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Conférence Européenne
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ICARUS

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

Guidelines providing an overview of and characterisation of adaptation options, with recommendations on implementation

Deliverable D2.3 Version 2.0

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CEDR call 2021: Climate Change Resilience

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Guidelines providing an overview of and characterisation of adaptation options, with recommendations on implementation

March 2024

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Summary

It is widely acknowledged that there is a growing need to adapt infrastructure to the differing and increased threats that climate change brings. Road authorities in Europe face increasing pressures with ageing infrastructure, growing populations, and increased traffic numbers and traffic loading on their networks, with minimal increases to budgets. In addition, climate change brings increased frequencies of extreme weather events increasing risk to road infrastructure.

This deliverable, as part of the ICARUS project, provides guidance to road authorities on how to implement climate change adaptation measures. In this guideline and accompanying adaptation option spreadsheet, we have provided a wide variety of adaptation options including Nature-based Solutions, and emerging technology solutions, which can be implemented at all stages of the project life cycle, for any or all asset types, at an object, connection and/or network level, to increase resilience to specific climate impacts. Guidance on how to select the most appropriate climate change adaptation options is provided, along with a review of gaps and barriers to implementation of adaptation. Key challenges for road authorities in implementing climate change adaptation are a lack of information and data, lack of resources, both financial and skills, and provision of incentives for organisations to act. Solutions are proposed to these barriers, using emerging technologies where appropriate. Finally, guidance is provided on how adaptation may be implemented at an organisation level in NRA processes.

An adaptation implementation process has been developed through which NRAs of different organisational maturity can progress from awareness of the requirement to protect their infrastructure against extreme weather and climate change, to implementing climate change adaptation in practice, either at an asset management level or an individual project level. Some NRAs may have a specific project in mind when starting the framework, whilst others may wish to raise their organisational awareness. The route through the framework will differ if concentrating on a project or the entire network.

The process indicates at which level or combination of levels (strategic, tactical and operational) at the NRA should be involved at each stage. It also details where expert input is required.

There are five building blocks (awareness, decision context, resilience assessment, adaptation plan and implementation in practice) within which there are individual stages. As NRAs progress through the stages, there are a series of 'yes/no' gates, where the NRA either moves along the process or reevaluates requirements. In some cases, resources (internal or external) may not be available to move immediately to the next stage, or the case might not be made to move the next stage. In such cases, there are loops to revisit previous stages, so there may be progression in the future, or if the decision contexts are changed.

Key take aways for implementing climate change adaptation are as follows:

1. To ensure that climate change adaptation finds its way in the daily processes of NRAs, many different NRA staff members must take an active role, and different layers of the organization need to be involved and engaged. This ranges from continuous shifts between strategic decisions at the strategic level, practical assessments at the tactical level and key input from the operational level. Engagement at all levels is a prerequisite for successful implementation. It is recommended to have one person in charge of the entire process. Depending on the organisation of the NRA this can be on different levels. In general, we deem it most effective when an NRA staff member, with a task in the field of climate change adaptation at the tactical level, takes the leading role. This person should be able to interact clearly with the other two levels.

2. Linking with the decision context of the NRA and the policy makers is of critical importance. It's a pitfall to start with a resilience and adaptation assessment right away. Ensuring decision making requires that the resilience assessment is designed such that the results make sense to the decision makers. Resilience and adaptation frameworks are abundantly available. It is key that use of these frameworks is tailored to the typical decision context of the NRA. This decision context includes the steering mechanisms and the criteria that are used for decision making. Customized resilience and adaptation assessments will produce outcomes that will push the right buttons for decision making.
3. Implementation may take place via two routes, which are interlinked. One route is via adapting the asset management that eventually will lead to an uptake of adaptation in all processes of an NRA. The other route is via implementation at an individual project level. Both approaches strengthen each other. Insights gathered at the project level will inform the process of adapting the asset management via changing the planning, design, construction, maintenance and operational guidelines.
4. Research may be necessary to understand how climate change may impact the KPIs that are used for monitoring the performance of the road network. If climate events, let alone climate change, are not reflected in the KPIs it generally won't be possible to make a case for adaptation, since climate events won't lead to a lower measured performance of the road. When it is not understood how climate change affects the performance of the KPIs, it won't be possible to underline in the resilience assessment how climate change will lead to a lower performance.

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1 INTRODUCTION

This deliverable is produced as part of the CEDR-funded ICARUS project which aims to support National Road Authorities (NRAs) in Europe to increase resilience of their road infrastructure to climate change. It is widely acknowledged that there is a growing need to adapt infrastructure to the differing and increased threats that climate change brings. How do you build and implement the business case for resilience via adaptation, balancing the service levels that the road network needs to achieve with the costs and benefits for enhancing resilience?

Key challenges for road authorities in implementing climate change adaptation are a lack of information and data, lack of resources, both financial and skills, and provision of incentives for organisations to act (Lehmann et al., 2015). In the ICARUS project, we propose ways to help road authorities to identify the critical elements of their infrastructure networks and provide adaptation options to increase the resilience of their infrastructure to climate change events. More specifically, in this guideline we aim to provide a wide variety of adaptation options with accompanying guidance on how to overcome barriers to implementation and how to implement in NRA processes.

1.1 Objectives of this guideline

A key challenge in the delivery of resilience and climate change adaptation is knowing what options are available to the organisation and how to implement them. This guideline, combined with the accompanying database of adaptation options, aims to provide road authorities with examples of options which can be implemented at all stages of the project life cycle, for any or all asset types, at an object, connection and/or network level, to increase resilience to specific climate impacts. Guidance on how to select the most appropriate climate change adaptation options is provided, along with a review of gaps and barriers to implementation of adaptation. Solutions are proposed to these barriers, using emerging technologies where appropriate. Finally, guidance is provided on how adaptation can be implemented at an organisation level in NRA processes.

1.2 Understanding the Context

Within ICARUS we adopt 6 main steps for incorporation of climate change adaptation in the processes of the NRAs, based on extensive research of state of the art and state of practice in the ICARUS baseline reports D1.1, D2.1 and D3.1 (De Jonge et al., 2022; Fonseca et al., 2022; Garcia-Sanchez et al., 2022). This is shown in Figure 1.1.

The first step is called framing and consists of understanding the decision-making process at NRAs, as well as the use of Key Performance Indicators, existing policies and wider benefits in that regard. Furthermore, other boundary conditions for decision making should be clear like the temporal and spatial scope, capacity and resources and data examination. And finally, a clear overview of all involved stakeholders should be present. By comprehensively understanding these aspects, road authorities can enhance their decision-making processes and effectively work towards implementation of adaptation options for enhancing the resilience of the road network.

In the second step, business as usual is being assessed to understand how resilient the road network is for natural hazards, both for the current and the future situation. Adaptation is not yet considered. Insight into the resilience without adaptation will form the base case and is key to understand the wider benefits of adaptation options.

In the third step, adaptation options , as well as their benefits and co-benefits, are considered. Adaptation options are being combined and placed on a timeline, to build adaptation strategies. The future resilience with use of these adaptation strategies is assessed, and benefits and wider benefits are evaluated in such a way that this aligns with the decision-making process of the NRAs.

The fourth step builds the decision case for adaptation. By comparing the resilience of the business-as-usual state with the estimated resilience including adaptation, one gains understanding of the benefits and co-benefits of adaptation strategies that can be evaluated with relevant methodologies. This step is key in providing the necessary information to decision makers while using the appropriate methods and metrics, allowing them to consider the decision case integrally with other decisions that need to be made.

In the fifth step, the implementation of the chosen strategies needs to take place. By following the previous steps all relevant pre-processing has been done. However, now it needs to be ensured that all the valuable work will be implemented in practice.

The final step consists of monitoring the results of adaptation. How is the performance of the road network developing towards the future? And does this link to the performance that was expected during the resilience assessments and appraisal of adaptation strategies? A proper monitoring regime enables evaluation of the performance and may lead to further steering of plans towards the future. Also, it further eases the decision case for adaptation, as it provides the metrics for the evaluation of adaptation strategies. This entails a feedback loop from this last step to the very beginning of the framework and all intermediate steps.

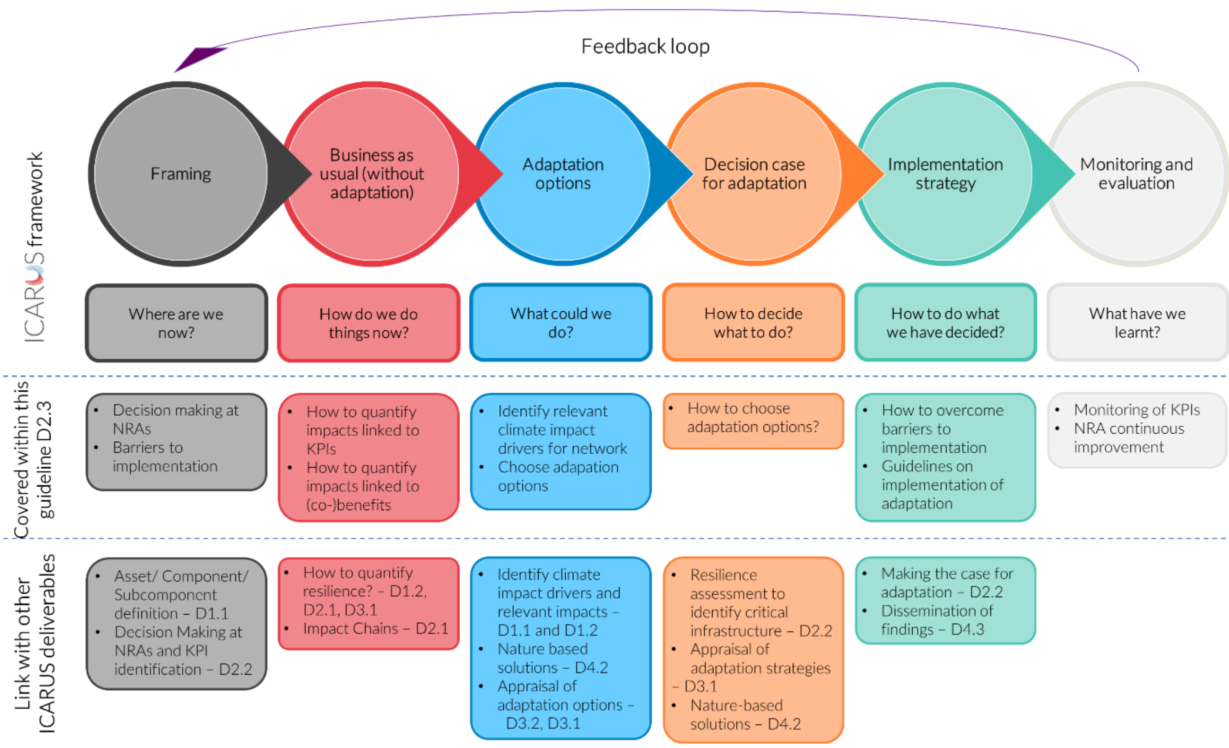


Figure 1.1 Overview of the steps in the ICARUS framework regarding decision-making and implementation of climate adaptation at NRAs, as well as how these steps are addressed in the underlying guidelines and other ICARUS deliverables.

2 Overview of Adaptation Options Database

With the increasing number of extreme weather events taking place due to climate change, there are additional risks to transport infrastructure. Many infrastructure managers have begun to implement climate change adaptation options to increase resilience to climate change events, increasing infrastructure availability and reliability, reducing the risk to lives and businesses in the affected areas.

Many ways to adapt road infrastructure to increase resilience to climate change events exist, and it can be difficult to choose the most appropriate options. The aim of this deliverable is to provide road authorities with a selection of adaptation options, guidance on how to choose the most appropriate options for their infrastructure, along with guidance on how to implement adaptation.

An Excel database of adaptation options has been developed as part of this project and accompanies this deliverable. It may be found on the ICARUS website. The adaptation options have been developed to address the climate impact drivers identified in ICARUS Deliverable 1.1 (Garcia-Sanchez et al., 2022), and may be used by road authorities as a starting point to address climate change adaptation of their networks. It is not intended to be a complete suite of options, and users may have additional adaptation options that they may indeed add to the database. Guidance on how to use the database, as well as guidance on adaptation implementation has also been developed for road authorities and is contained in this deliverable.

As well as traditional adaptation options, nature-based solutions (NbS), and options where emerging technologies can assist adaptation have also been reviewed and highlighted in the database.

In this chapter, an introduction to the adaptation options database is provided, along with guidance on how to use the database. The methodology used in the development of the adaptation options is presented, why NbS has been specifically considered, then how adaptation options can be characterised. Finally, assessment of the adaptation options using a multi-criteria analysis is explained.

2.1 Using the Adaptation Options Database

The Adaptation Options Database is provided to assist road authorities in making decisions on what adaptation options are best suited to their infrastructure. As described earlier, adaptation options have been provided for all Climate Impact Drivers as presented in ICARUS Deliverable 1.1 (Garcia-Sanchez et al., 2022), to alleviate various impacts of climate change on infrastructure. These adaptation options have been characterised based on the applicable asset type , the asset scale, stage of implementation along the project life cycle, and disaster risk management cycle, as well as whether they are a Nature-based Solution or can use Emerging Technology (as outlined in Section 2.3). They were further assessed with a multi-criteria analysis under categories of Benefits and Co-Benefits, Additional Criteria including Impact on Reputation, and Road User Experience, and finally assessed under User Inputs such as cost. It is important to note that the analysis scores provided are guidance based on the authors' experience, but may differ for each user's organisation or jurisdiction. In this case, users are free to amend scores that best reflect their own organisation.

Each adaptation option has been assessed for its potential as a Nature-based Solution and potential to use an Emerging Technology to enable adaptation. Further explanations of these have been provided in Sections 2.3.1 and 2.3.2 of this chapter respectively. Additionally, there are two tabs with references in the database which should help to guide the user towards examples of where these are already in use. These are 'Reference List NbS' and 'Reference List EmT'. Under the 'Reference list NbS' tab, you will find relevant references for each NbS, listed in alphabetical order that are mentioned in column P (NbS evidence base) of the Adaptations Options main overview. The evidence base provides at least 1 relevant literature reference, for the user to find more information on the specific NbS. For a brief overview of the information available in the reference, please see Annex A.

Prior to use of the database, it is advised that the user has decided which climate impact driver or impact on infrastructure is of concern, and what the other priorities for their organisation are, whether these are costs, availability, safety or other factors. Adaptation options may then be identified, reviewed and filtered based on the user's priorities.

Step by Step Guide to using the Adaptation Options Database

1. On first use of the database it is advised to take some time to familiarise oneself with how it works, and the various analysis criteria. The database is set up in such a way so that all columns may be filtered. This means that regardless of the priority of the user or user's organisation, adaptation options may be found by filtering for the specific requirements.
2. Once the climate impact driver of interest has been identified, the user should click on the drop-downs of Columns B, C and D to choose the relevant threat, and the set of adaptation measures for this particular threat will be provided in column F.
3. The user may then filter the other columns from G to AH to select criteria of interest to them. For example, if the user wishes to implement an adaptation option at maintenance stage that is an NbS, columns I and N may be filtered to reflect that.
4. Additional user inputs for costs, organisational experience, and legislative requirements may also be added under the User Inputs section from columns AI to AM. Space has also been left in columns AN and AO for the user to add in any other criteria they wish to use as part of the analysis.
5. The chosen options for the chosen climate impact drivers could then be saved by the user for further deliberation.
6. Alternatively, if a user has a particular adaptation option in mind, they can search for that adaptation option using the filter options in column F. In this way, the user can investigate the characteristics of a particular adaptation option if so interested.

2.2 Development of Adaptation Options

As a starting point for this project, we have assessed the adaptation options first presented in the CEDR-funded ROADAPT project (Bles et al., 2015). The aim of the ROADAPT project was to help road managers "prioritise adaptation options in order to maximize availability within reasonable costs". A list of more than 500 adaptation measures was compiled during the project to assist road managers in reducing the risk of climate change to their infrastructure, and these were used as a foundation for the adaptation options characterised in ICARUS.

The adaptation measures developed for the ROADAPT project were reviewed and ways to map them to the characterisation criteria developed for the ICARUS project and framework were established. The original ROADAPT adaptation measures, along with new measures have been presented in a database which has been provided in parallel with this report to assist road authorities in decision-making in relation to climate change adaptation.

For the most part, the adaptation measures originally developed for the ROADAPT project were retained as they are still relevant, and in addition, some new ones were developed for ICARUS. This was generally where none previously existed for a particular Climate Impact Driver (CID), more modern techniques were available with the assistance of emerging technologies, or adaptation options using nature-based solutions were added.

2.2.1 ICARUS Climate Impact Drivers (CIDs)

The Climate Impact Drivers (CIDs) used for the ICARUS project were identified in Deliverable 1.1 (Garcia-Sanchez et al., 2022) based on a framework developed by IPCC (Masson-Delmotte et al., 2021) and shown in Table 2.1.

Table 2.1 CID for impact chain validation based on IPCC definitions (Masson-Delmotte et al., 2021) as presented in D1.1 (Garcia-Sanchez et al., 2022)

	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	Heavy snowfall and ice storm	Coastal flood	
	Cold spell	Heavy precipitation and **pluvial flood**	Tropical cyclone	Hail	Coastal erosion	
	Frost	**Landslide**	Sand and dust storm	Snow avalanche		
		Hydrological **drought**				
		Fire weather				
Slow-onset processes and trends	Mean air temperature	Mean precipitation	Mean wind speed	Decreasing glaciers, ice sheet, permafrost, **Freeze-thaw cycle changes**	Sea level rise	Radiation at surface
					Ocean and lake acidity	Subsidence

Most of the adaptation options were easily mapped from the "threats" used in ROADAPT, to "climate impact drivers" in ICARUS, however there were some climate impact drivers where no adaptation options existed so new ones were assigned in those cases. These were:

- Heat and Cold
  - Cold Spell (Extreme event)
  - Mean Air Temperature (Slow-onset processes and trends)

- Wet and Dry
  - Wildfire Conditions (Extreme event)
- Wind
  - Tropical Cyclone (Extreme event)
  - Sand and dust storm (Extreme event)
  - Mean wind speed (Slow-onset processes and trends)
- Snow and Ice
  - Hail (Extreme Event)
- Coastal and Oceanic
  - Ocean and Lake Acidity (Slow-onset processes and trends)
- Others, radiation, subsidence
  - Radiation at Surface (Slow-onset processes and trends)

For these climate impact drivers, additional measures were researched through literature review and partner experience, so that adaptation options could be provided for all climate impact drivers. Where there were existing examples for these in the literature, references to the literature have been included in the database so that users may see evidence of these in practice.
In the ROADAPT project, for each main threat identified, specific threats were also identified, followed by the climate parameter that was responsible for causing these threats to occur. Adaptation measures were then developed and assigned to each climate parameter to help infrastructure owners adapt their infrastructure for climate change.

To align with ICARUS terminology and language, these climate parameters were mapped to the CIDs identified in ICARUS D1.1 (Garcia-Sanchez et al., 2022). Once the climate impact driver and associated impact on infrastructure had been identified, the associated adaption measures to increase infrastructure resilience were then listed and characterised based on asset type.
The numbering convention from ROADAPT was also retained in the ICARUS adaptation option database where possible for ease of comparison as shown in Table 2.2.

Table 2.2 Threats and climate parameters as identified in ROADAPT project (Bles et al., 2015)

Main threat	Specific Threat	Climate Parameter	ICARUS CID
01 Flooding of road surface (assuming no traffic is possible)	01-1 Flooding due to failure of flood defence system of rivers and canals	Snowmelt, rainfall in the catchment area, extreme wind speed, wind direction	Wet and Dry – River Flood
	01-2 Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	Extreme rainfall events (heavy showers, long periods of rain)	Wet and Dry - Heavy Precipitation and pluvial flood
	01-3 Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	Sea level rise, extreme wind speed, wind direction (-> storm surge)	Coastal and Oceanic – Coastal Flood
	01-4 Flooding from snow melt (overland flow after snow melt)	Temperature	Wet and Dry – Groundwater Flooding
02 Erosion of road embankments	02-1 Overloading of hydraulic systems crossing the road	Extreme rainfall events (heavy showers, long periods of rain)	Wet and Dry - Heavy Precipitation and pluvial flood

Main threat	Specific Threat	Climate Parameter	ICARUS CID
and foundations	02-2 Erosion of road bases	Sea level rise, extreme wind speed, wind direction (-> storm surge), extreme rainfall events (heavy showers, long periods of rain)	Coastal and Oceanic – Sea Level Rise
	02-3 Bridge scour	Sea level rise, extreme wind speed, wind direction (-> storm surge), extreme rainfall events (heavy showers, long periods of rain)	Coastal and Oceanic – Sea Level Rise
03 Landslips and avalanches	03-1 External slides affecting the road	Extreme rainfall events (heavy showers, long periods of rain), after drought (consecutive dry days)	Wet and Dry - Landslide
	03-2 Slides of the road embankment	Extreme rainfall events (heavy showers, long periods of rain), after drought (consecutive dry days)	Wet and Dry - Landslide
	03-3 Debris flow	Extreme rainfall events (long periods of rain)	Wet and Dry - Heavy Precipitation and pluvial flood
	03-4 Rock fall	Extreme rainfall events (heavy showers, long periods of rain), frost-thaw cycles (number of days with temperature zero-crossings)	Wet and Dry - Landslide
	03-5 Snow avalanches	Frost-thaw cycles (number of days with temperature zero-crossings), snowfall	Snow and Ice – Snow Avalanche
04 Loss of road structure integrity	04-1 Impact on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels	Seasonal and annual average rainfall, sea level rise, extreme wind speed, wind direction (-> storm surge)	Wet and Dry – Mean Precipitation
	04-2 Weakening of the road base by standing water	Seasonal and annual average rainfall	Wet and Dry – Mean Precipitation
	04-3 (Unequal) settlements of roads by consolidation	Drought (consecutive dry days)	Wet and Dry - Hydrological drought
	04-4 Instability / subsidence of roads by thawing of permafrost	Thaw (number of days with temperature zero-crossings)	Heat and Cold - Frost
	04-5 Uplift of tunnels or light weight construction materials by increasing water levels	Extreme rainfall events (long periods of rain), seasonal and annual average rainfall, sea level rise, extreme wind speed, wind direction (-> storm surge)	Wet and Dry - Heavy Precipitation and pluvial flood
05 Loss of pavement integrity	05-1 Cracking, rutting, embrittlement	Maximum and minimum diurnal temperature and number of consecutive hot days (heat waves)	Heat and Cold - Extreme Heat
	05-2 Frost heave	Frost	Heat and Cold - Frost

Main threat	Specific Threat	Climate Parameter	ICARUS CID
	05-3 Aggregate loss and detachment of pavement layers	Maximum and minimum diurnal temperature and number of consecutive hot days (heat waves)	Heat and Cold - Extreme Heat
	05-4 Cracking due to weakening of the road base by thaw	Frost-thaw cycles (number of days with temperature zero-crossings)	Heat and Cold - Frost
	05-5 Thermal expansion of pavements	Maximum temperature and number of consecutive hot days (heat waves)	Heat and Cold - Extreme Heat
06 Loss of driving ability due to extreme weather events	06-2 Reduced visibility during snowfall, heavy rain including splash and spray	Snowfall or rainfall	Snow and Ice - Heavy snowfall and ice storm
	06-3 Reduced vehicle control	Extreme wind speed (worst gales and wind gusts)	Wind – Severe Wind Speed
	06-4 Decrease in skid resistance on pavements from slight rain after a dry period	Drought (consecutive dry days)	Wet and Dry - Hydrological drought
	06-5 Aquaplaning in ruts due to precipitation on the road, splash and spray	Extreme rainfall events (heavy showers)	Wet and Dry - Heavy Precipitation and pluvial flood
	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen	Maximum and minimum diurnal temperature and number of consecutive hot days (heat waves)	Heat and Cold - Extreme Heat
	06-7 Icing and snow	Snowfall, frost and rainfall	Snow and Ice - Heavy snowfall and ice storm
07 Reduced ability for maintenance	07-2 Ice removal costs	Frost	Heat and Cold - Frost
	07-3 Impact on road works: decreased time window for paving	Maximum and minimum diurnal temperature and number of consecutive hot days (heat waves)	Heat and Cold - Extreme Heat

A list of adaptation options for each climate impact driver has been provided to help road authorities to increase resilience to climate change adaptation at all stages of the project life cycle and also aligning with the impact chains defined in ICARUS D1.2 (Garcia-Sanchez et al., 2023) which are as follows:

1. Hazard
2. Exposure
3. Vulnerability
4. Impact

The characterisation and analysis criteria for the adaptation options will be discussed in further detail in Sections 2.3 and 2.4.

2.2.2 NbS adaptation options

World-wide, Nature Based Solutions (NbS) are gaining recognition as key adaptation approaches, because they offer a holistic approach to road infrastructure development that aligns with climate resilience, cost-efficiency, environmental compliance, and sustainability goals. In Europe, NbS is integrated into several policy frameworks like the European Green Deal, EU's Biodiversity Strategy for 2030, and in EU's Strategy on Adaptation to Climate change. Embracing NbS can help NRAs address current and future challenges while simultaneously reaping a range of environmental, social, and economic benefits.

As an adaptation option for the NRA the NbS should directly improve the situation (reduce the impact induced by climatic threats) that is under consideration. Preferably they also provide other co-benefits. There are various types of 'green concepts' where the co-benefits focus on improvements of the natural surroundings/ natural habitat. Such 'green concepts' include amongst others:

- EbA = ecosystem-based adaptation
- Eco-DRR = ecosystem-based disaster risk reduction
- GI = green infrastructure
- BI = blue infrastructure
- GBI = green-blue infrastructure
- UF = urban forestry
- SuDS = sustainable urban drainage systems
- EE = ecological engineering
- BMPs = best management practices
- LID = low-impact design
- WSUD = water-sensitive urban design
- ESS = ecosystem services

See also Figure 2.1, where the concepts are further grouped and classified. As the figure suggests all are collected under the NbS umbrella. The ICARUS project also applies the overarching concept of NbS instead of the detailed definitions.

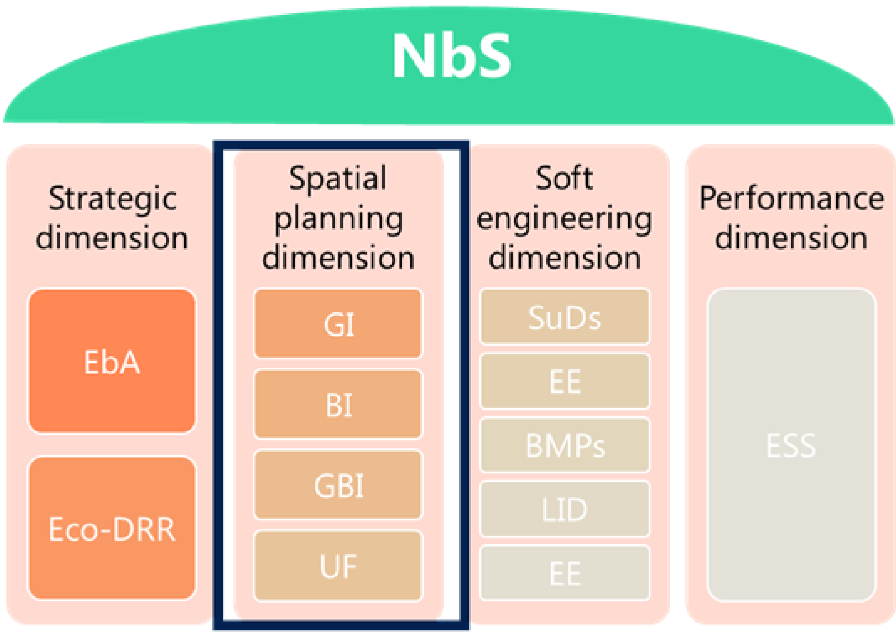


Figure 2.1 Nature-based solutions as an umbrella concept and the relation of NbS to key existing concepts (original figure EC 2021). EbA = ecosystem-based adaptation; Eco-DRR = ecosystem-based disaster risk reduction; GI = green infrastructure; BI = blue infrastructure; GBI = green-blue infrastructure; UF = urban forestry; SuDS = sustainable urban drainage systems; EE = ecological engineering; BMPs = best management practices; LID = low-impact design; WSUD = water-sensitive urban design; ESS = ecosystem services.

Given the broad scope of NbS, it is unsurprising that there are also different nuances/ perspectives in how the concept of NbS is defined. Sowinska-Swierkosz (2022), mentions reviewing 20 definitions of NbS. The article notes that, the main core ideas shared by all definitions are:

- are inspired and powered by nature.
- address (societal) challenges or resolve problems.
- provide multiple services/benefits, including biodiversity gain.
- are of high effectiveness and economic efficiency

Consequently, and because the ICARUS project falls under the CEDR umbrella and is geared towards application in Europe, we have chosen to follow the NbS definition by the European Commission.

"Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions".

This definition was used to identify NbS for the database of adaptation options that has been developed as a part this deliverable. In the database all adaptation options have been evaluated against the question 'Is this a NbS?' with the options 'Yes', 'No' and 'Potentially'. See Section 2.3.1 for details.

2.3 Adaptation Option Characterisation

As described in Section 2.2, the adaptation measures developed in the ROADAPT project were used as a starting point for the ICARUS database of adaptation options. Additional adaptation options were also developed in ICARUS where there were gaps identified. The characterisation of adaptation options used for ROADAPT is a little different to how it is done in ICARUS and so a mapping process was developed to align characterisation of the adaptation options with the terminology and framework used in ICARUS. This is explained in greater detail in Annex C – Mapping of Adaptation Options from ROADAPT to ICARUS.

The characteristics chosen to describe the adaptation options are shown in Table 2.3 along with the complete options for each characteristic. Some of these characteristics were assigned directly based on characteristics from the ROADAPT project, whilst others were "translated" or mapped to terminology used in ICARUS. Other characteristics are new for ICARUS and did not previously exist for ROADAPT.

Table 2.3 Adaptation Options Characteristics

Asset type	Asset Scale: Object / Connection / Network	Road Project Life Cycle Stage	Impact Chain Stage	Disaster Risk Management Cycle Stage	Short / Long Term Solution	Is this a Nature Based Solution?	Can Emerging Technology be applied?	Stakeholders Involved
Geotechnics, including landslips and rock falls, cuts	Object	Initial Proposal Stage	1. Hazard	Prevention	Short term (operational and tactical)	Yes	Yes	National Road Authority
Drainage of earthworks and pavements, sewers	Object - Connection	Appraisal Stage	2. Exposure	Preparedness	Long term (tactical and strategic)	No	No	Local Authority
Pavements: bituminous, concrete, semi-rigid	Object - Connection - Network	Planning and Detailed Design	3. Vulnerability	Response		Potential		Environmental Agencies
Pavements: bituminous, semi-rigid	Connection	Construction	4. Impact	Recovery				Meteorological organisations
Bituminous pavements	Connection - Network	Operation and Maintenance		All				National Health Services
Concrete pavements	Network							Department of Defence
Semi-rigid pavements								Government Ministries
Brick pavement								Infrastructure Owner
Unpaved roads								Infrastructure Operator/ Manager
Mobility services								Road Users
All road infrastructure								Other affected members of the public (community groups etc.)

Asset type	Asset Scale: Object / Connection / Network	Road Project Life Cycle Stage	Impact Chain Stage	Disaster Risk Management Cycle Stage	Short / Long Term Solution	Is this a Nature Based Solution?	Can Emerging Technology be applied?	Stakeholders Involved
Tunnels, low lying stretches and light weight embankments								Planning Authority
Structures: bridges, culverts, tunnels, retaining walls, restraint systems, gantries, masts								
Signs and signals, CCTV systems, emergency systems, lighting, road markings								
Non-motorized users' facilities								

2.3.1 Characterisation of Nature based Solutions (NbS)

The criteria used to classify a measure as NbS is directly derived from the NbS definition by the European Commission given in section 2.2.2. Hence, for an adaptation option to be labelled as NbS it must fulfil all of the following NbS sub-criteria:

- Is the measure inspired and supported by nature?
- Is the measure cost effective?
- Does the measure simultaneously provide environmental, social and economic benefits?
- Does the measure help build resilience?

If one of the answers to the above questions is 'no' the measure is not labelled as a Nature based Solution.

Even with these sub-criteria the characterisation of the adaptation options has not been straightforward, because several are ambiguous (i.e. what does 'inspired and supported by nature' actually entail?) so is some of the adaptation options, and in most cases the context, i.e. where the adaptation option is to be implemented, need to be taken into account, in order to evaluate if there are any significant environmental, social and economic benefits. This is sought addressed by defining three different classifications in answer to the question 'Is this a NbS':

- 'Yes': all answers to the NbS sub-criteria questions are 'yes'.
- 'No': at least one answer to the NbS sub-criteria questions is 'no'.
- 'Potential': depends on how the measure is implemented.

The diagram in Figure 2.2 describes the applied NbS characterization.

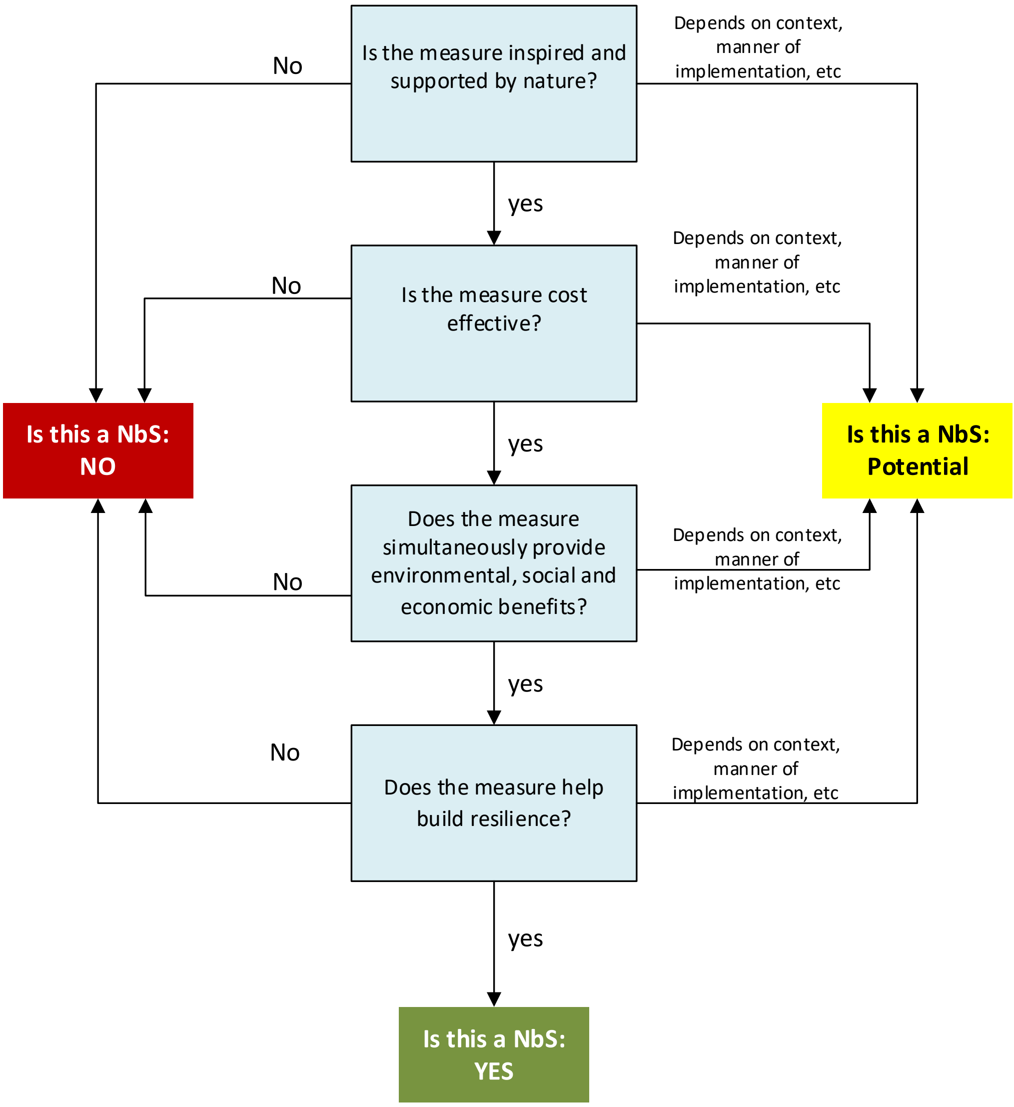


Figure 2.2 Diagram showing the questions asked in the NbS characterisation process.

Measures that are described as 'Development of plans…' are an example of measures that have 'NbS potential'; depending on how the plans are implemented, such a measure may lead to making the case for NbS measures. For all options classified as 'Yes', there should be a deliberate focus in the design process on maximising the NbS benefits (environmental, social, and economic benefits). As an example, 'Protection of wind exposed road sections and assets with planted forests and other vegetation', can be realized in many different ways and the benefit for i.e. biodiversity will depend on the tree and vegetation species and the design of the landscape.

In the Excel database of adaptation options, the user will find three columns related to NbS. Where the column 'Is this a NbS' contains the three classifications described above as filtering options. All options classified as 'yes' have an associated reference in the 'NbS Evidence Base' column. These references are also given in Annex A with additional information on their content and recommendation. All options classified as 'Potential' have an associated comment in the 'NbS Comment' column, that clarifies how the potential can be realized.

For NbS many different aspects influence the decision-making process, including the benefits and co-benefits the solutions bring (see Section 2.4.1) and the stakeholders involved to realize these.

2.3.1.1 Additional considerations

Some additional considerations for NbS are given below:

As mentioned above the definition of NbS leaves some ambiguity to the extent in which a measure is actually a NbS. This is due to the fact that the NbS questions (see Figure 2.2) do not all lead to measurable answers. In other words, there is always an amount of subjectivity in the characterisation.

Alternatively, this also means that some measures may be characterised as NbS if there is sufficient focus maximizing the 'green aspects' on NbS i.e. 'inspired and supported by nature'. The following example is used to identify some of the additional considerations for NbS:

For example, if a slope is prone to landslides/ rockfall, various types of measures can be taken, amongst others to stabilize the surrounding area. This can be done by implementing retaining structures, netting, driving anchors or planting vegetation to stabilize the slope through a mature root system. The range of solutions shows that there are more and less 'green' ways to do this and that 'stabilizing the surrounding area' has the potential to be an NbS but that this depends on how the measure is designed and implemented in practice.

Note that in this example the effectiveness of the chosen measure also depends on the specific situation. Also note that the effectiveness of 'planting vegetation to stabilize the slope through a mature root system' also requires time for the root system to become effective. Potentially this can take years, depending on the type of vegetation and the specific location. Finally, many NbS requires a different type of maintenance schemes compared to the more traditional solutions. If these are not in place the NbS cannot fulfil the purpose it was designed for and/or provide the long-term benefits and co-benefits.

Also, depending on the extent of the slope, the area to be stabilized may fall outside of the jurisdiction of the road authority. Especially for measures that require a lot of area to become effective this can provide additional challenges for implementation.

ICARUS Deliverable 4.2 on NbS will provide advice on how these aspects can be addressed.

2.3.2 Characterisation of Emerging Technologies

Emerging technologies in climate adaptation for road infrastructure represent innovative solutions aimed at addressing the challenges posed by climate change on transportation systems. In this perspective, emerging technologies include concrete measures and tools, such as drones used for surveillance and climate-resistant materials, as well as strategic data processing methods. These technologies can be utilized as new adaptation options to enhance existing adaptation options or to collect information for planning the use of conventional methods in various environments.

A key challenge in designing functional and effective climate adaptation lies in the unpredictability of varying climate conditions and the road network environment. In this scenario, emerging technologies can be employed for data mining and simulating possible scenarios with significantly less effort compared to person-hours, but there are many other possible applications. To simplify the evaluation, emphasis is put on four different classes of Emerging technologies:

1) Engineering advances: This class covers new inventions, like Asphalt Solar Collectors (Bobes-Jesus, et al., 2013) or innovative materials, such as thermal-resistant asphalt (Wang et al., 2018).
2) Monitoring techniques: This class covers a wide range of data collection technics, both including physical sensors, drones and other means of aerial photograph like (Shift2Rail, 2016; Ramboll - National Highways, u.d.). Similarly, within the area of monitoring techniques, it is an emerging technology to utilize information available from IoT (internet of things). This covers digital 'everyday' devices like mobile phones and surveillance cameras that, through their internet connection, can send and receive data (MistraInfraMaint, u.d.). Recent experience from the railway industry indicates a shift toward remote monitoring systems which act as a warning system to make operators aware when the infrastructure becomes compromised due to a climate event or other hazards (GoSAFE Rail, 2018). These types of systems are not used to predict failure or optimise lifecycle analysis, but instead provide an indirect resilience enhancement by allowing trains to be stopped if the infrastructure may not be fully serviceable. Members of the ICARUS consortium have worked in this space designing failure warning monitoring systems including tilt sensors for embankment / cutting failure, accelerometers and inclinometers to monitor bridges which may undergo scour failure following a flood, as well as flood monitoring equipment to inform operators when the track becomes inundated. As an additional benefit, these monitoring systems may also be designed with optimised lifecycle analysis in mind in order to allow specialised engineers to make use of the available data.
3) Digitalisation: The most well-known example of an emerging technology within digitalisation is the concept of 'Digital twins'; digital copies of the physical world, where scenarios can be tested. Digital twins can be constructed for whole cities (Goteborgs Stad, 2024) or for process plants (Stjepandić et al., 2024). Without reaching the level of a digital twin, many companies work with digitalization strategies to make all kinds of data assessable for analysis and decision making.
4) Artificial intelligence and machine learning: These technologies encompass software that imitates the human learning process, and hence via training can learn to recognise patterns in very extensive dataset, make predictions on this basis or even create new content. The infamous chatGPT in an example of the latter. This class is often combined with monitoring and/or digitalization techniques that collects extensive data material. Specific examples of applied machine learning covers processing satellite images and predicting biodiversity development (Ramboll – National Highways, u.d.), creating forecasts of water consumption (Ramboll – Smarter Water u.d.).

In the Excel database of adaptation options, the user will find two columns related to EmT. All adaptation options are classified according to the question 'Can Emerging technologies be applied?', if 'yes' the type/types of EmT are given in the 'Emerging Technology Comment' and for Engineering advances a reference is given. All these references are also given in Annex B. Note that for some adaptation options, several emerging technologies can be applied.

2.4 Multicriteria Analysis

As described in ICARUS Deliverable 3.1 (Fonseca et al., 2022), there are many evaluation methods which can be used to assess the most appropriate adaptation option to suit the needs and requirements of the road authority. Cost-benefit analysis, life-cycle costing, or multi-criteria analysis can all be used to support the decision-making process. In this case, since accurate costs are difficult to estimate at the time of preparation of the database, a multi-criteria analysis was chosen to be the most appropriate way of assessing the adaptation options. In this way, all the necessary information may be viewed together in the database in a structured way, and comparisons may be made easily.

Following characterisation of the adaptation options as described in Section 2.3, they were then assessed under several categories. These categories are sub-divided into:

- Benefits and Co-Benefits (as described in ICARUS Deliverable 2.2 (Bles, Fonseca, et al., 2023));
- Additional Criteria, based on (Bles, van Marle, et al., 2023); and
- User Inputs.

These categories will be described in greater detail in the following sections.

2.4.1 Benefits and Co-Benefits

The multicriteria analysis was developed based on the benefits and co-benefits defined in Table 5.1 of ICARUS Deliverable 2.2 (Bles, Fonseca, et al., 2023), as well as additional criteria which were deemed to be beneficial to road authorities in selecting climate change adaptation options. The benefits and co-benefits were evaluated to have a positive effect, negative effect or no change from the current situation and assigned a score of +1, -1 or 0. The scores attributed to the adaptation option evaluation criteria in the provided database are to be used as guidance only and will be dependent on several factors such as road authority maturity level, asset type, climate impact driver and local circumstances. The scores may be updated by the road authorities or infrastructure managers to reflect their situation more accurately.

The benefits and co-benefits along with scoring criteria are listed in Table 2.4.

Table 2.4 Benefits and co-benefits as presented in ICARUS D2.2 (Bles, Fonseca, et al., 2023)

Benefit/Co-benefit	Negative effect, -1	Neutral / no change, 0	Positive effect, +1
Availability	Decreased network availability	No change	Increased network availability
Durability	Decreased asset durability	No change	Increased asset durability
Impact on Safety	Increase in no. of collisions	No change	Decrease in no. of collisions
Impact on Health	Negative health impacts	No change	Positive health impacts
Ecosystem Services	Decrease in level of greening of area	No change	Increase in level of greening of area
Water Quality	Decrease in water quality	No change	Increase in water quality
Climate: Embodied Carbon	Increase in carbon emissions	No change	Decrease in carbon emissions

2.4.2 Additional Criteria

The additional criteria were selected to assist infrastructure managers and road authorities in their decision-making processes and were based on the model presented in (Bles, van Marle, et al., 2023). The scoring mechanism is explained in Table 2.5.

Table 2.5 Additional Criteria and scoring

Criterion	Negative effect, -1	Neutral / no change, 0	Positive effect, +1
Maintainability	More difficult to maintain than current	No change	Easier to maintain than current
Impact on Reputation / Politics	Negative impact	No change	Positive impact
Road User Experience	Negative impact	No change	Positive impact
Flexibility	Not easy to switch to another option	Neutral	Can easily switch to another option
Robustness for Future	No capability to cope with future events	Neutral	Increased ability to cope with future events

2.4.3 User Input: Costings and Organisational Parameters

The final part of the adaptation options multi-criteria analysis is the User Input section which includes costings and other organisational information. This section has purposely been left blank as it is impossible to predict in advance how each measure will compare with others and the current scenario in place. These will vary by organisation, and by asset, and are best completed by the user once the adaptation options have already been narrowed down. The costs have been split into CAPEX and OPEX costs, where CAPEX costs refer to Capital Expenditure costs, and OPEX refers to Operating Costs. The user inputs and scorings are shown in Table 2.6.

Table 2.6 User Input Section

Criterion	Negative effect, -1	Neutral / no change, 0	Positive effect, +1
CAPEX Costs	-3: High cost; -2: Medium cost; -1: Low cost; 0: No cost		
OPEX Costs	More expensive than current costs	No change	Cheaper than current costs
Cost of do-nothing scenario	More expensive than current costs	No change	Cheaper than current costs
Organisational Experience	No prior Experience	Capability exists but no prior experience	Prior experience
Is Legislation Required?	Yes	No	-

2.5 Summary

In summary, all adaptation options have been assessed using multi-criteria analysis under a large variety of categories related to their own properties, benefits and co-benefits they bring, as well as user information in relation to costs and other organisational information.

The user information has been left blank for the user to complete as this will differ for each organisation and cannot be known prior to use of the database.

Users may filter information on the database to select adaptation options that suit their organisation's needs, prioritising cost, co-benefits or other criteria.

3 Identification of knowledge gaps and barriers to implementation, and Proposed Solutions

To implement climate change adaptation, it is important for road authorities to identify why it's important, what's driving the change, and what gaps and barriers there are to implementation. These may be internal, coming from within the organisation, or external, from outside the organisation, such as government policy, funding etc.

In this chapter, drivers for implementation, knowledge gaps and barriers to implementation are reviewed, as well as potential solutions to removing the barriers using emerging technologies.

3.1 Identification of Knowledge Gaps and Barriers to Climate Change Implementation

All processes involving change may be hindered by barriers or obstacles. Barriers to implementation of climate change adaptation may be defined as challenges or obstacles which delay the implementation of climate change adaptation (PIARC, 2023).

Several barriers have been identified through literature review and discussions with Project Executive Board (PEB) members through two workshops; one which took place in June 2023 where five members of the PEB completed online questionnaires, followed up with discussion, and secondly at the ICARUS workshop in held in person in November 2023 where again members of the PEB shared experiences and concerns around barriers. These are presented in the following sections, together with general findings from the literature.

3.1.1 Literature

A number of researchers have studied the barriers that exist which prevent or impede adaptation planning. Lehman et al (Lehmann et al., 2015), developed a framework characterising factors influencing the decision-making process based on expert interviews they conducted. They classified the barriers as three main categories which were also presented by PIARC (PIARC, 2023):

- Lack of Information [Information] consisting of lack of information on climate impact drivers, climate projections, data on infrastructure, adaptation options, no KPIs to monitor benefits of adaptation etc.;
- Lack of Resources [Resources] consisting of financial as well as personnel (expertise and time); and
- Lack of Incentives on which decision-makers act [Organisation], such as co-benefits, lack of awareness at decision-making levels, lack of corporate understanding, or organisational culture that does not support change.

Furthermore, these were then grouped under three additional classes including personal traits of the decision-maker themselves, the organisation, including governance system and wider environment, and the socio-economic environment by Lehman (Lehmann et al., 2015).

3.1.2 Workshop (June 2023)

In June 2023 a workshop was held with five members of the Project Executive Board (PEB) to gain an understanding of the barriers that they face with implementation of climate change adaptation in road authority organisations. A questionnaire was issued to the attendees seeking information on what the barriers and challenges they see in the implementation of climate change adaptation.

There were several common themes with the primary barriers emerging as:

1. Costs/funding. [Resources]
2. Lack of longer term planning. [Organisation]
3. Lack of climate change adaptation knowledge [Information]
4. Incomplete asset information/data [Information].
5. Lack of engagement across the NRA and difficulty in getting buy-in. [Organisation]

Although this workshop was conducted with a small sample number, the barriers identified align well with those seen in the literature which have been assigned in square parentheses [] alongside the responses in the list above.

The barriers were seen by the respondents as both internal and external to their organisations and existing mostly at the Strategic and Operational levels of the organisation. There was general agreement that legal barriers were not a factor, aligning with barriers presented in the literature, but all either agreed or strongly agreed that organisational barriers do exist. Again, in line with the literature, monitoring wasn't seen to be a barrier while some agreed and some disagreed that operational barriers exist, classed as organisational in the literature.

3.1.3 ICARUS Workshop with PEB members (November 2023)

In November 2023, an ICARUS workshop was held in Cardiff, and during this workshop, barriers to implementation of climate change adaptation were discussed with members of the PEB who were present at the meeting. Again, some similar issues to those seen previously were highlighted, particularly around lack of data / information, and lack of resources, but additional issues also arose, such as managing risk and scope in the procurement process (organisation), and ensuring that climate change adaptation is balanced alongside cost.

Additional questions / issues that arose were as follows:

- What climate change scenario should we follow? [Information]
- What level of adaptation to choose? [Information]
- How can the procurement process be managed to reduce risk and increase specificity of scope delivered? [Organisation]
- How to consider climate change adaptation when reviewing tender submissions? [Organisation]
- How to address safety? [Information]

3.1.4 Summary of Barriers

There were many common themes amongst the literature and feedback from NRA members mainly again following the three main barriers of lack of information, lack of resources, and organisational barriers such as difficulty in getting buy-in from decision-makers. The complete list of barriers found is as follows:

- Lack of Information consisting of:
  - Lack of information on climate impact drivers, climate projections, climate adaptation knowledge including adaptation options;
  - Information and data on infrastructure / assets, including as-built information;

- KPIs to monitor safety, benefits of adaptation etc.
- Lack of Resources consisting of financial as well as personnel (expertise and time); and
- Organisational Barriers such as:
    - Lack of Incentives on which decision-makers act, such as co-benefits;
    - Lack of awareness or understanding at decision-making levels;
    - Lack of longer-term planning;
    - Organisational culture that does not support change.
    - Difficulties in specifying appropriate detail during procurement process.

In the next section, solutions will be proposed to assist barrier removal.

3.2 Overcoming Barriers to Climate Change Adaptation

Why is it important for road authorities to implement climate change adaptation? The reason or driver for change may vary depending on the location and maturity level of the road authority, and these may provide solutions to some of the identified barriers. The primary drivers to implementing climate change adaptation, were identified in ICARUS Deliverable 2.2 (Bles, Fonseca, et al., 2023) and are summarised as follows:

- Maintaining network performance and service levels into the future and meeting KPIs.
- Government Direction: In most countries, the road authorities are accountable to a Department for Transport or similar Government ministry. As governments have potential to change every four or five years, the policies and direction may also change, leading to a greater or lesser focus on climate change resilience.
- Road Authority reputation / Public Image: If the government or road authority has made decisions or developed policies in certain areas, then the need to implement climate change adaptation may become more or less important for them. If sustainability is a core aspect of government policies, then adaptation options which are Nature-based Solutions (NbS) may be more favourable to ensure consistency with the policies.
- Budgets: The amount of available budget to spend on climate change adaptation will certainly govern whether it is implemented, and what measures. This may vary from country to country, as some schemes may be more affordable in some countries than others. Often, climate change adaptation measures may not seem cost effective in the short term, but taking a longer term view may increase the argument for climate adaptation.
- Compliance with national strategies and / or policies such as climate change adaptation policies where road authorities may have to achieve a certain level of climate resilience within a specific timeframe.
- NRA Maturity and Priorities: The level of maturity of the NRA and the age of network infrastructure may also influence whether or not climate change adaptation is a priority. A more mature NRA may be more likely to implement climate change adaptation options and more specifically Nature Based Solutions.

A change in government towards a leadership who are more focused on green principles, for example, may enhance the case for the NRA to make for increased funding for implementation of Nature-based solutions to enhance their road network. Or a more mature NRA in a geographic location where climate change is anticipated to impact severely may allocate additional resources towards climate change adaptation measures. And so depending on what the drivers for climate change adaptation are locally, they may help the NRA in overcoming some of the barriers identified in Section 3.1.

3.2.1 Solutions to Overcome Barriers

Along with solutions proposed by the ICARUS team, the PEB members made some interesting suggestions as to how these barriers could be removed. These solutions are recorded in addition to those proposed by ICARUS team members and presented in Table 3.1. There are opportunities for emerging technologies to assist particularly in areas where there is a lack of information. Where emerging technologies have been identified to assist with barrier removal, these have been highlighted *in italics*.

Table 3.1 Proposed solutions to barriers to climate change adaptation with emerging technology solutions in italics

Barrier		Proposed Solutions
Lack of Information	Lack of knowledge / information on climate Change Adaptation	Road Authorities should review national climate change guidelines if they exist as this will vary by jurisdiction. See ICARUS deliverable D1.1 for guidance. The service life of the asset should be considered, and then an appropriate scenario suited to the life-span should be chosen. If the asset has a longer service life (30 years for example), then a wider range of scenarios should be considered. Further guidance on this is given in the ROADAPT project (Bessembinder, 2015). The level of adaptation to follow will depend on national policies, available resources, and level of engagement of the organisation. Adaptation will require multi-disciplinary teams to work together, which can take time to align processes and even the language used (Veerkamp et al., 2021). Following the three approaches in D2.2, may assist in providing arguments for a certain level of adaptation. See also examples of case studies on ICARUS website, reference lists provided in adaptation options database, and examples in literature for guidance (Cork County Council, 2019). Standards and specifications need to include specific details on climate change adaptation and how adaptation options may be implemented. Detailed information on what materials should be used as well as detailed drawings and methodologies are needed so that road authorities can specify how it should be completed. Unless these are available for the contractor, then the finished result may not be as required.
	Lack of Asset Information	*Increase Infrastructure Monitoring Data. Digitalization can greatly improve system data overview, ultimately in the form of a digital twin.* *AI and automation can help to keep the digitalized system data up to date.* Require contractors / sub-contractors to send back as-built drawings prior to final payment. Maintain up to date asset management systems.
	Lack of information on system network performance	*Lack of knowledge on the system performance can be reduced by monitoring campaigns using; drones, satellites, or some of more agile approaches for collecting data (like google maps, mobile apps and Internet of things)* *Methods like Data Analytics and Predictive Maintenance can help road authorities predict infrastructure vulnerabilities and prioritize maintenance and repair activities to ensure road safety and resilience using big data analytics and AI and machine learning algorithms. This also includes processing observations and making forecasts.*

Barrier		Proposed Solutions
	Lack of KPI information	Use asset monitoring data and traffic data to analyse KPIs on Safety, Asset Condition etc. Keep asset inspection and maintenance data up to date to assist with this. The correlation between extreme weather / natural hazards and safety is qualitatively understood, but a quantitative understanding is not known. Understanding this in a quantitative way is essential to be able to monetize effects of adaptation options on safety and will most likely enhance the decision case. It is recommended to conduct research on how safety is affected due to climate events.
Lack of Resources	Lack of Skilled Personnel / Financial Resources	Use guidance in ICARUS deliverables to help build business cases and support argument to attain increased resources for implementation of climate change adaptation (Bles, Fonseca, et al., 2023). *With innovative solutions driven by emerging technologies, it might be easier to help ensure funding, by innovation funds or partnerships making pilot projects.*
	Lack of funding	Highlight the long-term costs and effects of a changing climate of no adaptation measures are taken, to help change the prioritization of available resources. *Different emerging technologies can help reduce the cost:* *AI and machine-learning can help reduce the number of manhours during the design process. The adaptation options where this potential can be present is classified accordingly (see section 2.3.2).* *Engineering advances can reduce the construction cost directly, reduce the maintained cost and/or prolong the service life, or reduce the cost indirectly by providing additional benefits. Examples are new inventions, like Pavement Solar Collectors and heat-reflecting surfaces (Sen & Khazanovich, 2021). New materials like metal alloys, climate resistant material (Wang et al., 2018) and low CO_2 concrete.* *Furthermore, technologies are developed to enhance possibility for recycling and/or reuse of materials.* *Being more a strategy than a technology, cost reduction can also be obtained by optimizing the use of space and create multi-functional solutions*
Organisational	Lack of engagement / awareness	Build awareness within organisation through presentations to staff at strategic level. Ensure that any adaptation implementation is recorded as such.
	Lack of planning	*Data collected and processed to help improve the knowledge on climate hazards and climate performance can help the long-term planning.*

Barrier		Proposed Solutions
	Lack of buy-in from other stakeholders	Involve other stakeholders e.g. landowners or members of the community at an early stage to ensure buy-in to projects.
	Challenges in Procurement Management	To reduce the risk of unsatisfactory work being delivered, it is important that climate change adaptation options, and Nature-based Solutions in particular, are specified in great detail in tender documents. Road authorities can find guidance and some examples within the database provided and are encouraged to review evidence of examples provided which can help with specification. It is important to ensure that as-built drawings and information is also provided at the end of a project or upgrade. Withholding part-payment for example until these are delivered can assist in ensuring that this information is made available for operation and maintenance of the infrastructure. Regulations need to be adapted to include climate change. In a lot of organisations, current regulations only state for instance that climate change adaptation must be considered. How this needs to be done should be included in the technical standards. Therefore, adaptation should be part of the technical documents which must be followed by contractors. The decision framework in Chapter 4 provides guidance.

For each barrier and for each adaptation option the actual EmT potential is content specific. The Adaptation Options Database can help point towards solutions where the EmT potential is present, which in turn can help bring down barriers. Engineering advances especially target the resource barrier by providing potential savings (lower cost of adaptation and/or higher impacts); monitoring techniques target the information barrier by bring more data and better grounds for decision making, which in turn can reduce the organisational barriers as well; digitalisation also targets the information barrier by bringing more systematic system overview; artificial intelligence and machine learning can reduce cost and bring down the resource barrier, but also target the information barrier by analysing extensive data material and thereby providing better grounds for decision making.

Several guides exist that can serve as an inspiration for the steps to go though in the evaluation of the realisable EmT potential. With these a simple roadmap for EmT assessment could be:

- Outline purpose of EmT, what do you expect to obtain?
    - Is EmT the only solution to remove the barrier or what are the alternatives?
- Assess available data on the EmT implementation.
- Assess gaps and barriers for the EmT implementation.
- Assess potential of the EmT benefits.
- Time plan for implementation, assess how quickly are the benefits realized.

3.3 Summary

Through literature searches and discussions with PEB members, it is clear that the barriers to implementation of climate change adaptation are relatively common amongst road authorities, regardless of geographic location or level of maturity of the organisation. The key barriers are lack of information, lack of resources, and organisational constraints such as lack of awareness or buy-in to climate change adaptation. A number of potential solutions to these have been proposed and are summarised in Table 3.2 below. Emerging technologies may further aid in overcoming the barriers. The ICARUS database of Adaptation Options might help identify adaptation with a high potential for emerging technologies, these may be reviewed and assessed using the various parameters for multicriteria analysis embedded in the database (see Section 2.4), selecting those options which satisfy the priorities of the user's organisation.

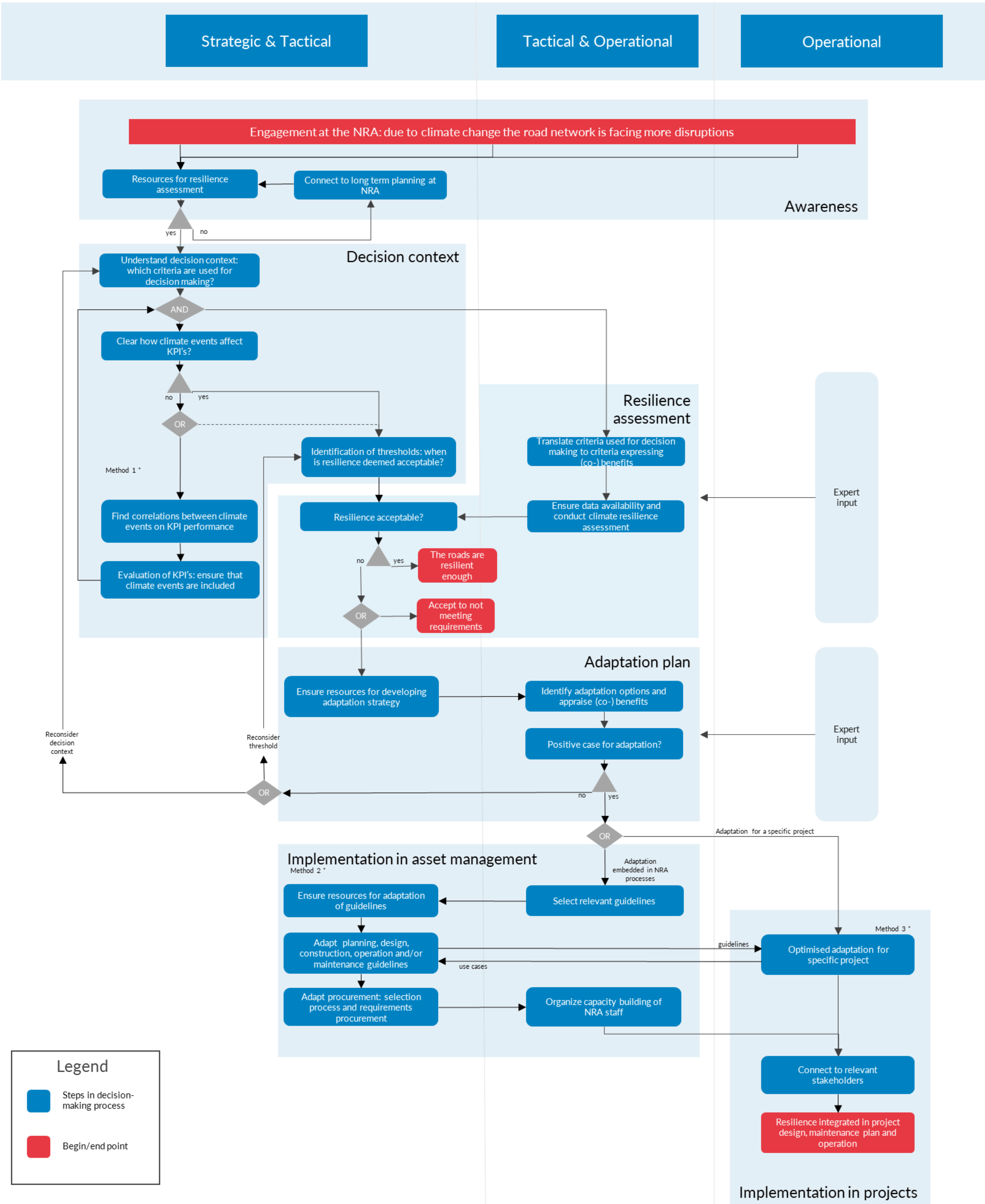
Table 3.2 Summary of Solutions to Climate Change Implementation Barriers

Barrier	Solution
Lack of Information	
Lack of knowledge / information on climate Change Adaptation	Review national climate change guidelines if they exist. Consider service life of the asset.
Lack of Asset Information	Increase asset monitoring data.
Lack of information on system network performance	Implement monitoring campaigns using; drones, satellites, or some of more agile approaches for collecting data (like google maps, mobile apps and Internet of things
Lack of KPI information	Use asset monitoring data and traffic data to analyse KPIs on Safety, Asset Condition etc. Keep asset inspection and maintenance data up to date to assist with this.
Lack of Resources	
Lack of Skilled Personnel / Financial Resources	See guidance in ICARUS deliverables to assist in building business case for adaptation implementation.
Lack of funding	Emerging Technologies can help reduce costs of manhours.
Organisational	

Lack of engagement / awareness	Build awareness within organisation through presentations to staff at strategic level.
Lack of planning	Data collected on climate hazards and climate performance can help the long-term planning.
Lack of buy-in from other stakeholders	Involve other stakeholders e.g. landowners or members of the community at an early stage to ensure buy-in to projects.
Challenges in Procurement Management	Adapt regulations, include climate change adaptation in tenders, include specific detail on nature based solutions.

4 IMPLEMENTATION OF CLIMATE CHANGE ADAPTATION

This chapter covers guidelines on how to Practically Implement Climate Change Adaptation in the NRA processes, using the ICARUS adaptation implementation process (below); a step-by-step process covering different organisational levels in the NRA. The symbols are explained in Table 4.1 on the next page. A larger version of the figure is to be found in Annex D.



ICARUS

Figure 4.1 ICARUS adaptation implementation process

Table 4.1 Symbols used in ICARUS Implementation Process

Red box	Begin / End Point – states starting point and end when adaptation is completed
Large blue box	Each of the five building blocks with processes contained within
Dark blue box	Each of the individual steps in the decision-making process
no yes	Decision gate to determine whether to proceed or return
AND	AND-gate indicates that process goes two ways that should both be followed
OR	OR-gate indicates a choice of two options as the next step
←	Arrow in any direction to determine process to take, or input / information required
Method 1/2/3	Refers to the three approaches that are recommended in D2.2 (Bles et al, 2023)

4.1 Introduction to ICARUS process for implementing climate adaptation

The ICARUS adaptation implementation process is designed to help road owners and operators understand the steps needed to integrate climate change adaptation in their daily processes. It does this by understanding the context in which decisions regarding climate change adaptation are made. Here, we present the process in which the resilience assessment and development of an adaptation strategy are positioned in line with this decision context. Barriers for implementation as well as solutions to overcome these are integrated in the process. The final integration in NRA operations may be on the asset management level, leading to climate change integrally being considered in planning, design, construction, maintenance, rehabilitation and operation as well as in procurement. Final integration may also take place via individual projects.

4.1.1 Involvement of different levels of the NRAs

Implementation of climate change adaptation is a process in which all organisational levels of the NRA are and should be involved. These levels consist of the strategic, tactical and operational levels at the NRAs, as have been introduced in D2.2 (Bles et al., 2023). When implementing adaptation, it is necessary to understand at what level of the organisation specific actions are performed. This is visualised in the presented process with three columns, the position of the boxes within the columns indicates whether that part of the process is undertaken largely at 'strategic and tactical levels' at 'tactical and operational' levels, or purely at an operational level.

It is recommended that a single level within the NRA is in the lead for the entire adaptation implementation process to keep track of progress. For most NRAs this would probably fit best at the tactical level.

4.1.2 Building blocks of the process

The implementation process consists of five main building blocks. These are:

1. Awareness
2. Decision Context
3. Resilience Assessment
4. Adaptation Plan
5. Implementation (at asset management or project level)

Within each of the five boxes, there are several steps or processes that need to be followed. At various stages between the boxes, there are assessments to be made or inputs to be provided. In some cases, feedback loops exist for situations when implementation is becoming bothersome. Finally, decision gates exist where one of the boxes needs to be refined before proceeding to the next step. The process is uniformly visualised using symbols, which are explained in Table 4.1.

As the framework starts with awareness and decision context, it is applicable for NRAs with different levels of maturity regarding resilience and adaptation of infrastructure to climate change. It is also suitable for NRAs considering implementation on a specific project, e.g. a road section or asset, or those considering implementation as part of their asset management processes. As the level of maturity increases, it is likely that asset management will support the implementation in projects, whilst project learnings will inform revisions to asset management.

4.2 Goals of the ICARUS adaptation implementation process

The goals of the process are as follows:

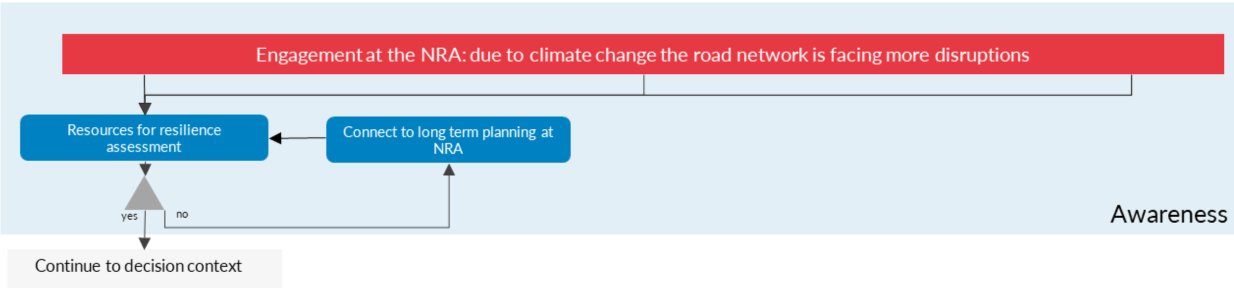
- Provide a holistic overview of the start-to-end process for implementing climate change adaptation in the daily processes of road authorities.
- Be applicable to NRAs with advanced resilience assessment and climate adaptation processes and those with less experience.
- Provide key recommendations on which part of the NRA (strategical, tactical, operational) will be in the lead or key stakeholders for different stages of the process.
- Provide comprehensive information on resources and information requirements at each stage of the process.

One key step in the ICARUS adaptation process is the execution of a resilience assessment, both for a *business-as-usual* scenario as well as for a scenario with adaptation. The process described here is not intended to include detailed guidance on how such an assessment needs to be done. Many frameworks have been developed in past research and are publicly available. An overview of these frameworks is provided in D2.1 (De Jonge et al., 2022).

4.3 ICARUS implementation process explanation step by step

The five main building blocks are described in more detail below.

4.3.1 Awareness



Aim	To ensure awareness and engagement throughout the NRA that the consequences of climate change on the road network should be analysed to understand whether action is needed. Without a clear awareness, implementation will be very difficult to achieve.
Enablers	All levels (strategic, tactical and operational) of the NRA should be engaged. The resources and long-term planning should be initiated by the strategic and tactical level.
Barriers	In some NRAs there may be a lack of resources (both financial as well as personnel --expertise and time) Some NRAs lack a longer-term planning regarding climate change adaptation
Outcomes	Engagement of the people involved at the different levels of the NRA and a common understanding on why climate change adaptation should be part of NRA processes.

Description of the steps

Engagement at the NRA: due to climate change the road network is facing more disruptions

This first building block of the implementation of climate change adaptation in NRAs processes starts with the Engagement within the NRA. The engagement is characterised by the involvement of all levels of the NRA (strategic, tactical an operational) and provides the boundaries to start with implementation. Without this first step the NRA might encounter problems when implementing adaptation plans in asset management or in projects. The outcome of this first step includes a common understanding that climate change is happening and that it is likely to affect the performance of the road network. It also results in a clear overview of the people involved at the different levels of the NRA.

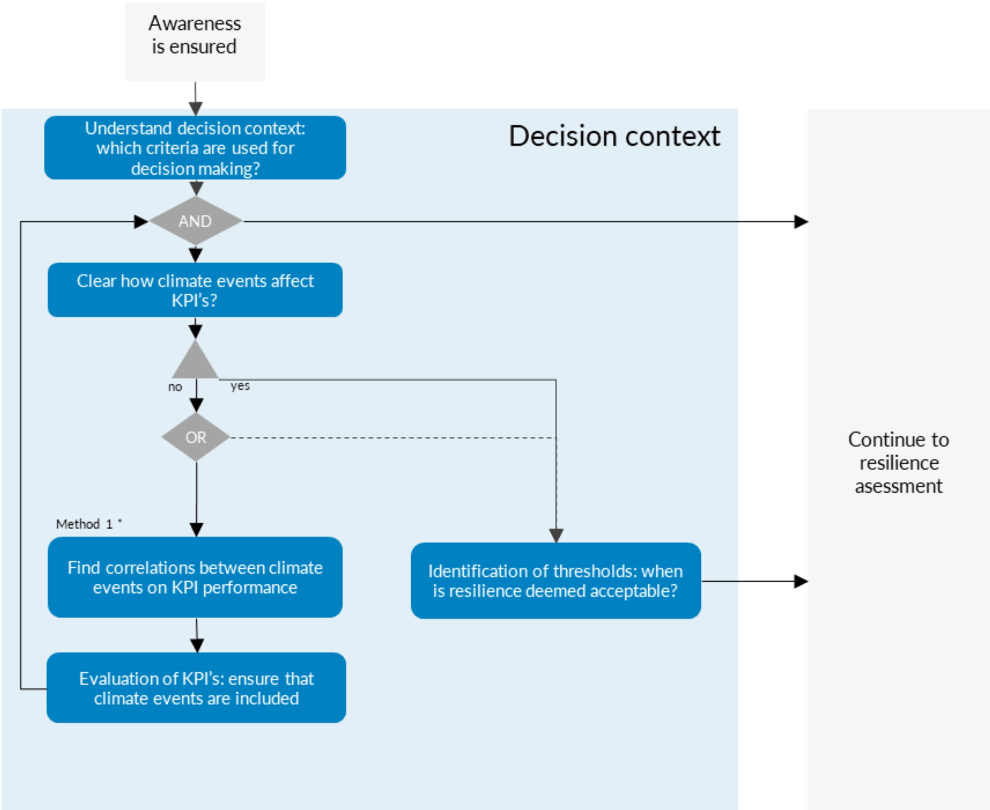
Resources for resilience assessment

The next step is to ensure that resources to perform the resilience assessment are available. Although the execution of the resilience assessment is at a later stage. The resources – both the financial as well as the expertise in knowledge and time – should be ensured in time to prevent delays in implementation.

Connect to long term planning at NRA

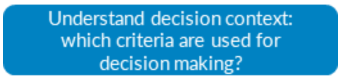
In case resources are not available, one way to organise these is to connect to long-term strategy at the NRA in terms of for example maintenance, renewal, developments of the road network. This way it can be made clear that climate change may affect these. This can then give the rationale that research is needed. It might be that climate change adaptation is not yet part of the long-term plans, which means that this should be developed. In case climate change adaptation is part of the longer-term strategy, this could be a rationale to allocate the funding to perform the resilience assessment.

4.3.2 Decision context

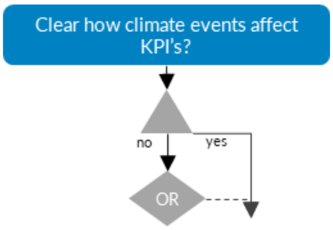


Aim	To have a clear understanding of the decision context within the NRA and how climate events are embedded in KPIs and what thresholds determine acceptable levels of resilience.
Enablers	Expertise is needed to find correlation between climate events and KPIs and which thresholds are acceptable. This involves policy makers as well as the strategic and tactical level of the NRA. Also experts on data analysis and statistics will be necessary.
Barriers	A lack of understanding on how climate effects are embedded in NRAs decision criteria
Outcomes	Clarity on which steering mechanisms are used for decision-making within the NRA, what are the KPIs used as decision criteria and how they are related to the climate indicators, and which thresholds are used to decide when resilience is acceptable or not.

Description of the steps



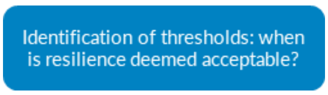
For each NRA it is essential to understand the decision context (D2.2, Bles et al., 2023). More specifically, which criteria are used for decision making. It is important to have these criteria clear before starting with the resilience assessment or development of the adaptation plan. Out of this first step should follow which steering mechanism is used at the NRA. The steering mechanisms can be service-driven (ensuring a minimum service level e.g. the road should be available for 95% of the time'), budget-driven (based on a given budget find the maximum service to be delivered), optimum service-driven (investments based where maximum service is achieved where costs and benefits are balanced) or policy-driven (ensuring to achieve goals based on policies e.g. biodiversity, carbon reduction and/or equity). Furthermore, this step results in an overview of KPIs used to make decisions (D2.2, Bles et al., 2023). The most used KPIs are availability, safety, durability, health effects, environmental quality and ecosystem services. Often, they are used in the context of an asset management (RAMS – Road Asset Management System) approach. And furthermore, other policies will be used by the NRA for matters that not directly influence the primary functions of the road, but that still are relevant for decision making. Examples are sustainability, decarbonization, biodiversity among others. All three elements (steering mechanisms, policies in place and KPIs) are necessary information before the resilience assessment can be performed.



When the KPIs are known, a check should be made whether it is clear how climate effects affect the KPIs. For example, when there is a KPI regarding availability (The road should be available for x% of the time), a check should be made whether they also include a component which describes the performance while including the climate effects. It should be clear to what extent performance of a KPI is affected by climate events: do climate events have a (potential) significant contribution to the performance of the infrastructure or are other factors (much) more important? After this step are two options.

1. In case it is clear how climate events affect KPIs the next step will be to identify acceptable thresholds for resilience.
2. In case it is unclear how climate events affect KPIs the next step involves method 1 (See below). These steps will be described hereafter and are described in more detail in Deliverable 2.2 (Bles et al, 2022).

In case method 1 is not possible or not wanted, a second-best option can be considered. This is visualised with the OR gate and the dotted line. Using expert judgement one can still try to identify thresholds. However, a high risk is present that at a later stage, this may result in difficulties for making the case for adaptation as no factual argumentation can be provided for the desired resilience levels.



When both the decision context with a common understanding of the steering mechanism at the NRA is clear <u>and</u> it is clear how climate events can be measured with key performance indicators it is possible to decide what thresholds to use for the determination of acceptable level of resilience. For this input is needed from experts at the strategic and tactical level.
<u>Note</u>: When it is unclear how climate events are measured in key performance indicators it is possible to identify thresholds in expert sessions. However, this is a suboptimal route to ensure thresholds are embedded in the NRAs processes.

Method 1

When it is unclear how climate events affect KPIs, it is possible to gain insight into the effects of extreme weather and climate hazards on the performance of the roads, for those threats that occur on a relatively frequent basis. When this information is obtained, this will aid in making a case for adaptation by showing that when no adaptation is considered, the performance is expected to decrease. The following steps should be executed.

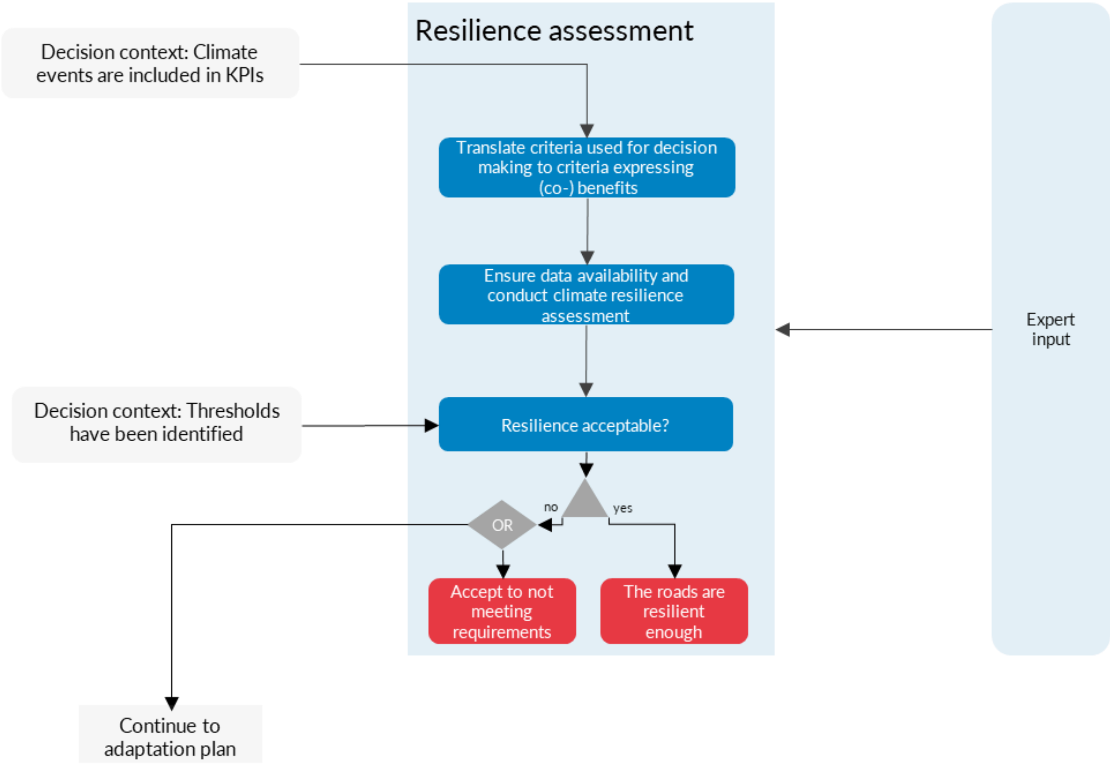
Find correlations between climate events on KPI performance

Firstly, find correlations between climate events on KPI performance. This can be done by performing trend-analyses of past years events to understand the relation between the performance of the KPIs and climate events. For example, by making use of monitoring data of performance during past events (for example, precipitation data and the delays/number of accidents during these events) a correlation can be found. This needs to be corrected for other causes than climate events, for example determine the change in travel time both under normal circumstances and rush hours as well as in the case of disruptions due to climate events. This process is time consuming and is advised to be done for the most prominent climate events only.

Evaluation of KPI's: ensure that climate events are included

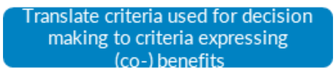
The next step is to ensure that the climate events are included in the KPIs and to proceed to the identification of thresholds (See above).

4.3.3 Resilience Assessment



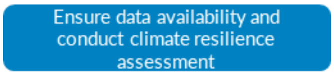
Aim	Stress-testing the network for climate events while expressing the decision-making criteria by means of benefits and co-benefits that fit the decision context of the NRA. Based on this, evaluate whether resilience is acceptable and whether an adaptation plan needs to be developed.
Enablers	Decision-makers at tactical and operational level who can understand the KPIs and co-benefits at network level, connection level and asset level and are able to connect these to criteria that can be assessed in a resilience assessment. Experts that can perform a resilience assessment. This includes experts with economic expertise. Expert input on the operational side that provide insights in failure of infrastructure when performing a stress-test/resilience assessment
Barriers	Lack of data. Lack of specific expertise on performing a resilience assessment: This should have been addressed when resources for the resilience assessment were assured in building block "Awareness". Expert input is needed which results in organisational barriers.
Outcomes	Baseline or *business-as-usual* scenario, which can incorporate future changes to the current situation. Decision whether the resilience is acceptable in the *business-as-usual* scenario, or whether adaptation is needed to enhance resilience to acceptable levels.

Description of the steps

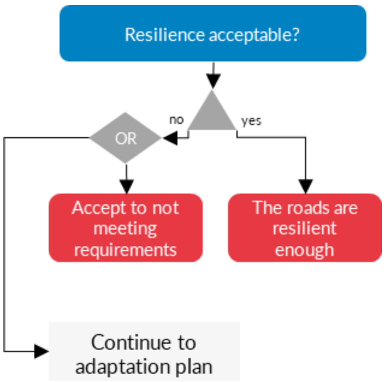


In the resilience assessment the resilience is measured/described such, that it can be compared with the decision criteria used by the NRA. Therefore, it is necessary to first translate the criteria for decision-making in how the benefits and co-benefits will be valuated.

When doing this, the starting point is a description of the relevant effects that are expected to be associated with potential interventions and how they relate to the identified KPIs. It is suggested, in general, that tangible (or monetary) outcomes are included as these values are usually quite straight-forward to elicit. For example, when availability is a KPI or decision criterium by the NRA: The effects of climate disruptions on the performance of the road can be expressed and valuated by the extra travel time and the corresponding costs of delays. When it comes to intangible outcomes, it is suggested to translate these to parameters defining the magnitude of the outcome. For example, whether the level of change in the effect is significant and/or how many individuals will be affected by the change. Other examples on the valuation of benefits and co-benefits have been identified and described how to be used in a resilience assessment in D2.2 (Bles et al., 2023)

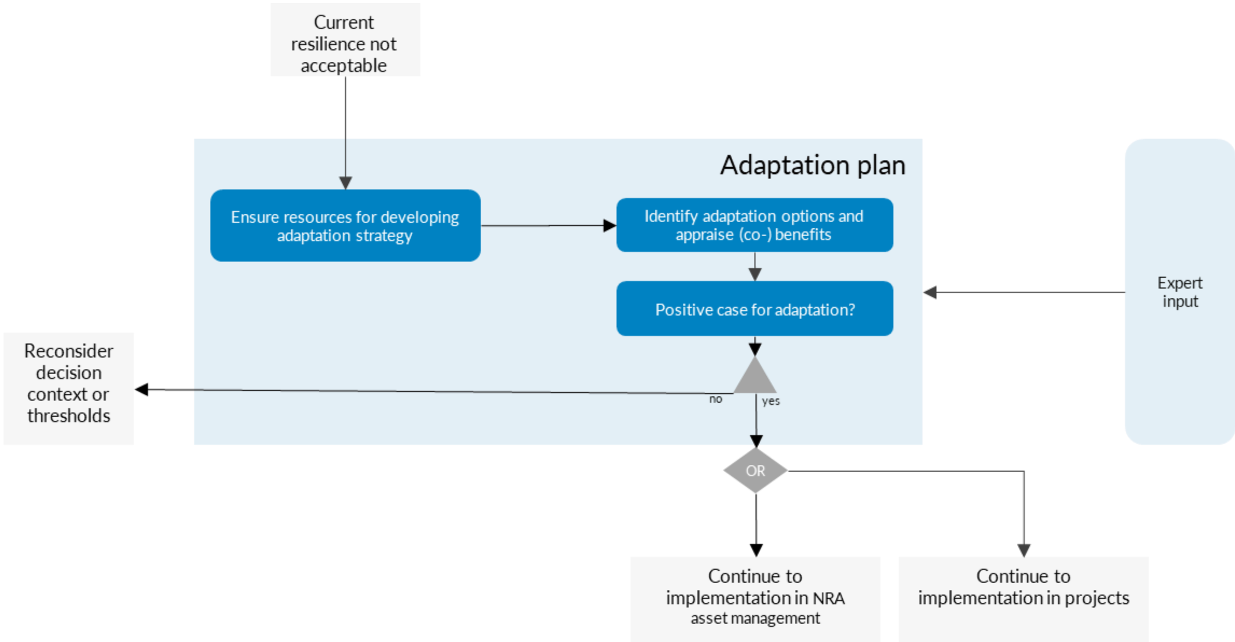


Ensure that all data is available before executing the resilience assessment. When performing the climate resilience assessment, a baseline should be defined, against which the expected changes can be described. In most cases, the baseline should be defined as a *business-as-usual* scenario which incorporates expected future changes to the current situation, importantly in relation to climate change. This will lead to meaningful results. The resilience assessment can consider future situations with a changing climate, for example by making use of hazard scenarios based on future climate. How a climate resilience assessment can be performed is described in more detail in Chapter 3 of Deliverable 2.1 (De Jonge et al., 2022.



Ultimately, this building block ends with a conclusion whether the resilience is acceptable or not. To do this, the thresholds stemming from the decision context are combined with the outcomes of the resilience assessment. For example, when the threshold is set that the road should be 95% available and out of the resilience assessment comes that in 2030 it is expected that the 50-year event will occur every 10 years and that the availability of the network will drop below 95%. This means that it would make sense to continue to develop an adaptation plan. Unless the NRA decides not to meet the requirements. If in the described examples the availability of the network would still prove to be above 95%, the network is resilient enough and no action is required. This process will typically be undertaken in dialogue between the tactical and strategic level of the NRA and policy makers.

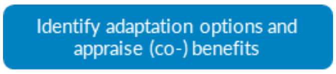
4.3.5 Adaptation plan



Aim	Determine whether there is a positive case for adaptation, based on appraisal of benefits and co-benefits of the different adaptation options
Enablers	Expert input from the operational level and experts from the tactical level. Expertise on adaptation options and how to appraise the different adaptation options. Preferably with experience in bow-tie methodology and/or decision-making under deep uncertainty. Experts with an economic background for performing the appraisal of adaptation options.
Barriers	A lack in resources (expertise and/or budget) for the development of the adaptation plan. Data is needed on effectiveness of measures and investment costs. Co-benefits can be hard to quantify.
Outcomes	Adaptation plan based on appraisal of different adaptation options

Description of the steps

Before the adaptation strategy can be developed, the availability of resources should be ensured. These resources involve budget, but also expertise and time. Expertise necessary for the adaptation strategy are specialists who understand what the adaptation options are and how to identify which options are best suited to increase the resilience of the road at asset, connection or network level. For example, experts with experience in cost-benefit analyses for adaptation options, that know how to apply bow-tie methodology, event-tree methodology and/or decision-making under deep uncertainty. Furthermore, experts with an economic background for performing the appraisal of adaptation options.



The next step is to identify the adaptation options and the appraisal of the benefits and co-benefits. The development of the adaptation plan builds upon information that was developed and gathered in previous steps. This includes a description of benefits or co-benefits, linked to the defined KPIs (coming from the building blok 'Decision-Context'). Furthermore, to meaningfully describe the expected changes, the baseline should be used as developed in the previous building block ‘Resilience Assessment’, against which the expected changes can be described. The adaptation plan therefore makes use of the resilience assessments that can serve as a basis scenario. *Note*: it is preferred to use the same units as done in the resilience assessment.

To identify what adaptation options should be considered, we refer to Chapter 2 of this deliverable. Significant effects associated with the implementation of adaptation/resilience measures should be considered for the quantification and eventually valuation of these. During the appraisal of the benefits and co-benefits new data is needed and includes:

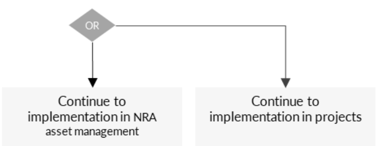
- Data of costs and effectiveness of adaptation options. Table 5.1 in D2.2 (Bles et al., 2023) provides an overview of relevant parameters to consider, to assess the magnitude of the benefits.
- Identify means of possible quantification/measurement of benefits: To enable valuation of the benefits of the adaptation option, it is necessary to consider possible means of measurement of the identified benefits. Also, whether data of sufficient quality can be gathered.

Depending on the data availability a decision can be made which method is best for the appraisal of the adaptation options. ICARUS Deliverable 3.1 (Fonseca et al, 2022) provides an overview of what economic appraisal methods are currently being used (e.g. cost-benefit analyses, multi-criteria analyses) for road infrastructure.

Positive case for adaptation?

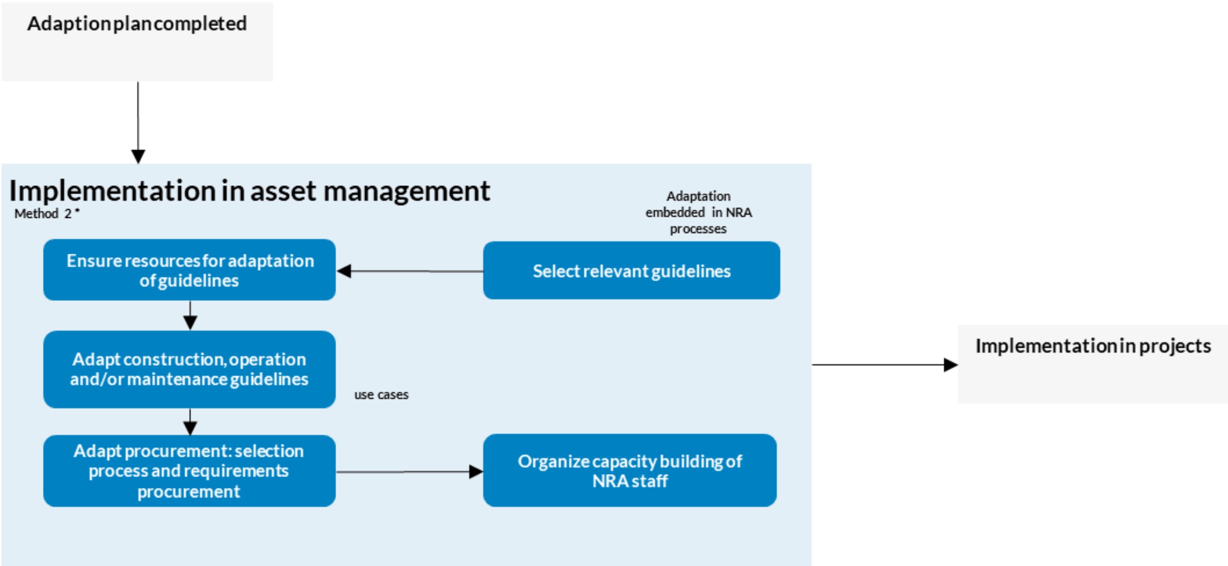
When deciding whether there is a positive case for adaptation, i.e. whether it makes sense to invest in adaptation options, the adaptation needs to be compared to the *business-as-usual* situation as used in the resilience assessment. Also, this depends on what steering mechanism is used by the NRA (coming from the building block ‘Decision-Context’). It might be that the cost benefit ratio is not positive but based on a policy-based steering mechanism, it is still decided to invest.

When there is no positive case for adaptation, for example when the costs don’t outweigh the benefits, the NRA can decide to go back to the decision context to either change the criteria or KPIs to include climate effects in decision-making or by reconsidering the thresholds, which may result in less investments or maybe an acceptable level of resilience in building block ‘Resilience assessment’.



When there is a positive case for adaptation the NRA has two options: The first is to continue towards implementation in NRA asset management and adjusting relevant guidelines (Methods 2, see Chapter 4.3.6). The second option Is to continue in specific projects (see Chapter 4.3.7).
These two are however interlinked, because experience in projects is needed for alteration of the guidelines and improved guidelines will help implementation in projects

4.3.6 Implementation in asset management



Aim	Implement the adaptation plan into NRA asset management processes. The asset management processes entail all NRA processes from planning, to design, construction, rehabilitation, maintenance and operation, as well as procurement.
Enablers	The enablers are the preceding steps having been completed. Having the awareness, resilience assessment and adaptation plan completed provides the basis for the processes to be embedded into the organisation's asset management practices. Additionally, engagement throughout the NRA is an important enabler to implement different asset management practices. Next to that the NRA experience in asset management operations will be an enabler, which are primarily undertaken by tactical and operational staff.
Barriers	The barriers are insufficient resources to adapt all asset management guidelines. This includes both budgets to adapt the guidelines as well as possibly larger budget needs for using the guidelines (due to higher cost for design, construction, rehabilitation, maintenance and operation). When moving from the adaptation plan to implementation, these challenges should be recognised and resources either made available from internal staff or external experts to be procured to provide support. Procurement processes may be difficult to adapt to ensure that climate resilience and climate change adaptation are appropriately considered for new and existing schemes. The engagement of all NRA areas at the outset (strategic, tactical and operational) should help ensure that common goals in this area are agreed.
Outcomes	The successful outcome will be to have implemented the adaptation plan into NRA asset management processes, so that it becomes 'business as usual'.

Method 2

Method 2 covers the scenario of the implementation of adaptation at the asset management level. The decision to implement adaptation at this level will vary depending on the specific priorities of the NRAs. Some NRAs may have implemented adaptation schemes on projects and now want to make this the 'new normal' by updating their asset management guidelines. Others may choose to update or develop processes to support future adaptation on schemes or as part of their maintenance regime.

Description of the steps

Once the Adaptation Plan has been completed, there is an ‘OR’ box, where one chooses to implement either at the asset management level (Method 2) or at project level (Method 3). Whilst these are two separate processes, there are some links between them, where the learnings feed across.

Select relevant guidelines

Having chosen to implement at the asset management level, the first step is to select the relevant guidelines in the existing asset management process where the implementation of adaptation will be included. In the adaptation block it has become clear what adaptation options result a positive decision case. In the current step, the guidelines in the asset management process need to be selected where these adaptation options can be implemented. Here a distinction needs to be made between adaptation of current assets and planned assets. There may be different requirements for these and different guidelines may need to be updated for the different goals.

Ensure resources for adaptation of guidelines

Adapt planning, design, construction, operation and/or maintenance guidelines

Once these are selected, they will need to be adapted for implementation of climate change adaptation, either internal or external resources will be required to make the relevant changes to the planning, design, construction, maintenance and operational guidelines. Changes to the guidelines should be in line with the adaptation plan and the established decision context of NRAs. D2.2 (Bles et al, 2023) and D3.2 (to be developed in ICARUS) provide specific recommendations on how changes to guidelines can be determined in terms of optimal resilience levels to be thrived for. Changes of the guidelines will involve engagement with appropriate experts, and once checked and agreed, will need sign-off at the strategic level. At this point, there is a link to implementation at (potentially future) project level, where the guidelines created will help in the adaptation at a project level. Similarly, adaptation at the project level will provide use cases to either refine asset management guidelines, or to inform the creation of amended guidelines, should implementation at the project level happen first.

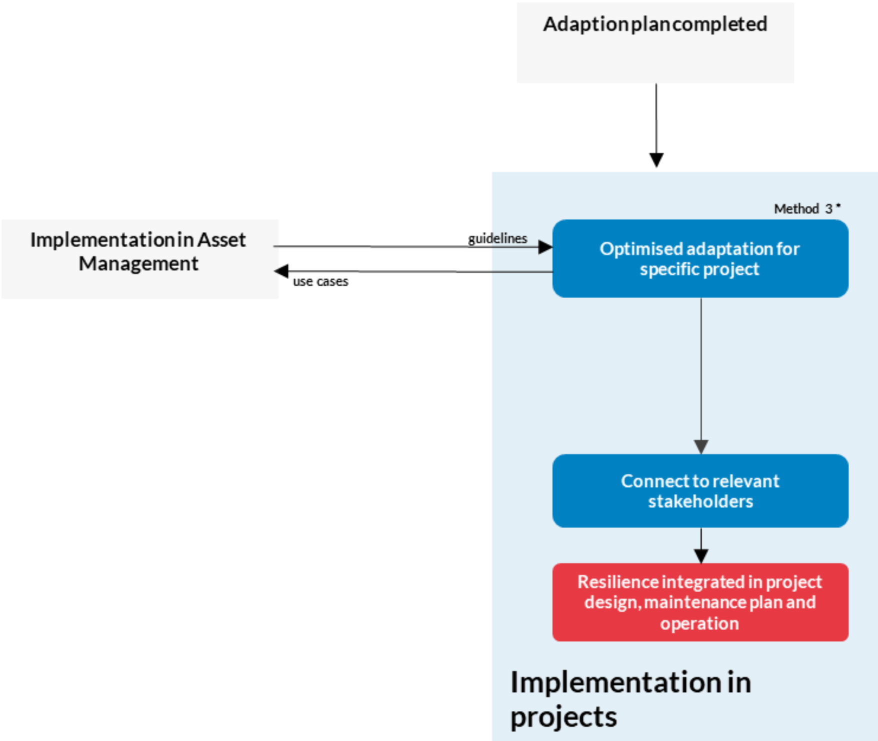
Adapt procurement: selection process and requirements procurement

The next step in the process will be to adapt the procurement processes to ensure that implementation of adaption is included for future schemes and projects. This represents a major potential blocker and will require ongoing engagement with procurement experts.

Organize capacity building of NRA staff

Finally, there will be the requirement for organisational capacity building within the NRA to ensure that this becomes the new normal.

4.3.7 Implementation at project level



Aim	Implement adaptation for a specific project
Enablers	The specific and defined nature of an individual project simplifies some elements of the process. This will generally be undertaken mostly at an operational level, with potential expert input. Liaison will be required at the strategic and tactical level.
Barriers	• If undertaken before implementation at asset management level, the asset management guidelines, standards and procurement have probably not been updated to support the implementation in the project. It should be made clear that this will be a trial (or series of trials) to build capacity and provide an evidence base from the individual projects to inform guidelines. • The adaptation options are too costly for implementation. It is necessary that climate change adaptation is an objective of the project. • Also, external stakeholders (e.g. permits, land-owners) should be involved, which may complicate this step.
Outcomes	Implementation completed for a specific project against a specific identified threat(s). Lessons learned prepared and disseminated.

As before, once the Adaptation Plan has been completed, there is an 'OR' box, where one chooses to implement either at the asset management level (Method 2) or at project level (Method 3). It is assumed in this case, that this will be separate and will precede implementation at the asset management level, although the results and lessons learned may inform it.

Method 3

Method 3 covers the scenario of the implementation of adaptation being undertaken in a specific project or projects, for example, the design or maintenance of an individual asset or road section. The decision to implement adaptation at this level may be to act as a 'Pathfinder project' or series of projects, where adaptation can be undertaken on discrete projects, where improvements will be made and used to inform the development of guidelines. Procurement at a project level, particularly if it is understood to be a trial, may be easier to achieve, and can serve as an evidence base to make changes to the procurement processes.

Description of the steps

Optimised adaptation for specific project	The first step (optimise adaptation for a specific project) will be to assess the specific threat(s) against which adaptation is taken place and the adaptation measures to be used. Here, the list of adaptation options identified as part of the ICARUS project will be of significant benefit, as well as the results of previous work such as ROADAPT.
Connect to relevant stakeholders	The second step will be to identify and connect to relevant (external) stakeholders (e.g. permits, land-owners) who will be involved. Depending on the project, this could include different levels of the NRA including procurement, environmental agencies, technical experts, designers, consultants and contractors. As part of the design, future maintenance requirements need to be identified, in particular if a nature-based solution has been chosen, as this will likely differ from the processes normally undertaken by the maintenance contractor. An enhanced level of monitoring may be required for the first schemes.
Resilience integrated in project design, maintenance plan and operation	This point represents the end-point for adaptation, both at a project level, as well as at the level of adaptation of the asset management processes. Once the work has been completed, a review should be undertaken to determine what worked well and what could be improved if the scheme was repeated.

4.4 Key take-aways

1. To ensure that climate change adaptation finds its way in the daily processes of NRAs many different NRA staff members have an active role and different layers of the organization need to be involved and should be engaged. This ranges from continuous shifts between strategic decisions at the strategic level, practical assessments at the tactical level and key input from the operational level. Engagement at all levels is a prerequisite for successful implementation. It is recommended to have one person in charge of the entire process. Depending on the organisation of the NRA this can be on different levels. In general, we deem it most effective when an NRA staff member, with a task in the field of climate change adaptation at the tactical level, takes the leading role. This person should be able to interact clearly with the other two levels.

2. Linking with the decision context of the NRA and the policy makers is of critical importance. It's a pitfall to start with a resilience and adaptation assessment right away. Ensuring decision making requires that the resilience assessment is designed such that the results make sense to the decision makers. Resilience and adaptation frameworks are abundantly available. It is key that use of these frameworks is tailored to the typical decision context of the NRA. This decision context includes the steering mechanisms and the criteria that are used for decision making. Customized resilience and adaptation assessments will produce outcomes that will push the right buttons for decision making.

3. Implementation may take place via two routes, which are interlinked. One route is via adapting the asset management that eventually will lead to an uptake of adaptation in all processes of an NRA. The other route is via implementation at an individual project level. Both approaches strengthen each other. Insights gathered at the project level will inform the process of adapting the asset management via changing the planning, design, construction, maintenance and operational guidelines.

4. Research may be necessary to understand how climate change may impact the KPIs that are used for monitoring the performance of the road network. If climate events, let alone climate change, are not reflected in the KPIs it generally won't be possible to make a case for adaptation, since climate events won't lead to a lower measured performance of the road. When it is not understood how climate change affects the performance of the KPIs, it won't be possible to underline in the resilience assessment how climate change will lead to a lower performance.

4.5 Summary

An adaptation implementation process has been developed through which NRAs of different organisational maturity can progress from awareness of the requirement to protect their infrastructure against extreme weather and climate change, to implementing in practice, either at an asset management level or an individual project level. Some NRAs may have a specific project in mind when starting the framework, whilst others may wish to raise their organisational awareness. The route through the framework will differ if concentrating on a project or the entire network.

The process indicates at which level or combination of levels (strategic, tactical and operational) at the NRA should be involved at each stage. It also details where expert input is required.

There are five building blocks (awareness, decision context, resilience assessment, adaptation plan and implementation in practice) within which there are individual stages. As NRAs progress through the stages, there are a series of 'yes/no' gates, where the NRA either moves along the process or reevaluates requirements. In some cases, resources (internal or external) may not be available to move immediately to the next stage, or the case might not be made to move the next stage. In such cases, there are loops to revisit previous stages, so there may be progression in the future, or if the decision contexts are changed.

The end goal is to move through each of the five blocks, with implementation of climate adaptation undertaken either on a specific project, or at an asset management level as the end point.

A summary of the process and outputs is outlined below.

1. Awareness – engagement at all areas of NRA. If resources are available to undertake a resilience assessment, move to stage 2. If resources are unavailable, connect to long term planning at NRA, with potential to move to stage 2 in the future.
2. Decision Context – determine the KPIs to choose and understand how climate event impact them. When these are understood and thresholds have been agreed, move to stage 3 or reevaluate KPIs.
3. Resilience Assessment – determine whether current resilience is acceptable or not. If it is, this is an end point, with the framework to be revisited in future. If it is not, there is an end point of accepting that requirements will not be met, or the option to move to stage 4.

4. Adaptation Plan – here resources are required to develop the strategy and benefits and co-benefits are assessed to determine if there is a positive case for adaptation. If there is, this should be implemented in stage 5, or otherwise, this loops back to stage 2.
5. If there is a positive case for adaptation, there is choice of implementing this either at an asset management level or an individual project level.

5 Conclusions

In this guideline and accompanying database of adaptation options, we have provided a wide variety of adaptation options which can be implemented at all stages of the project life cycle, for any or all asset types, at an object, connection and/or network level, to increase resilience to specific climate impacts and to help overcome some of these barriers. Guidance on how to select the most appropriate climate change adaptation options is provided, along with a review of gaps and barriers to implementation of adaptation. Key challenges for road authorities in implementing climate change adaptation have been identified through literature review, and workshops with NRA members as a lack of information and data, lack of resources, both financial and skills, and provision of incentives for organisations to act. An interesting finding was that similar barriers were identified across all NRAs who participated, regardless of maturity level or geographic location of the NRA, and these also aligned with barriers found in the literature. Solutions are proposed to overcome these barriers, using Nature Based Solutions and Emerging Technologies where appropriate.

Finally, guidance has been provided on how adaptation may be implemented at an organisation level in NRA processes. A decision framework has been developed through which NRAs of different organisational maturity can progress from awareness of the requirement to project their infrastructure against extreme weather and climate change, to implementing in practice, either at an asset management level or an individual project level. Some NRAs may have a specific project in mind when starting the framework, whilst others may wish to raise their organisational awareness. The route through the framework will differ if concentrating on a project or the entire network.

The framework indicates at which level or combination of levels (strategic, tactical and operational) at the NRA should be involved at each stage. It also details where expert input is required.

Key take aways for implementing climate change adaptation are as follows:

1. To ensure that climate change adaptation finds its way in the daily processes of NRAs, many different NRA staff members must take an active role, and different layers of the organization need to be involved and engaged. This ranges from continuous shifts between strategic decisions at the strategic level, practical assessments at the tactical level and key input from the operational level. Engagement at all levels is a prerequisite for successful implementation. It is recommended to have one person in charge of the entire process. Depending on the organisation of the NRA this can be on different levels. In general, we deem it most effective when an NRA staff member, with a task in the field of climate change adaptation at the tactical level, takes the leading role. This person should be able to interact clearly with the other two levels.
2. Linking with the decision context of the NRA and the policy makers is of critical importance. It's a pitfall to start with a resilience and adaptation assessment right away. Ensuring decision making requires that the resilience assessment is designed such that the results make sense to the decision makers. Resilience and adaptation frameworks are abundantly available. It is key that use of these frameworks is tailored to the typical decision context of the NRA. This decision context includes the steering mechanisms and the criteria that are used for decision making. Customized resilience and adaptation assessments will produce outcomes that will push the right buttons for decision making.
3. Implementation may take place via two routes, which are interlinked. One route is via adapting the asset management that eventually will lead to an uptake of adaptation in all processes of an NRA. The other route is via implementation at an individual project level. Both approaches strengthen each other. Insights gathered at the project level will inform the process of adapting the asset

management via changing the planning, design, construction, maintenance and operational guidelines.

4. Research may be necessary to understand how climate change may impact the KPIs that are used for monitoring the performance of the road network. If climate events, let alone climate change, are not reflected in the KPIs it generally won't be possible to make a case for adaptation, since climate events won't lead to a lower measured performance of the road. When it is not understood how climate change affects the performance of the KPIs, it won't be possible to underline in the resilience assessment how climate change will lead to a lower performance.

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ANNEX A – NBS SUPPORTING LITERATURE

Reference	Summary
(A. M. Tang et al., 2018)	Atmosphere-vegetation-soil interactions in a climate change context; Impact of changing conditions on engineered transport infrastructure slopes in Europe Link: https://www.lyellcollection.org/doi/10.1144/qjegh2017-103 NBS: Vegetation along the slope of the road embankment to reduce wave action and stream velocity Threat: Sea level rise Location: Europe Remarks: The stability of new and existing infrastructure slopes depends on how the atmosphere, vegetation and the near-surface soil interact with each other. These interactions are influenced by climate- and vegetation-driven processes, such as suction generation, erosion, desiccation cracking, and freeze–thaw effects. Climate change will alter the frequency and intensity of these processes, which will have implications for the design of engineered transport infrastructure slopes. This paper reviews the current state of knowledge on these topics, based on recent literature and the impacts of climate change on engineered slopes for infrastructure. The article also discusses the key challenges and research gaps that need to be addressed in the future.
(Akter et al., 2018)	Impacts of climate and land use changes on flood risk management for the Schijn River, Belgium Link : Impacts of climate and land use changes on flood risk management for the Schijn River, Belgium - ScienceDirect NBS: Avoid urbanization and watersheds diversions in vulnerable areas Threat: Flooding Location: Schijn River, Belgium Remarks: The aim of this paper is to study how urbanization affects the water cycle under present and future climate scenarios with high rainfall in summer and winter for 20 sub-catchments of the Schijn River, which is located near Antwerp, Belgium in the Flanders region. A hydrological model based on a simple reservoir concept was developed and applied to the existing rainfall-runoff model (PDM) flow to capture the specific urban runoff behavior, which is ignored by the current models. The results showed that the urban runoff peak flow and the total peak flow (i.e. the sum of rural and urban runoff) were much higher (i.e. from 200% to 500%) than the existing rainfall-runoff model (PDM) flows, due to the faster and sharper urban runoff response. The paper also evaluated the effect of climate change on the current and future conditions by estimating peak flows for different return periods from the flood frequency curve.
(Anderson et al., 2011)	Wave Dissipation by Vegetation Link : https://apps.dtic.mil/sti/pdfs/ADA613773.pdf NBS: Wetland restoration Threat: Flooding resulting from hurricanes and other extreme storm events, sea level rise Location: England

	Remarks: The ability of coastal plants to dissipate wave energy and wave heights in low-energy environments is demonstrated and documented in both field and laboratory studies.
(Apollonio et al., 2021)	Hillslope Erosion Mitigation: An Experimental Proof of a Nature-Based Solution Link : Sustainability | Free Full-Text | Hillslope Erosion Mitigation: An Experimental Proof of a Nature-Based Solution (mdpi.com) NBS: vegetation on hillslopes Threat: Erosion regarding Intense rainfall Location Tested: Cape Fear, located at Tuscia University in Viterbo, Central Italy Experiment: experimental hillslope with natural and artificial rainfall and for different vegetation heights for erosion control Infrastructure: No specific reference to infrastructure Remarks: Discusses the ideal vegetation height for maximum efficiency in terms of soil erosion reduction and soil loss reduction.
(Arzoo & Pradhan, n.d.)	A Review On Cyclone Resistant Plants Found In Cyclone Prone Odisha, India Link : A-Review-On-Cyclone-Resistant-Plants-Found-In-Cyclone-Prone-Odisha-India.pdf (ijstr.org) NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Cyclones Location: India Remarks: The text is a review of the major cyclonic storms that hit the Odisha coast in India and the cyclone resistant plants found in Odisha. The text lists some of the cyclone resistant trees that can be planted to protect from damage, such as Azedirachta indica, Millettia pinnata, Mimusops elengi, Syzygium cumini, and others. The text describes the criteria for selecting cyclone resistant plants, such as the root system, the trunk strength, the crown symmetry, and the resistance to termites. The text also mentions the benefits of planting trees during cyclones, such as reducing the impact of debris and wind.
(Bakr et al., 2012)	Evaluation of compost/mulch as highway embankment erosion control in Louisiana at the plot-scale Link : Evaluation of compost/mulch as highway embankment erosion control in Louisiana at the plot-scale - ScienceDirect NBS: Spread mulch over the soil to protect it Threat: Soil Erosion under storm water runoff Location: Louisiana Remarks: The study was conducted on two highway locations to assess the effectiveness of compost/mulch used for erosion control applications. Based on the results of this study, the effectiveness of compost/mulch cover in reducing runoff, TSS, and turbidity from soils susceptible to high-intensity storms in Louisiana was confirmed.
(Belgrade, 2021)	Guidelines for establishment and maintenance of forest windbreaks in Serbia

	Link : https://www.undp.org/serbia/publications/guidelines-establishment-and-maintenance-forest-windbreaks-serbia NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Wind related hazards Location: Serbia Remarks: Report made with a complete outline on establishment of forest windbreaks for Serbia. Outlines: the state of forest protective belts and guidelines for establishment and management of windbreaks with examples from several countries. The document further proposes specific legislation and an independent management unit for protective windbreaks, as well as possible sources of funding. The document also collects the opinions of relevant stakeholders who support the environmental value and multifunctionality of protective windbreaks.
(Bitog et al., 2012)	Numerical simulation study of a tree windbreak Link: : https://www.sciencedirect.com/science/article/abs/pii/S1537511011001814?via%3Dihub NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Wind related hazards Location: South Korea Remarks: The study focuses on tree porosity as the factor that has the most influence on windbreak efficiency. In this study, computational fluid dynamics (CFD) was utilised to investigate the flow characteristics around tree windbreaks. The simulation provides analysis of the effect of gaps between trees, rows of trees, and tree arrangements in reducing wind velocity. The results can potentially to design an effective windbreak system for use in the reclaimed lands and in the coastal areas of Korea.
(Bowler et al., 2010)	Urban greening to cool towns and cities: A systematic review of the empirical evidence Link : https://linkinghub.elsevier.com/retrieve/pii/S0169204610001234 NBS: Vegetation for shading of concrete and asphalt pavements against sun Threat: UHI Location: Remarks: The paper is a systematic review of the evidence on the effects of urban greening on air temperature. Urban greening is the use of natural or semi-natural elements, such as trees, parks, or green roofs, to reduce the heat stress caused by climate change. The text finds that most studies support the idea that green sites are cooler than non-green sites, especially during the day.
(Brandle et al., 2004)	Windbreaks in North American agricultural systems Link : Windbreaks in North American agricultural systems | SpringerLink NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Winds Location: North America

	Remarks: The book chapter discusses the importance of windbreaks towards control erosion and blowing snow, improve animal health and survival under winter conditions, reduce energy consumption of the farmstead unit, and enhance habitat diversity, providing refuges for predatory birds and insects. Also contains descriptions of design conditions of a windbreaker to be effective.
(Bridges et al., 2022)	Coastal Natural and Nature-Based Features: International Guidelines for Flood Risk Management Link : https://www.frontiersin.org/articles/10.3389/fbuil.2022.904483/full NBS: Improvements to coastal wetlands and plants: Wetland Restoration Threats: Coastal Flooding and climate change Remarks : Paper discussing coastal Natural and Nature-Based Features and Guidelines for Flood Risk Management. Discusses the importance of NBS to protect critical infrastructure in several places.
(Casteller et al., 2018)	Assessing the interaction between mountain forests and snow avalanches at Nevados de Chillán, Chile and its implications for ecosystem-based disaster risk reduction Link : NHESS - Assessing the interaction between mountain forests and snow avalanches at Nevados de Chillán, Chile and its implications for ecosystem-based disaster risk reduction (copernicus.org) NBS: Vegetation on slopes to decrease the debris runout distance . retaining and restoring native / mixed forests on slopes, vegetation Threat :Landslides and Avalanches Location: Valle Las Trancas, in the Biobío region in Chile Infrastructure: potential impact on infrastructure along the road Remarks: Discusses the influence on vegetation/forests on the slopes towards snow avalanches runout distances
(Connell, 2004)	Assessing the Potential of Floodplain Woodland in Flood Amelioration Link: (PDF) Assessing the Potential of Floodplain Woodland in Flood Amelioration (researchgate.net) NBS: Improve forest management in the catchment area Threat: Flooding Location: Mawddach catchment, mid-Wales, United Kingdom Remarks: The document discusses the impact of floodplain woodlands to reduce the intensity of flooding. The study concludes that woodland in flood amelioration does have considerable potential with additional flood defence mechanisms.
(Cooper et al., 2021)	Role of forested land for natural flood management in the UK: A review Link : Role of forested land for natural flood management in the UK: A review - Cooper - 2021 - WIREs Water - Wiley Online Library NBS: Improve forest management in the catchment area Threat: Flooding Location: United Kingdom

	Remarks: This review explores the idea and history of Natural flood management (NFM) and examines the current research on how different kinds of woodland can help achieve the goals of NFM. It discusses four types of woodland (catchment, cross-slope, floodplain, and riparian) and refers to studies, mostly from the United Kingdom, that compare their benefits and effectiveness in reducing flood risk.
(Dalir & Naghdi, 2015)	Assessing the effects of native plants to slope stabilization in road embankments: a case study in Siyahkal forest, northern Iran Link : [(PDF) Assessing the effects of native plants to slope stabilization in road embankments: a case study in Siyahkal forest, northern Iran (researchgate.net)] NBS: native plants to slope stabilization Threat: appeasing flooding and landslide hazard in forest lands. Location: case study: Siyahkal forest, northern Iran Relation to Infrastructure: Road Embankments Remarks: Discusses to reduce destructions to road network through vegetation on the slopes with focus on selecting appropriate native plants. The selection was done considering geological features and soils. . Results revealed that there is a relation between plant species and variables such as land type, soil moisture, soil texture, aspect, slope, and soil depth of study area.
(Devanand et al., 2023)	Innovative Methods for Mapping the Suitability of Nature-Based Solutions for Landslide Risk Reduction Link : [Land | Free Full-Text | Innovative Methods for Mapping the Suitability of Nature-Based Solutions for Landslide Risk Reduction (mdpi.com)] NBS : Covering Slopes with vegetation (restoration of terraces, bio-engineering, and vegetative measures) Threat: Landslides due to hydro-meteorological extreme events and climate change Location: Portofino ,Italy Infrastructure: No mentions Remarks: Focuses on mapping the spatial suitability of large-scale NBS and spatial allocation of NBS for Landslide Risk Reduction.
(Dorobăţ & Udroiu, 2015)	Study regarding the side erosion processes on the middle reach of Doamnei river and methods of preventing them Link : https://www.natsci.upit.ro/media/1523/paper-10.pdf NBS: Avoid deforestation on river banks Location: Romania, Doamnei river Threat: Pluvial Flooding and erosion of river banks Remarks : The paper focuses on identifying the eroded banks in the river as a result of human intervention. Discusses methods that can be used to diminish action-erosion. The paper concludes that avoiding deforestation and maintaining the forest, bush or herbal vegetation on the slope can reduce the degradation processes of the shores.
(Feng et al., 2021)	Urbanization impacts on flood risks based on urban growth data and coupled flood models

	Link : Urbanization impacts on flood risks based on urban growth data and coupled flood models | Natural Hazards (springer.com) NBS: Avoid urbanization and watersheds diversions in vulnerable areas Threat: Flooding Location: A sub-watershed in Toronto, Canada Remarks: The effects of urbanization on urban flood risk were studied by using land use maps from six different years (1966, 1971, 1976, 1981, 1986, and 2000) and six simulated land use scenarios (with impervious surface area percentages ranging from 0% to 100%) as inputs for coupled hydrologic and hydraulic models. The results indicate that urbanization increases the surface runoff and river discharge rates and reduces the time to reach the peak runoff and discharge.
(Francini et al., 2021)	Biological Contribution of Ornamental Plants for Improving Slope Stability along Urban and Suburban Areas Link : Horticulturae | Free Full-Text | Biological Contribution of Ornamental Plants for Improving Slope Stability along Urban and Suburban Areas (mdpi.com) NBS: vegetation on hillslopes Threat: Erosion related to rainfall Location tested : Review article discussing the biological contribution of plants for improving slope stability has been reported and discussed with a special focus attention on the Mediterranean environment. Infrastructure : Slopes in the proximity of roads along Urban and Suburban Areas Remarks: Discusses the use of ornamental plants as a dual usage. More attention has been paid to root biomass changes and root growth parameters, considering their role as potential markers for selecting suitable plants to be used for enhancing slope stability. Brief explanations on of planting on slopes and root growth has been also considered and discussed.
(Franti, 1996)	Bioengineering for Hillslope, Streambank and Lakeshore Erosion Control Part of the Agriculture Commons, and the Curriculum and Instruction Commons Link : https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2341&context=extensionhist NBS: Bioengineering, a method of construction using live plants alone or combined with dead or inorganic materials, to produce living, functioning systems to prevent erosion, control sediment and provide habitat. Threat: Soil Erosion Location: - Remarks: describes bioengineering techniques for hillslope, streambank and lakeshore erosion control. Tips for a successful bioengineering installation and demonstration project are described
(Gedan et al., 2011)	The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm Link : (PDF) The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm (researchgate.net)

	NBS: Mangroves restoration to reduce wave run-up and shore erosion Threat: Wave run-up and shore erosion Location: Remarks: The paper consists of reviewing literature that show mangrove and salt marsh vegetation can protect the shorelines from erosion, storm surge, and possibly small tsunami waves, depending on the context. In biophysical models, field experiments, and natural observations, the wetlands lower the wave heights, property damage, and human deaths. Meta-analysis of wave attenuation by vegetated and unvegetated wetland sites emphasizes the important role of vegetation in reducing waves. However, we also recognize that wetlands cannot defend the shorelines in all situations or places; in fact, large-scale regional erosion, river meandering, and large tsunami waves and storm surges can overpower the attenuation effect of vegetation.
(Goudie & Middleton, 2006)	Desert Dust in the Global System : Chapter – Dust storm control Link: https://link.springer.com/chapter/10.1007/3-540-32355-4_8 NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Dust storms Location: Northern Europe Remarks: The book chapter discusses the controlling of dust storms using agronomic measures with examples of techniques used in Northern Europe.
(Gracia et al., 2018)	Use of ecosystems in coastal erosion management Link : Use of ecosystems in coastal erosion management - ScienceDirect NBS: Wetland restoration, dune vegetation Threat: Coastal erosion due to Storm waves and sea level rise Remarks: Review Paper. This paper seeks to undertake a general review of adaptation and protection measures against coastal erosion issues, based on incorporation of ecology and ecosystem services into coastal erosion management strategies.
(Greene, 2014)	The Role of Wetland Ecosystems as Critical Infrastructure for Climate Change Adaptation Link : The Role of Wetland Ecosystems as Critical Infrastructure for Climate Change Adaptation - The IAFOR Research Archive NBS: Wetland Restoration and importance of wetlands Threat: Climate change, flooding Location: References to Indonesia, Switzerland, Cambodia, Sri Lanka for state of wetlands For flood abatement : Thailand Relation to Infrastructure: In general mentioned as all critical infrastructure Remarks: Shows cases where wetlands have used as infrastructure for climate adaptation – successfully or unsuccessfully.
(Gumiero et al., 2013)	Linking the restoration of rivers and riparian zones/wetlands in Europe: Sharing knowledge through case studies

	Link : Linking the restoration of rivers and riparian zones/wetlands in Europe: Sharing knowledge through case studies - ScienceDirect NBS : Wetland Restoration Threat : Flooding Remarks: This paper uses a set of case studies based in Europe that discuss the current issues surrounding wetland/floodplain restoration and connectivity with rivers in the context of balancing conservation, agricultural, economic and societal needs.
(Hall & Cratchley, 2005)	The role of forestry in flood management in a Welsh upland catchment Link : EconStor: The role of forestry in flood management in a Welsh upland catchment NBS: Increase Forest management in the catchment area Threat: Flooding Location: Dolgellau in North Wales, England Remarks: The findings show that forestry has a significant impact on increasing the temporary storage capacity for floodwater that overflows the river banks. According to a model, the water depth can rise by up to 1m when compared to grassland. Natural broadleaf woodland also helps to stabilise the river banks and prevent the erosion of periglacial gravels, which can accumulate downstream and reduce the effectiveness of flood defences. A forestry management scheme that takes into account these processes is suggested to lower the flood risk for Dolgellau.
(Jia et al., 2020)	Analysis of Runoff and Sediment Losses from a Sloped Roadbed under Variable Rainfall Intensities and Vegetation Conditions Link : Sustainability | Free Full-Text | Analysis of Runoff and Sediment Losses from a Sloped Roadbed under Variable Rainfall Intensities and Vegetation Conditions (mdpi.com) NBS: Cover slope with vegetation Threat: soil erosion Location: Jianning Qi Railway in Nantong City, Jiangsu Province, China Relation to Infrastructure: Experimental setup was conducted in a sloped roadbed Remarks: The paper focuses on getting a better understanding on the effect of grass-planting or shrub-grass planting on reducing runoff and soil erosion and increasing soil water infiltration. Investigation on the rainfall yield and sediment yield using runoff plots for a sloped system with three different treatments and five different rainfall intensities. The objectives of this study were to: (i) explore the law of runoff and sediment yield under different rainfall intensities, and (ii) evaluate which types of planting and vegetation allocation have the best soil and water conservation benefits. In this experiment runoff and sediment losses on a shrub-grass planted, grass-planted, and bare slope under different rainfall intensities was studied.
(Kavian et al., 2020)	The Use of Straw Mulches to Mitigate Soil Erosion under Different Antecedent Soil Moistures Link : https://www.mdpi.com/2073-4441/12/9/2518/htm NBS: Spread mulch over the soil to protect it Threat: Soil Erosion Location: Iran

	Remarks: The paper discusses a study investigated the separate and combined effects of two straw mulch types: colza (Brassica napus L.) and corn (Zea mays L.), to mitigate the activation of soil loss and runoff in sandy-loam soils, under different antecedent soil moisture conditions, in a rainfed plot in Northern Iran. The study concludes that the application of straw mulch is affordable and useful in reducing soil loss and runoff, instead of bare soils.
(Kingsford et al., 2011)	A Ramsar wetland in crisis – the Coorong, Lower Lakes and Murray Mouth, Australia Link : CSIRO PUBLISHING | Marine and Freshwater Research NBS : Bio-inspired or nature based solution for ph stabilisation in local areas Threat: Lake Acidification Location: Rome, Italy Remarks: The paper discusses a solution where the authors modeled a scenario through river management where the annual flows were increased during low flow periods to reduce lake acidification
(Kumar et al., 2020)	Towards an operationalisation of nature-based solutions for natural hazards Link : Towards an operationalisation of nature-based solutions for natural hazards - ScienceDirect NBS: Threat: Natural Hazards Location: Europe Remarks: The paper discusses the concept of nature-based solutions (NBS) as a way of adapting to the increasing risks of hydrometeorological hazards (HMHs) such as heatwaves, floods, landslides, droughts, and storm surges. NBS are interventions that use natural or semi-natural elements to provide multiple benefits for humans and ecosystems, such as reducing disaster impacts, enhancing biodiversity, and improving well-being. The paper proposes a novel approach of using Open-Air Laboratories (OAL) to operationalise and implement NBS in different contexts and scales. OAL are platforms that involve stakeholders from various sectors and levels in the co-creation, monitoring, and evaluation of NBS, as well as in the dissemination of their results and benefits. The paper identifies the main challenges and opportunities for the adoption of NBS in policy and practice, such as the lack of evidence, knowledge, and awareness, the fragmentation of policy frameworks, the financial and technical barriers, and the need for multi-risk assessment and management. The paper concludes that OAL can help overcome these challenges and foster the integration of NBS into the mainstream adaptation strategies for HMHs in Europe and beyond.
(Li et al., 2013)	Impact assessment of urbanization on flood risk in the Yangtze River Delta Link : Impact assessment of urbanization on flood risk in the Yangtze River Delta | Stochastic Environmental Research and Risk Assessment (springer.com) NBS : Avoid urbanization and watersheds diversions in vulnerable areas Threat: Flooding Location: Yangtze River Delta, China Remarks:

	For the study area, different urbanization stages, 1991, 2001 and 2006 were assessed. The study concludes that flood hazard and the exposure of disaster bearing body in the 6 areas are all with an increasing trend in the process of urbanization.
(Marando et al., 2019)	Regulating Ecosystem Services and Green Infrastructure: assessment of Urban Heat Island effect mitigation in the municipality of Rome, Italy Link : Regulating Ecosystem Services and Green Infrastructure: assessment of Urban Heat Island effect mitigation in the municipality of Rome, Italy - ScienceDirect NBS : Green Infrastructure, peri-urban forest,urban forest, street trees Threat: Urban Heat Island effect Location: Rome, Italy Remarks: This article examines how green infrastructure (GI) contributes to climate regulation in Rome, Italy, a city with a diverse landscape and a Mediterranean climate. The method used in this article measures the urban heat island (UHI) effect by using the Land Surface Temperature (LST) data from Landsat-8 satellite images. The method also evaluates the cooling effect of different types of GI (such as forests, parks, and street trees), as well as the influence of vegetation cover and tree diversity on this regulating ecosystem service.
(Mazda et al., 2006)	Wave reduction in a mangrove forest dominated by Sonneratia sp. Link : Wave reduction in a mangrove forest dominated by Sonneratia sp. | Wetlands Ecology and Management (springer.com) NBS: Mangrove (forests) Threat : Severe sea waves in coastal areas Location: Tong King delta, and Vinh Quang coast, Vietnam Remarks: Paper discusses how mangroves help towards protecting coastal areas from sever sea waves. Decrease of wave heights up to 20% per 100 m of mangroves. The results indicate that the thickly grown mangrove leaves effectively dissipate huge wave energy which occurs during storms such as typhoons, and protect coastal areas.
(McPherson & Muchnick, 2005)	Effects of street tree shade on asphalt concrete pavement performance Link : https://www.pavingandrepairhouston.com/uploads/1/0/4/8/104898903/effects_of_street_tree_shade.pdf NBS : Vegetation for shading of concrete and asphalt pavements against sun. Threat: Radiation, UHI Location : US California Remarks: The paper calculates Pavement Condition Index (PCI) and Tree Shade Index (TSI) to analyze the responsibility of trees towards pavement fatigue cracking, rutting, shoving, and other distress. The findings show greater PCI was associated with greater TSI, indicating that tree shade was partially responsible for reduced pavement damage.
(Norwegian Geotechnical	Hydrological effects (NBS) Category: Modifying the Surface Water Regime – Surface drainage (https://www.larimit.com/mitigation_measures/1027/) Link : https://www.larimit.com/mitigation_measures/1027/

Institute, 2023)	NBS: Vegetation on Slopes Remarks: - Effects of vegetation on induced soil suction - Effects of vegetation on infiltration rate - Design methods -Selection of vegetation species. - Establishment period
(Phillips et al., 2019)	The capacity of urban forest patches to infiltrate stormwater is influenced by soil physical properties and soil moisture Link: The capacity of urban forest patches to infiltrate stormwater is influenced by soil physical properties and soil moisture - ScienceDirect NBS: Improve forest management in the catchment area Threat: Pluvial flooding Location: Baltimore, Maryland Remarks: This study examines how urban forest patch soils can absorb rainfall by measuring rates of unsaturated hydraulic conductivity (K) in 21 forest patches in Baltimore, Maryland. We also tested soil bulk density, organic matter, soil moisture, percent of coarse fragments (≥2 mm), and texture at the same locations to see what affects K. The K was much higher in soils with a lot of sand and related positively with the percent of coarse fragment material in the soil. Forest patch size did not matter for K. We estimate that urban forest patch soils could soak up 68 percent of historic rainfall at the measured K rates. We also monitored one forest patch continuously and found that K changes over time and depends on how wet the soil is before. We cautiously estimate that unsaturated urban forest patch soils alone can soak up most rain events of low to moderate intensities that happened within these forest patches in the Baltimore region. This ecohydrologic function shows that protecting and expanding forest patches can help a lot with stormwater management.
(Pińskwar et al., 2019)	Changing Floods in Europe Link : Changing Floods in Europe | 5 | Changes in Flood Risk in Europe | Iwon (taylorfrancis.com) NBS: Avoid urbanization and watersheds diversions in vulnerable areas Threat: Flooding Location: Europe Remarks: The chapter examines how floods have changed across Europe and explores the observed trends of climatic factors that influence them. It shows how maximum precipitation and streamflow have changed, how flood exposure has increased, and how the number of major floods in Europe has varied, based on different data sources and time periods.
(Rickli & Graf, 2009)	Effects of forests on shallow landslides – case studies in Switzerland Link : https://www.researchgate.net/publication/228691482_Effects_of_forests_on_shallow_landslides_-_Case_studies_in_Switzerland

	NBS: Forest management and cover slope with vegetation Threats : Shallow landslides – Rainfall induces Location : Switzerland Remarks : Discusses whether with comparable rain landslide densities, the dimensions of the slides and certain site characteristics near the slides in forest areas are different from those in open land.
(Ruangpan et al., 2020)	Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area Link : NHESS - Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area (copernicus.org) Threat: Hydrometeorological Hazards Remarks: Review paper on NBS
(Sanon et al., 2012)	Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria Link : Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria - ScienceDirect NBS: Wetland restoration as part of a strategy of multiply lines of flood defences Threat: Pluvial Flooding Location: Vienna , Austria Remarks: This paper used trade-off and multi criteria decision analysis methods to evaluate and measure the explicit trade-offs between the objectives of different stakeholders regarding the restoration options for an urban floodplain, the Lobau, in Vienna, Austria.
(Shah et al., 2023)	Quantifying the effects of nature-based solutions in reducing risks from hydrometeorological hazards: Examples from Europe Link : Quantifying the effects of nature-based solutions in reducing risks from hydrometeorological hazards: Examples from Europe - ScienceDirect Several European examples on the usage of NBS and its implementation OAL Italy (Panaro river basin,Emilia-Romagna region, Italy): Flooding, Installing herbaceous plants on the embankment of the Panaro River to reduce soil erosion and strengthen the embankment, Mentions damages to infrastructure (e.g., roads, power lines and water supply pipeline) OAL Austria (Watten valley, Tyrol,Austria): Landslides, First NBS: sealing off leaky streams and channels in the upslope contributing area ,Second NBS: optimization of the forest management OAL UK (Catterline Bay,Aberdeenshire, Scotland): Landslide,NBS include soil and water bioengineering techniques such as live pole drains, live cribwalls, brush layers, live slope lattice, live palisades, high-density planting of native woody species Norwegian DC (Øyer,Gudbransdalen Valley, Norway):Flooding, NBS project includes the creation of a creek bed instead of a 600 mm diameters pipeline. The region is mentioned as a residential area.

	French DC (Artouste, Pyrenees,France): Rockfalls , The NBS project consists of wooden tripods and wooden meshes made of larch trunks, fixed to the ground or anchored in the bedrock at different depths. The region belongs to along a primary regional road (RD-934 – A-136) connecting several small towns located along the Spain-France borders.
(Singh & Singh, 2011)	Rapid urbanization and induced flood risk in Noida, India Link : Rapid urbanization and induced flood risk in Noida, India: Asian Geographer: Vol 28, No 2 (tandfonline.com) NBS: Avoid urbanization and watersheds diversions in vulnerable areas Threat: Flooding Location: India Remarks: The paper explores how different ways of measuring the amount of hard surfaces affect the estimation of peak water flows using a computer model (WetSpa) that simulates how rainfall turns into runoff. The paper uses satellite data to map the hard surfaces in the River Yamuna and Hindon basin area and shows how they influence the peak water flows for different kinds of urban land uses. The paper also analyzes the changes in land use and cover in Noida from 1981 to 2011 and the historical water flow data from 1957 to 2010. The paper finds that the runoff from urban areas is more likely to cause flooding than the runoff from other types of land use.
(Stephen O & O, 2018)	Measuring Urban Forest Canopy Effects on Stormwater Runoff in Guelph, Ontario Link : Measuring Urban Forest Canopy Effects on Stormwater Runoff in Guelph, Ontario (uoguelph.ca) NBS: Improve forest management in the catchment area Threat: Pluvial flooding Location: Ontario, Canada Remarks: This study measures how urban forest canopy affects stormwater runoff and how much canopy cover is needed to effectively lower runoff levels. It uses i-Tree Hydro, a semi-distributed hydrological model, to calculate the hydrologic impacts of Guelph's urban forest. It compares different proportions of canopy cover to see how Guelph's current and potential urban forest differ. It finds that increasing canopy cover in plantable spaces reduces overall flow in the City, but runoff over impervious surfaces rises.
(Sutton-Grier et al., 2018)	Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts Link : Sustainability | Free Full-Text | Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts (mdpi.com) NBS: Natural/living shorelines, Wetland restoration Threat :Sea level rise, flood risk and climate change Location: United States Infrastructure : Mentions to critical Infrastructure: roads, bridges, dams, levees, sewer and stormwater systems Remarks: Discusses the importance of investing in NBS views towards cost benefit analysis of implementation and maintenance to meet societal needs.

(Teich et al., 2012)	Snow Avalanches in Forested Terrain: Influence of Forest Parameters, Topography, and Avalanche Characteristics on Runout Distance Link : Full article: Snow Avalanches in Forested Terrain: Influence of Forest Parameters, Topography, and Avalanche Characteristics on Runout Distance (tandfonline.com) NBS: Improve forest management on slopes Threat: Snow Avalanches Location: Remarks: This study examines 60 variables on forest features, terrain attributes, and avalanche properties, and how they influence the avalanche runout lengths of small to medium avalanches that start in forests and medium to large avalanches that start above the treeline.
(Thorslund et al., 2017)	Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management Link : Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management - ScienceDirect NBS : Wetland Restoration Summary Literature survey on large scale wetlandscapes applied to provisioning of ecosystem services such as coastal protection, biodiversity support, groundwater level and soil moisture regulation, flood regulation and contaminant retention. This paper aims to provide suggestions can help bridge gaps between researchers and engineers, which is critical for improving wetland function-effect predictability and management..
(Van Coppenolle et al., 2018)	Contribution of Mangroves and Salt Marshes to Nature-Based Mitigation of Coastal Flood Risks in Major Deltas of the World Link : Contribution of Mangroves and Salt Marshes to Nature-Based Mitigation of Coastal Flood Risks in Major Deltas of the World | Estuaries and Coasts (springer.com) NBS: Mangrove Restoration Threat: Coastal Flooding Location : Major Deltas of the World; Mississippi, the Niger, part of the Ganges-Brahmaputra deltas, Yangtze and Rhine deltas Infrastructure: Abstract – No specific Mentions Remarks: The study focuses on contribution of salt marshes and mangroves to nature-based storm surge mitigation in 11 large deltas around the world. The results show the importance of conserving tidal wetlands as a NBS approach to mitigate flood risk.
(Volk, 2013)	A case-study example from a real living snow fence designed using this step-by-step protocol is provided at the end of the fact sheet. Link : (PDF) Living Snow Fence Design - Fact Sheet #3 (researchgate.net) NBS: Living snow fences Threat: blowing and drifting snow Location:

	Remarks: Fact sheet showing basic elements of designing : : Fence Orientation, Snow Fall, Fetch Distance, Snow Transport, Required Height, Selecting a Design Age, Optical Porosity, Fence Capacity, and Setback. A case-study example from a real living snow fence designed using this step-by-step protocol is provided at the end of the fact sheet.
(Webb et al., 2018)	Green Infrastructure Techniques for Coastal Highway Resilience Link : Henderson Point Connector (US HWY 90): Green Infrastructure Techniques for Coastal Highway Resilience (bts.gov) NBS: Vegetated berms (similar to dunes) Threats: Storm surge waves and coastal flooding Location: Henderson Point, Mississipi, USA (carries US HWY 90 over railroad tracks and a small tidal creek.) Remarks : Study done following Hurricane Katrina where number of coastal bridges and highways failed during the event. Multiple hydrodynamic models were used to determine the likely causes of failure at the Henderson Point bridge. A number of conventional gray adaptation solutions and green infrastructure adaptation options were considered in this study. The results show that even with a relatively low material cost (~$20,000 not including vegetation), the vegetated berms would reduce the likelihood of bridge span failure during its 50-yr design life from 64% to 39%, by protecting the bridge against the 1% annual chance coastal flood event (current protection level is to the 2% event).
(Weninger et al., 2021)	Ecosystem services of tree windbreaks in rural landscapes—a systematic review Link : Ecosystem services of tree windbreaks in rural landscapes—a systematic review - IOPscience NBS: Protection of wind exposed road sections and assets with planted forests. Threat: Cyclones, strong winds Location: Remarks: The article reviews the effects of windbreaks, which are rows of trees or shrubs that reduce wind speed and provide other benefits to the environment. Windbreaks are examples of nature based solutions, which are actions that use natural processes to address societal challenges. The article identifies eight types of ecosystem services (ES) that windbreaks can provide, such as soil protection, biodiversity, pest control, biomass production, nutrient and water balance, climate regulation, recreation, and cultural values. The article analyzes 222 publications that provide quantitative data on the effects of windbreaks on these ES. The results show that windbreaks have mostly positive effects on the landscape, especially for soil protection, biodiversity and pest control. However, some negative or neutral effects are also reported, such as reduced crop yields, increased water consumption, or altered microclimate. The article concludes that there is a need for more interdisciplinary research on the functionality of windbreaks in rural landscapes.
(Yan et al., 2020)	Quantifying the cooling effect of urban vegetation by mobile traverse method: A local-scale urban heat island study in a subtropical megacity Link : Quantifying the cooling effect of urban vegetation by mobile traverse method: A local-scale urban heat island study in a subtropical megacity - ScienceDirect NBS : Green Infrastructure, peri-urban forest,urban forest, street trees Threat: Urban Heat Island effect

	Location: Shenzhen, China Remarks: The paper concludes that the air temperature in the city can be more stable and less variable by increasing the amount of vegetation. The areas with more than 55% of vegetation cover can keep a relatively constant air temperature. This information can be useful for managing and planning the urban climate.
(Z. Tang et al., 2021)	A Review on Constructed Treatment Wetlands for Removal of Pollutants in the Agricultural Runoff Link: Sustainability | Free Full-Text | A Review on Constructed Treatment Wetlands for Removal of Pollutants in the Agricultural Runoff (mdpi.com) NBS: Bio-inspired or nature based solution for ph stabilisation in local areas Threat: Ocean and lake acidity Location: Remarks: The paper reviews the recent research on how different wetlands (such as surface flow, subsurface horizontal flow, subsurface vertical flow, and hybrid) can remove pollutants from agricultural runoff water. It also explains the mechanisms of removal and identifies the research gaps and needs for more resilient and sustainable treatment systems. The removal performance of the wetlands depends on various factors, such as the type and design of the wetland, the contaminant property, the aeration, the hydraulic parameters, the substrate medium, and the vegetation. The paper also points out that there is a lack of studies on the treatment of agricultural wastewater using nature-based solutions, such as wetlands, especially for pollutants other than nutrients and sediment. The paper concludes that wetlands are effective in treating agricultural wastewater.

Annex B - Emerging Technologies, Supporting Literature

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Annex C – Mapping of Adaptation Options from ROADAPT to ICARUS

In this chapter, the process for mapping adaptation options from ROADAPT to ICARUS database of adaptation options is described.

In the ROADAPT project, the adaptation measures were characterised by the following categories:

- Main threat: This is the main climate threat, e.g. flooding.
- Specific threat: This is the cause of the main threat, e.g. flooding due to failure of river flood defence system.
- Climate parameter: This is the climate event that caused the threat, e.g. snowmelt.
- Adaptation measure: This is the measure which can help overcome the main threat, e.g. avoid deforestation in the catchment area.
- Asset type: This is the asset which will be impacted, e.g. geotechnics, structures.
- Policy: This is the policy level at which the measure will be implemented e.g. prevention.
- Category of measure: This is the project life cycle stage at which the measure will be implemented.
- Stage: This is the Disaster Risk Management Cycle Stage
- Scale: This is the level at which the measure may be implemented e.g. object or connection.

Many of these categories overlap with the categories proposed for categorisation for ICARUS, and so could be easily mapped. In addition, new categories were proposed for ICARUS and so each measure was reviewed under each of these new categories. The additional categories for ICARUS as well as the mapping system from ROADAPT to ICARUS is demonstrated in and further explained in the following sections.

Table C.1 ROADAPT vs ICARUS adaptation option characterisation

ROADAPT	ICARUS	Categorisation Options	Reference
Main Threat	Climate Impact Driver	As shown in Table 2.2.	See Section 2.2.1.
Specific Threat	Impact on Infrastructure		
Climate Parameter	Climate impact Driver - Sub Driver	As shown in Table 2.2.	See Section 2.2.1.
Adaptation Measure	Adaptation Option		
Asset Type	Applicable Asset Type	As shown in Table 2.3.	Aligned with ROADAPT, no mapping required.
Policy	-		Not used in ICARUS.
Category of Measure	Road Project Life Cycle Stage	As shown in Table 2.3.	Mapped from ROADAPT, see Section 0.
Stage	Disaster Risk Management Cycle Stage	As shown in Table 2.3.	Mapped from ROADAPT, see Section 0.
Scale	Asset Scale	As shown in Table 2.3.	Mapped from ROADAPT, see Section 0.

ROADAPT	ICARUS	Categorisation Options	Reference
-	Impact Chain Stage	As shown in Table 2.3.	Assigned based on ICARUS criteria. See Section 0.
-	Short / Long Term solution	Does this adaptation option address the climate impact driver in the Short (operational and tactical) or longer term (tactical and strategic)?	Most maintenance measures are classified as short term whilst revisions to standards and regulations are classified as long term.
-	Is the climate impact driver addressed?	Yes or no	"Yes" was selected if measures taken to replace/upgrade road materials which will be less impacted by climate impact driver. No is selected otherwise.
-	Is this a Nature Based Solution?	Yes: the measure as described in the table falls within the NbS definition presented in Section 2.3.1. No: the measure as described in the table does not fall within the NbS definition Potential: depending on how the measure is implemented and its context, the measure may fall within the NbS definition.	See Section 2.2.2 and 2.3.1.
-	Can Emerging Technologies be applied?	Yes: Emerging Technologies within the one of the categories defined in Section 2.3.2 are by an initial screening assessed to have a realisable potential. No: The potential for Emerging Technologies within the one of the categories defined in Section 2.3.2 are by an initial screening assessed as minor.	See Section 2.3.2.
-	Stakeholders Involved	These are the stakeholders which may be involved or affected by this adaptation option as shown in Table 2.3.	

C.1.1 Impact Chain Stage

This characterisation of the Impact Chain Stage is to highlight where the adaptation option has an effect in the impact chain. When selecting the Impact Chain stage, the following criteria were used based on D1.2 (Garcia-Sanchez et al., 2023):

1. Hazard: If the measure can impact the hazard, then this is chosen. This is unlikely in this assessment as these are climate events.
2. Exposure: Exposure refers to the number of people/livelihoods/eco-systems which may be impacted by the hazard and is location dependent (affects soil, geology, altitude, presence of water, land-use, and topography all impact exposure). Monitoring should be considered to affect Exposure as early warning may reduce the number of people/businesses etc. affected.
3. Vulnerability: This is the propensity of the asset to be impacted and considers the state of the asset. If the adaptation option improves the state of the asset, then this will decrease its vulnerability. Changes to standards / regulations etc. will go here as well as measures which improve the condition of the asset.
4. Impact: If the measure will reduce the adverse consequences of the hazard, then this one is chosen. An adaptation option may also improve the impact or have benefits to the asset. Adaptation options lowering Hazard, Exposure and Vulnerability will also decrease the impact (by following the impact chain). Lowering the impact is the final aim of all adaptation options.

C.1.2 Road Project Life Cycle Stage

There was some mapping required for this category as shown in Table C.2 below.

Table C.2 Mapping of Road Project Life Cycle Stages from ROADAPT to ICARUS

ROADAPT	ICARUS
Capacity building	Initial Proposal Stage
Research	Initial Proposal Stage
Legislation, regulations	Initial Proposal Stage
-	Appraisal Stage
Planning	Planning and Detailed Design
Robust construction	Construction
Resilient construction	Construction
Traffic management	Operation and Maintenance
Maintenance and replacement	Operation and Maintenance
Monitoring	Operation and Maintenance

C.1.3 Disaster Risk Management Cycle Stage

There was some mapping required for this category as shown in Table C.3 below.

Table C.3 Mapping of Disaster Risk Management Cycle Stages from ROADAPT to ICARUS

ROADAPT	ICARUS
Pro-Action	Prevention
Prevention	Prevention

Preparation	Preparedness
Response	Response
Recovery	Recovery
All	All

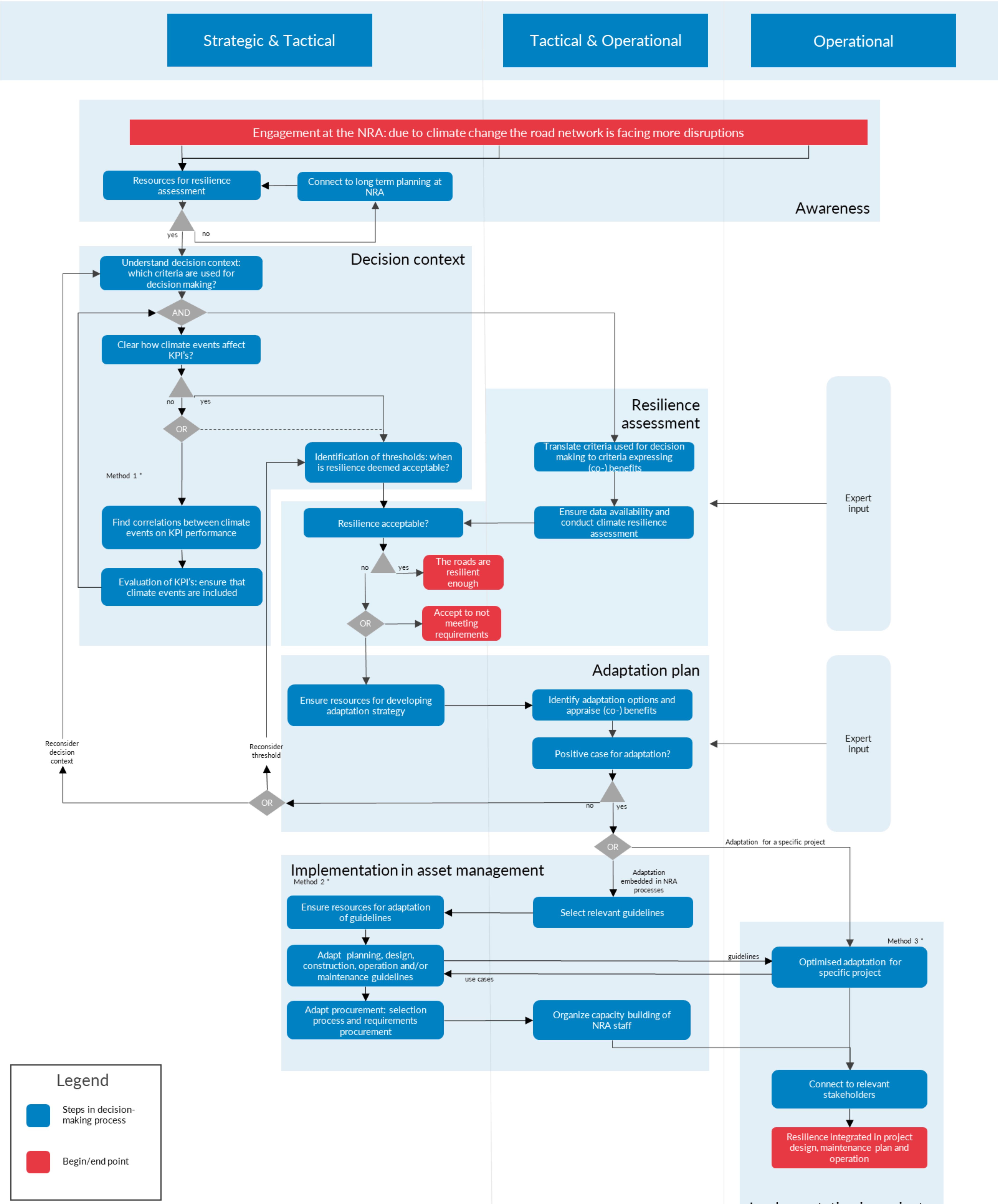
C.1.4 Asset Scale

There was some mapping required for this category as shown in Table C.4 below.

Table C.4 Mapping of Road Asset Scale from ROADAPT to ICARUS

ROADAPT	ICARUS
Object	Object
Object - Stretch	Object - Connection
Object - Stretch - Network	Object - Connection - Network
Stretch	Connection
Stretch - Network	Connection - Network
National Network	Network
Regional Network	Network
TEN-T - National - Regional	Network

Annex D – the ICARUS adaptation implementation process


Strategic & Tactical
Tactical & Operational
Operational
Engagement at the NRA: due to climate change the road network is facing more disruptions
Resources for resilience assessment
Connect to long term planning at NRA
Awareness
yes
no
Decision context
Understand decision context: which criteria are used for decision making?
AND
Clear how climate events affect KPI's?
no
yes
OR
Method 1 *
Identification of thresholds: when is resilience deemed acceptable?
Find correlations between climate events on KPI performance
Evaluation of KPI's: ensure that climate events are included
Resilience assessment
Translate criteria used for decision making to criteria expressing (co-) benefits
Ensure data availability and conduct climate resilience assessment
Resilience acceptable?
no
yes
The roads are resilient enough
OR
Accept to not meeting requirements
Expert input
Adaptation plan
Ensure resources for developing adaptation strategy
Identify adaptation options and appraise (co-) benefits
Positive case for adaptation?
Expert input
Reconsider decision context
Reconsider threshold
OR
no
yes
OR
Adaptation for a specific project
Implementation in asset management
Method 2 *
Adaptation embedded in NRA processes
Ensure resources for adaptation of guidelines
Select relevant guidelines
Adapt planning, design, construction, operation and/or maintenance guidelines
guidelines
use cases
Method 3 *
Optimised adaptation for specific project
Adapt procurement: selection process and requirements procurement
Organize capacity building of NRA staff
Connect to relevant stakeholders
Resilience integrated in project design, maintenance plan and operation
Implementation in projects
Legend
Steps in decision-making process
Begin/end point