which is also considered by the damage criteria), will also contribute to the recovery time in the resilience calculation. For example, longer warning time for a flood may also allow communities and local authorities to install temporary flood barriers, thus reducing impact and damage to infrastructure, reducing disruption time, and thus increasing resilience.

Event severity is also considered here implicitly in the recovery time and damage caused. For example, a 1-year flood event is more likely to have a quicker recovery time and cause less damage than a 100-year flood event. In this way, the event type does not need to be specified in the calculation, but the impact of the event will be considered. Similarly, event probability of occurrence which would ordinarily be considered in a risk assessment, is not included here, however the impact of any particular event may be assessed for its impact on the resilience of the asset.

4.4 Classifying Climate Impact Events with respect to Road Resilience

Now that the methodology has been presented, an example of how climate impact events should be classified with respect to how they impact resilience of the road object, connection or network of interest is presented.

Firstly, the system of interest must be chosen. This may be an object, connection, or road network. Then, the hazard should be chosen from the list of defined climate impact drivers provided in Table 3.1

¡Error! No se encuentra el origen de la referencia.¡Error! No se encuentra el origen de la referencia.. Wh en these are chosen, they should then be classified in terms of the event duration, expected recovery time, impact on service due to damage caused, and scale of impact as shown in Table 4.2. For each classification factor, the user may adapt the impact scales to suit their own system and a scale should be chosen that best represents the anticipated result. This scale is mostly qualitative, so it is just important to ensure consistency for the system being analysed. For example, the user may choose to measure the impact on service in terms of traffic flow at a specific point. Reduced traffic flow due to a lane closure as a result of an event may result in a 20% or 60% reduction in traffic flow, which may be a small or large impact on service. Similarly, other KPIs such as journey times, or number of incidents may also be used depending on the available data. The scales for each of these classification factors which may be used as a guide are shown in Table 4.1.

Table 4.1 Classification Factor Descriptions

Classification Factor	Event / CID Duration $(t_1\text{-}t_0)$	Recovery time $(t_2\text{-}t_1)$	Impact on Service due to Damage, Q_d	Scale of Impact, I
Impact Scale	0: Instant 1: < 6 hours 2: <1 day 3: > 1 day	0: No disruption 1: <1 day disruption 2: < 1 week disruption 3: < 1 month 4: > 1 month	0: No impact 1: Small impact 2: Medium impact 3: Large impact	1: Object 2: Connection 3: Network

The impact on resilience, or Resilience Impact Score, for the asset chosen, and for the particular hazard selected will then be calculated using Equation 4.2. For demonstration purposes, the following example illustrates how the Resilience Impact Score may be calculated.

Example: On the first row of the table shown in Table 4.2, a road network is selected as the type of asset. The impact on the resilience of this asset due to a cold spell occurring, which is an extreme event, is then calculated. The event is expected to last for several days, resulting in a score of 3 for event duration. This results in some small damage to the entire network so this will score 1 for damage, and 3 for Scale of Impact. As there is anticipated to be some small damage to the road network, recovery is expected to take less than one month resulting in a score of 2 for recovery time. The overall loss of resilience score is then calculated as:

$$Resilience\ Impact\ Score = 0.5 * (3 + 2) * (1 * 3) = 7.5$$

Equation 4.3

As this classification is calculating the <u>impact on resilience</u>, it is important to note that a higher value results in greater loss of service and thus greater impact on the infrastructure resilience.

The recovery time and the impact on service due to damage may be difficult to predict, however, to assist with this task, it may be worthwhile reviewing relevant service KPIs (as demonstrated in Deliverable 2.2).

Table 4.2 Hazard classification with respect to road resilience.

			Time		Factors affecting Service		
Type of Asset	Event / Climatic Impact-Driver (CID)	Event Type	Event / CID Duration (t_1-t_0)	Recovery time (t_2-t_1)	Impact on Service due to Damage, Q_d	Scale of Impact, *I*	Resilience Impact Score
			0: Instant 1: < 6 hours 2: <1 day 3: > 1 day	0: No disruption 1: <1 day disruption 2: < 1 week disruption 3: < 1 month 4: > 1 month	0: No Impact 1: Small Impact 2: Medium Impact 3: Large Impact	1: Object 2: Connection 3: Network	
Example 1: Road Network	Heat and Cold - Cold spell	Extreme Event	3	2	1	3	**7.5**
Example 1: Road Network	Wet and dry - River flood	Extreme Event	1	3	3	2	**12**
Example 1: Road Network	Wet and dry - Landslide	Extreme Event	1	4	3	3	**22.5**

Table 4.3 Interpretation of Resilience Impact Scores

Resilience Impact Score	Interpretation
<10	This may be considered to be a low score, indicating a low loss of system functionality.
>10 and <20	This may be considered to be a moderate score, indicating a moderate loss of system functionality.
>20	This may be considered to be a high score, and adaptation options should be considered to increase the resilience of the infrastructure to climate change.

Interpretation of the Resilience Impact Score will be different for each road authority, however a guide is provided in Table 4.3. It is important to note that this is not an absolute score but a relative sore which may be used for decision making purposes

4.5 Summary Guidance on how to Implement Resilience Impact Scores in Climate Change Adaptation

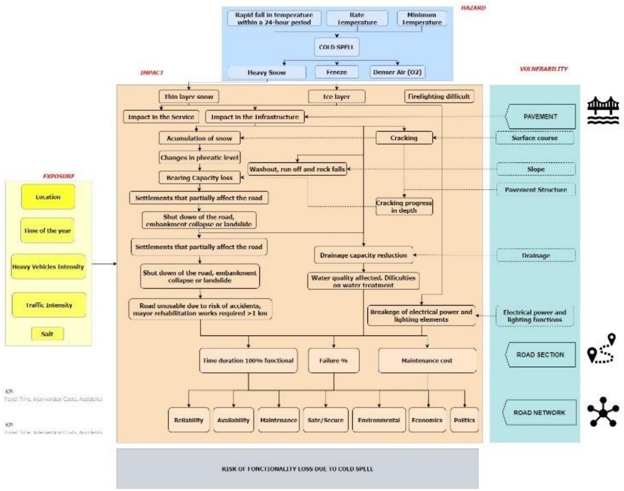
The methodology presented in this chapter may be used in decision-making, particularly at Operation and Maintenance life cycle stage of a project. It may be used at all levels of decision making (strategic, tactical and operational) to assist in prioritising areas which require additional resources to increase resilience to climate change. Additionally, it may be used to compare assets at object, connection or network level and identify those which may be vulnerable to climate change.

It is important to note that the resilience assessment methodology presented here does not consider the likelihood of hazard occurrence. A standard risk assessment would consider the probability of occurrence and consequences of the event. However, as described in Section 3.1, a resilience assessment goes beyond risk, and includes the system's ability to plan for, recover from and adapt to external events over time, and so the temporal component must also be considered.

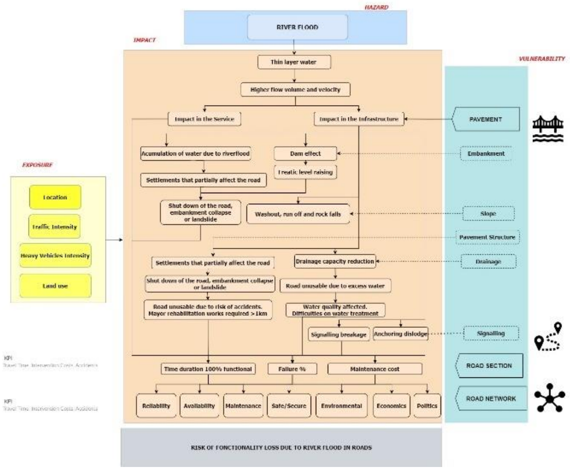
Following on from this assessment, the next step would be to use the information resulting from the resilience assessment to determine the most critical climate impact events for the assets under consideration and identify adaptation options to enhance the resilience of those assets with respect to the impact of climate change. Adaptation options for all asset types, in response to all climate impact drivers, will be presented in Deliverable 2.3 which will be delivered later in this project,

In the next page the methodology is applied for a hypothetic road network located in Eastern Europe (EEU) affected by three CID (cold spell, river flood and landslide) according to projected change in climatic impact-drivers in Europe as explained in Figure 4.5.

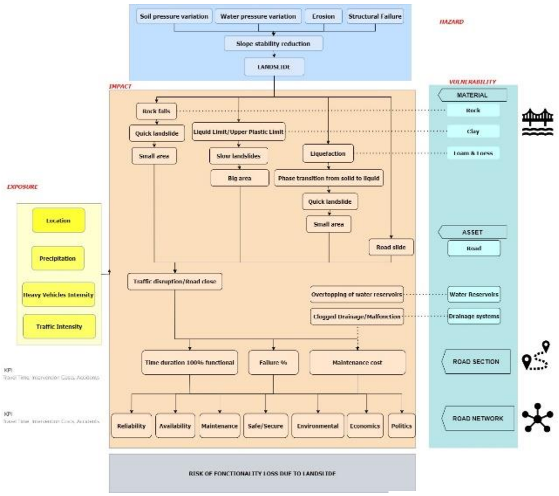
The three impact chains are useful to understand the impact in term of direct and indirect damages while the resilience impact score for these three CID ranks the impact in terms of time also.



Example 1: Impact chain 1



Example 2: Impact chain 2



Example 3: Impact chain 3

Type of Asset	Event / Climatic Impact-Driver (CID)	Event Type	Time		Factors affecting Service		Resilience Impact Score
			Event / CID Duration (t_1-t_0)	Recovery time (t_2-t_1)	Impact on Service due to Damage, Q_d	Scale of Impact, *I*	
			0: Instant 1: < 6 hours 2: <1 day 3: > 1 day	0: No disruption 1: <1 day disruption 2: < 1 week disruption 3: < 1 month 4: > 1 month	0: No Impact 1: Small Impact 2: Medium Impact 3: Large Impact	1: Object 2: Connection 3: Network	
Example 1: Road Network	Heat and Cold - Cold spell	Extreme Event	3	2	1	3	7.5
Example 1: Road Network	Wet and dry - River flood	Extreme Event	1	3	3	2	12
Example 1: Road Network	Wet and dry - Landslide	Extreme Event	1	4	3	3	22.5

Figure 4.5 Hazard classification and prioritisation in terms of resilience impact based on Integration of different impact chain scenarios.

5 CONCLUSION

When mapping the pathways of risk for all road assets in the context of National Road Authorities (NRAs), there are several factors to consider: climate projections (magnitude and geography), integration in the transport network, criticality of the infrastructure, damage categorisation, etc.

The approach developed in this D1.2 includes a methodology to close the gap between scientific committees' projections and NRA daily consequences of hazards, and quick classification and prioritisation of hazards opposed to the generally used classification regarding hazards themselves (Insana, 2021).

This deliverable has been developed to support decision-making at the different management levels at the NRAs and the roles and jurisdiction that come with these levels:

- Strategic level (top-down approach): IPCC climate change projections for different areas around the world are accepted by the scientific committee and European Commission so the long-term management of transport infrastructures must put the focus on them. Nevertheless, to not lose the balance between long term and short-term decision-making, classification and prioritisation is needed. In addition, the European Commission is providing technical guidance on the climate proofing of investments in infrastructure covering the programming period 2021-2027 on the best way to frame a well oriented strategy not only for climate resilience but also for climate neutrality for transport infrastructures (Commission Notice, 2021).
- Tactical level: ICARUS provides a methodology to bridge the gap between high level projections (expectancy of hazard, intensity, etc.) and direct and indirect damages affecting road infrastructures.

  On the one hand, this methodology makes use of impact chains (*3. Impact chains for road assets*[8]) including damage for hazard prioritisation based on magnitude and geography. On the other one, ICARUS provides the resilience score concept (*4. New approach to Classify the Effort of Hazards/Impacts on the Resilience of Roads*) to include time into the classification of hazards to the effect on the resilience of roads.

  This 2-step methodology (impact chain and resilience score) for hazard classification based on magnitude, geography, and time, is the real outcome of D1.2.
- Operational level (bottom-up approach): On the operational level it is key to understand what impacts (damages or opportunities, e.g., PIARC references) are and how these should be used to retrofit the process again considering the KPI proposed in WP2. This deliverable is built considering recent direct and indirect damages (ROADAPT, 2015), (CODEC, 2018), (CEN-CENELEC, 2021).

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[8] All the impact chains presented in this deliverable are examples to help NRAs in their own process for classifying climate impact events.

6 ACKNOWLEDGEMENT

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8 ANNEX

This annex tries to provide a better insight about changes in each of identified climatic impact-drivers (CID) in defined impact chains based on European Climate Databases. Furthermore, it provides the most relevant climate risk indexes for the road sector.

As can be seen, some of the descriptions are not fully uniform in structure. This is due to the fact that they are studied using different modelling chains. Temperature, precipitation, wind and atmospheric climate variables are mainly outcomes from global and regional climate models, with resolutions around 100km - 10km approximately these models are the best tools we have for evaluating the evolution of climate change. However, as they cannot solve small scale phenomena, other dynamics as landslides, ice melting, floods, etc. that require resolution of meters/centimetres require complementary simulations coupled to (or forced by) climate models.

Heat wave/ Extreme temperature

Table 8.1 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Extreme temperature	
Definition	Episodic high surface air temperature events potentially exacerbated by humidity. It can be described using different climate indices: hot days (maximum daily temperatures above 30°C), tropical nights (minimum night temperature of at least 20°C), warmest 3-day period (highest daily mean temperature in a year averaged over a 3-day window), heatwave days based on apparent temperature (number of heatwave days per year), climatological heatwave days (number of days per year within prolonged periods of unusually high temperatures).
European data source of the index	European Environment Agency: [Heat and cold — extreme heat — European Environment Agency (europa.eu)] European Climate Data Explorer: [Tropical Nights, 2011-2099 — English (europa.eu)]
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Heavy Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Past Experience with Temperature. Use of Polymer Modified Binders, Travel Time, Intervention Costs, Accidents

Commonly characterized by their intensity, duration and frequency, hot extremes can cause accelerated deterioration on different road components such as pavements.

This type of event is normally assessed by analysing changes in the magnitude of extreme day/night temperatures, the number of warm days/nights, and the number of heatwave days. Even though with significant regional variation, much of Europe has experienced intense heatwaves since 2000, in the form of hotter days, higher night-time temperatures and an increasing number of hot days, tropical nights and humid heatwaves. High maximum temperatures show increases in magnitude and frequency across Europe, including central and southern regions. In Northern Europe, a strong increase in extreme winter warming events has been observed.

In the future, an increase of hot extremes is expected, even faster than mean temperatures. Heat stress due to both high temperature and humidity is projected to increase across Europe under all emission scenarios and global warming levels by the middle of the century, with prolonged waves of extreme heat and duration of extreme humid heat conditions, especially in southern region. Under a high-emissions scenario:

- The number of hot days may increase fourfold in Europe by the end of the century, with the largest absolute increases in southern region.
- The number of tropical nights may increase up to 100 per year by the end of the century in southern Europe.
- The warmest 3-day mean temperature is projected to increase by 6.5 °C (by 1.5 °C in low-emissions scenario).
- It is virtually certain that the length, frequency and intensity of heat waves will increase in the future.

Next figure shows observed trends and projected changes in annual hot days.

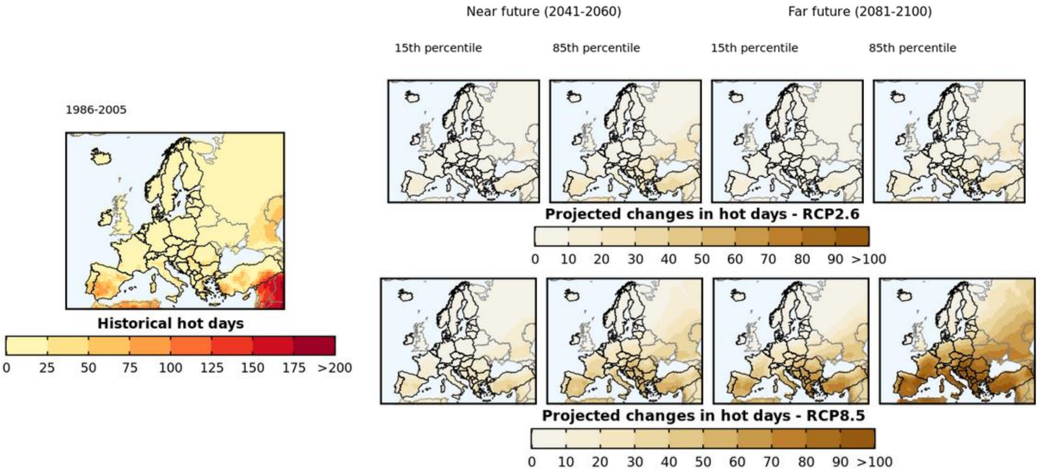

Figure 8.1 Observed trends from 1986 to 2005 and projected changes in annual hot days for RCP2.6 and RCP8.5 in near and far future (EEA, 2022a)

As mentioned before, extreme heat is particularly relevant for road pavement, contributing to initiate or accelerate some negative impacts in asphalt and concrete pavement, such as increasing levels of rutting and spalling, as well as softening and expanding the pavement[9]. During summer 2022, severe heatwaves affected Europe and brought record-breaking temperatures to several countries (France, Portugal, Spain and UK). As a result of the heatwaves, road pavements were softened in England[10] and water had to be poured on the road to prevent pavement from melting in France[11].

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[9] Also materials used for the foundation beneath the pavement like certain types of slag can be vulnerable to heat.

[10] https://www.mirror.co.uk/news/uk-news/uk-roads-seen-melting-black-27516311

[11] https://jalopnik.com/tour-de-france-pours-water-on-roads-to-keep-pavement-fr-1849190317

Cold spell

Table.8.2 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Frost days	
Definition	Cold spell are episodic cold surface air temperature events potentially exacerbated by wind. Frost can be described as freeze and thaw events near the land surface and their seasonality. Frost days index provides the number of days in a year with a daily minimum temperature below 0 °C.
European data source of the index	European Environment Agency: Heat and cold – frost days – European Environment Agency (europa.eu) European Climate Data Explorer: Frost Days, 2011-2099 – English (europa.eu) Copernicus: Heat waves and cold spells in Europe derived from climate projections (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Truck Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Presence of Bus Routes, Past Experience with Temperature. Use of Polymer Modified Binders.

This type of event could have great impact on electrical systems like controlling or monitoring units. However, even though year-to-year variability is considerable, trends show a decrease in the number of frost days in Europe since the 1980s, where northern regions show the fastest absolute decline.

This trend is projected to continue in the future. It is very likely that the frequency of cold spells and frost days will keep decreasing over the course of this century. The number of frost days may decline by about half during the 21st century under the high-emissions scenario (RCP8.5). Moreover, it is likely that, at the of the century, cold spells will virtually disappear.

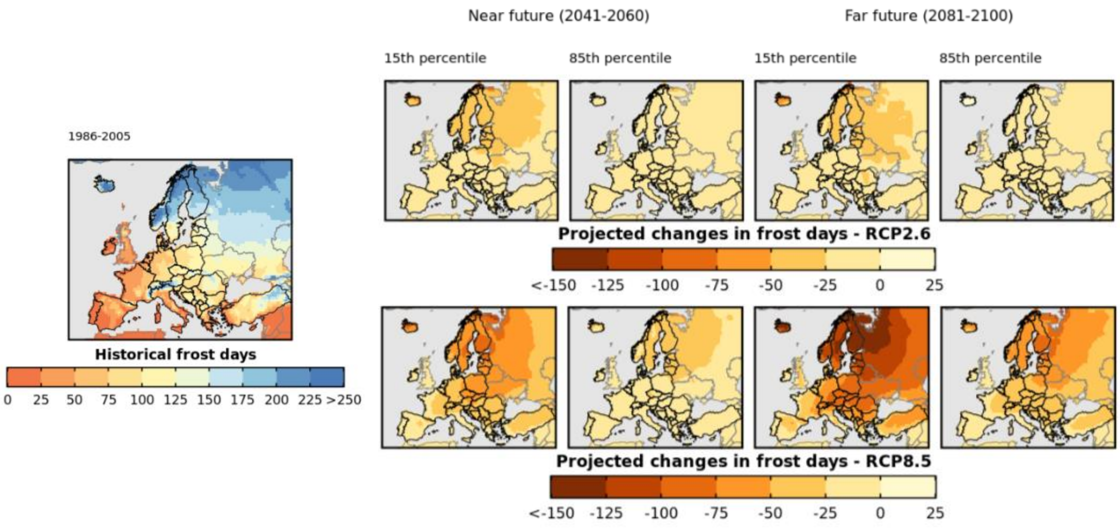

Figure 8.2 Observed trends from 1986 to 2005 and projected changes in annual hot days for RCP2.6 and RCP8.5 in near and far future (EEA, 2021a)

The consequence of milder winters as a result of a reduction in the frequency of cold spells and an increase in the number of freeze/thaw cycles on the roads could lead to a more brittle structure (CEDR, 2012). Transportation scheduling may also be altered due to reduced frost and mid-winter thaws. However, they will bring economic savings as during warmer winters less maintenance operations will be required and could mean less frost control for transport departments and safer travel conditions for passengers.

Drought

Table.8.3 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Hydrological droughts	
Definition	Hydrological and ground water drought is defined as surface and sub-surface water deficit. It combines runoff deficit and evaporative demand that led to dry soil.
European data source of the index	European Climate Data Explorer: [Meteorological and hydrological droughts (no further updates) — English (europa.eu)] European Environment Agency: [Wet and dry — drought — European Environment Agency (europa.eu)]
Variants of the index applicable to the road sector (if existing)	Flood level and stability, Channel modification, Scour, Settlement, Piles (Active), Backfill (Passive), Yielding point, Flexural Mechanism, Shear Mechanism, Tilting, Drift ratio δ/h, Curvature φ, Rotation ϴ, Displacement δ, Travel Time, Intervention Costs, Accidents

Focusing on hydrological droughts, important decreases in minimum runoff and river low flows have been observed in southern Europe and most of central regions, whereas those have increased in northern Europe.

In the future, most European regions are projected to suffer increasingly severe river flow droughts, with the exception of central-eastern and north-eastern Europe. Longer drought periods are projected in southern regions and central Europe, the former already in medium-emission scenarios and the latest in the highest emissions scenarios.

Figure 8.3 shows observed trends in runoff of driest month in Europe and Figure 8.4 provides projected changes in 10-year river water deficit between the reference period and the end of the 21st century in two emission scenarios.

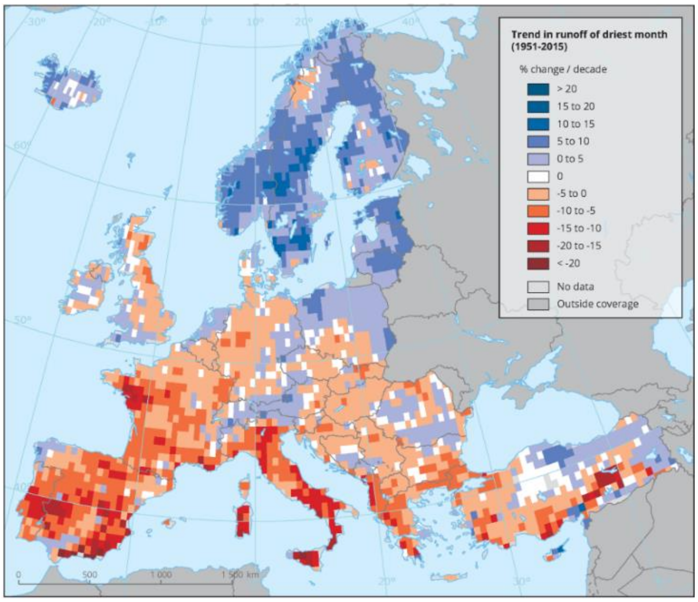

Figure 8.3 Observed trends in runoff during the month with the lowest river flow of the year in Europe (1951-2015) (EEA, 2021g)

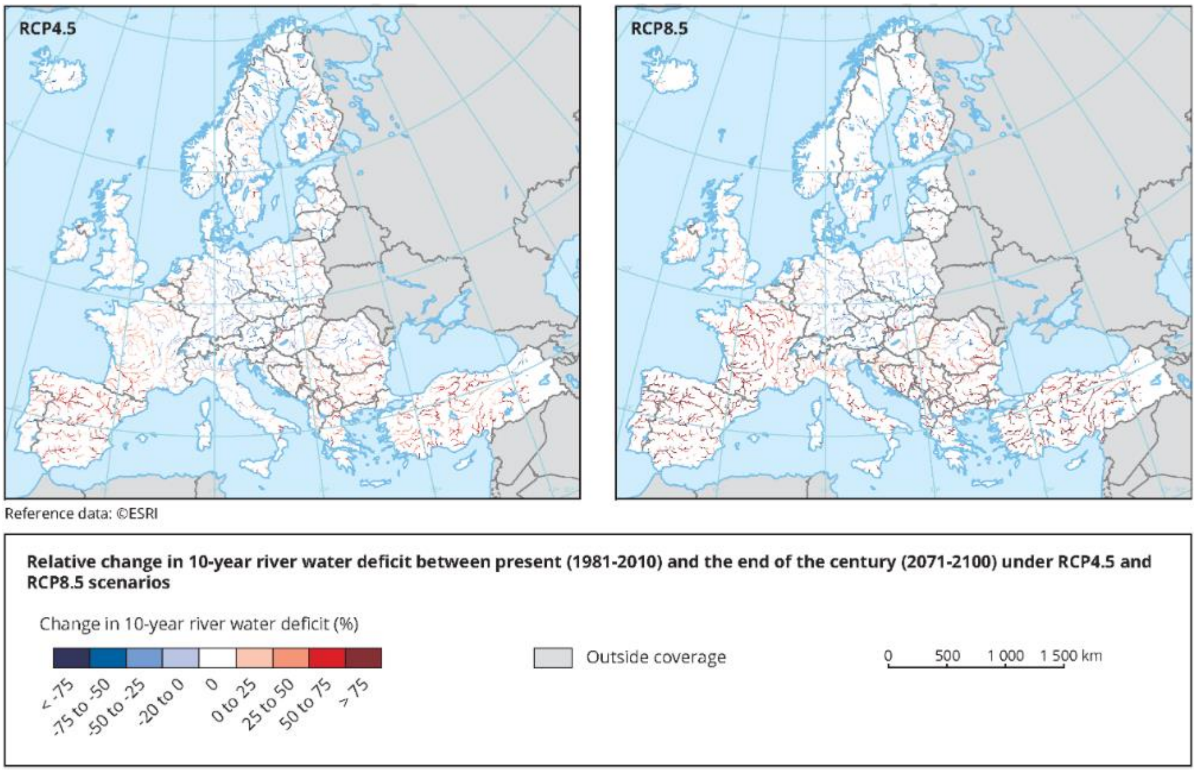

Figure 8.4 Projected change in 10-year river water deficit between the reference period (1981-2010) and the end of the 21st century, 2071-2100) in Europe, under RCP4.5 and RCP8.5 emission scenarios (EEA, 2021g)

Drought is a very important CID to be considered. In fact it has been serious in two years in the past five years at least in Northwestern Europe, and it is right now in Italy and Spain. Consequences are clear: risk of fires affecting assets and traffic, and increased soil subsidence. Drought in rivers and other waterways may also lead to less transport capacity for inland shipping which in turn leads to more road traffic and consequently more wearing and damage of the infrastructure.

River flood

Table.8.4 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

River flood	
Definition	River floods are episodic high-water levels in streams and rivers driven by basin runoff and the expected seasonal cycle of flooding. It represents the maximum river discharge for a given return period (e.g., 50 or 100-year period).
European data source of the index	Climate Data Store: River flow (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — heavy precipitation and river floods — European Environment Agency (europa.eu); River floods — European Environment Agency (europa.eu) Copernicus: Water quantity indicators for Europe (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	Extreme floods, Location in 100-Year Flood Zone, Location in 500-Year Flood Zone, Location in 10-Year Floodplain, Location in 25-Year Floodplain, Travel Time, Intervention Costs, Accidents

Over the period 1960-2010, annual river floods increased in north-western and parts of central Europe as a consequence of increasing autumn and winter rainfall. The trend was the opposite in southern and north-eastern Europe, caused by decreasing precipitation and increasing evaporation in the first case and decreasing snow cover and snowmelt in the second one. These trends can be observed in Figure 8.5.

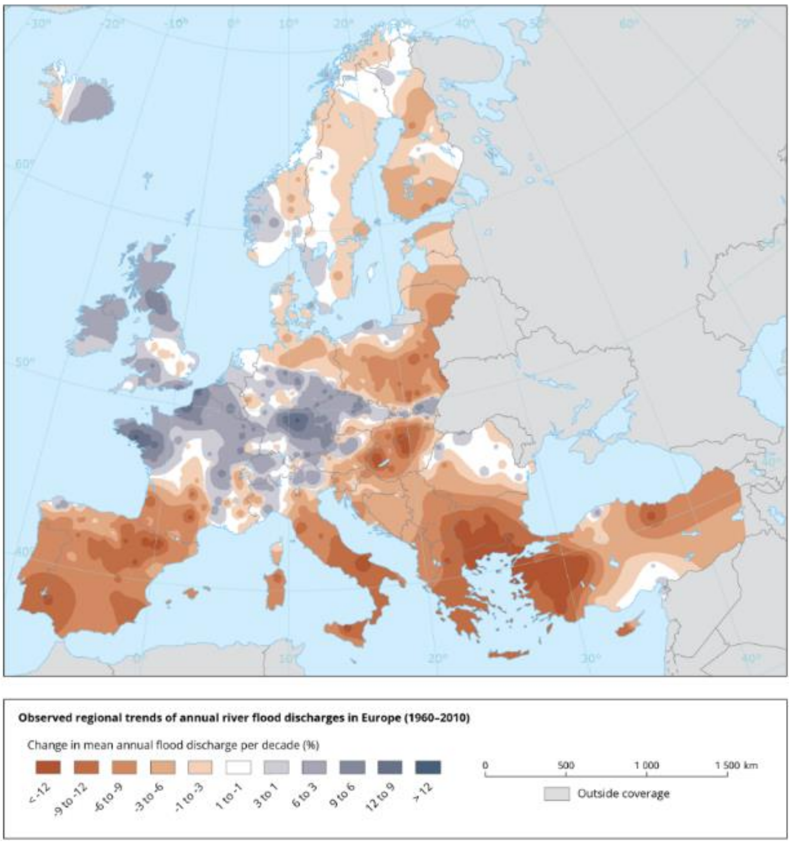

Figure 8.5 Observed trends from 1960–2010 in annual river flood discharges in Europe (EEA, 2021d)

In the future, the occurrence and frequency of 100-year river floods is projected to increase in most of the regions of Europe. The largest increases are expected in northern, central and central-eastern Europe, while in Spain, Italy, Balkan, Greece and Turkey maximum 100-year daily river discharge is expected to decrease. On the other hand, the 3 °C global warming scenario will exacerbate these trends causing three times the direct damages if additional adaptation actions are not implemented. Figure.8.6 summarizes projected changes in maximum 100-year daily river discharge for two global warming levels.

From a UK perspective, average river flows may be lower (as shown in the picture). However, the risk is likely to increase in those areas with more urbanisation that drain into the rivers themselves.

It is important to note all countries will have their own climate change scenario's, eg. in the Netherlands KNMI will publish new IPCC based climate scenario's in October 2023.

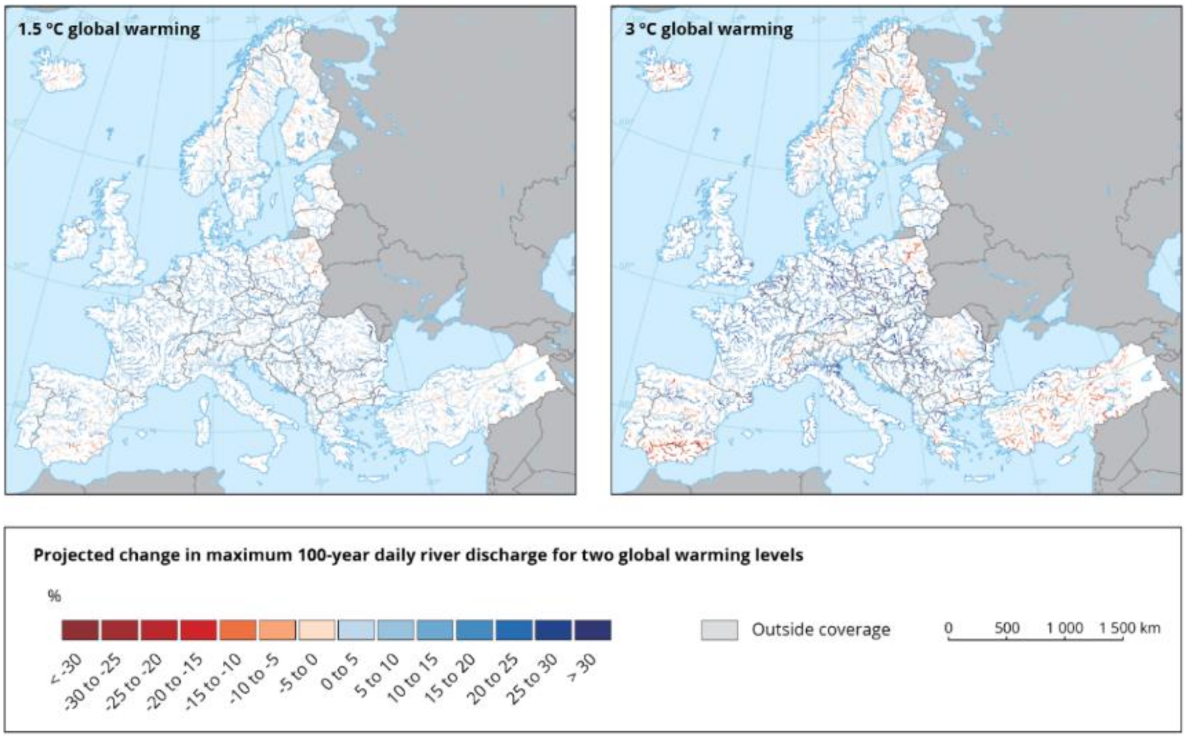

Figure.8.6 Projected changes in maximum 100-year daily river discharge between the reference period (1981–2010) and 1.5°C and 3°C global warming levels (ensemble mean of model simulations) (EEA, 2021d)

To better understand the possible future impacts of river flooding, it is necessary to analyse not only the climate indices related to this hazard and flood zones, but also the changes in land-use affecting infiltration and run-off (contributing to more severe 100-year events) and changes in river velocities (impacting, for example, scouring).

Flood effects can cause severe disruptive impacts on the road network with significant socio-economic consequences. This is the case of the floods that occurred in July 2021 in multiple regions across central and western Europe (Hallegatte, 2019; Wang, 2019). For instance, in the German Ahr Valley, extreme rainfall caused catastrophic flooding and damaged many roads and almost all bridges, hampering crisis response, reconstruction work, and economic recovery of the region. According to several studies (Kreienkamp, 2021), the occurrence of such event has become 1.2–9 times more likely today than in the 1.2 °C cooler pre-industrial climate.

The level of impact is also greatly factored by geography. There is much difference between situations where roads run along/above rivers and situations -like in the Netherlands- where roads are below water level and are protected against flooding by dikes/levees.

All this has many other implications for engineering designs. Another example can be found in the potential impact that increased flooding can have in culvert sizing and the methodology used to calculate the carrying capacity. Significant cost implications as road elevation may need to be raised if culverts are increased in size.

Heavy precipitation and pluvial floods

Table.8.5 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Heavy precipitation	
Definition	Changes in the type and intensity of precipitation and the impact on infrastructure maintenance and operations. High rates of precipitation can result in episodic, localized flooding of

	streams and flat lands. Heavy precipitation can be described using different indices: maximum consecutive 5-day precipitation (greatest precipitation total over five consecutive days in a year), extreme precipitation total (total precipitation on all days with heavy precipitation) and frequency of extreme precipitation (number of days in a year with extreme precipitation).
European data source of the index	European Climate Data Explorer: Heavy precipitation (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — heavy precipitation and river floods — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents, Operations costs, impact on CO2eq generation

Pluvial floods and flash floods are triggered by intense local precipitation events and also influenced by non-climatic factors (e.g., land use, changes to river basins, urban planning). Although it is clear to distinguish from river floodings, there are pluvial causes for flooding in many smaller river catchments. Periods of abnormally high rainfall can also result in groundwater flooding of basements and the emergence of groundwater at the ground surface, causing damage to property and infrastructure (BGS, 2023). Also it may cause water on the road with lane closures as a result.

It is important to differentiate between thunderstorm like extreme rain showers and two-day events with more steady rain (like in summer 2021 as mentioned above). Different impacts on infrastructure would be observed in both cases.

Since the 1950s, the frequency and magnitude of unusual precipitation events (precipitation exceeding the 99th percentile of daily precipitation values) has increased in Europe as a whole, with clearer increases in northern and central Europe. No significant changes are observed in southern Europe.

Figure.8.7 shows observed trends in maximum annual 5-day consecutive precipitation in winter and summer.

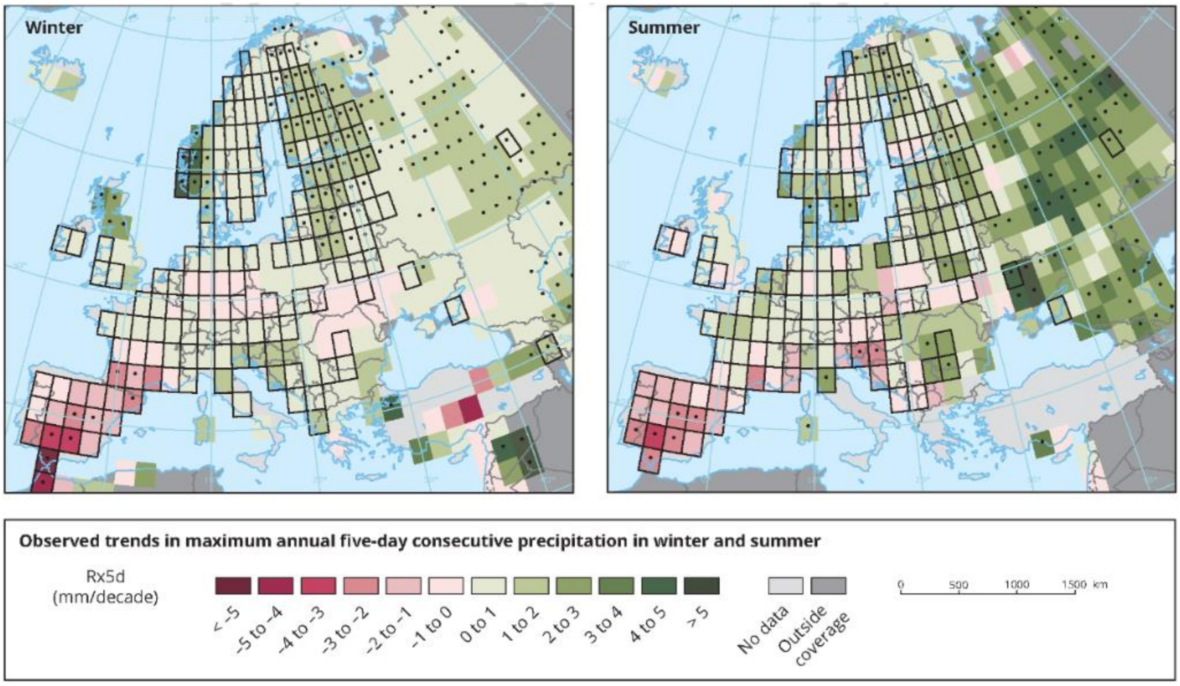

Figure.8.7 Observed trends in maximum annual 5-day consecutive precipitation in winter (December-January-February) and summer (June-July-August) across Europe between 1960 and 2018 (EEA, 2021e). Grid boxes outlined in solid black contain at least three stations and so are likely to be more representative of the grid box. Significant (at the 5% level) long-term trend is shown by a black dot.

The same trend is projected for the future, with the largest increases projected in frequency and intensity of extreme precipitation in northern Europe and smaller increases in central Europe, continuing without significant changes in southern Europe. The strongest changes are projected in Scandinavia and eastern Europe in winter.

Figure 8.8 summarizes observed trends and projected changes in extreme precipitation total.

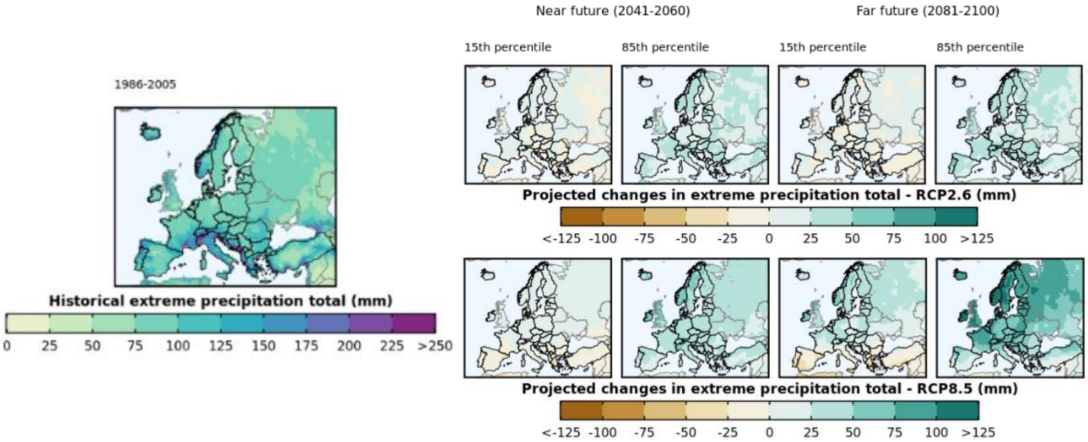

Figure 8.8 Observed trends from 1986 to 2005 and projected changes in extreme precipitation total for RCP2.6 and RCP8.5 in near and far future (EEA, 2021f)

Engineering designs will be influenced by the level of expected impact, that will mainly depend on the hazard (type of storm event, flooding), exposure factors (like traffic volume) and vulnerability factors as the type of vegetation and soil (contextual site factors) or infrastructure intrinsic factors. As an example, road drainage system capacity is designed using intensity-duration-frequency curves (IDF curves), based on short duration rainfall events (20 mins or less). Culverts are also designed to accommodate needed water volumes within a short period of time. By contrast, long duration storm events are used to calculate attenuation systems (such as wetlands, detention basins). In case of flooding, hazard level would be described by water depth and flow velocity.

Landslides

Table.8.6 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Landslides	
Definition	Ground and atmospheric conditions that lead to geological mass movements, including landslide, mudslide, and rockfall.
European data source of the index	European Climate Data Explorer: European Environment Agency: Landslide susceptibility for weather induced landslides: ICG (left) and b) JRC models (right) — European Environment Agency (europa.eu); Expected variations in abundance or activity of four landslide types, driven by the projected climate change — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Erosion, Tilting and bulging, Overflow, Settlement, Earthquake induced landslide, Earthquake induced rockslide, Earthquake induced failure of Anchors, Earthquake induced damage to concrete wall, Material defects or degradation, Concrete degradation (carbonation, alcali-silika reaction, chlorine ingress), Rebar corrosion, Loss of tension, Anchor corrosion, Excessive Settlement, Cracking (mm), Damage to geotextile, Cracking (mm), Overload, Travel Time, Intervention Costs, Accidents

Climate models cannot resolve these complex slope failure processes, so most studies rely on proxies or conditions conducive to slope failure (ROADAPT, 2015).

Too much rain falling too fast not only can trigger floods, but also landslides. The spatial and temporal patterns of precipitation, the intensity and duration of rainfall, and antecedent rainfall are important factors in triggering shallow landslides. Climate indices analysed in previous section are also relevant for the assessment of landslide and erosion risks. But climate and landslides act at only partially overlapping spatial and temporal scales, complicating the evaluation of the climate impacts on landslides. Moreover, landslide susceptibility is not only related to climate conditions, but also to three spatial criteria: terrain gradient (e.g., slope), shallow subsurface lithology, and land cover.

Quantification of possible trends in the frequency of landslides is difficult due to incomplete documentation of past events, especially those that happened before regular satellite observations became available. The projected increase in intensity and frequency of rainfall events and extreme precipitation events is expected to have an effect in landslides in some regions. Where the frequency and/or the intensity of the rainstorms will increase, shallow landslides, including rock falls, debris flows and debris avalanches, and also ice falls and snow avalanches in high mountain areas, are also expected to increase. In Central Europe, rainfall periods are projected to increase by mid-century: by up to 1 more period per year in flat areas in low altitudes and by up to 14 more periods per year at higher altitudes. By the end of the century, they are projected to become even more evident. Another hazard that might increase, at least in Norway and in the mountainous parts of Sweden are slush flows/slush avalanches.

Landslides are projected to increase by up to +45.7% and +21.2% by mid-century under both RCP4.5 and RCP8.5 in Southern Italy (Calabria region) and by up to 40% in Central Italy (Umbria) during the winter season in the Peloritani Mountains in Southern Italy, a decrease is projected by mid of the century under both RCP4.5 and RCP8.5. In the Eastern Carpathians, the Moldavian Subcarpathian and the northern part of the Moldavian Tableland, a slight increase (10-year return period) is projected in landslides, while higher increase is projected in the western hilly and plateau areas of Romania (100-year return period).

Figure.8.9 shows landslide susceptibility for weather induced landslides according to two independent models developed separately at the International Centre for Geohazards (ICG) and at the Joint Research Centre (JRC). They cover the same study area and both models were developed using the same datasets to model the landslide susceptibility (slope, lithology, soil moisture, vegetation cover and others) and triggering factors (extreme precipitation and seismicity). However, different weights were assigned to each dataset and different approaches where used for modelling: the ICG model is purely expert-based or heuristic and the JRC model uses a statistical technique in the form of logistic regression.

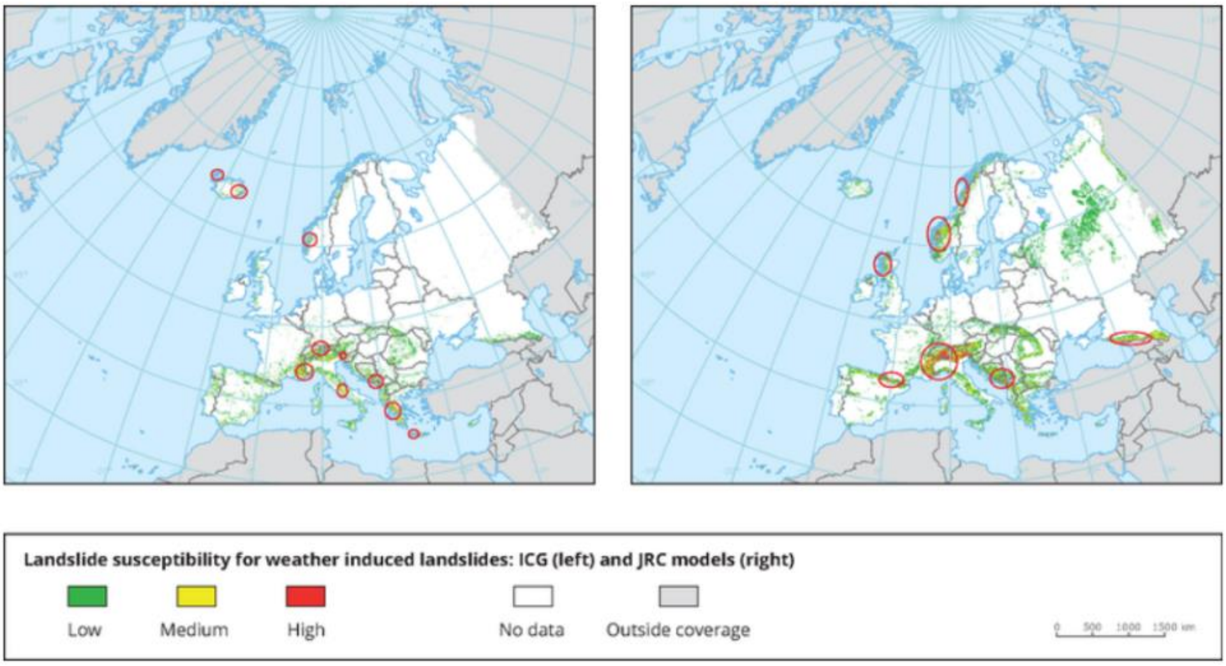

Figure.8.9 Landslide susceptibility for weather induced landslides: ICG (left) and JRC models (right). (EEA, 2017) Red circles show possible hotspots while white represents regions without landslide hazard.

Landslide risk was quantified by counting the number of exposed people and exposed kilometers of roads and railways in each country. The highest relative exposure to landslides is observed in small alpine countries such as Lichtenstein. Moreover, Italy shows the highest score in the extent of exposed area and population (Jaedicke, 2014).

Figure.8.10 provides the expected variations in abundance of four types of climate change driven landslides: rock fall/avalanche, debris flow, shallow landslide and deep-seated landslide.

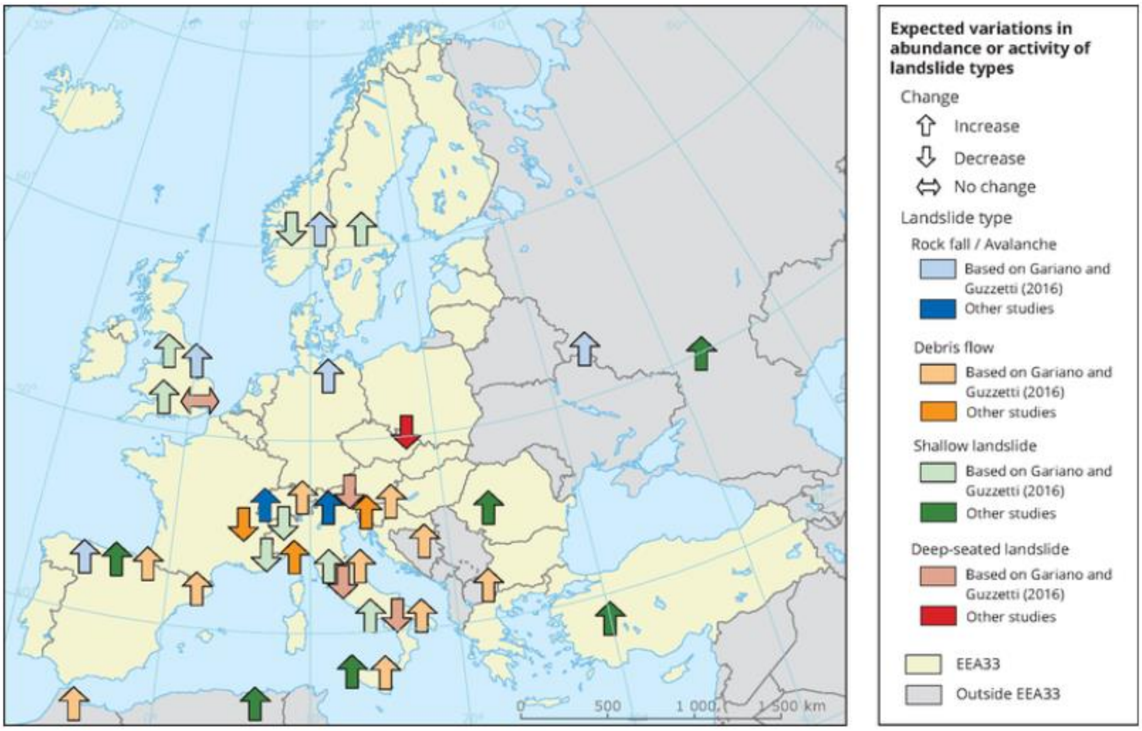

Figure.8.10 Expected variations in abundance or activity of four landslide types, driven by the projected climate change (EEA, 2017a).

Decreasing glaciers, ice sheet, permafrost and freeze-thaw cycle changes

Table.8.7 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Decreasing glaciers, ice sheet, permafrost	
Definition	Snow cover, ice sheets, mountain glaciers, frozen ground including permafrost and seasonal ground ice are all key components of the terrestrial cryosphere. This is the part of the Earth's surface that is seasonally or perennially frozen.
European data source of the index	European Climate Data Explorer: European Environment Agency: Snow and ice — snow, glaciers and ice sheets — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents

Projections show (high confidence) that glacier ice volume could be reduced in the European Alps and Scandinavia. According to GlacierMIP projections, glaciers in the Central Europe region are projected to lose 63 ± 31% (RCP2.6), 80 ± 22% (RCP4.5) and 93 ± 13% (RCP8.5) of their 2015 mass by 2100. In Scandinavia, the projected lost is 55 ± 33% (RCP2.6), 66 ± 34% (RCP4.5) and 82 ± 24% (RCP8.5). Other simulations bolster this shrink in glaciers.

With regard to permafrost, in Europe, it is found in high mountains and in Scandinavia, as well as in Arctic Islands. Trends in recent decade show that permafrost has been lost and its temperature has increased in the order of 0.2 ± 0.1°C between 2007 and 2016 as a consequence of accelerated warming at high altitudes and latitudes. In the future, over the 21st century, increasing thaw and degradation of permafrost is projected, being virtually certain its decrease in extension and volume.

Permafrost thawing is projected to affect the frequency and magnitude of high-mountain mass wasting processes. By 2100, even the lowest emissions scenarios show (medium confidence) the disappearance of most of the Northern Europe periglacial processes. Moreover, debris-flow season may last longer in a warming climate (medium confidence). Quantitative data for the European Alps is highly site dependent.

Infrastructure in circumpolar areas, key to developing sustainable economic models, could be seriously damaged by the middle of this century as a result of thawing permafrost, according to a study published in Nature (Hjort, 2018). Permafrost researchers are analysing the factors driving the rapid change of Arctic coastlines and the implications for humans and the environment.

Permafrost in Arctic regions stores nearly 1,700 gigatonnes of frozen and thawing carbon, and global warming, they say, could release an unknown amount of that carbon into the atmosphere, which further contribute to climate change.

Permafrost degradation can also cause the ground to become unstable and impose various threats to infrastructure in relation with warming, active layer thickening and thaw-related ones such as thermokarst and mass wasting. Moreover, permafrost warming and loss of bearing capacity may decrease the stability of slopes contributing to landslides and related infrastructure damage in mountain terrain (Streletskiy, 2023). Roads, buildings, and other infrastructure built on permafrost can experience settlement, shifting, or even collapse as the ground thaws and loses its stability. Specifically, permafrost thaw caused by anthropogenic warming could put 30-50% of "critical circumpolar infrastructure" in the Arctic at risk as a consequence of a loss in soil mechanical strength. Arctic coasts are characterised by sea ice, permafrost and land ice. This makes them particularly vulnerable to the effects of climate change, which is already accelerating rapid coastal erosion and loss of land. The University of Oulu researchers estimate that by the middle of this century, around 69% of residential, transport and industrial infrastructure in permafrost regions will be located in areas with a "high potential for near-surface thawing". As a result, the cost of maintenance, repairing or replacing damaged infrastructure can be extremely costly and reach "billions of dollars" by the second half of the century.(Hjort, 2022)

According to OpenStreetMap data (Streletskiy, 2023), 358000 km of roads are located in permafrost-affected regions[12], and almost 50% are in Russia’s permafrost regions. Costs of maintaining Russian current road network affected by permafrost deterioration between 2020 and 2050 is estimated that could reach $7 billion (about 6.175 billion euros). In European countries, the economic impact of permafrost-related road damage (moderate and high potential risks of damage due to ground subsidence) by the 2055–2064 period (SSP245 climate scenario) has been estimated at 0.15 billion for Iceland, $0.8 billion for Finland, $1.0 billion for Sweden, and $18 billion for Norway (Streletskiy, 2023).

Apart from the projections, nowadays in Sweden there are few roads in the vicinity of permafrost. The damage on roads and road banks caused by annual freeze-thaw processes and dynamic load from traffic is a much bigger problem. After each freezing and thawing cycle, the tensile strength ratio

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[12] Taking into account territories of Arctic countries or states where permafrost is present, including: North America (parts of Alaska in the USA and Canadian provinces of the Northwest Territories, Nunavut, and Yukon), western Europe (Iceland; Lapland, Northern Ostrobothnia, and Kainuu (Finland); Finnmark, Nordland, and Troms (Norway); Norrbotten and Västerbotten (Sweden)), Russian Federation (Murmansk Oblast’, Northeast of Republic of Komi, Nenets AO, Yamal-Nenets AO (YNAO), north of Khanty-Mansi AO (KMAO), north of Krasnoyarsk Krai, Republic of Sakha, Chukotka AO, Magadan Oblast). (Streletskiy, 2023)

decreases, affecting fatigue life of asphalt. In particular, anti-icing asphalt pavements can reduce their anti-icing overall effectiveness and salt storage capacity. In regions experiencing higher temperatures, the storage capacity may decrease due to increased evaporation, leading to a reduced amount of salt available for anti-icing purposes. Rising temperatures can also affect the effectiveness of salt in melting ice and snow, requiring higher concentrations or different types of de-icing chemicals to achieve the desired anti-icing effect. Moreover, extreme weather events (heavy rainfall, flooding, intense storms), can also cause structural damage to the pavement, compromising its ability to withstand freezing and thawing cycles or hold the stored salt effectively.