Conférence Européenne des Directeurs des Routes

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ICARUS

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

Nature-based Solutions Report

Deliverable D4.2 Version 2

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CEDR call 2021: Climate Change Resilience

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Nature-based Solutions Report

June 2024

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Summary

The concept of 'Nature-based Solutions' (NbS) is receiving global attention as a societal solution to address climate change, biodiversity loss and water quality management among other challenges. NbS promotes the maintenance, enhancement, and restoration of biodiversity and ecosystems, effectively and efficiently addressing major social, economic and environmental challenges. Regardless of many benefits, there is no single, universally accepted definition for NbS. In this report we follow the definition of the European Commission due to its wide adoption, multidisciplinary nature and its inclination with ICARUS project's findings. The European Commission defines NbS as 'solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience'.

NbS can be viewed as an umbrella concept for several other related concepts such Green Infrastructure. NbS covers different dimensions and it encompasses wide range of nature-based interventions. NbS is a systemic and holistic approach that emphasizes the integration of natural solutions with built environment, and it's the core of NbS is broad scope that addresses global challenges. Adopting NbS in the infrastructure sector is a proactive and forward-thinking approach to climate resilience. Implementation of NbS is a way of putting regenerative thinking into practice and a contribution to moving from doing less harm to more good.

NbS have not been yet widely adopted in the road sector. In traditional road asset management, environmental aspects, such as biodiversity, have not been given a high priority, even though transport infrastructure has a big impact on nature during all its life cycle phases. When facing societal challenges, asset owners and managers need to come up with new solutions. Understanding the value brought by implementing NbS is one way to address the challenges.

When considering NbS, there are generally more stakeholders than when considering grey infrastructure. By fostering inclusive decision-making processes and leveraging local knowledge, expertise, and resources, collaboration and participatory planning enhance the effectiveness, equity, and sustainability of NbS interventions. One special aspect of NbS is collaboration with stakeholders and inclusion of local communities, which means that the discussions and negotiations are an essential part of implementing NbS.

There is no straightforward answer on how climate change will affect roads. An assessment of climate change risks provides a base for identifying and reducing risks and defining measures for strengthening of the road system resilience. Climate change adaptation and mitigation strategies in the road sector should consider cross-sectoral linkages, synergies, and trade-offs to optimize co-benefits and minimize unintended consequences. NbS often rely on ecosystem-based approaches, however, ecosystems are complex and dynamic systems that can be affected by climate change-induced stressors, which may undermine the effectiveness of NbS and require adaptive management strategies.

The ICARUS project provides an Excel database of adaptation options where measures have been classified according to the definition of NbS by the EC, classification being 'Yes', 'No' or 'Potential'. In the implementation of NbS there must be space for innovation, flexibility and adjusting the measures so that they can be adapted to local conditions and situations. The ICARUS project has described evaluation methods for assessing adaptation options and the most appropriate way of assessing the adaptation options was chosen to be multi-criteria analysis, which can be used for NbS adaptation options.

Guidelines for implementation of NbS are presented in this report. The most important elements to consider for implementation of NbS are getting buy-in from the organisation, involvement of stakeholders and local communities, including maintenance as an essential part of the planning process, monitoring and detailed design specifications These guidelines, along with NRAs' increasing embracement of sustainability and funding depending on sustainability goals, can help lower and overcome the barriers to NbS implementation. and adaptation implementation.

NRAs use KPIs to measure progress and steer decisions. When assessing adaptation options, it is important to link the assessment criteria to KPIs. NbS have several benefits and co-benefits that are either tangible or in-tangible in relation to valuation. ICARUS suggests a four-step method for applying valuation in decision-making contexts. The approach also covers valuation of NbS adaptation options. A fictive case study presented shows an example of how the NbS adaptation can be assessed through KPIs and how the value can be determined for the benefits and co-benefits.

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1 INTRODUCTION

1.1 Nature-based Solutions

1.1.1 NbS for road infrastructure

Climate change poses significant challenges to road infrastructure. Improving the resilience of road infrastructure is a proactive approach to minimizing the negative impacts of disasters and disruptions on society and the economy, including those related to climate change and natural disasters. Enhancing resilience is critical to ensuring that essential systems and services can withstand and recover from various shocks and stressors. By building infrastructure that can adapt to changing conditions, such as rising sea levels, increased temperatures, and extreme weather events, National Road Administrations (NRAs) will be able to manage the risks associated with climate change in a better way.

Transport infrastructure has a big impact on biodiversity, as linear assets cut through wildlife habitats, increase death rates of wildlife populations, and prevent wildlife spreading and immigrating to new areas. Furthermore, long stretches of roads and railways increase landscape fragmentation. (Seiler et al. 2023.) Climate change, biodiversity loss and landscape fragmentation are all societal challenges where implementation of NbS can be the solution. The future climate will have to be the in minds of the transport asset owners and managers when planning and managing their networks. In the daily asset management decision making, it must be ensured that environmental protection and improvement are taken into account. Asset managers need to understand and embrace the value brought from implementation of NbS. (IAM 2024.)

The goal of asset management is to ensure the value of the organization's assets through managing risk and opportunity (ISO 55000). In traditional engineering-oriented road asset management, the environmental issues like biodiversity loss, landscape fragmentation and climate change have been assessed mainly in the design and construction stages and less in the maintenance stage. However, even in the design and construction stage, the environmental aspects have not been necessarily given high priority. Good asset management practices contribute to environmental preservation and climate change adaptation. (PIARC 2017).

Implementation of NbS is a way to address climate change impacts on road infrastructure while enhancing socio-economic benefits. Integrating climate-resilient and nature-based design principles into road infrastructure design helps in adapting to changing conditions. NbS offer a range of benefits for road infrastructure, making them a valuable approach to enhance the resilience and sustainability of transportation networks.

NbS are often more cost-effective than traditional grey infrastructure solutions (Reguero et al. 2018, Le Coent et al. 2021). Investing in NbS requires lower upfront capital and they have lower long-term maintenance costs. NbS can also act as infrastructure protection from damage caused by e.g., erosion and landslides and thus extend the lifespan of roads and consequently lower maintenance costs. NRAs are actively taking part in creating more sustainable societies by minimizing the environmental impact of roads, decreasing the loss of biodiversity and contributing to a fossil-free transport system. Reaching these objectives requires ways to incorporate sustainable and environmentally friendly practices in the road life cycle.

Several NRAs have strategies and plans towards environmental sustainability or decreasing biodiversity loss (e. g. National Highways Environmental Sustainability Strategy (2023), Transport Infrastructure Ireland Biodiversity Plan (2023)). NbS offer a holistic approach to road infrastructure development that aligns with climate resilience, cost-efficiency, environmental compliance, and sustainability goals. Holistic approach (systems thinking) provides basis for more effective, multifunctional solutions that add value for both society and nature (Bridges et. al 2021). Embracing NbS can help NRAs address current and future challenges while simultaneously reaping a range of environmental, social, and economic benefits.

1.1.2 Definitions of Nature-based Solutions

The concept of 'Nature-based Solutions' (NbS) is receiving global attention, both as a field of research, but also as a societal solution to address climate change, biodiversity loss and water quality management, among other challenges. In Europe, NbS is integrated into policy frameworks like the European Green Deal, EU's Biodiversity Strategy for 2030, and in EU's Strategy on Adaptation to Climate change. At international level, international organizations such as the Organisation for Economic Co-operation and Development (OECD) and UN bodies like the Intergovernmental Panel on Climate Change (IPPC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) are taking an interest in NbS and the concept is included in UN's Kunming-Montreal Global Biodiversity Framework for Targets 8 and 11 (El Harrak & Lemaitre F., 2023).

The main motivation of NbS is that it promotes the maintenance, enhancement, and restoration of biodiversity and ecosystems, effectively and efficiently addressing major social, economic and environmental challenges (ILO et al., 2022). Despite, or perhaps due to, the high focus and the many stated NbS benefits, there is no single, universally accepted definition for NbS.

The International Union for Conservation of Nature (IUCN) defines Nature-based solutions as 'the actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (IUCN, 2016). This definition emphasizes the dual benefits of addressing societal challenges while promoting human well-being and biodiversity conservation.

The United Nations Environment Programme's (UNEP) definition of NbS follows closely the IUCN's definition: 'Nature-based solutions are actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits.' The scope of the UNEP's definition is broad, and it recognizes the major challenges that NbS can help to address. (UNEP, 2022.)

The Nature-based Solutions Initiative defines NbS as 'working with nature to address societal challenges, providing benefits for both human well-being and biodiversity. Specifically, they are actions that involve the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands such as croplands or timberlands; or the creation of novel ecosystems in and around cities.' (Nature-based Solutions Initiative, 2022.) This definition focuses on preserving natural ecosystems and sustainable use of land and water.

The European Commission defines NbS as 'solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience'. It states that 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. (EC, 2023.) The Commission's definition emphasizes the importance of local adaptation and resource efficiency. Furthermore, it underscores the multifaceted benefits of NbS, including environmental, social, and economic aspects.

These definitions are among the most widely adopted definitions of NbS. While they share common themes and objectives, there are some differences in emphasis and focus. The IUCN and UNEP definitions are closely aligned, the UNEP definition being broader in its scope. These two definitions highlight the dual role of NbS in addressing environmental and societal needs. The Commission's definition emphasizes the cost-effectiveness of NbS and their role in simultaneously providing environmental, social, and economic benefits. The Commission's definition also places a strong emphasis on integrating more diverse nature and natural features and processes into cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions. It underscores the need for interventions to be part of a broader, integrated approach and also included technical solutions.

In this report, we follow the definition of the European Commission, given its wide adoption, multidisciplinary nature and its compliance with ICARUS project's findings and consortium's understanding. The Commission's definition connects NbS with resilience, which is one of the main areas of focus in ICARUS project. NbS can be viewed as a broad umbrella concept for several other concepts that are linked to NbS (Figure 1.1). In Figure 1.1, four dimensions of NbS are recognized:

- Strategic dimension
- Spatial planning dimension
- Soft engineering dimension
- Performance dimension

As the figure 1.1 shows, NbS can be applied in different levels of operation from the strategic level to the performance level and thus help increase the resilience.

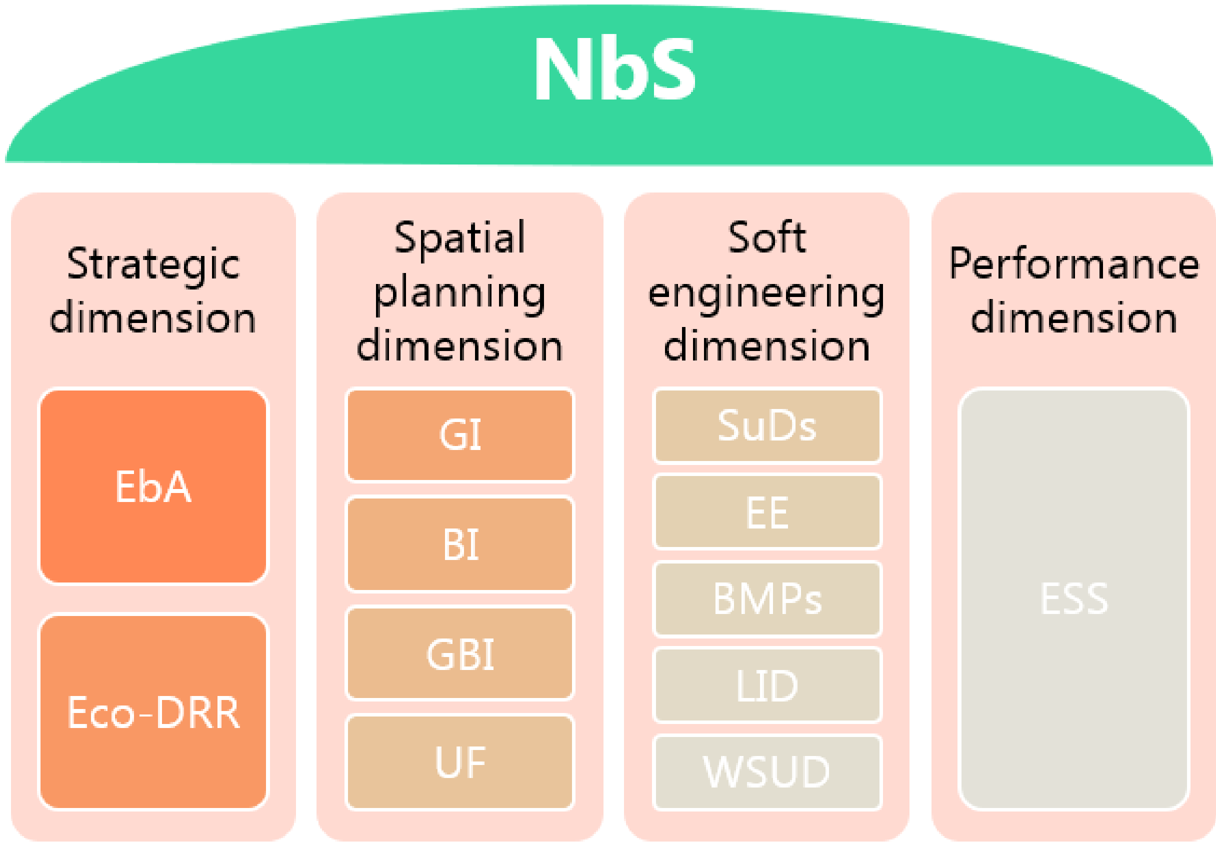

Figure 1.1. Nature-based solutions as an umbrella concept and the relation of NBS to key existing concepts (original figure EC 2021). EbA = ecosystem-based adaptation; Eco-DRR = ecosystem-based disaster risk reduction; GI = green infrastructure; BI = blue infrastructure; GBI = green-blue infrastructure; 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.

The Swedish road and railway administration Trafikverket (2024) has developed a list of indicative criteria for assessing if the solutions should be defined as NbS and has regarded several road projects in Sweden based on the criteria. The criteria are:

- the solution addresses the challenge
- local prerequisites are considered
- co-operation with other actors is included from planning to implementation
- biodiversity is regarded
- negative effects on reducing the emissions or people's health are avoided
- solution is multifunctional
- solution is resource effective and economically sustainable
- solution is implemented through an iterative learning process with an adaptive approach to management

All of these criteria must be met so that a solution is regarded as NbS. If only one of these criteria is not met, the solution cannot be classified as NbS. One example of applying these criteria is that if a solution does not include co-operation with other actors, it is not classified as NbS. When regarding the definition of NbS from European Commission used by the ICARUS project, several of these criteria are present. In this report we further discuss many of the aspects that are included in the criteria above.

1.1.3 Green Infrastructure under the umbrella of NbS

Green Infrastructure (GI) has been recognized in the discussions of the ICARUS project as one of the most relevant concepts of the NbS dimensions. Both NbS and GI involve the use of natural elements to address environmental challenges, NbS tend to have a broader and more integrated scope, addressing global challenges, whereas GI is often more localized and focuses more on enhancing the sustainability of urban environments.

As with the concept of NbS, there is not a universally agreed definition of GI and individual aspects of definitions can be underlined in different contexts. European Commission (2013) defines GI as 'a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services[1]. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings.' As stated in the definition, key components of GI may include natural elements (e.g., parks or green spaces), built elements (such as green roofs or bioswales), connectivity and multi-functionality. GI can be seen as sustainable and resilient approach in addressing climate change and the loss of biodiversity.

As shown in Figure 1.1, GI can be included as one of the approaches that constitute the concept of NbS and this is how ICARUS project defines the relationship of NbS and GI. GI being one of the components under the umbrella of NbS, they share similarities in their principles and goals as they both involve leveraging natural elements to address environmental challenges and improve the overall sustainability of built infrastructure. Both NbS and GI aim to provide a variety of ecosystem services and both concepts involve incorporating natural elements into the built environment. They both can also contribute to climate change adaptation and mitigation by carbon sequestration and enhancing the resilience to extreme weather events.

These two concepts have slightly distinct focuses and applications. In scope and purpose, NbS is a broader concept that encompasses a wide range of approaches beyond GI. NbS often involves a holistic and integrated approach that considers social, economic, and environmental aspects, where GI specifically refers to the planned use of natural elements to provide various ecosystem services in urban and rural settings. The scale of these two concepts is also different; NbS can can involve large-scale initiatives to address global challenges like climate change or more localized efforts to improve ecosystem services in a specific area. GI is typically implemented at a more local or municipal level. Considering the built environment, NbS often emphasizes the integration of natural solutions with built infrastructure and may involve a more holistic approach that considers the interconnectedness of human and natural systems, whereas GI primarily focuses on the incorporation of natural elements into the built environment, with a particular emphasis on the benefits of green spaces.

[1] Ecosystem services are the benefits that flow from nature to people. They can be provisioning (e.g. supply of food, clean air, water and materials), regulating (e.g. water and climate regulation, nutrient cycling, pollination, formation of fertile soils), or cultural (e.g. recreation opportunities, inspiration we draw from nature). Natural ecosystems can provide a wide range of these services simultaneously. This multi-functionality is one of the key attractions of green infrastructure. (EC n.d.)

Table 1.1. Comparison of the two concepts. Developed based on Pauleit et al. (2017) and Naturvårdsverket (2021).

Concept	Background	Focus	Application in infrastructure
NbS	Relatively new but highlighted during the climate negotiations in Paris in 2015. Sprung from work on climate adaptation and limiting climate impact.	Broad concept for dealing with multiple societal challenges; biodiversity seen as central to solutions.	Systemic and holistic approach; interconnectedness of built and natural systems.
GI	Began to be used at the beginning of 2000. Sprung out of EU work to preserve biological diversity.	Broad socioecological focus, the goal is to strengthen and increase biodiversity that can deliver ecosystem services.	Incorporating natural elements into built environment.

GI, among other approaches shown in the Figure 1.1, is vastly relevant to implementing NbS, as they function as specific operational approaches that can be deployed in implementing solutions to a societal challenge (IUCN 2020). While GI represents a critical component of NbS, it is just one aspect of a broader spectrum of nature-based interventions. It complements other NbS strategies by contributing to urban greening efforts, enhancing ecosystem services provision, and promoting sustainable urban development practices.

1.1.4 Why NbS?

Adoption of Nature-based Solutions is increasing throughout Europe and beyond (EC 2015; Voskamp et al 2021; World Bank 2021). Existing research has focused on defining NbS as a new paradigm in infrastructure resilience and the co-benefits that arise from it.

There are several reasons why NbS should be adopted to address climate change in infrastructure sector:

Natural Resilience: NbS leverage natural systems, such as wetlands, forests, and green spaces, which have evolved to withstand environmental stressors. These systems provide inherent resilience against climate impacts like extreme weather events.

Cost-Effectiveness: NbS are often more cost-effective than traditional "grey" infrastructure solutions. They can provide similar or even superior resilience outcomes while requiring less upfront investment and lower long-term maintenance costs.

Multiple Benefits: NbS offer multiple co-benefits beyond climate resilience, e.g. improved air and water quality, enhanced biodiversity, and recreational opportunities. These additional benefits contribute to overall sustainability and community well-being.

Adaptability: NbS are adaptable to changing climate conditions. Natural systems can adjust to evolving climate patterns over time, providing a flexible and dynamic approach to climate resilience.

Reduced Environmental Impact: Unlike some traditional infrastructure projects that can have significant environmental impacts, NbS typically have a smaller ecological footprint and can even contribute to ecosystem restoration and protection.

Enhanced Social Equity: NbS can help address social equity by providing green spaces, reducing heat islands in urban areas, and improving overall quality of life. Vulnerable communities often benefit disproportionately from these improvements.

Community Engagement: NbS projects often involve local communities in planning and implementation, fostering a sense of ownership and stewardship. This community involvement can lead to more effective and sustainable climate resilience solutions.

Long-Term Viability: NbS are designed to be resilient over the long term. They can withstand climate-related challenges without the need for frequent repairs or updates, making them a reliable and durable solution.

Enhanced Reputation: Organizations and governments that prioritize NbS in their infrastructure projects can benefit from enhanced reputations for sustainability and climate leadership.

Overall, adopting NbS in the infrastructure sector is a proactive and forward-thinking approach to climate resilience. By harnessing the power of nature, we can build infrastructure that not only is resilient against climate impacts while being cost-effective but also enhances the well-being of communities and ecosystems. Implementing NbS is a step towards putting regenerative thinking into practice and a contribution to moving from doing less harm to more good.

1.1.5 NbS stakeholders

Generally, when considering NbS, there is a need for more extensive engagement with certain stakeholders than required for grey infrastructure. Some relevant stakeholders include:

Road Owner / Operator / National Road Administration: As with grey infrastructure, the relevant road owner will be the primary stakeholder. They will be the budget-holder, be responsible for design standards, and ultimately procure the solution. Here, the design standards and procurement rules may be a significant barrier to NbS if they are geared towards traditional 'grey' infrastructure solutions. Another aspect is that NRAs must follow legislation which could hinder the use of NbS, e.g. for which purposes NRAs can use the state's budget or restrictions around agreeing contracts with private landowners. Equally, NRAs may have strategic objectives around biodiversity and embodied carbon which may favour NbS.

Consultants and Contractors: Generally, NRAs and other road owners do not design or construct the road. Here, the responsibility will largely fall within the realm of consultants for design and contractors for construction (and potentially for future maintenance). As NbS are an emerging solution, some consultants may propose 'traditional' solutions they are more familiar with, and which they know will work. Many contractors will be unfamiliar with construction of NbS, whilst maintenance regimes are also likely to be different, meaning that closer supervision of early schemes may be required. This emphasises the need for NRAs have the procurement of NbS as an option to highlight to consultants and contractors that novel solution can be proposed. As both become more familiar with the design, construction and maintenance of NbS, they are more likely to be offered as business as normal alongside grey or hybrid solutions.

Environmental Authorities: Environmental authorities will have a significant role to play as part of the NbS consultation phase. They will likely to be advocates for implementation of NbS that enhance biodiversity, improve ecosystem services, and mitigate environmental impacts, as these will align with their strategic objectives. Nonetheless, there will be statutory considerations to be made regarding permitting and planning that are consistent regardless of the type of solution proposed.

Local Authorities and Municipalities: Local governments play a critical role in planning, permitting, and managing road infrastructure within their jurisdictions. Collaboration with local authorities is essential for gaining approvals, accessing resources, and coordinating with other local initiatives and projects.

Local Communities: Residents living near the roads, as well as those who will use the roads, are important stakeholders. Their input is valuable for understanding local needs, concerns, and preferences. Community engagement can help ensure that NbS align with community priorities and benefit residents.

Financial Institutions and Investors: Banks, investment firms, and other financial institutions may provide funding for road projects. They have a stake in ensuring that investments are financially viable, socially responsible, and environmentally sustainable. A potential barrier could be a perceived risk of an 'unproven' technology when considering funding or insurance. It is important that the documentation of successful schemes is available to ease these concerns and to demonstrate the benefits and co-benefits of NbS.

Landowners and Land Managers: Private landowners, as well as public land managers (e.g., parks departments, forestry agencies), may have a stake in road projects that affect their land. Equally, how adjacent landowners manage their land can impact positively or negatively on the resilience of the road. Collaboration with landowners and managers is essential for securing access to land, obtaining permissions, and coordinating land use planning. Whilst these considerations would be the case for grey infrastructure, for NbS, there is an additional consideration in that the best way of mitigating risks to the road may in fact be from the land adjacent to the road, rather than in the (often narrow) road 'envelope' itself. For example, restoration of an adjacent peat bog or creation of a pond may be the best way to reduce the flooding risk in certain locations, whereas changes in planting may be an effective slope stabilisation approach in others.

Academic and Research Institutions: Universities and research organizations can contribute scientific expertise, data, and research findings to inform the design, implementation, and monitoring of NbS in road projects. Peer reviewed articles and case studies, as provided in the ICARUS project can help demonstrate the effectiveness of NbS to reassure NRAs, investors and other stakeholders.

Utilities Companies: Companies providing utilities such as water, electricity, and telecommunications often have infrastructure within or adjacent to roads. Coordination with these stakeholders is important to minimize disruptions and ensure that NbS do not interfere with utility operations.

Transportation Users and Businesses: Road users, including motorists, cyclists, pedestrians, and businesses that rely on transportation infrastructure, are stakeholders in road projects. Their needs for safe, efficient, and sustainable transportation should be considered in NbS implementation.

1.2 NbS in the ICARUS framework

During the research carried out in the ICARUS project, 6 central steps have been identified for incorporation of climate change adaptation in the processes of the NRAs. These 6 steps have been formulated as the ICARUS framework. The ICARUS deliverables are all classified according to their contribution into the various steps of the framework, see Figure 1.2.

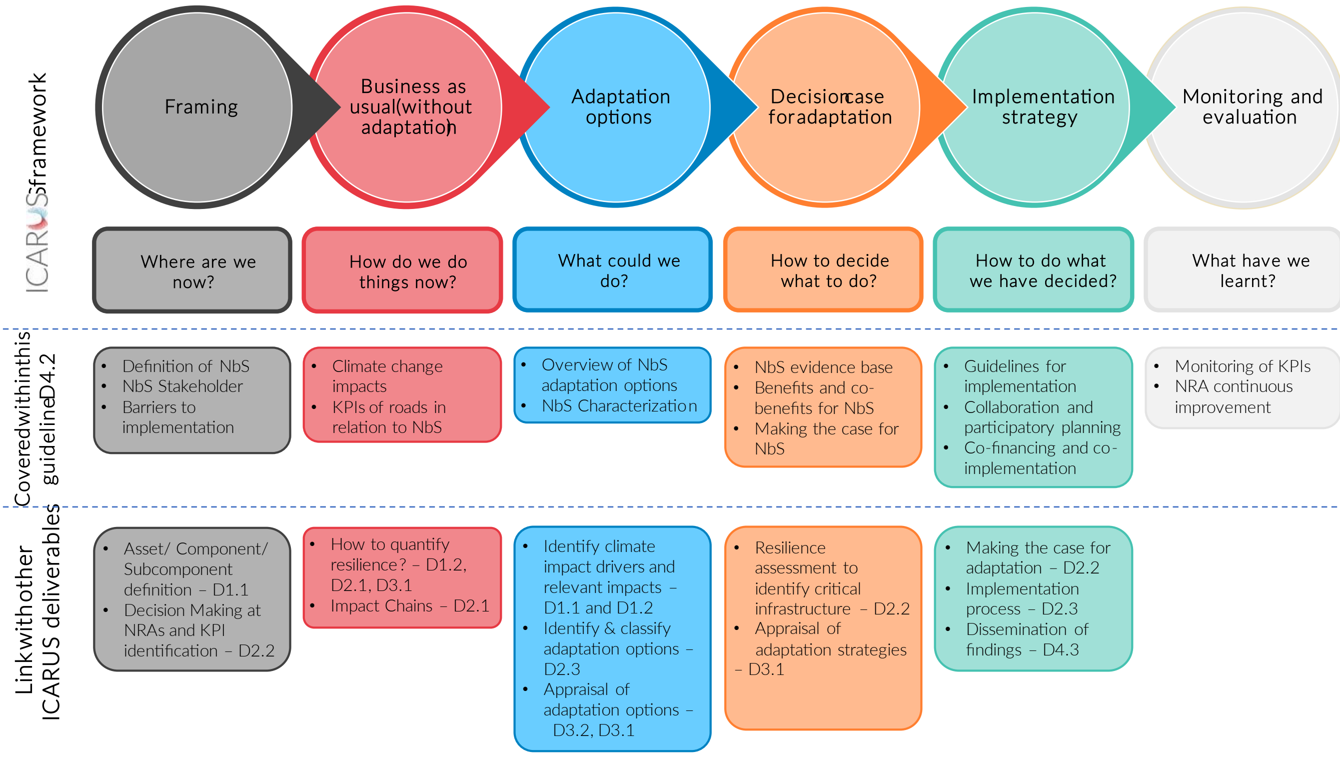

Figure 1.2. Overview of the steps in the ICARUS framework regarding decision-making and implementation of climate adaptation at NRAs, as well as how these steps are addressed in the underlying guidelines and other ICARUS deliverables (available at https://icarus.project.cedr.eu/icarus-resources/).

The **first step** is called framing and consists of understanding the decision-making process at NRAs. This includes especially the existing policies and guidelines, as well as the use of Key Performance Indicators. A clear overview of all involved stakeholders should be present. Furthermore, other boundary conditions for decision making should be clear, like the temporal and spatial scope, capacity and resources and data examination.
* In terms of enhanced resilience and achieved benefit and co-benefits, for NbS to realize full potential the solutions require participatory planning and a co-implementation procedure that goes beyond the traditional jurisdiction of the NRA. This makes the framing even more important.

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 in the resilience without adaptation will form the base case and is key to understand what the (wider) benefits are of adaptation options. This step is carefully reviewed in the preceding deliverables and only touched lightly upon in this report, as the assessment will be similar regardless of NbS being considered as an option or not.

In the **third step** adaptation options come at stake. Adaptation options, as well as their benefits and co-benefits, are identified.

* NbS as an adaptation solution can be compared with the more traditional solutions. Options can be 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 valued in such a way that this aligns with the decision-making processes of the NRAs.

The fourth step builds the decision case for adaptation. By comparing the resilience for the business as usual with the resilience including adaptation one gains understanding of the benefits and co-benefits of adaptation strategies that can be evaluated with relevant evaluation methodologies.
* NbS potentially bring other benefits and co-benefits than the more traditional adaptation options. 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 decided strategies in practice 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.
* For NbS this might require new guidelines for implementation and maintenance. Depending on the solution stakeholders co-financing schemes might come into play.

The final step consists of monitoring of the results of adaptation. How is the performance of the road network developing towards the future? And does this comply to the performance that was expected during the resilience assessments and appraisal of adaptation strategies?
* A proper monitoring enables evaluation of the performance and may lead to further steering of plans towards the future and can strengthen the NbS evidence base. Also, it further eases the decision case for adaptation in general, 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. Monitoring and evaluation is not specifically addressed in this deliverable.

1.3 Objective of this report

This report presents NbS in the context of climate change adaptation for road infrastructure. The objective of the report is to summarize and present the NbS approaches and findings of the ICARUS project. The report is to serve as a guideline for NRAs to make the case for implementation of NbS as climate change adaptation options for road infrastructure. Additionally, the report discusses drivers and barriers to implementation of NbS to equip the NRAs with the knowledge and skills to identify future opportunities and overcome challenges for NbS implementation.

The report is structured as follows:

- Chapter 1 introduces NbS and presents NbS in the context of road infrastructure and ICARUS.
- Chapter 2 provides an overview of climate change impacts on road infrastructure and the use of impact chains to identify NbS opportunities and challenges.
- Chapter 3 presents NbS adaptation options to enhance resilience.
- Chapter 4 presents an approach for assessment and performance evaluation of NbS adaptation options to make the case for NbS and presents a case study to demonstrate its application.
- Chapter 5 summarizes the report conclusions and recommendations.

2 NbS AND OPPORTUNITIES WITHIN CLIMATE CHANGE IMPACT CHAINS

2.1 Climate change impacts on road infrastructures

Although the impacts of climate change on roads in Europe are impossible to predict accurately, it can be said that the foreseeable impacts are different for individual assets and that climate change will impact all phases of the road life cycle. Because there is no straightforward answer to questions like 'how and where will climate change affect roads?' or 'how likely extreme weather conditions are and what are their consequences?' a risk management approach is a way to stay in control. An assessment of climate change risks provides a base for identifying and reducing risks and defining measures for strengthening of the road system resilience. (Garcia-Sanchez et al. 2022.)

Within the road sector, "impact" is almost always referred to as a negative consequence for the infrastructure due to a hazard or extreme weather event. Within ICARUS it is proposed to use the term impact-drivers. The concept of Climatic Impact-Driver (CID) was developed in the IPCC Sixth Assessment Report (AR6). CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems (SwissRe 2021). This effect could be negative or positive, which opens the door to innovative solutions sometimes based on nature.

In this regard, it can be said that over the last decade or so, NbS have gained attention as sustainable solutions for infrastructure struggling to cope with an increasing number of extreme weather events and climate-related hazards. The European Environment Agency (EEA) published a report in 2015 exploring the possibility of using NbS, rather than concrete and steel, to mitigate the impacts of weather and climate change-related hazards on infrastructure (EEA 2015). In the report, suggestions were made on ways to implement NbS to mitigate adverse effects of landslides, avalanches, flooding, storm surges and carbon destabilization by ecosystems. One of the key points, as summarized in IPPC AR6, is that both people and biodiversity benefit, whilst contributing to achieving other sustainable development goals (IPCC 2022).

2.1.1 Overview of impact chains for road assets

An impact chain is an analytical concept to better understand, systemize and prioritize climate factors as well as environmental and socio-economic factors that drive climate related threats, vulnerabilities, and risks in a specific system (see ICARUS deliverable D1.2 Report on impact chains, vulnerability and hazard classification). Impact chains serve as the backbone for an operational climate vulnerability assessment with indicators based on quantitative approaches (data, models) combined with expert assessments (Zebisch et al. 2021).

ICARUS proposes (Garcia-Sanchez et al. 2023) the use of impact chains as a methodology to understand how the various climate hazards can affect the roads including, also, the opportunity for adaptive responses (grey and green solutions). In this regard, it's necessary to be aware that adaptive response to the impact chains may well have impacts of their own, for instance responses that include new construction may increase the carbon impact of the road. The four pillars on which impact chains are built are: hazard, exposure, vulnerability and impact (Commission Notice 2021).

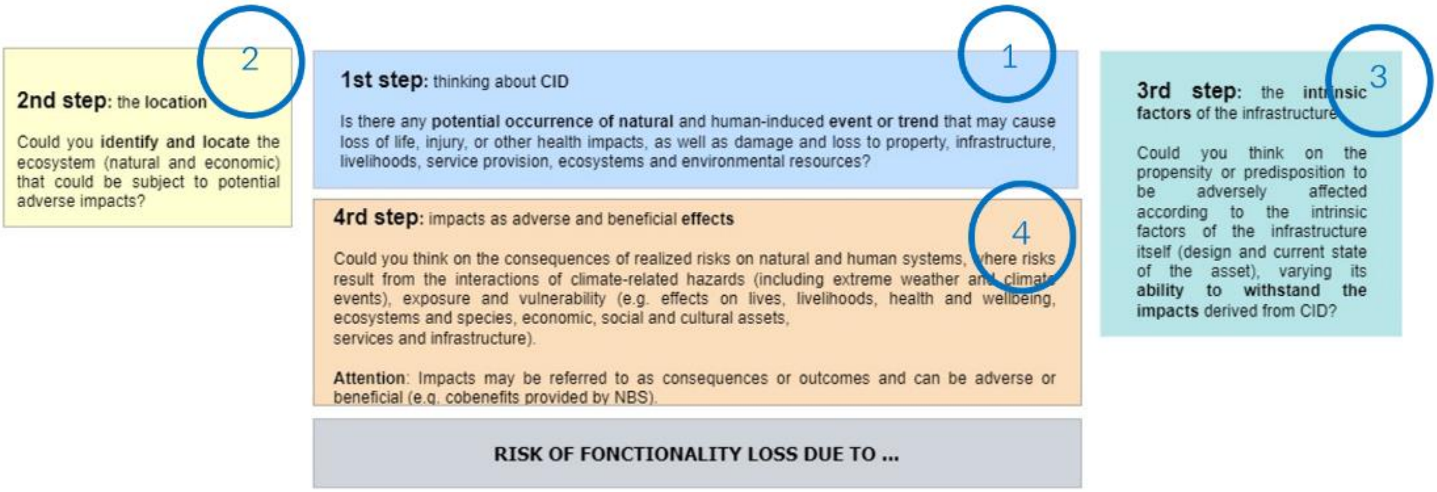

Figure 2.1. General impact chain graph for hazards and road infrastructure, with steps 1 to 4. Another approach to the question posed in step three is: Could you think on the predisposition of infrastructure to be negatively affected by CIDs as a function of its capacity?

Figure 2.1 shows the structure that is recommended to define impact chains. The methodology consists of answering the questions posed in each of the steps. It is a flexible methodology and should be adapted to the needs of each NRA. Although in ICARUS only the conceptual part is developed, the impact chains are the basis for the development of more sophisticated quantitative studies (e.g. Bayesian networks).

When defining impact chains for CID, it is valuable to consider where in the impact chain opportunities of different measures to change the impact could be used. In the ICARUS deliverable D1.2 Garcia-Sanchez et al. (2023) have provided several examples of impact chains and identified that NbS opportunities could be detected in many of them when considering the vulnerability of a road asset or the impact itself. For example, when considering landslide impact on road, the vulnerability for this impact can be reduced using NbS, such as planted embankment mats and/or living fascine and thus increase the resilience of the road. When developing the impact chains, it is important to recognize where different solutions, such as NbS, could be used.

2.2 NbS in the context of climate change

Climate change leads to more frequent and severe weather events such as heavy rainfall, floods, storms, and heatwaves, which can damage road infrastructure. NbS can help to mitigate the effects of climate change. Intense local precipitation events can trigger pluvial flooding which causes for example high/more surface runoff on roads. Due to increased flooding and erosion drainage systems and erosion protection of the roads may prove to be insufficient. Flood defense systems and flood risk systems can be improved using NbS, for example by integrating sustainable drainage systems (SuDS) into road design, which can help manage stormwater runoff more effectively, reducing the risk of flooding and erosion. Increased flooding may also bring new demands to the design and maintenance of culverts and bridges. Implementing NbS such as permeable pavements, green walls and infiltrations trenches, total runoff volume and peak discharges can be reduced and infiltration, detention and retention can be improved (Huang et al. 2020, Majidi et al. 2019, Ercolani et al. 2018).

Possibility of landslides and avalanches is predicted to increase due to increased precipitation and changes in the precipitation patterns. Increased occurrences of slush avalanches and debris flows result in road blockages, infrastructure damage and safety hazards. Introducing green or hybrid solutions can help in reducing runoff and stabilizing loose soils. Examples of NbS (green) solutions include retaining and restoring native or mixed forests on slopes and using vegetation as soil stabilizer (Casteller et al. 2018, Sutherland et al 2014). Planting trees, shrubs, and grasses on slopes can help stabilize soil, reduce erosion, and enhance slope stability. Implementing erosion control measures such as slope terracing, and bioengineering techniques can help stabilize slopes and prevent soil erosion thus protecting infrastructure. (Shah et al. 2023.)

Mean air temperature is one of the predicted consequences of climate change. Increasing air temperature will strengthen the heat island effect which can affect the durability of weakened asphalt, result in higher pavement temperature and increased rutting. These challenges can in some degree be met also with green infrastructure. Especially in urban and more densely built areas green roofs, bioswales and rain gardens can help in reducing the heat island effect. Cool pavement technologies also include nature-based approaches. For low-traffic areas vegetated permeable pavements, where plastic, metal, or concrete lattices provide support and allow grass or other vegetation to grow in the interstices, can provide cooling through evapotranspiration. (U.S. Environmental Protection Agency 2008.)

2.2.1 Challenges caused by climate change for NbS

Climate change poses several challenges to the design and implementation of NbS. As stated, climate change is altering precipitation patterns, temperature regimes, and increasing occurrence of extreme weather events, making it challenging to predict future environmental conditions. This creates challenges for designing NbS that are resilient to climate variability and uncertainty. NbS are designed to harness natural processes to mitigate environmental hazards. However, as the extreme weather events become more common, they pose a risk of overwhelming the capacity of NbS. This means that the systems designed to reduce risks might no longer be able to cope with the increased scale and intensity of these events, leading to a reduced ability to protect against environmental hazards effectively.

NbS often rely on ecosystem-based approaches that leverage natural processes and biodiversity to address environmental challenges. However, ecosystems are complex and dynamic systems that can be affected by climate change-induced stressors, such as habitat loss, invasive species, disease outbreaks, and ecosystem disruptions. These stressors may undermine the effectiveness of NbS and require adaptive management strategies. Landscape fragmentation brings also challenges for designing and implementing NbS. Climate change may aggravate habitat fragmentation, land-use changes, and complicate infrastructure development, making it difficult to establish and maintain contiguous networks of NbS that support biodiversity, ecosystem services, and ecological resilience.

Resources and local communities should be considered when designing NbS. Designing and implementing NbS requires significant resources, including funding, technical expertise, land availability, and materials. Climate change may aggravate resource limitations and competition for natural resources, making it more difficult to prioritize and invest in NbS projects, particularly in regions facing socioeconomic challenges and environmental vulnerabilities. NbS should be designed and implemented in consultation with local communities to ensure that they address community needs, priorities, and values. Climate change impacts may aggravate social inequalities, displacement, and vulnerability. This requires inclusive approaches to NbS planning and governance that prioritize social equity, justice, and resilience-building.

Intersectoral considerations are also an aspect to be taken into account when planning NbS in changing climate. Roads intersect with various sectors such as water, energy, agriculture, and urban development, creating interdependencies and trade-offs in NbS planning and implementation. Climate change adaptation and mitigation strategies in the road sector should consider cross-sectoral linkages, synergies, and trade-offs to optimize co-benefits and to minimize unintended consequences.

Overcoming the challenges posed by climate change to the design and implementation of NbS requires a multi-faceted and integrated approach involving various stakeholders, innovative strategies, and adaptive management practices. The competencies of stakeholders involved in planning and implementation of NbS can be enhanced by investing in capacity building, training and knowledge exchange. Stakeholders can be engaged by involving them in all phases from planning to monitoring of NbS and thus ensure inclusiveness and ownership of solutions. Stakeholder feedback is one way to evaluate and assess the effectiveness of NbS and implement adaptation in decision making. Adaptive management can be applied to deal with uncertainties and performance. It is a iterative decision-making method and can be applied on project-specific basis.[2] Innovations in technology and financing mechanisms are worth exploring to leverage resources and expertise for NbS implementation. Supporting interdisciplinary research and knowledge networks generate evidence-based solutions and good practices.

[2] For more information on AM in NbS see e.g. Bridges, T. S. et al. (2021)

3 NBS ADAPTATION OPTIONS TO ENHANCE RESILIENCE

3.1 Overview of NbS adaptation options

There are many ways to adapt road infrastructure and increase resilience to climate change events, and it can be difficult to choose the most appropriate options. Within ICARUS, a key focus area is to provide road authorities with a selection of adaptation options, guidance on how to choose the most appropriate options for their infrastructure, and guidance on how to implement adaptation. An Excel database of adaptation options has been developed as part of this project and is presented in ICARUS Deliverable D2.3 (de Paor et al., 2024). The database builds on the ROADapt project (Bles et al., 2015) and contains traditional adaptation options as well as NbS adaptation options. Further introduction and a step-by-step guide to using the database can be found in ICARUS Deliverable D2.3 (de Paor et al., 2024).

The sub-sections below present the characterization of NbS adaptation options identified as part of the database and the criteria for their evaluation.

3.1.1 NbS characterization

For the purpose of the ICARUS project, the adaptation options in the table have been characterized to show if they are NbS or not. (Bles et al., 2015, specifically the Adaptation database). NbS adaptation options are highlighted in the ICARUS adaptation options database as these are gaining recognition as key adaptation approaches, because they offer a holistic approach to road infrastructure development, which aligns with climate resilience, cost-efficiency, environmental compliance, and sustainability goals.

The criteria used by ICARUS project to classify a measure as NbS are directly derived from the NbS definition by the European Commission given in section 1.1.1. Hence, for an adaptation option to be labelled as NbS it must fulfil all 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.

Adaptation options in the Excel database have been classified following the Commission's definition and the criteria derived from it, since the adaptation options are single measures to be implemented in road infrastructure, whereas e.g. the criteria developed by Trafikverket (see section 1.1.2) can be applied on full scale projects.

Even with these sub-criteria, the characterization of the adaptation options has not been straightforward, because several of the criteria are ambiguous (i.e. what does 'inspired and supported by nature' actually entail?). Also, some of the adaptation options themselves are ambiguous in the sense that in most cases the context, i.e. where the adaptation option is to be implemented and how, needs to be taken into account, in order to evaluate if there are any significant environmental, social and economic benefits. This is 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 3.1 describes the applied NbS characterization. The figure is to be read in way that if the answer for any question is No, the adaptation options is not NbS. If the answer is Yes or Potential, the next question can be considered.

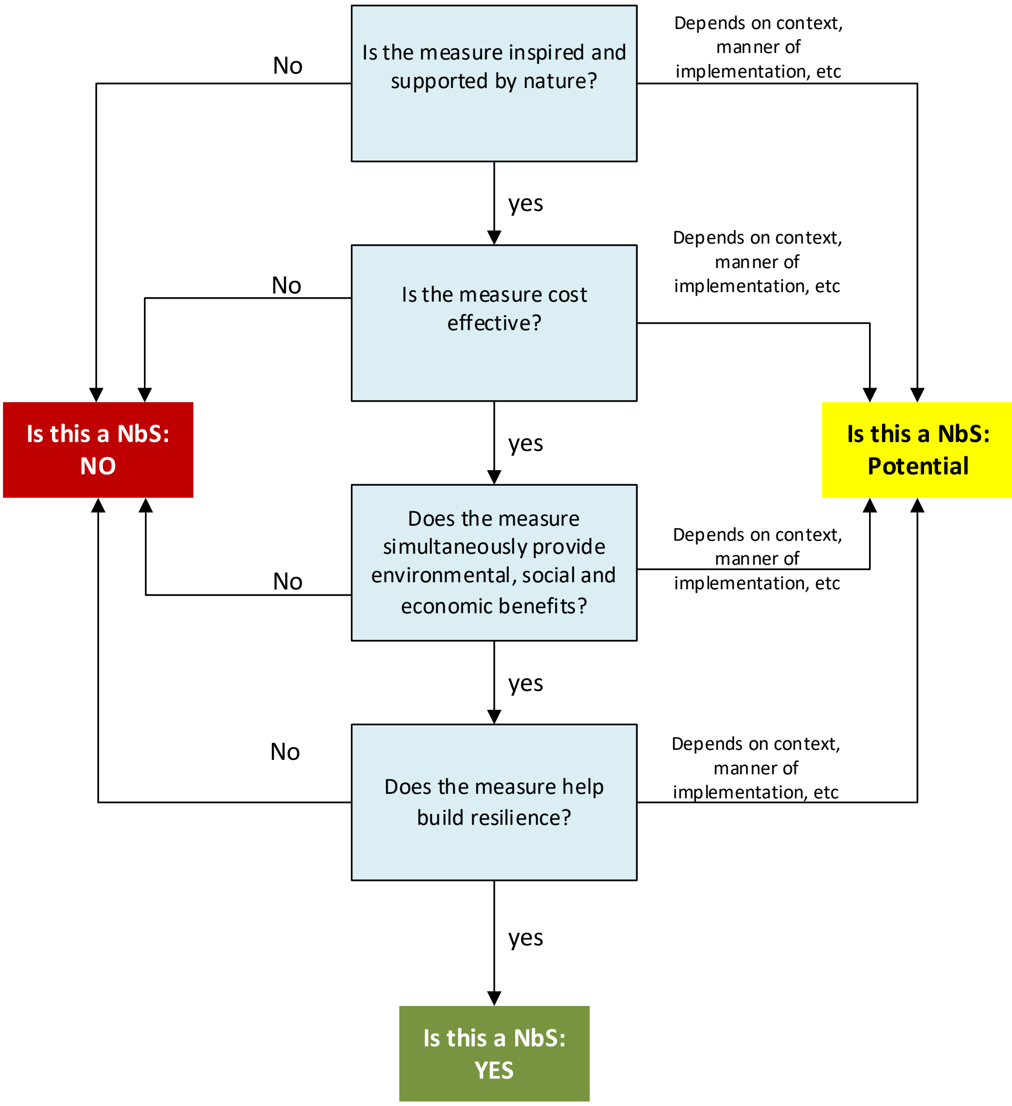

Figure 3.1 Diagram showing the questions asked in the NbS characterization process.

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 maximizing 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 e.g. 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 ('Yes', 'No', 'Potential') 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.

3.1.2 Considerations and limitations of NbS

For NbS many different aspects influence the decision-making process, including the benefits and co-benefits the solutions bring and the stakeholders involved to realize these. As described in the section above, the definition of NbS leaves some ambiguity regarding the extent to which a measure is actually an NbS. This is because the NbS characterization process (see Figure 3.1) includes non-measurable questions. Hence, there is a degree of subjectivity in the characterization.

Alternatively, this also means that some measures may be characterized as NbS if there is sufficient focus on 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:

- If a slope is prone to landslides/rockfall, various types of mitigation measures can be taken 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 this depends on how the measure is designed and implemented in practice. In this example the effectiveness of the chosen measure also depends on the specific situation. The effectiveness of e.g., '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. Furthermore, 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.

The above leads to some practical challenges of NbS:

- Some measures take time to become fully effective, e.g. measures that rely on fully grown/ mature vegetation cover. Vegetation may also need specific kind of maintenance which needs to be organized and financed for several years.
- Also, to be effective, some measures may need to be implemented in areas where they are the most effective which may fall outside the jurisdiction of the road authority.

Because ecosystems are composed with living organisms and their growth is based on several factors, it can be difficult to predict exact results when implementing NbS. As Huang et al. 2020 show in their research, the context where an NbS is implemented may impact the effectiveness of the measure. Ruangpan et al. 2020 further argue that in many cases, a single NbS may not be sufficient. In such cases, multiple-NbS combinations might be required. They further suggest that the increased efficiency of the NbS can be achieved by combining NbS with grey infrastructures, e.g. retrofitting urban drainage systems. In the implementation of NbS there has to be space for innovation, flexibility and adjusting the measures so that they can be adapted to local conditions and situations.

3.1.3 Multicriteria analysis of NbS adaptation options

As described in ICARUS Deliverable D3.1 (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. Evaluation is essential to building knowledge about the effectiveness of the NbS to achieve desired change for the specific decision-making context and ultimately choosing the most suitable adaptation option. In the adaptation options database developed for ICARUS, a multi-criteria analysis was chosen to be the most appropriate way of assessing the adaptation options, as accurate costs and benefits are location- and project-specific. In this way, all the necessary information may be viewed together in the database in a structured way, and comparisons between options can be made easily.

The multicriteria analysis was developed based on the benefits and co-benefits defined in ICARUS Deliverable 2.2 (Bles et al., 2023a), as well as additional criteria which were deemed to be beneficial to road authorities in selecting climate change adaptation options (Bles et al., 2023b).

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, as presented in Table 1.1. The benefits related to nature and environment are expected to be positive for NbS and in many cases, NbS is required to ensure realization of co-benefits. The benefits which are often maximized by selecting an NbS adaptation option include: Impact on Health, Ecosystem Services, and Water Quality. The scores attributed to the adaptation option evaluation criteria in the ICARUS 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.

Table 3.1 Benefits and co-benefits of adaptation options and scoring.

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

Additional criteria (Table 3.2) for evaluation were included in the multicriteria assessment to assist infrastructure managers and road authorities in their decision-making processes (Bles et al., 2023b).

Table 3.2 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

3.2 Drivers for implementation of NbS

One of the main drivers for implementing of NbS is combating climate change. The EU Strategy for 2030 recognizes the value of NbS to combat climate change and biodiversity loss (Majidi et al. 2019). It's been estimated that NbS can help to provide 37 % of climate change mitigation until 2030 to achieve the targets of the Paris Agreement (IPBES 2019). According to IPCC (2016) land use activities represent 23 % of global greenhouse gas (GHG) emissions and infrastructure related carbon emissions account for 16 % of the global emissions (UNOPS 2021). NbS function by either increasing carbon storage (e.g. through the planting of more trees) or by mitigating GHG emissions (e.g. limiting deforestation or providing an alternative solution for emission intensive, grey engineering solutions). Often NbS provide multiple benefits, for example the restoration of native forest along riverbanks to avoid erosion and landslides can also act as a carbon sink.

Another driver for implementation of NbS is increasing biodiversity. NbS does not only support climate change mitigation and adaptation, but also increases the livability of cities (European Union, 2021). The European Union while leading numerous global agreements including, the Paris Agreement (2015), the New Urban Agenda (2016) and the Sendai Framework for Disaster Risk Reduction, has emphasized NbS and ecosystem based adaptation in mainstreaming climate change and biodiversity (Faivre et al. 2017). NbS are sustainable approaches that support biodiversity and can address various environmental challenges, particularly in the context of climate change. NbS encompass a range of strategies and practices aimed at mitigating and adapting to climate change impacts while simultaneously promoting biodiversity conservation (United Nations Environment Programme 2022).

A well-known example of this is in the restoration and creation of mangrove habitats on coastal tropical areas. NbS using mangrove habitats are used to stop flooding and storm surges during storm occasions while at the same time creating coastal marine habitats, which in turn supports local fishing industries and protection to coastal communities. IUCN literature (2022) showed that restored mangroves alone provide flood protection benefits and protect more than 15 million people per year. In the context of roads, NbS have been used widely to deal with surface water runoff and prevent flooding on road networks. Woodland creation schemes intercept overland flow of water and encourage infiltration and storage within the soil, trapping floodwaters before they can reach the roadside; whilst the integration of wetland grassland habitat and reedbeds into the landscape can provide valuable flood attenuation as well as reducing downstream flood risk.

Perhaps the strongest link with regards to NbS and climate change is the creation of new habitats that support biodiversity, which can play a significant role in carbon sequestration and storage. Wetland habitat creation used as part of NbS to help and control surface water runoff from roads can absorb carbon from the atmosphere. It is well known that wetland habitats absorb and hold onto large volumes of carbon and have an enormous capacity to contribute to carbon sequestration and climate change (Malak et al, 2021). Although small in area and scale, wetland habitats as NbS can contribute to mitigating the effects of climate change.

It has long been recognized that fragmentation of habitats within the landscape can have a detrimental effect for biodiversity, as species cannot move between habitats and can become isolated and thus more vulnerable to extreme climate change conditions. A natural environment report (Lawton et al, 2010) from the UK found that fragmentation of protected areas and habitats was one of the biggest reasons for biodiversity loss. Nature improvement areas on a large landscape scale were needed to connect habitats within a wider area. NbS that incorporate new habitats for biodiversity can create steppingstones and contribute to wildlife corridors, linking up habitats in the wider area, connecting to protected areas, making species and habitats more resilient to climate change.

According to the IPBES Global Assessment Report on Biodiversity and Ecosystem Services (2019) about 25% of assessed plant and animal species are threatened by human actions, and one million species are facing extinction. The alarming rates of biodiversity loss worldwide, driven by factors such as habitat destruction, climate change and pollution, create an urgent need for effective conservation measures. NbS are seen important to reversing these trends and protecting endangered species and habitats whilst at the same time providing essential ecosystem services.

Healthy ecosystems provide essential services for human well-being, including clean air and water, pollination of crops and disease regulation. NbS can help support ecosystem services by providing the essential natural habitats that are needed, which can also be considered as a driver for implementing NbS. NbS that contain woodland and wetland schemes for example, can function as buffers, absorbing excess rainfall and reducing the risk of flooding, whilst at the same time natural systems can filter and purify water, improving its quality by removing pollutants and sediment. Additionally, NbS can provide essential habitats for pollinator species. The Nature based Solution Initiative literature has shown that green roofs implemented in city planning increase the number of pollination species in urban environments. Green roofs are integral in urban beekeeping, because they provide valuable food resources for pollinators. The increased number of pollinating insects in urban environments helps also in pollinating natural trees, shrubs, and wildflowers, which in turn provide valuable habitats for urban wildlife.

NbS have also been considered important for contributing to biodiversity net gain (BNG) in infrastructure projects such as new road schemes. BNG is a way to contribute to the recovery of nature while developing land. It is making sure the habitat for wildlife is in a better state than it was before development. The UK government has introduced a BNG condition for planning permissions, where developers will need to achieve at least a 10% BNG in all development projects. This means they will have to create or enhance habitats either on-site or off-site for a 10% BNG.

3.3 Barriers to NbS implementation

Many of the barriers to general climate change implementation apply also to implementation of NbS. As outlined previously in ICARUS Deliverable 2.3 (ICARUS D2.3, 2024), similar barriers were identified from both literature review and from communications with Project Executive Board (PEB) members. The primary barriers include a lack of resources e.g. in maintenance (both financial and personnel), lack of information and data related to both infrastructure and climate change scenarios, and organizational engagement. Additionally, PEB members identified a lack of longer-term planning when it comes to climate change adaptation, and that it can be difficult to make the argument for adaptation when much of the planning is really done on the short term.

A lack of financial resources and budgets are a major barrier to implementation of NbS as seen in the literature (Veerkamp et al., 2021) and as noted by members of the NRAs in workshop feedback and questionnaires (ICARUS D2.3, 2024). Projects that may be dependent on external funding in particular, can take longer than anticipated and may require additional time investment from NRAs (Veerkamp et al., 2021).

As with any new or different approach, it can take time to achieve a common understanding and "buy-in" from all parties involved in the process. Additional time may be required to ensure that all parties understand why NbS are being chosen and how it can be achieved (Veerkamp et al., 2021). Uncertainty around how effective the measures will be in the longer term or how they will perform compared with traditional solutions can also be a barrier, as described by Ramirez (Ramírez-Agudelo et al., 2020). Local resistance to implementation can also be a challenge, but early communication particularly around the benefits to the community can help to remove this resistance as demonstrated in the ETC/CCA Technical Paper (C. (PBL, E. Veerkamp et al., 2021).

Another widely cited barrier in the literature and from discussion with NRA representatives is the lack of information and uncertainty related to climate change, and also a lack of infrastructure data (International Coalition for Sustainable Infrastructure (ICSI), 2023; PIARC, 2023; C. Veerkamp et al., 2021). It is important that uncertainty is recognized and acknowledged, but also important that it doesn't delay decision-making. Additional information or monitoring data can help to build the argument for NbS through cost-benefit analysis.

A final barrier that was recognized by NRA representatives was the lack of detail and data available for specific Nature-based Solutions when applied in practice. It is recognized that unless standards and specifications include specific details on how to implement and construct NbS, that they won't be completed correctly (de Paor et. al., 2024).

3.4 Guidelines on implementation of NbS adaptation options

Guidelines on the implementation of general climate change adaptation have been provided in ICARUS D2.3 (de Paor et. al., 2024) and the Adaptation Implementation Process diagram has been provided in Annex B of this document for reference. However, there are some differences when it comes to implementation of NbS. These are primarily due to novelty of NbS, lack of experience of NRA organizations and operations teams with NbS, and the requirement for more maintenance than that which may be required with traditional "grey" solutions.

IPCC has provided a framework for decision-makers on the implementation of natural systems and how to maximise benefits and co-benefits of implementation as shown in Figure 3.2. In addition to the primary benefits of reduced carbon emissions, and alignment with Sustainable Development Goals (SDGs), NbS implementation can also provide co-benefits such as enhanced biodiversity, additional recreational areas, clean water resources, and better health impacts amongst others. To allow for uncertainty around climate change projections, the framework presented in Figure 3.2 keeps as many options as possible open for as long as possible.

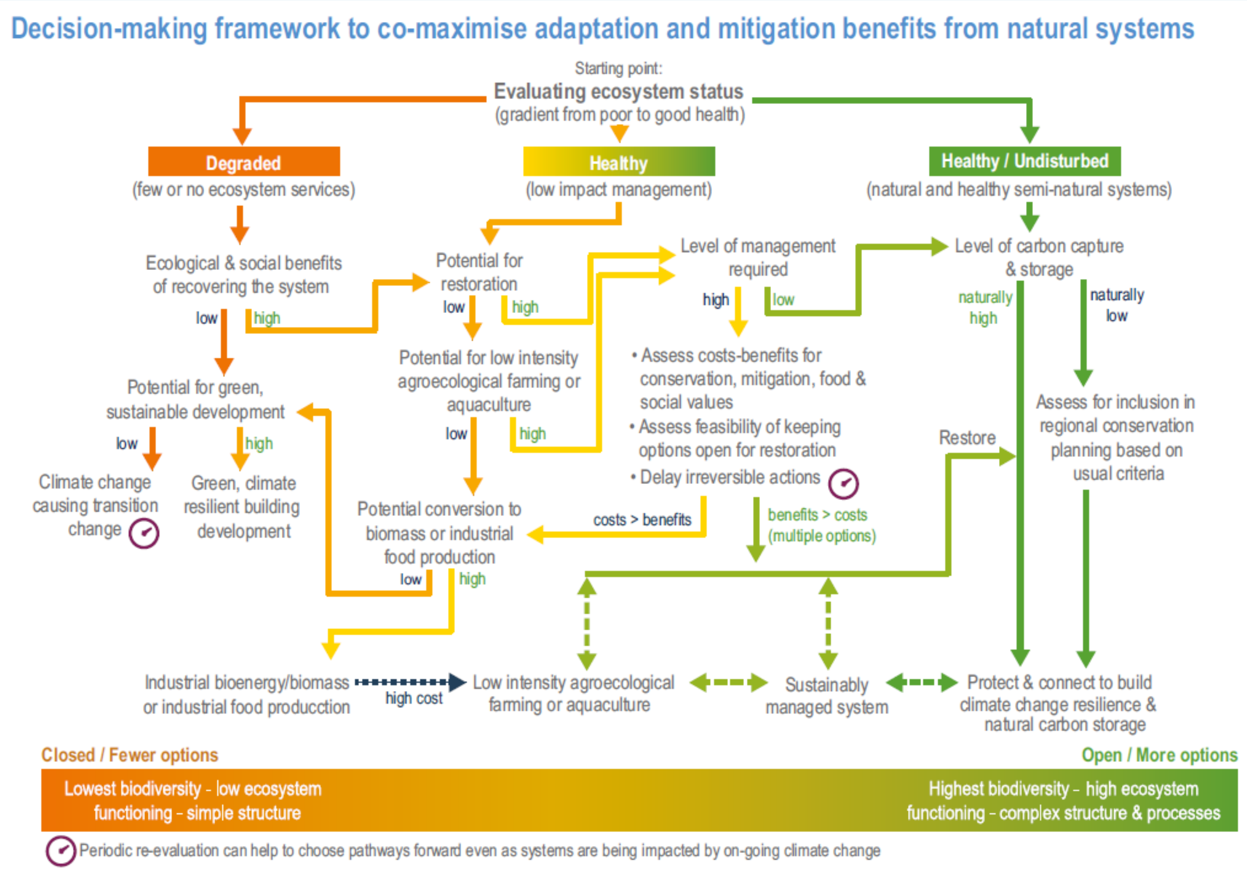

Figure 3.2 Decision-making framework to co-maximise adaptation and mitigation benefits from natural systems (IPCC, 2022)

The most important elements to consider for implementation of NbS are:

- Getting buy-in from the organization: Building the business case for climate change implementation is essential to achieving the goal of implementation. The inclusion of NbS may assist the case for implementation as much funding now is dependent on achieving sustainability targets. The ability to show benefits and co-benefits to the community in terms of reduced carbon emissions and increased health etc. can help build the business case and achieve buy-in from the strategic level of the organisation. In addition, many benefits of NbS are really demonstrated over the longer term, and so it is important to present the case for NbS over the longer term.
- Involvement of stakeholders and local communities: Involving stakeholders and local communities in the planning process can help to uncover issues or additional benefits that may otherwise have been unforeseen by the design team (C. Veerkamp et al., 2021). Getting locals onboard through citizen engagement can also help to increase the positivity towards the solution, and even help with maintenance of the NbS. If communities can take ownership, this can help with maintenance, as seen in the example of Cardiff Rain Gardens (ICARUS case study).
- Including maintenance as an essential part of the planning process: Almost all NbS require some regular maintenance, which needs to be factored into the budget and planned from the outset. Poorly maintained NbS have potential to be detrimental for biodiversity, become eyesores in the local community and may erode other ecosystem services essential for human well-being (IPCC, 2022). If maintenance is not included in the original budget, the NbS will not be effective.

Maintenance activities may include pruning, grass/hedge cutting, litter/debris collection and disposal, replanting or fertilisation (World Bank, 2021).

- Monitoring: Monitoring of NbS can also help to reduce health and safety risks. In the Barcelona Tree Masterplan, trees were planted and managed to provide shade relief and transpiration on hot days, monitoring fallen trees and branches so that the local authority could respond quickly helped to improve the business case for further expansion of the project into other areas (C. Veerkamp et al., 2021).
- Detailed design and procurement specifications required: As mentioned in Section 3.3, it is crucial that clear design specifications are specified for NbS. If left vague or unclear, a contractor will choose the most cost-effective or easiest method. Therefore, it is essential that NbS are detailed accurately for the solution to be successful.

Further guidance on NbS implementation may be found in many examples which are demonstrated in the following resources: World Bank, (2021); Cohen-Shacham et al., (2016); International Coalition for Sustainable Infrastructure (ICSI), 2023, (2023); Ramírez-Agudelo et al., (2020); C. Veerkamp et al., (2021) and on the Case Studies section of the ICARUS website (https://icarus.project.cedr.eu/icarus-case-studies/).

3.5 Evidence for effectiveness of NbS to increase resilience

A summary of identified NbS is given in Table 3.3. For all the mentioned NbS options, associated references have been listed. The references provide an indication of how such NbS have been implemented in other projects and in some cases considerations with regard to the NbS and its implementation.

Table 3.3. Summary of impacts of climate change on road infrastructure and possible Nature Based Solutions.

Impacts of CC	Impacts on Roads	Possible Solutions	Examples of NbS	References
Increased river flooding and coastal erosion	Challenge for drainage systems and erosion protection Challenge for the design and maintenance of culverts and bridges	Reduction for total runoff volume and peak discharges Infiltration, detention and retention, filtering, storing, evaporating, and detaining runoff close to the source point Runoff management measures Improving of slope stability	Permeable pavements Green walls Infiltration trenches Bioretention systems Rain barrels/cisterns Green roofs Wet ponds and dry ponds Vegetation for slope stability improvement	Huang et al., 2020; Majidi et al. 2019; Ercolani et al., 2018; Dalir & Naghdi, 2015
Landslides and avalanches	Increased occurance of slush avalanches and debris flow blocking roads	Reducing surface runoff Stabilising loose soils	Vegetation covering of slopes by e.g. retaining and restoring native / mixed forests on slopes	Casteller et al., 2018; Sutherland et al. 2014; Francini et al. 2021
Increased mean air temperature	Urban Heat Island-effect High pavement temperature Reduced durability of asphalt	Urban Heat Island mitigation Cooling pavement techniques (porous materials) Temperature controlling asphalt Concrete using phase change material	Green infrastructures (combination of many GI rather than one GI); e.g. trees to provide shade and permeable pavements to reduce surface temperature	Balany et. al., 2020; McPherson & Muchnick, 2005
Heavy precipitation and pluvial flood	High surface runoff and flow volume Sweeping away of infrastructure such as bridges Scouring of the foundations,	Flood defense systems Flood risk management systems Infiltrating, filtering, storing, evaporating, and detaining runoff close to the source point, Runoff management measures	Green roofs Multiple NbS combination intervention Grey-Green Infra combination such as retrofitting urban drainage systems, dike strengthening Low Impact Development controls (LIDs) Bioretention systems Porous pavements Permeable patios Rain barrels/cisterns	Ruangpan et al. 2020; Klijn et al. 2013; Huang et al. 2020; Majidi et al. 2019

Impacts of CC	Impacts on Roads	Possible Solutions	Examples of NbS	References
			Green roofs Wet ponds and dry ponds	
Droughts and high summer temperatures	Problems for the asphalt surfacing, run-off Roadside fires Increased soil subsidence due to lower permeability	Heat stress mitigation and thermal comfort enhancement, UHI mitigation through green infrastructures	Green roofs Rain gardens Urban trees Green spaces	Lennon et al. 2014; Rozos et al., 2013; Ercolani et al., 2018; Balany et al., 2020
Sea level rise	Erosion of road base Bridge scour	Coastal Management Strategies, Storm surge mitigation Storm surge attenuation or reduction	Salt Marshes Tidal wetlands and mangroove forests	Van Coppenolle et al., 2018; Ruangpan et al., 2020; Anderson et al. 2011

4 Assessment of NbS adaptation options

4.1 Key performance indicators of roads in relation to NbS

This paragraph highlights the need to connect the assessment of NbS adaptation options to the decision-making context of road authorities. Using the right criteria for the assessment and by speaking the right 'language' of decision makers will enhance the likelihood that NbS adaptation options are seriously considered alongside more conventional options. This process has been described in detail in ICARUS deliverable D2.2, (Bles et al., 2023a) and a summary is provided here to highlight the relevant aspects for NbS.

Decision making at road authorities however is complex. Different staff from the strategic, tactical and operational levels in the organisations are involved in the decision-making process. This also links to the different scales at which decisions are being made, ranging from the network level to the connection and object level. In principle, steering of decisions to ensure a desired performance of the road network can take place via two mechanisms:

1. Output oriented steering mechanisms using Key Performance Indicators (KPIs) to measure performance of the road (network). This mechanism is often used by road owners or policy makers and thresholds are being set at the strategic level. The KPIs typically focus on a network scale. This mechanism guides decisions on the necessity of action (e.g. climate adaptation) based on road performance against these indicators (KPIs).
2. Input and process-oriented steering mechanisms based on guidelines/standards/regimes for design, maintenance, or operation (hereafter called guidelines): This mechanism operates from a more bottom-up approach. The mechanism considers specific object design, maintenance and/or operational requirements to achieve adequate performance of the road (network).

Furthermore, different decision criteria may be in use by the road authority. Decisions can be made related to the following criteria:

1. Service driven: The NRA strives to always reach a certain minimum or target service level (e.g. the KPIs as described above), for the minimum cost.
2. Budget driven: the NRA strives for the highest possible service within the budget available for managing the road network. The service can be described using the KPIs.
3. Optimum service: The NRA strives for providing optimum road service to society, by balancing costs and benefits. Benefits are likely to be described using KPIs.
4. Policy driven: The NRA may have policies in place that direct the decision-making process, while not necessarily being explicitly mentioned in the performance indicators of the road.

Key Performance Indicators thus play a key role in the decision making of NRAs. This means that, while assessing the NbS adaptation options, it is of high importance to link the assessment criteria to the KPIs as much as possible. In ICARUS deliverable D2.2, (Bles et al., 2023a), a long list is provided of KPIs that are being used by NRAs. For the purpose of NbS, we now make the following distinction:

1. Key objectives that every NRA is likely to have: KPIs that are linked to availability and safety. While it could be difficult to express effectiveness of NbS in terms of availability and safety, it is oftentimes essential to do that to make the case for adaptation. An example is provided ICARUS deliverable D2.3 (de Paor et. al., 2024)

2. Other objectives: At the same time, more and more NRAs realize that the road network that they are maintaining is part of a bigger system. This means that NRAs may also have KPIs that relate to the *environmental effects* of the road. If those are present, it will be much more straightforward to link the assessment of the NbS to the KPIs. An overview of the possible KPIs for environmental effects is provided in Table 4.1 below.

Table 4.1 Examples of KPIs for environmental effects that can be used to make the case for adaptation via NbS.

KPI	Metric	Possible unit
Environmental effects	Noise	Clear in time reporting Mitigation of noise critical areas
	Biodiversity	% increase in biodiversity
	Greenhouse gas reduction	% reduction from a baseline of corporate NRA % reduction from a baseline of road users
	Air quality	% or number in compliance with requirements
	Water quality	% or number in compliance with requirements

4.2 Performance of NbS adaptation options

Understanding and assessing the performance of NbS (e.g. quantifying the multiple benefits and trade-offs of NbS), is crucial for mainstreaming NbS into regulations, guidelines, and plans. As outlined in the section above, key performance indicators are valuable for NRAs to measure progress and steer decisions, however, there is a need to translate KPIs from the decision-making context to an accessible metric for measuring resilience and effectiveness of adaptation options including NbS.

The performance of resilience enhancing adaptation options is described in ICARUS Deliverable D2.2 (Bles et al., 2023a). The report introduces the concept of benefits and co-benefits of adaptation options as a metric for resilience and effectiveness. The sections below summarize these concepts and their application for NbS adaptation options.

4.2.1 Benefits and co-benefits of NbS

A benefit is directly linked to a KPI, whereas a co-benefit is an additional benefit not directly linked to KPIs (see ICARUS deliverable D2.2, (Bles et al., 2023a)). Co-benefits are the additional benefits that are achieved as a result of achieving the primary benefit. Based on national priorities, different European NRA's will set their own criteria, hence, a benefit for one NRA may be a co-benefit for another NRA. In general, it is easier for the NRA to make the case for implementation of adaptation options when more positive effects are linked to KPIs (benefits). However, depending on the design choices made for adaptation options, co-benefits may be maximized and thus aid in making the case for implementation.

Integrating NbS into adaptation strategies can bring about multiple co-benefits beyond the primary benefits, in relation to climate resilience, water management, green space management, ecosystem restoration and biodiversity, air quality, place regeneration and liveability, knowledge and social capacity building, social justice and cohesion, participatory planning and governance, health and wellbeing and new economic opportunities and green jobs. Including co-benefits in a cost-benefit assessment provides a better understanding of the full effects that climate adaptation options introduce in addition to the expected primary benefits linked to KPIs. It therefore often provides a better, stronger, and more realistic case for climate adaptation options.

As each NRA may define benefits and co-benefits differently depending on their defined KPIs, the following section will simply refer to benefits. Table 4.2 presents a list of benefits, likely to be associated with options for climate adaptation and resilience including NbS options. The table provides a brief description of each benefit and potential means of quantification and valuation. Furthermore, indicators to assess the magnitude of impact are included. These are provided to allow for screening/assessments of the significance of each benefit in relation to the specific project. Furthermore, an indication of the impact on the benefit when choosing an NbS option is also provided. Some cells are empty because quantification and therefore valuation or indicator for magnitude cannot be defined in the context of climate adaptation and resilience.

Table 4.2 List of potential benefits associated with climate adaptation and increased climate resilience of road networks.

Benefit	Description	Quantification	Valuation	Indicator for magnitude of impact	NbS impact
Availability					
Travel time, leisure	Value of travel time for persons in their leisure time	Minutes of increase/decrease in travel time	Travel loss hours / value of travel time	Number of users of network and level of change	-
Travel time business	Value of travel time for businesses	Minutes of increase/decrease in travel time	Travel loss hours / value of travel time	Number of users of network and level of change	-
Reliability of travel time	The value of reliability of predicted travel time for users	Reliability of predicted travel time measured as e.g., percentage of average travel time of a road network	Value of reliability	Number of users of network and level of change	-
Availability of network	The value of being able to always access public services and critical infrastructure	-	-	-	-
Availability: Connectivity and social inclusion	Connectivity and travel time to basic everyday activities	-	-	-	-
Durability					
Replacement	Costs associated with wages, materials etc.	Hours worked, units of material, fuel machine hours etc	Wages, costs of materials, fuels, machinery, etc.	-	-
Upgrading	Costs associated with wages, materials etc.	Hours worked, units of material, fuel machine hours etc	Wages, costs of materials, fuels, machinery, etc.	-	-
Safety	Value of injuries/fatalities	Increase/decrease in the risk of injuries/fatalities	Value of statistical life	Number of users of the network and level of change	-
Health effects					
Air quality	Improved air quality from increased coverage of plants	Increase/decrease in the level of air pollutants, increase/decrease in temperature for assessment of cooling effects	Value of statistical life, quality adjusted life year	Number of affected individuals and level of change	Very positive
Noise	Lowered noise levels from noise barriers of coverage from plants	Increase/decrease in the level of decibel	Value of statistical life, quality adjusted life year	Number of affected individuals and level of change	Positive
Job creation	Job creation from investment in climate adaptation/resilience	-	-	-	-
Ecosystem services	Value assigned to areas due to their aesthetics, opportunities for	Increase/decrease in level of greening or hectares of green areas	Stated/revealed preference methods	Number of users of the area, and level of change in provision of	Very positive

Benefit	Description	Quantification	Valuation	Indicator for magnitude of impact	NbS impact
	walking, socializing etc.			environmental good	
Water quality	Value assigned to good quality of water, e.g., stemming from contaminants from run-off	Increase/decrease in quality status, e.g., ecological status based on threshold values	-	Number of affected individuals and level of change.	Very positive
Climate					
Embodied carbon	Emissions arising from construction materials, transport, and installation	Increase/decrease in the number of embodied carbon emissions	Social cost of carbon	Level of change in the number of embodied carbon emissions	Very positive

4.2.2 Valuation of benefits and co-benefits

Valuation of costs and benefits in relation to decision making provides a convenient and potentially informative way of evaluating different options in decision making. The comparison of costs and benefits of implementing adaptation options or resilience measures provides a transparent way of considering different alternatives. Applying valuation in decision-making contexts should be systematic with consideration of project scope and objective to provide the intended transparency and relevance for decision-making.

Benefits of NbS and other adaptation options will often be defined as either tangible or intangible in relation to valuation, as illustrated in Figure 4.1. Tangible benefits are values that can be elicited a value based on the prices we observe in the market. For example, damage to infrastructure assets can be priced based on how they are booked in the accounts, or costs for repairs can be assessed in terms of the estimated value of that production. Benefits may be either positive or negative, depending on the context and impact of the implemented adaptation option. Although benefits are framed as positive effects, it is possible that these might take the form of negative effects in some cases. More specifically a negative benefit is the reduction/negative effect on one of the defined benefits. For example, reduced speed limits result in longer journey times but increased safety and journey time reliability.

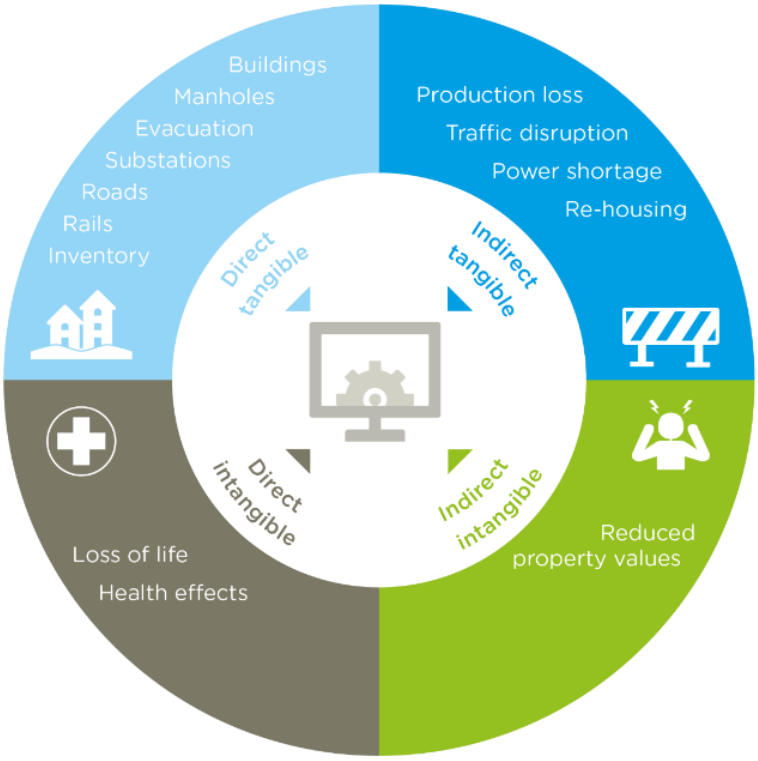

Figure 4.1 Illustration of the differentiation between direct and indirect tangible and intangible benefits. Benefits may be either positive or negative, depending on the context and impact of the implemented adaptation option.

The benefits linked to NbS adaptation options are often intangible, hence, there is no universally adopted approach to measure and quantify these in valuation. For intangible values, different methods have been applied in studies seeking to uncover people's *willingness to pay* (i.e., their valuation) (Atkinson et al. 2018). The most applied methods are revealed preference studies and stated preference studies. Revealed preference studies seek to elicit the value placed on specific goods, by observing how people act in other markets. Stated preference methods are based on simply asking people about their willingness to pay for a specified good e.g., in a survey or interviews (Atkinson et al. 2018; Navrud & Ready 2005).

Intangible benefits are different from tangible benefits in the way that the monetary value of these is not possible to observe in existing markets. However, the fact that it is not possible to observe the market prices of a given benefit does not mean that it does not have a value. For example, if one choses to take a leisure walk on a Sunday afternoon, one does not pay $10 to do so. Although the Sunday leisure walk is not paid for, the activity still has a value, assuming that it is a voluntary choice to go for a walk. The person who decides to go for a walk pays for that walk by choosing to go for a walk rather than other potential ways of spending the Sunday afternoon. Valuation of such activities or options can, for example, be done by estimating the transportation costs of the leisure activity (e.g., cost of fare by bus or car) or simply by asking people about their willingness to pay (Atkinson et al. 2018). Thus, valuing intangible assets includes identification of a method to estimate the value of such benefits as leisure walks.

ICARUS suggests a four-step staged method for applying valuation in decision-making contexts. This approach also covers valuation of NbS adaptation options. The valuation approach is presented in Figure 4.2 and further described in ICARUS deliverable D2.2 (Bles et al., 2023a).

1. Define and describe project and scope of impact of adaptation/resilience measure and hereunder the expected associated costs and benefits. Benefits should be defined as either benefits or co-benefits, depending on the defined KPIs.
2. Assess the magnitude of identified effects. Table 4.2 provides an overview of relevant parameters to consider, to assess the magnitude of the benefits. Significant effects associated with implementation of adaptation/resilience measures should be considered for quantification and eventually valuation.
3. Identify means of possible quantification/measurement of benefits: To enable valuation or at least quantification to include in the decision-making process, it is necessary to consider possible means of measurement of the identified benefits. Also, whether data of sufficient quality can be gathered.
4. Identify potential means of valuation. Depending on whether identified benefits are defied as either tangible or intangible goods. Different means of quantification exists.

Figure 4.2 Summary of the four steps included in the overall approach suggested for valuation of benefits.

Valuation of identified NbS-specific benefits

While all benefits listed in Table 4.2 may materialize through the implementation of NbS, some socio-economic and environmental benefits are linked to the effects of nature. These bevefits will *likely only* be present if a NbS is chosen as the adaptation measure.. Valuation of the identified NbS-specific benefits is described below, while detailed descriptions of all benefits listed in Table 4.2 are provided in ICARUS report D2.2 (Bles et al., 2023a).

Ecosystem services

Effect/expected outcome	Level of change of ecosystem services
Parameter for assessing magnitude of effect	Level of change: Change in the size, number or level of ecosystem services and the number of affected individuals/users.
Possible means of measurement	Size, quality indicators, level etc.
Possible means of valuation	Primary revealed or stated preference studies or benefit transfer.

Ecosystem services is an umbrella term for the various services ecosystems potentially can provide. Some of the most important mentions in relation to infrastructure and investments in climate adaptation and resilience, are the aesthetic and recreational value of green areas, parks, forests and green landscapes. Moreover, preservation of biodiversity and habitats are also often mentioned.

Considering these values might especially be relevant in relation to new investments, where green elements and nature play a role. Or in relation to new investments that might require removal of green landscapes or forests, and therefore cause a negative benefit impact. When larger areas are removed and/or disturbed, this could give rise to potential value loss. Or similarly, in more urban areas, where greening is more sparse, even minor changes in the greening of built environments could yield positive values.

Valuation of ecosystem services covers a multitude of various values, that are in turn also highly dependent on the specific context. Generally, valuation of ecosystem service-related values should be based on benefit-transfer (or value-transfer) of values elicited in primary revealed- or stated preference studies. Such studies can be sought out e.g., from databases like Evri.ca, which includes valuation studies on many different environmentally related values.

It is important to state that benefit transfer generally is associated with more uncertainty than other forms of economic valuation. It is, however, a recognized method for application in settings where environmental goods potentially form an important part of a decision-making process, but consideration needs to be given to the trade-off between the detail level of information and resource use to add more detail. Guidelines on best practice for benefit-transfer exist, and are continuously being updated as the field develops (Johnston et al., 2021).

Water quality

Effect/expected outcome	Adaptation/resilience measures to affect especially run-off to impact soil and water quality
Parameter for assessing magnitude of effect	Level of change in the impact of run-off and e.g., through monitorization of water flows and the movement of pollutants through a catchment area
Possible means of measurement	Data on water quality, e.g., threshold values for ecological status
Possible means of valuation	Estimates on *willingness to pay* where readily available and applicable estimates exists, otherwise a qualitative assessment of the measures.

Adaptation and/or resilience measures could be designed to address the negative impacts of run-off from roads. The negative impacts from run-off stems from various contaminants like heavy metals, oil and salts from the road. Therefore, run-off from roads can have a significant effect on water quality.

In cases where the effect of reducing the negative impacts of run-off is expected to be significant, the impact can be measured based on water quality data with reference to specified threshold levels for quality assessment. Many European countries have quality standards on ecological quality of different kinds of surface waters.

Valuation studies have been conducted on the value of water quality, especially in relation to surface waters that hold significant recreational and biodiversity value. However, to apply measures based on stated or revealed preferences in a benefit transfer would be highly site and context dependent. Thus, it is suggested to apply qualitative assessments of water quality measure in decision-making, when sufficiently accurate applicable studies are lacking, and primary valuation is unfeasible.

Health effects

Effect/expected outcome	Change in the level of noise, particulate matter or mortality rates to affect mortality and morbidity
Parameter for assessing magnitude of effect	Level of change: expected magnitude of change, e.g., to surpass a specified threshold level, and the number of individuals affected.
Possible means of measurement	E.g., by threshold levels or by data on dose-response effects.
Possible means of valuation	Value of statistical life and estimates on *willingness to pay* through stated or revealed preference studies (Anderson et al., 2018; Day et al., 2006; Lavine, 2021).

Human health is greatly affected by the environment in various ways. Effects on our health can be categorized as either an effect on our lives (*mortality effect*), effects on our physical health, (*morbidity effect*) or an effect on *mental stresses and strains* to affect our mental health. Such effects on our health can be caused by changes in the physical environment e.g.:

- Increased greening of the neighbourhood to improve air quality by reducing pollutants.
- Lowered noise levels by increased green coverage of buildings to cause a reduction in stress levels for residents.

These effects are suggested to be some of the most important health related effects that could be impacted by investing in changes to road infrastructure. Figure 4.3 suggests modes of quantification for noise and air quality. In addition, it may also be relevant to assess improvements of thermal comfort and micro-climate (reduction of urban heat island effects) by the addition of greenery.

Reductions in noise level can be measured as the reduction in decibel to a given threshold value. For example, to calculate the number of households that will have the noise level reduced to that threshold value.

Reductions in pollution levels can be measured by the reduction in particle matter in the air for an area. For example, to calculate the number households that will have the levels of particle matter reduced below a given threshold value.

Figure 4.3 Important health-related effects.

As mentioned above, health effects relate to both mortality, morbidity and our mental health. It is thus suggested to consider the value for both mortality effects and morbidity effects, under the assumption that mental health can be considered a morbidity-related effect[3]. The differentiation between mortality and morbidity rests from the fact that there is a significant difference between increasing the risk of losing one's life and experiencing discomfort linked to decreases in health and illness.

The following two sections include descriptions of possible valuation methods for mortality and morbidity, respectively.

Valuing mortality

Health-related mortality effects associated with increased noise and pollution relate to the fact that they constitute stressors which, over time, could lead to premature death. For example, increases in noise levels are connected to increased stress levels, blood pressure and cardiovascular diseases (WHOa, n.d.; WHOb, n.d.).

The inclusion of mortality related effects should be considered as relevant, especially when climate adaptation and resilience measures are expected to have significant effect on, in particular, noise, pollution or thermal comfort. Effects could for example be measured through application of threshold values of decibel, particulate matter or degrees Celsius.

Valuing mortality in relation to health-related effects can be done by applying measures of value of statistical life (as elaborated on in previous section). National measures should be applied to ensure the most accuracy, as values are highly location specific.

Valuing morbidity

Valuing the morbidity related effects of air pollution, noise pollution but also the urban heat island effect has been done using both revealed and stated preference methods[4]. Noise pollution is generally related to cardiovascular diseases, sleep disturbance, mental and cognitive disturbances. Valuation has predominantly been conducted using revealed preference methods, where the housing market have been used to elicit the implicit prices paid to reduce the noise levels, so-called hedonic pricing method (Anderson et al., 2015).

Similarly, the effects of air pollution have been valued in studies using the housing market (Lavine, 2019; Gyo Kim et al., 2010). The studies include elicitation of the implicit price being paid in the housing market for reductions in levels of air pollution. The most important health related issues are respiratory problems, cardiovascular diseases, cancer and so on.

In addition, the Canadian database Evri.ca provides a search engine of more than 5.300 economic valuation studies, with a particular focus on studies in relation to the impact of road networks on noise and pollution.

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[3] This is a simplifying assumption. It is important to underline that the suggestion rests on the value of presenting a simplified assumption. Various health related measures for valuation exists, also including social value measures of both physical and mental health related issues. When such effects are expected to be of significant importance, valuation method and measure should be carefully applied in the correct context.

[4]Quality *adjusted life year (QALY)* and *disability adjusted life years (DALY)* are also metrics sometimes used in relation to measuring morbidity. For reference, see for example: Sassi & Hurst (2008).

4.3 Making the case for NbS

4.3.1 Roadmap for evaluation of NbS adaptation options

This chapter presents the stepwise approach that is introduced in Deliverable 2.3 (ICARUS D2.3, 2024). This approach is recommended to be used to identify suitable adaptation options and how to define optimum service levels when the suitable adaptation options have been identified. This is a general approach that is also valid for NbS adaptation options.

Further explanation of the use of the process is done, based on a fictive case concerning the impact of extreme events and described in Chapter 4.4. It considers the case of extreme rainfall, and thus how to make the case for adaptation via NbS for a climate hazard which is characterised by low probability and high potential consequences. Chapter 4.4 starts with describing this case followed by two sub chapters on how to identify NbS options and how to evaluate these.

Figure 4.4 explains the stepwise approach for adapting guidelines to optimise performance with the right-side of the figure proving specific elements related to our example on extreme events, which is included in the following demonstration.

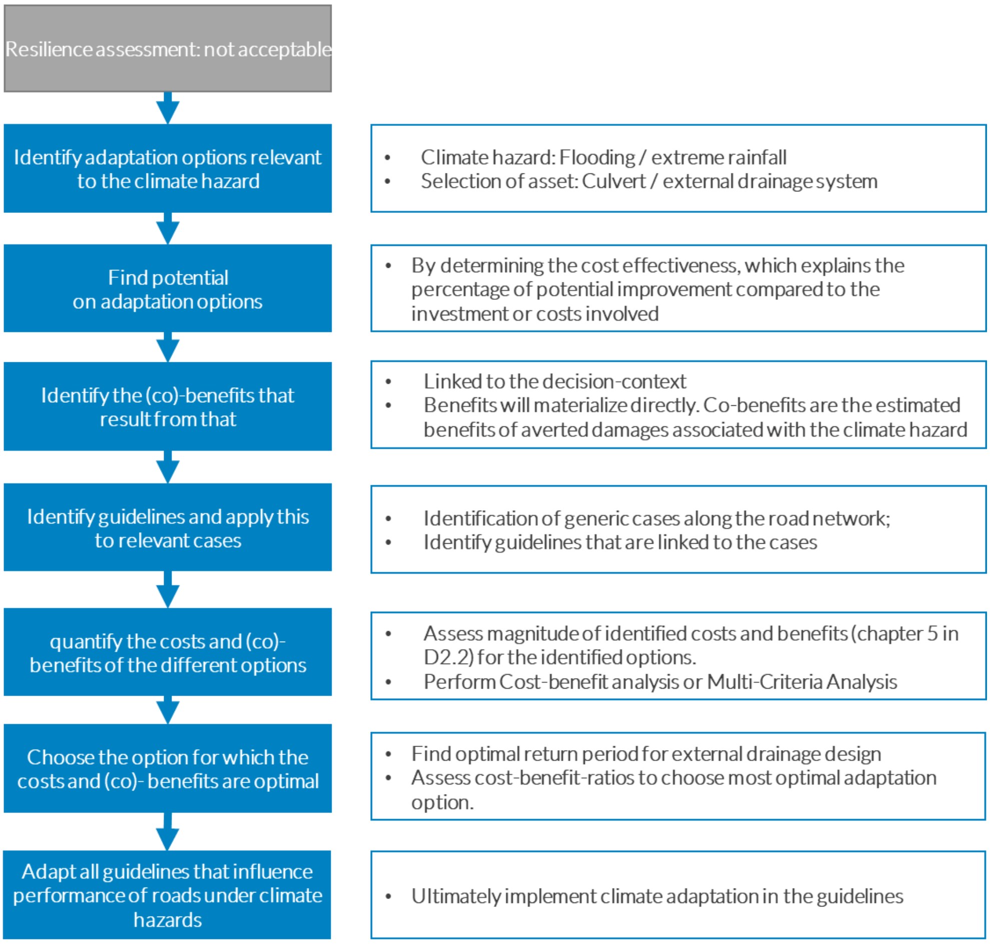

Figure 4.4 Process to make the case for climate adapting maintenance guidelines to optimize performance. In our case study: extreme events.

4.3.2 Collaboration and participatory planning

Collaboration and participatory planning are integral components of developing NbS for protecting transport infrastructure. These approaches involve engaging diverse stakeholders, including government agencies, local communities, academia, and the private sector, in the design, implementation, and monitoring of NbS projects. By fostering inclusive decision-making processes and leveraging local knowledge, expertise, and resources, collaboration and participatory planning enhance the effectiveness, equity, and sustainability of NbS interventions.

Engaging stakeholders early in the planning process helps to identify local priorities, concerns, and opportunities, ensuring that NbS interventions are contextually appropriate and socially acceptable. It needs to be recognised that different stakeholders will have different motivations for developing the NbS, and indeed, the main element of the scheme might serve a different purpose, such as active travel or public realm, and the NbS will be a 'nice to have' element, rather than a key motivation.

4.3.3 Co-financing and co-implementation

At its core, co-financing NbS involves leveraging public and private sector investments to integrate nature-based approaches to increase infrastructure resilience, whilst offering other co-benefits. Co-financing NbS offers a pathway to achieving synergies between climate adaptation, mitigation, and biodiversity conservation goals.

Co-implementation of NbS can foster collaboration and partnership among diverse stakeholders, including government agencies, multilateral institutions, private sector entities, civil society organizations and local communities. By pooling financial resources, technical expertise, and local knowledge, stakeholders can co-design and implement NbS projects that are tailored to the unique socio-economic, ecological, and cultural contexts of specific regions. This collaborative approach promotes ownership, inclusivity, and resilience-building at the local level while fostering innovation and knowledge-sharing across sectors and jurisdictions.

Budget constraints may limit what any one organisation could achieve on their own. If a scheme can achieve multiple objectives, beyond achieving climate resilience, this might be an opportunity for organisations to pool resources to jointly deliver it. Beyond finance, there may be knowledge and capacity that can be leveraged.

Co-implementation implies that there will be multiple stakeholders involved, not just in the financing and delivery of the scheme, but potentially also in the regulatory approval process, as NbS might not fall within traditional regulatory processes. This needs to be addressed at the outset, and lessons learned captured, which will make implementing subsequent schemes easier.

In the same vein, quantifying the ecosystem services provided by NbS and the co-benefits can be complex and not fall easily within traditional cost-benefit analyses and decision-making processes. Guidelines presented in other ICARUS deliverables and case studies can help in this regard (available at https://icarus.project.cedr.eu/).

Integrating NbS will generally require more community engagement than traditional grey solutions. For example, installing a larger drainage culvert will cause some disruption during installation, then be largely hidden, whereas a retrofit SUDS system will be visible on an ongoing basis. Such community engagement will be required to ensure that their views are heard and that the solution will be something they value.

4.4 Case study: application of roadmap for evaluation of NbS adaptation options

The evaluation of NbS adaptation options is demonstrated by applying the proposed evaluation approach outlined in section 4.3.1 on a fictive case study. The case study is presented in the ICARUS deliverable D3.2 *'Demonstration report showing how principal adaptation measures can be evaluated'*. The demonstration case focuses on adaptation to extreme rainfall in relation to a road asset and the decision-making case between different options. In the fictive case study, the resilience assessment of the road concludes that the current resilience is not acceptable. The evaluation of the identified NbS adaptation option in the case study will be summarized below alongside the identification of an optimum service level for the NbS. For a full description of the case and all suitable adaptation options identified, please see ICARUS deliverable D3.2 (van Marle et. al., 2024).

4.4.1 Introduction to case study

The case regards a 5 km road stretch of a major highway with three lanes. The highway was built 15 years ago and is the main connection between two large industrial cities. The highway is designed to support both the transit between cities and the link to other major roads and highways across the country, thus contributing to the larger road network. Following feasibility studies, the design was decided to include 6 lanes, 3 in each direction, separated and margined by a metal safety barrier. There is an approximate distance of 5 km between the cities and the highway crosses fields, forests, and neighbours a few small villages.

There is a traditional closed culvert midway, between the 34 and 39 km mark, where a river crosses beneath the highway. The culvert is designed for a 2-year event with a climate factor of 1.0. Hence, there has been no consideration of climate change impacts. The culvert has a diameter of 2 m with a max flow of 7,500 L/s. The river catchment upstream the culvert is 4,411 ha and primarily consists of green fields and forest.

Overall, the highway is a key element in the local economy. The average number of daily users is 76,400 and the average travel time to complete the stretch between the two cities is three minutes.

The catchment area of the river upstream is currently not considered to have any significant environmental or recreative value. Several years ago, the river was canalized, and adjacent areas used for agricultural purposes. Today, the land is no longer cultivated, but is not accessible for recreative purposes or the likes.

In 2021, intense rainfall caused flooding, as the capacity of the culvert was exceeded. Although the water did not reach the lanes during the event, the accumulation of water at the brinks of the highway raised concerns on the structural integrity of the highway.

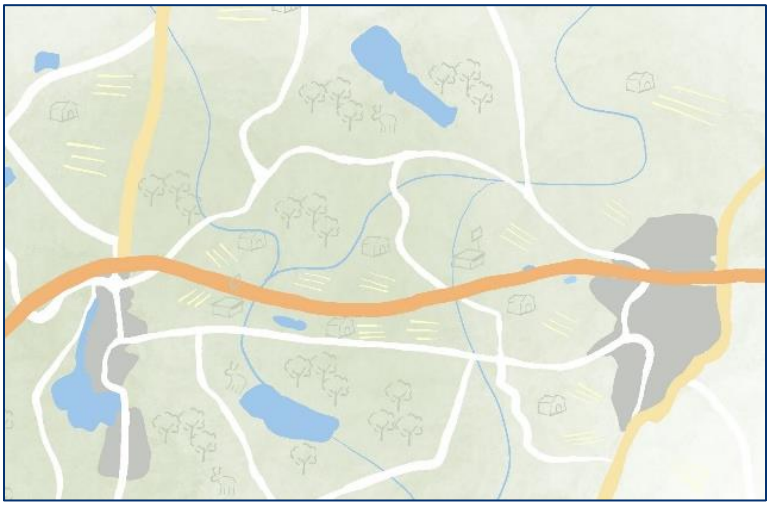

Figure 4.5 Illustration of the case area where the road under consideration is depicted. The bold orange line indicates the road stretch and the two larger grey areas the cities.

Hydraulic assumptions and climate change

The catchment area of the stream is assumed to be 44 km2 and has a runoff coefficient of 0.1. The stream has a total length of 14 kilometres with a 2‰ slope. The time of concentration is 240 min.

The culvert has a diameter of 2,000 mm and is designed for a 2-year event using a climate factor of 1 (17L/s/ha). Maximum flow is 7,500 L/s.

It is estimated that a 2-year event in 2123 will have a peak flow of 9,200 L/s (climate factor = 1.25) and that a 50-year event in 2123 will have a peak flow of 22,600 L/s (climate factor = 1.45)

Case elements and decision context

After the event in 2021, concern is raised as to whether recent changes in weather patterns pose a challenge to the traditional design of the external highway drainage, as heavy rain affects optimal functionality. The intense rainfall event in 2021 that raised concerns on the structural integrity of the highway, motivated an assessment which showed that for many culverts rainfall intensities corresponding to that of a 5-year event will cause water accumulation on the road. With this finding it was decided that the level of resilience was unacceptable.

Key figures for the road:

Annual average daily traffic: 76,400

Average speed: 105 km/h

Average travel time: 3 minutes

Average number of fatalities: 0.3/year

Average number of injuries

- Severely injured: 7 /year
- Minorly injured: 19/year

Figure 4.6 Key figures for the road and of relevance to the KPI's in the case example.

The road stretch is a main contributor to the larger national road network, and an important connection between the two larger industrial cities. Thus, the road is central for the general connectivity and plays a major role in the economic activity and cohesion, especially for the larger two industrial cities.

The governing NRA of the road stretch has an overarching objective regarding connectivity and safety of the road. These objectives are reflected in the KPI's of the NRA being:

- Availability measured simply in as the value of travel time.
- Safety measured simply as the value of yearly fatalities and injuries.
- Cost of repair and maintenance

The NRA decision criteria include policy-driven policies regarding biodiversity and carbon. Co-benefits of adaptation should be considered regarding the effect on environment and biodiversity and that carbon reduction targets should be achieved by 2045.

4.4.2 Assumptions and advice for use

The case study and calculations presented here reflect a real-life situation for demonstration purposes. Still the case is constructed with the main purpose of demonstrating how climate change adaptation options can be selected. The values of the costs and effectiveness of adaptation options, as well as the calculations are done with inherent simplifications of reality to clearly demonstrate the point. Therefore, the examples should only be used as a demonstrator for NRAs to gain understanding in how to choose and appraise adaptation options. In this report only a NbS adaption option is evaluated. For evaluation of grey solution together with NbS, please see ICARUS deliverable D3.2 (van Marle et.al., 2024).

4.4.3 Identification of NbS option

After the resilience assessment has been performed for the road asset the first step is to determine what are the suitable adaptation options for implementation. This step builds upon the resilience assessment which concluded that resilience is not acceptable, because the outcomes of the resilience assessment exceed the thresholds of key performance indicators as defined by decision-makers.

One of the potential pluvial flooding adaptation options identified for the case study is an NbS:

- Retention: Implementation of an upstream NbS would increase retention capacity in the stream and reduce flooding on the road.

4.4.4 Evaluation of NbS adaptation option

As a first step in the evaluation of the adaptation option, an assessment of the impact on the NRA's KPIs and description of the catchment area is conducted to identify potential benefits for assessment. In this process the NRA distinguishes between the benefits associated with the KPIs and the broader benefits (co-benefits) not linked to the KPIs. This process begins with a description and evaluation of the current status of the asset under consideration (in this case, the 5 km stretch of road) and the adjacent areas of the road network likely to be influenced. This is referred to as the reference scenario.

The NbS adaptation option is assessed for two different service levels to identify the optimum level:

- Optimization level 1 is defined as an increase in the drainage capacity, so that water will not start to accumulate on the road until a 5-year event in year 2045.

- Optimization level 2 is defined as an increase in the drainage capacity, so that water will not start to accumulate on the road until a 10-year event in year 2045.

Values associated with the road network (KPIs) include availability (travel time for business and leisure) and safety (value of the lack of injuries/fatalities on the road network). Availability and safety are the two measures, on which the NRA's performance is based on, and thus are of importance in their decision-making.

In addition to the KPI's, the NRA looks for any wider benefits that might be realised from implementing climate adaptation options. The NRA sees that the nearby catchment area has the potential to provide additional ecosystem services in the form of increased recreational value for any visitors. Currently, the areas illustrated on the map below are not accessible due to dense vegetation and very wet and swampy soil. The NRA realises that if the areas are made accessible, e.g., in connection to implementing a nature-based solution, they might provide value to the local citizens.

Figure 4.7 Illustration of the identified green areas in the nearby catchment area, with potential to provide additional ecosystem services in the form of increased recreational value.

The next step is to quantify the costs and benefits of the NbS adaptation option. There are several ways to do this including a multi-criteria analysis (MCA) or a cost-benefit analysis (CBA), see ICARUS deliverable D3.1 for further details. In this case, the costs and benefits are assessed through a CBA with a project time horizon of 50 years.

Costs and benefits that need to be considered in the process are:

- Value of availability and safety decrease during extreme rain events. Thus, the benefits of implementing a climate adaptation option can be estimated as the averted damages associated with Optimization Level 1 and Optimization Level 2, respectively.
- Value of averting repair and maintenance costs associated with extreme rainfall: The status quo scenario is linked to maintenance and repair costs in the case of a 100-year event. For both Optimization Level 1 and 2, these costs will be eliminated for a 100-year event.
- Value of co-benefits of increased recreational value of the adjacent areas: The implementation of a nature-based solution will enhance the recreational value of the catchment area for the citizens in neighbouring cities and other visitors.
- Costs associated with implementing the different adaptation options: Increasing the retention capacity by implementation of a NbS will be associated with construction and maintenance costs.

Benefits associated with the KPIs

Estimation of the benefits associated with increasing the drainage capacity are quantified with reference to the reference scenario. To do this, the damages associated with extreme rain events are estimated for both the reference scenario, optimization level 1 and optimization level 2. The benefit of increasing the drainage capacity to optimization level 1 and 2, respectively, can then be estimated as the difference in associated damages compared to the reference scenario.

The NRA conducts hydraulic simulations for four different return periods to assess the damages associated with these in the reference scenario. Simulations are run for 5-year, 10-year, 25-year, and 100-year events. Based on the quantification of the effects, it is possible to subsequently value the effects. An assessment of the quantified effects on safety and travel time for the four extreme events is included in Textbox 1.

Damages associated with KPI's in the status quo scenario:
The current dimensioning of the culvert is designed for a 2-year event. Thus, availability will be affected already at events exceeding the intensity of a 2-year event. The hydraulic simulations show that at a 5-year event, water will start accumulating on the road, especially in the outer lane. In effect, speed will be slowed and there will be an increase in the travel time for users on the road stretch, due to the reduced speed and (possible) traffic jams in places where water has accumulated in the outer lane. The average percentage increase in travel time in this case is estimated to be around 50 pct. The increase in travel time is estimated based on the national traffic model, which can calculate the change in travel time from the decrease in speed due to water accumulation of water.

At a 10-year event, the level of water accumulation will increase, and two out of three lanes will be affected in specific places on the road stretch. Chance of aquaplaning is high and travel time is increased by around 110 pct., compared to normal.

By a 25-year event all three lanes are heavily impacted by the accumulated water and travel time is increased by more than 200 pct. At a 100-year event the road will practically be blocked due to very high levels of accumulated water, resulting in an estimated increase in travel time of around 400 pct.

As for availability, safety will be impacted by a five-year event in the status quo scenario. The impacts on safety are simply measured as an increase in probability of a fatality or injury as per 24 hours[5].
In the status quo scenario this decrease in safety is estimated to be 15 pct. at 5-year event, 20 pct. at a 10-year event, and 25 pct. at a 25-year event. By a 100-year event the safety level is assumed not to be impacted, since the road will not be used.

In addition to the damage costs associated with availability, the NRA estimates a 100-year event to be associated with cleaning and repair costs of around 1,000,000 kr. This estimate is based on experience from previous events.

Optimization level 1 increases the drainage capacity, so that damages will not occur until a 10-year event. Therefore, the damages associated with a 5-year event in the reference scenario will not occur with optimization level 1 until a 10-year event. Similarly, the damages associated with a 10-year event in the reference scenario will not occur until a 25-year event at optimization level 1, and similarly for a 100-year event. The cleaning and repair costs associated with a 100-year event is estimated to be 750,000 kr.

Optimization level 2 increases the drainage capacity even further. The result is still that both availability and safety will be affected at a 10-year event, however only by half of the impact of a 10-year event at optimization level 1. The hydraulic simulations show that this will also be the case for the 25-year event and 100-year event; damages will occur as for optimization level 1, however only by half of the estimated damages. The cleaning and repair costs associated with a 100-year event is estimated to be 500,000 kr.

Textbox 1 Assessment of damages associated with extreme rain events on safety and availability in the status quo scenario, optimization level 1 and 2.

Based on the quantification of the effects described in Textbox 1, the *monetized value* of the effects can be estimated, by applying unit price values, for the cost of delay, fatalities and injuries (both severe and minor). Such values are in Denmark provided by the Danish Ministry of Transport and are updated

[5] The quantification of safety in the case example is based on an ideal example, where data availability enables quantification of all effects on KPIs. However, the Danish Road Authority do not collect data on the effects of extreme weather events on road safety. Thus, it has been necessary to base the case example on fictive numbers with regard to the level change in safety within the 24 hours of an extreme rain event. If the NRAs are to implement climate adaptation in their decision making and this is to be based on quantifiable measures to make the case for adaptation, it is suggested that collecting data on extreme events impact on safety would be of value. This is because safety plays a central role as a KPI for most NRAs and data would enable valuation of climate adaptations impact on this.

yearly[6]. Table 4.3 below provides the valued effects of each of the three scenarios (reference scenario, optimization level 1 and optimization level 2). These are referred to as damage costs. In addition to the damage costs associated with the KPI's, availability and safety, the table includes cleaning and repair costs in the category 'Other'. This damage cost is estimated based on historic data from the NRA and will only occur for a 100-year event.

Table 4.3 Presentation of the calculated damage costs associated with availability, safety and maintenance costs associated with extreme rain events for the reference scenario, optimization level 1 and 2.

	Reference scenario			Optimization level 1			Optimization level 2		
	Availability	Safety	Other	Availability	Safety	Other	Availability	Safety	Other
5-year event	602,375	222,337	-	-	-	-	-	-	-
10-year event	1,204,750	232,003	-	602,375	222,337	-	240,950	207,836	-
25-year event	2,409,500	241,670	-	1,204,750	232,003	-	481,900	212,670	-
100-year event	4,818,999	-[7]	1,000,000	2,409,500	241,670	750,000	963,800	217,503	500,000

The damage curves can be used to estimate a cashflow for the expected annual damages (EAD) over the 50-year project period for all three scenarios. The EAD is an expression of the damage costs, which the NRA should expect to experience, for a given drainage capacity. The EAD therefore accounts for all the probable rain intensities that might cause damage and their associated probabilities combined.

An EAD is calculated for two points in time for all three scenarios (reference scenario, optimization level 1 and optimization level 2); an EAD for today (project start) and for the assumed end of the project period. By interpolating linearly between these two points, the EAD cashflow for the whole project period is estimated.

EAD cashflows are calculated for both the reference scenario, optimization level 1 and optimization level 2. These are depicted in Figure 4.9 over the 50-year project horizon. The EADs are increasing over time, since the probability of experiencing extreme rain events will increase in the future. Therefore, a climate factor has been applied in the estimation of the cash flow. Ideally, the sensitivity analysis on the results from varying the climate factor should be conducted. This is however left out of this example for simplicity.

Figure 4.9 illustrates that the reference scenario has the highest EAD cashflow, and the EAD for optimization level 2 has the lowest. Based on the EAD, it is possible to calculate the total benefits of increasing the drainage capacity from the reference scenario to optimization level 1 and 2, respectively. By deducting the cashflows from each other, two benefit cashflows are estimated for the project period.

[6] TERESA og Transportøkonomiske Enhedspriser

[7] It is assumed that in case of a 100-year event the road would be closed, hence the safety costs would be zero

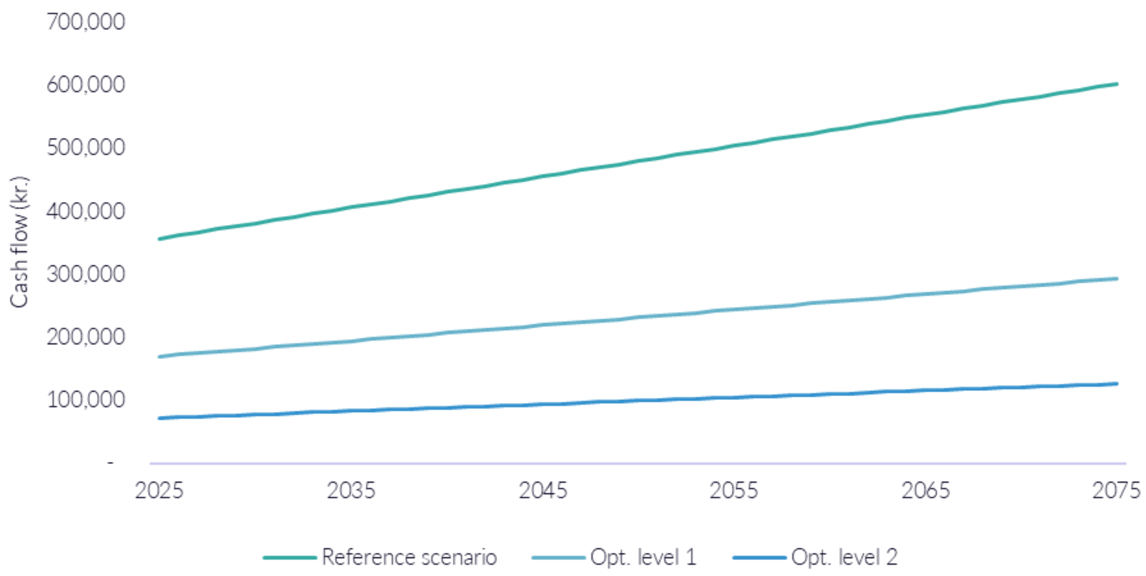

Figure 4.9. Expected annual damage for the three scenarios: reference scenario, optimization level 1 and optimization level 2.

Based on the estimated EADs it is now possible to express the benefit associated with optimization level 1 and 2, respectively, as the difference between the reference scenario and the new optimization level. This results in two net-benefit cashflows for optimization level 1 and 2. It is possible to express the cashflows as one single value, a *present value*, by discounting them.

These present values related to the primary benefits associated with KPI's amount to:

- 6.3 million DKK for optimization level 1
- 9.6 million DKK for optimization level 2

Recreational value of applying nature-based solution

The nature-based climate adaptation option will increase the recreational value of the nearby catchment area in addition to increasing the external drainage capacity.

Currently, the areas both upstream and downstream of the river crossing the road are inaccessible due to the surrounding areas being an overgrown and swampy area. The adaptation solution is based on the principles of retention. The flow directed to the downstream part of the river and the culvert under the highway is reduced by creating a large natural basin, where the flow is diverted into during periods of high rainfall. The excavated soil is used to create the banks of the basin and a system of small foot paths with the purpose of making the river and surrounding areas accessible for recreative purposes. Attention is given on the conditions for flora and biodiversity. A total of three hectares are made accessible for recreative purposes. Implementation of this solution requires collaboration with other stakeholders including the local municipality and adjacent landowners and may in some cases require co-financing depending on the jurisdiction of the NRA.

The Danish National Environmental Agency provides a catalogue for key figures of unit values on environmental economic assessments, including recreative values per hectare. From the catalogue, the specific value is chosen based on nature-type and the specific region. Furthermore, the unit value is inflation adjusted. The applied unit value for the increase in recreational options are 26,000 DKK/year/ha. for the specific region.

This means that the total value of increasing the recreational area by 3 hectares will be 78,000 DKK/year. It is assumed that the value is the same for both optimization level 1 and 2.

Cost-estimation

The adaptation cost of the nature-based solution is also based on cost estimates from previous projects. This indicates a construction cost of around 50 kr./m^3 drainage needed for projects around 100,000 m^3 and a construction cost of around 60 kr./m^3 drainage needed for projects around 150,000 m^3. The higher costs stem from typically higher costs associated with environmental investigations for larger projects. Optimization level 1 requires a drainage capacity of 114,000 m^3 and thus has an adaptation cost of an estimated 5,0 million kr., based on a cost of 50 kr./m^3. For optimization level 2 a maximum drainage capacity of 145,000 m^3 is needed and thus has an adaptation cost of 8,7 million kr. with a cost of 60 kr./m^3.

The case for NbS

For the nature-based solution, the net present values of the benefits including co-benefits and the cost curve are illustrated in Figure 4.10. Subtracting the cost curve (pink) from the (co-)benefit curve (dotted blue) results in the net gain curve (green) for increasing the drainage capacity. As seen in Figure 4.10 the net gain from increasing the drainage capacity to optimization level 1 is 3,1 million kr., and 2,4 for optimization level 2. Based on this result, increasing the drainage capacity to optimization level 1 is the more optimal choice, when applying the nature-based solution as adaptation option.

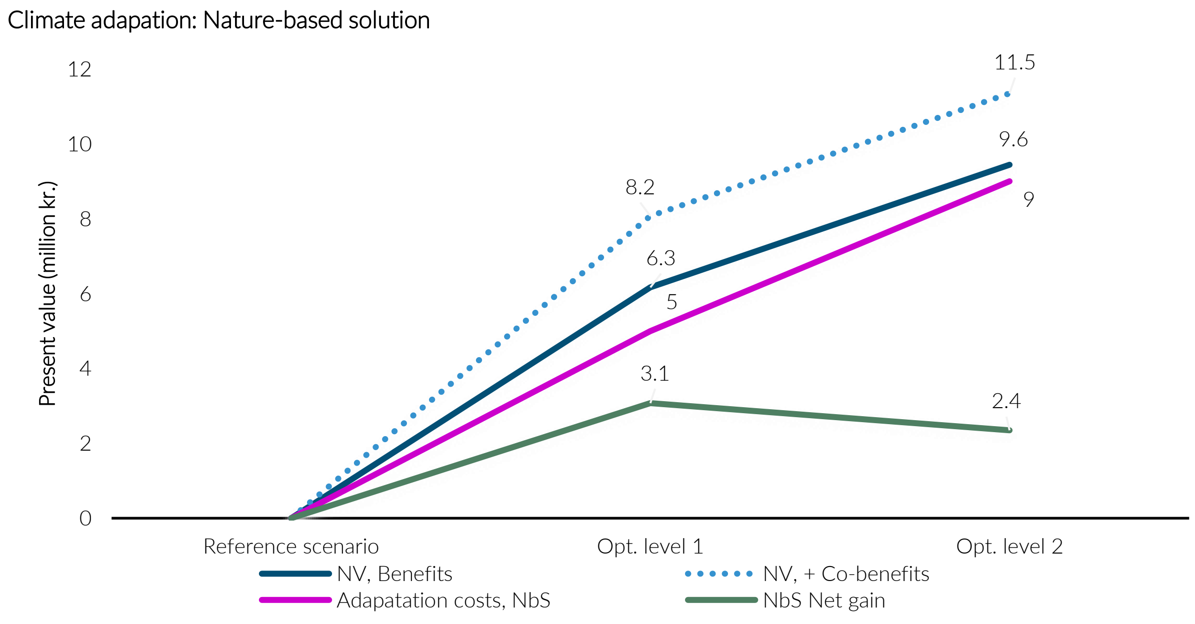

Figure 4.10 Benefits and costs of climate adaptation on the road stretch using a NbS.

5 CONCLUSION AND RECOMMENDATIONS

This document introduces the concept of Nature-based solutions as an adaptation option for road infrastructure to increase resilience to climate change. This report draws from other deliverables in ICARUS project and provides NRAs a way to assess NbS as an adaptation option. NbS have been brought up because they are gaining recognition in the infrastructure sector.

NbS is a relatively new concept, and several definitions of the concept have been introduced in the report. The European Commission defines NbS as 'solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience'. This definition underscores integrated approach while placing emphasis on building resilience and providing systemic benefits. NbS can be viewed as an umbrella concept for several other concepts such as Green Infrastructure. This report describes why NbS should be adopted as a way to address climate change. These reasons include leveraging natural systems to provide resilience against climate change impacts, cost-effectiveness, multiple benefits and flexibility among others.

NbS have not been yet widely adopted in the road sector and environmental aspects such as biodiversity have not been given a high priority in traditional road asset management. When facing societal challenges, asset owners and managers need to come up with new solutions. Understanding the value brought about by implementing NbS is one way to address the challenges.

When considering NbS, the engagement with stakeholders should be more extensive than when with grey infrastructure. The stakeholders include among others, NRAs, consultants and contractors, environmental authorities, local authorities and municipalities and landowners. By fostering inclusive decision-making processes and leveraging local knowledge, expertise and resources, collaboration and participatory planning enhance the effectiveness, equity, and sustainability of NbS. Individual stakeholders have different views on implementation of NbS and one significant issue is collaboration with stakeholders that own or use the land adjacent to the roads. NbS may take more space than grey infrastructure, while the NRAs usually manage only the space reserved for the road itself and its immediate surroundings. Therefore, it is important to plan and implement NbS with e.g., landowners. On the other hand, one special aspect of NbS is collaboration with stakeholders and inclusion of local communities which means that the discussions and negotiations are an essential part of implementing NbS.

There is no straightforward answer on how climate change will affect roads. An assessment of climate change risks provides a base for identifying and reducing risks and defining measures for strengthening of the road system resilience. ICARUS proposes the use of impact chains as a methodology to understand how the various climate hazards can impact the roads including, also, the opportunity for adaptive responses, of which NbS should be one.

Climate change poses several challenges to the design and implementation of NbS. NbS often rely on ecosystem-based approaches, however, ecosystems are complex and dynamic systems that can be affected by climate change-induced stressors, which may undermine the effectiveness of NbS and require adaptive management strategies. Climate change adaptation and mitigation strategies in the road sector should consider cross-sectoral linkages, synergies, and trade-offs to optimize co-benefits and minimize unintended consequences.

Within ICARUS, a key focus area is to provide road authorities with a selection of adaptation options, (see ICARUS deliverable D2.3, Excel database of adaptation options) guidance on how to choose the most appropriate options for their infrastructure, and guidance on how to implement adaptation. An Excel database of adaptation options has been developed as part of this project. This database was reviewed from the aspect of NbS. The adaptation option measures are classified according to the definition of NbS by the EC, the classification being 'Yes', 'No' or 'Potential'. As there is some ambiguity to the extent to which a measure is a NbS there is a degree of subjectivity in the characterization. This means also that some measures may be considered as NbS if there is sufficient focus on maximizing the green aspects. In the implementation of NbS there must be space for innovation, flexibility and adjusting the measures so that they can be adapted to local conditions and situations. The ICARUS project has described evaluation methods for assessing adaptation options and multi-criteria analysis was chosen to be the most appropriate way of assessing the adaptation options. The benefits related to nature and environment are expected to be positive for NbS and in many cases, NbS is required to ensure realization of co-benefits.

It has been recognised in this report that there are both drivers and barriers for the implementation of NbS. The drivers include answers to societal challenges, e.g. providing carbon storage and mitigating greenhouse gas emissions, contribution to biodiversity net gain and providing ecosystem services. Barriers on the other hand include lack of resources, lack of information and uncertainty to climate change, organisational engagement and lack of longer-term planning in climate change adaptation. Guidelines for implementation of NbS are presented in this report. The most important elements to consider for implementation of NbS are getting buy-in from the organisation, involvement of stakeholders and local communities, including maintenance as an essential part of the planning process, monitoring and detailed design specifications. The guidelines, along with NRAs' increasing embracement of sustainability and funding depending on sustainability goals, can help lower and overcome the barriers to NbS implementation.

Understanding and assessing the performance of NbS is crucial for mainstreaming NbS into regulations, guidelines, and plans. Key performance indicators are valuable for NRAs to measure progress and steer decisions. KPIs thus play a key role in the decision making of NRAs. This means that, while assessing the NbS adaptation options, it is of high importance to link the assessment criteria to the KPIs as much as possible. In general, it is easier for the NRA to make the case for implementation of adaptation options when more positive effects are linked to KPIs. Depending on the design choices made for adaptation options, co-benefits may be maximized and thus support making the case for implementation. Integrating NbS into adaptation strategies can bring about multiple co-benefits beyond the primary benefits. Including co-benefits in a cost-benefit assessment provides a better understanding of the full effects that climate adaptation options introduce, in addition to the expected primary benefits linked to KPIs. A list of benefits likely to be associated with options for climate adaptation and resilience including NbS options is presented in this report.

Valuation of costs and benefits provides a way of evaluating different options in decision making. The comparison of costs and benefits of implementing adaptation options or resilience measures provides a transparent way of considering different alternatives. Benefits of NbS and other adaptation options will often be defined as either tangible or intangible in relation to valuation. The benefits linked to NbS adaptation options are often intangible, hence, there is no universally adopted approach to measure and quantify these in valuation. ICARUS suggests a four-step method for applying valuation in decision-making contexts. This approach also covers valuation of NbS adaptation options. While all benefits listed in the report may materialize through the implementation of NbS, some socio-economic and environmental benefits are linked to the effects of nature and will likely only be present if an NbS is chosen as the adaptation measure for implementation. Examples of these benefits are ecosystem services, water quality and health effects.

In this report, a fictive case study is presented where the evaluation of NbS adaptation option is demonstrated. The NbS evaluation option is assessed through the NRA's KPIs and potential benefits are identified. Co-benefits are also identified. Two different service levels are defined to identify the optimum level. In the case study, costs and benefits for the NbS adaptation option are quantified. Through these, the optimal level of NbS adaptation can be determined. The case study shows an example of how the NbS adaptation can be assessed through KPIs and how value can be determined for the benefits and co-benefits.

6 Acknowledgement

The research presented in this deliverable was carried out as part of the CEDR Transnational Road Research Programme Call 2021: Climate Change Resilience. The funding for the research was provided by the national road administrations of Finland, Ireland, Netherlands, Norway, Sweden and the United Kingdom.

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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 Institute, 2023)	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/ 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

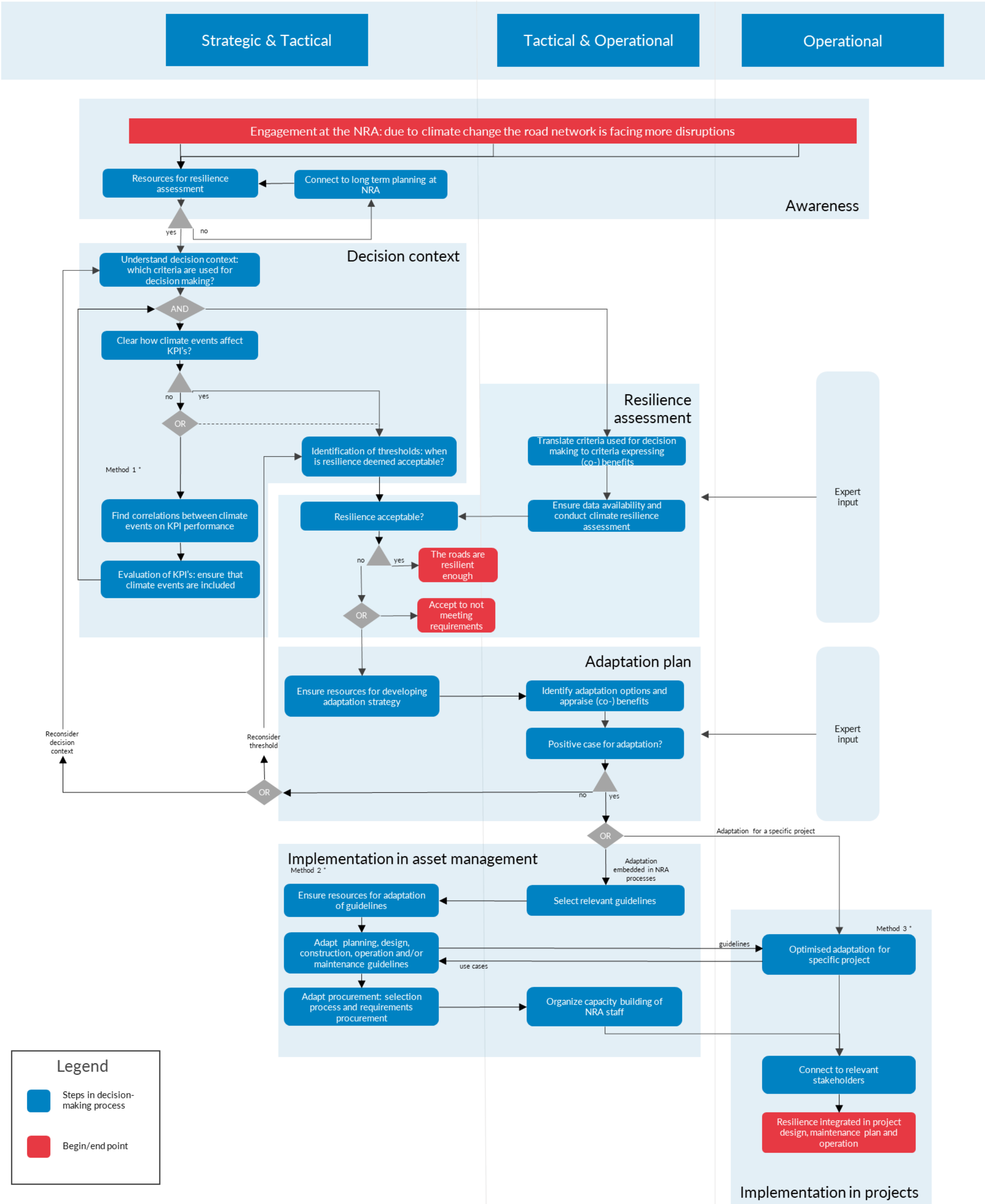
	Remarks: Discusses the importance of investing in NBS views towards cost benefit analysis of implementation and maintenance to meet societal needs.
(Teich et al., 2012)	Snow Avalanches in Forested Terrain: Influence of Forest Parameters, Topography, and Avalanche Characteristics on Runout Distance Link : 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 – THE ICARUS ADAPTATION IMPLEMENTATION PROCESS



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