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ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION  
AND MANAGEMENT OF THE BUILT ENVIRONMENT

# MBUILD

## A METHODOLOGY TO DELIVER CLIMATE CHANGE ADAPTATION IN TRANSPORT INFRASTRUCTURE

RABAB RAYDAN

Supervision: JRH JORGE RODRIGUEZ HERNANDEZ (UC University of Cantabria)

Co-supervision: DGS DAVID GARCIA SANCHEZ (TEC TECNALIA Research and Innovation)

Santander, July 2024



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Dedicated to every person who supported me to be here.

Thank you for believing in my potential.

"It's a matter of time" R.R

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## ABSTRACT

The integration of climate change resilience into the management of Transport Infrastructure (TI) presents a critical and complex challenge, requiring a delicate balance between aspirational goals and practical realities. As climate-induced hazards become increasingly severe and frequent, the essential role of TI in supporting societal, economic, and environmental functions underscores the urgency of enhancing its resilience. Central to this challenge is the need to navigate the uncertainties associated with climate projections and extreme events while translating scientific insights into actionable adaptation strategies.

This work explores the existing gaps in decision-making within the context of climate adaptation for TI and identifies three primary obstacles: facilitating informed decision-making, overcoming data scarcity, and improving the comprehension of climate change impacts. To address these challenges, the study introduces a methodology grounded in the Impact Chain concept, designed to streamline decision-making processes by incorporating the perspectives of policymakers, designers, and engineers and the users.

The proposed approach advocates for a paradigm shift from conventional grey infrastructure solutions to nature-based solutions, which provide holistic, system-wide benefits. This shift necessitates comprehensive stakeholder engagement, robust resilience assessments, and sustainability considerations. Despite the availability of numerous methodologies and climatic datasets aimed at mitigating climate impacts, there remains a significant disconnect between the planning and implementation of adaptation measures. This work seeks to bridge that gap by offering a simplified, integrated framework that enhances decision-making efficacy and promotes the implementation of climate adaptation strategies within TI management.

Keywords: Climate Change, Sustainability, Resilience, Transport Infrastructures, Nature-based Solutions



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## **SYMBOLS, ACRONYMS AND ABBREVIATIONS**

MBUILD – Erasmus Mundus Joint Master in Sustainable Design, Construction And Management of The Built Environment

ICARUS –Improving the uptake of Climate change Adaptation in the decision-making processes of Road aUthoritieS

SDGs – Sustainable Development Goals

CC – Climate Change

IPCC – Intergovernmental Panel on Climate Change

Ref - Reference

Fig – Figure

IC – Impact Chain

NbS – Nature-based Solutions

QRA – Quantitative risk assessments

GDP – Gross Domestic Product

KPIs- Key Performance Indicators

MCDA – Multi-criteria Decision Analysis

EWM– Entropy Weight Method

ESG – Environmental, Social, and Governance

CEDR – Conference of European Directors of Roads

UNCHAIN – Unpacking Climate Impact Chains

CRVAs –Climate Risk and Vulnerability Assessments

GCMs–global climate model

AADT–Annual Daily Traffic

USLE – Unified Soil Loss Equation

RCMs –regional climate models

TBA- To be altered



# 1

## INTRODUCTION

### 1.1. INTRODUCTION

Climate change (CC) and its effects, including variability, significantly impact various sectors, both public and private. As global temperatures rise, these effects become more pronounced. Currently, the impacts of CC are evident and ongoing, persisting despite efforts to reduce global emissions. Instances of flooding, droughts, and heatwaves are increasing in frequency, duration, and severity, posing significant threats to public health, environment, and economic stability showcasing significant gap in climate protection measures thereby strengthening environmental, societal, and economic resilience ability to recover from its impacts is crucial and an urgent need [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. Transport infrastructure such as roads, railways and canals tend to be essential for promoting connectivity, driving economic growth, ensuring resource distribution. Its adaptation to CC serves as a fundamental strategy for achieving various Sustainable Development Goals (SDGs), driving economic growth while minimizing environmental and social impacts [12] [13], [14], [15], [16], [17]. This is due to the potential for enhancing emergency response capabilities and supporting environmental conservation efforts. Thus, its importance underscores the need for sustainable planning, investment, and management to maximize its benefits while minimizing adverse impacts on communities and the environment.

Resilience in the context of CC, as expressed by the Intergovernmental Panel on Climate Change (IPCC), refers to the capability of systems to absorb and rebound from disturbances induced by climate variations while maintaining functionality. This encompasses the capacity to withstand sudden shocks, such as extreme weather events, as well as the flexibility to adjust to longer-term shifts in climate patterns. The IPCC underscores that resilience extends beyond physical infrastructure, encompassing social, economic, and institutional dimensions. It emphasizes the importance of proactive measures aimed at reducing vulnerability, enhancing adaptability, and fostering sustainable development in response to CC impacts[18].

Implementing adaptation measures such as constructing infrastructure resilient to hazards and utilizing Nature-based Solutions (NbS) are essential steps in mitigating climate risks. NbS encompass a diverse array of strategies that leverage the fundamental resilience of natural ecosystems to address CC impacts. These solutions range from restoring degraded ecosystems such as forests and wetlands to incorporating natural features like dunes and marshes into infrastructure systems for enhanced resilience against climate-related hazards to not only mitigate climate risks but also provide additional benefits such as carbon sequestration, biodiversity conservation, and improved water quality[3], [19], [20], [21], [22], [23].

Adaptation involves integrating different approaches and engaging stakeholders through several ways including risk management frameworks. The key criterion for assessment is to be effective in addressing adaptation challenges and managing climate and non-climate related risks considering all relevant factors to maintain the balance of enhancing resilience and reducing disaster risks for all individuals [24], [25].

The aim of this thesis dissertation and the outcome of the MBUILD is to analyse the barriers limiting the integration of sustainable and resilient practices in the built environment with a special lens on the transport infrastructure. The goal is to understand the climate change related risks on the resilience of the studied infrastructure. Then create a roadmap towards combining resilience and sustainability in decision-making through a simplified manner. This opens doors to showcase the importance of NbS as effective solutions for climate change adaptation measures and how they can be put into consideration. This work will revolve around a project that tackles improvement to the uptake of CC Adaptation in the decision-making processes of Road authorities. The project "Improving the uptake of Climate change Adaptation in the decision-making processes of Road authorities (ICARUS)", used in this work is an ongoing project funded by the Conference of European Directors of Roads (CEDR), through the Call 2021 Climate Change Resilience, where Tecnalia Research and Innovation is a partner in and provided this opportunity for this master thesis development. ICARUS aims to develop a framework to aid the national road authorities in identifying current barriers and gaps in technical execution of resilience assessments in transport infrastructure and suggesting methods to overcome these challenges. Climate threats and hazards across various climatic regions of Europe, along with solutions, processes, and implementation are considered with an initiative aiming to build upon existing examples of good practice within the community and serve as a spotlight for innovative projects, products, or technical solutions that can cause a positive change in the decision making of the road authorities[26].

The aim is to build on it and propose a methodology that helps implement the sustainable resilience measures in a simplified way considering the background of each stakeholder and ensuring their involvement in management of infrastructure. Work towards improving the efficiency and the effectiveness climate adaptation in transport infrastructure, facilitate reaching the decision making and validate of the preselected adaptations faster and cheaper than the complete detailed analysis

## **1.2. OBJECTIVES**

The methodology established shall identify the processes necessary for determining adaptation options through case studies on experiences with vulnerability and resilience assessment, solutions developed for CC adaptation, and the implementation of adaptation strategies in practice will be conducted [27]. The motivation of this work aims to provide 2 main benefits:

The first is to propose a simplified methodology that can fit to any type of event and is capable of being understood and performed by different stakeholders. It is important to note that this framework should not replace the standard resilience assessment methods and should be evaluated accordingly to ensure that it simulates the real conditions. However, in a context where understanding where and how can climate change be implemented in decision making, this can show the relationship it has with the transport infrastructure resilience and pave the way for choose more effective adaptation options to improve its performance and withstand the impacts of climate change leading to better infrastructure management.

The second is to include of sustainability in the decision-making process, considering not only the resilience performance but also the benefits the chosen adaptation solution has in its context. While several solutions can solve a certain consequence, this methodology gives a direction to narrow down the list of options, include nature-based solutions for consideration and work towards not only an

adaptive solution but also a regenerative solution that can improve the overall performance and directs when they are recommended for use.

### **1.3. HYPOTHESIS**

When unwanted events pose an unacceptable risk, mitigation and adaptation measures must be implemented which requires a methodology to prioritize these measures and track their effectiveness yet due to the significant uncertainties associated with climate change, there is no universally applicable solution. Additionally, uncertainties arise from shifting demands for road infrastructure driven by socioeconomic developments and evolving technologies. In such uncertain situations, a base management approach widely accepted as a method to maintain control that is not too complex to implement and cost effective enough to be followed with the minimum requirements is in demand.

For that, the initial hypothesis is that it is possible to develop a new procedure composed of two preliminary selection stages and two detailed evaluation stages. The basis of the methodology starts from the concept of the impact chain concept map to visualize the effects of climate impact drivers on the infrastructure and the risks resulting on the infrastructure. This is further analysed by expanding it into a checklist where project specific parameters can be highlighted. The next stage is to proceed to the detailed evaluation of risks. This stage is usually done using simulations or detailed calculations however the proposal here is to use literature fragility curves to try to make an easier process that can be used in areas where data is a scarce or expertise is not available, or funding is not possible such that this can be a cost-effective simplified method for vulnerability assessment. Based on the vulnerability state, the selection of the type of measure that should be taken can be made. According to the extensive study made, the creation of a new standardized way to sort the key performance indicators that should be tackled in any selection process putting resilience and sustainability as basis of this stage and help this methodology be sufficient to be utilized in impoverished or developing countries regardless of their characteristics or data sources. A new weighing criterion is also developed putting a categorized set of KPIs covering the basic needs for choosing and adaptation measure then justifying the different perspectives in the decision-making process and showcasing how this subjective choice affects the choices made. The five perspectives considered are the technical, environmental, political, neutral or average of all. The chosen alternative is then validated based on their resilience and sustainability performed and compared with the baseline scenario. Although the methodology carried high optimism for effectiveness, this hypothesis could not be fully validated due to the limitations of data availability. Regardless, even without evaluating in detail the guidance on how the adaptation should be was proven and provided which can be a starting point for evaluation and validation in the future works.

## LITERATURE REVIEW

### 2.1. CLIMATE CHANGE AND THE BUILT ENVIRONMENT

Climate Change (CC) stands as a formidable challenge to human society, representing a substantial risk to essential global elements such as food, water, ecosystems, energy, infrastructure, and the well-being of individuals, including the safety of their lives and property [28][22]. Climate change intensifies existing land degradation processes and introduces new patterns of degradation. Human-induced global warming has already led to changes in factors contributing to land degradation, such as increased frequency and intensity of heavy precipitation and heightened heat stress. Coastal erosion has worsened in some areas due to rising sea levels and future global warming is expected to exacerbate these processes further through more frequent and severe floods, droughts, intensified cyclones, and continued sea level rise, with the effects being influenced by land management practices. Permafrost thaw and coastal erosion, driven by warming and rising sea levels, are affecting regions where such issues were previously uncommon [1], [7], [11], [29], [30], [31]. Additionally, increased coastal erosion is anticipated worldwide, and in cyclone-prone regions, the combination of sea level rise and intensified cyclones will lead to significant land degradation with severe impacts on people and livelihood. Considering the built environment which is a complex network of buildings, infrastructure, and nature and communities its susceptibility to climate change impacts is intricately interwoven within a complex relationship among one another where a risk on one component may impact the whole chain within [32], [33], [34], [35].

Frequent storms for example result in excessive rainfall, leading to both localized and widespread flooding, as well as occurrences of landslides, rockslides, and sinkholes. Storm events may also bring about destructive winds, hail, and even tornadoes. Conversely, prolonged periods of dryness with heightened temperatures are common, elevating the risk of drought. Additionally, winter storms and severe cold temperatures have the potential to immobilize an area for an extended duration, illustrating the varied challenges posed by extreme weather [6], [36], [37] [38]. This also poses a challenge to the routine functioning of urban systems. Infrastructure is frequently damaged, putting lives, property, and food security at risk [37], [39], [40]. The diverse topography on the other hand is one of the main contributors to a range of climate conditions that give rise to different forms of extreme weather.

Since the Paris agreement was signed, it has been a reference framework for decision-making. Yet, decision making is a complex to approach practically. Several reasons contribute to this difficulty from which include lack of knowledge of all the alternatives that can be considered or in the possible conflict that may appear between individual and collective values. Deciding implies having to take responsibility for the short- and long-term consequences, and if this involves a human factor it becomes much more

complex [41]. Unless inherently resilient, risk succumbing to decay or collapse will be unprecedented when subjected to a range of shocks and stresses impacting millions and giving rise to far-reaching economic, environmental and social consequences[11], [27], [30].

## 2.2. PROJECTIONS OF CLIMATE CHANGE

Climate scenarios are not intended as predictions or forecasts but rather as tools for exploring plausible future outcomes under different circumstances typically through involving and adjusting a baseline climate, often derived from regional observations of climate during a reference period, predict the absolute or proportional changes between the simulated present and future climates. Incorporating climate projections and scenarios into the planning, design, and operation of transport infrastructure necessitates deliberate consideration and management. This facilitates the identification of the climate risks imposed on various components of transport infrastructures and necessitates the consideration of the predefined set of scenarios and the urgency of action. Climate change scenarios serve as projections illustrating potential future climate conditions based on various factors, including societal decisions, policy implementations, and resulting climate forcing, primarily greenhouse gas (GHG) concentrations in the atmosphere. The primary drivers of climate change mentioned in the IPCC reports, such as carbon dioxide (CO<sub>2</sub>) from burning fossil fuels and methane are key components of these scenarios. The scenarios explore how different levels of emissions, as well as variations in other factors, can lead to varying degrees of global warming, sea level rise, extreme weather events, and other impacts on Earth's climate systems. National and global data sources facilitate the process of obtaining climate data of a certain area and the projections expected in the near or far future. The projections are done according to the Representative Concentration Pathways (RCPs) which serve as fundamental frameworks within climate science, delineating potential future emissions trajectories and their corresponding atmospheric concentrations of greenhouse gases. These scenarios serve as pivotal tools for understanding and contextualizing the range of potential climatic outcomes, thereby guiding critical decision-making processes in climate policy, adaptation strategies, and infrastructure planning. Fig. 1 describes how the 2 scenarios vary in perception.

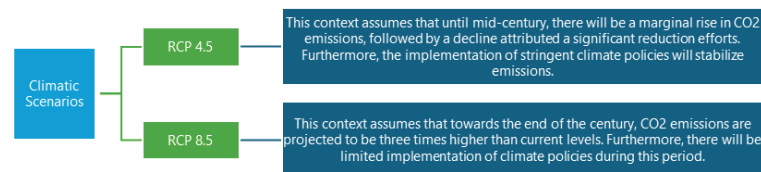


Figure 1 RCP 4.5 and RCP 8.5 Explained

The climatic scenarios serve as robust contribution to the framework for vulnerability assessments of transport infrastructures. This is due to its representation of a high emissions trajectory throughout the 21st century. It portrays a future where greenhouse gas emissions continue to escalate rapidly, resulting in heightened climate impacts including elevated temperatures, intensified weather extremes, and accelerated sea level rise providing critical insights into potential risks and challenges. This then results in them being the main drivers of current climate change, influenced by population trends, energy use changes, economic growth.[1], [2], [6], [7], [8], [9], [31], [37], [42]

Extreme weather events induced by CC, such as heatwaves, storms, and floods, present significant challenges to transport infrastructure, resulting in road closures, disruptions to public transit, and operational delays. Consequently, initiative-taking consideration of these risks is paramount in the design and planning of transportation systems. This necessitates the development of resilient infrastructure capable of withstanding the impacts of extreme weather and adapting to changing climatic conditions. Ensuring the resilience of transportation infrastructure to weather variability entails updating existing regulatory frameworks, including codes and standards related to road safety and

public transportation, to incorporate climate change considerations comprehensively. Such measures are imperative to uphold infrastructure functionality and ensure the continued provision of safe and reliable transportation services to communities[26], [34], [43], [44] [45].

The impacts of hazards and the associated climate-induced dynamics exhibit variability across different sectors and hazards. The extent of actual damage and the degree of change are influenced by sector-specific vulnerabilities to distinct hazards, along with the rate and magnitude of change in these hazards attributable to CC. Considering different contexts, Europe on one hand by the end of this century will have hazard impacts on the energy sector by more than 60% of drought and 30% of heat damage. Other hazards mainly affect energy transport systems, and over time, hazard impacts display less distinct increases (wildfires, inland flooding, and windstorms), undergo significant frequency escalation but maintain low magnitude (coastal flooding), or decline sharply (cold waves)[15]. In the transport sector, heatwaves are projected to comprise 92% of total hazard damage by the 2080s, primarily affecting roads and railways with issues like buckling of rails and melting asphalt. Anticipated losses from inland and coastal flooding are expected to increase moderately and drastically over time, while cold wave impact is projected to decline. Inland waterway transport will face growing challenges due to droughts, reducing navigation capacity, while windstorm damage to river navigation is expected to show a slight trend[15]. Concurrently, in the industry sector, floods and windstorms currently dominate hazard losses, primarily causing structural damage to infrastructures, machinery, and equipment. Although flood and windstorm damage are on the rise, their contribution will be quickly overshadowed by droughts and heatwaves in the coming decades. These impacts primarily relate to the degradation of water quality and a reduction in the decomposition rate of water and waste management systems, resulting in higher costs for water treatment. Additionally, sea level rise and increased storm surges are expected to lead to strong increases in damage to ports in the coming century[26].

Estimating future annual damage involved applying damage relations to the projected changes in accumulated assets at high/very high-risk levels. This assumption hinges on the constancy of components of risk calculation including measures of the hazard, sensitivity, and the spatial distribution of infrastructures. The fundamental idea is that the alterations in the frequency distribution associated with impacts (occurring every 50 years or less for overly sensitive infrastructures and every 100 years or less for medium sensitivity infrastructures) faithfully represent the actual changes in the frequency of damaging events [15]. Calculations for both baseline and future expected annual damage values were conducted separately for each climate hazard, scenario period, and climate experiment. This method ensures a comprehensive evaluation of potential impacts, contributing to a nuanced understanding of the evolving risk landscape [15].

One example considers the global threat posed by CC presents a significant challenge to communities worldwide, resulting in heightened occurrences of extreme weather events capable of overpowering Stormwater Management Systems. Positioned at the forefront of these impacts, stormwater drainage infrastructure not only bears the immediate brunt but also plays a pivotal role in enabling cities to enhance their climate resilience. Alterations in the distribution of precipitation, a critical factor in the design of conventional infrastructure, correspond significantly to shifts in the risk profile borne by communities in terms of flooding, property damage, and human safety. Unlike natural watersheds that undergo adaptive processes, enhancing flow capacity through the evolution of channels in response to CC over time, rigidly dimensioned grey infrastructure lacks inherent adaptability [46].

Furthermore, there are differing classifications for hazard interactions and cascading effects, but there's not internationally established or agreed-upon modelling approach for multiple hazards yet [32]. Examining the actions of different sectors provides insight into the regions and industries that might need significant efforts to enhance the resilience of existing and planned critical infrastructures to future climate conditions[7], [13]. This underscores the importance of integrating Climate Change (CC) adaptation into various EU policies and funding instruments [15]. Systemic adaptation necessitates

moving beyond technical and climatic factors to consider the varying adaptive capacities of regions, assets, and communities. However, there are gaps in effectively incorporating these considerations into adaptation strategies, which may result in inadequate responses to climate-related challenges[6]. Although there has been extensive literature regarding quantifying vulnerability and adaptive capacities of infrastructure affected by climate change impact and on evaluating adaptation measures, the methods developed still need improvement to reach needs for decision making[47] and reduce the envelope of uncertainty as shown in Fig. 2 below.

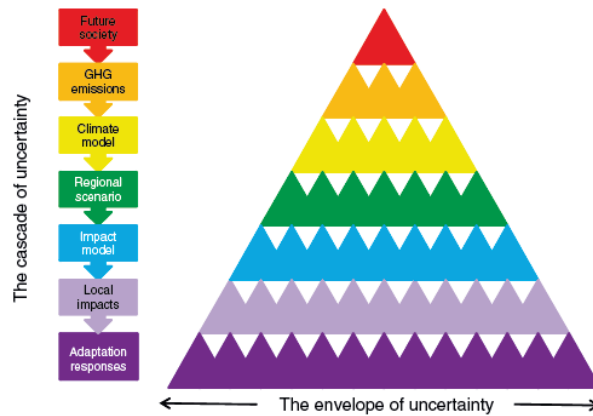


Figure 2 Climate risk assessment uncertainty development

A primary issue across many frameworks is the necessity for highly localized solutions to address diverse climatic and geographical conditions. This demand for specificity requires detailed, high-resolution data, which is often scarce or inconsistent, which is a challenge in developed and developing countries. Consequently, while these tools offer valuable guidance, their implementation is frequently hindered by data limitations and the varied conditions they must accommodate. Another significant challenge is integrating new vulnerability assessments and adaptation strategies into existing management systems. This integration requires extensive coordination among various stakeholders, including government agencies, policymakers, and local communities. The complexity of this coordination often leads to fragmented and less effective implementation. Moreover, the availability of funding and resources remains a persistent barrier. Effective climate adaptation demands substantial investment, which is not always accessible, particularly in under-resourced areas. This financial constraint limits the ability to implement comprehensive and sustained adaptation measures. While looking up the existing literature to understand the correlations between these different areas, it showed that they are intricately related and connected as shown in Fig. 3 below.

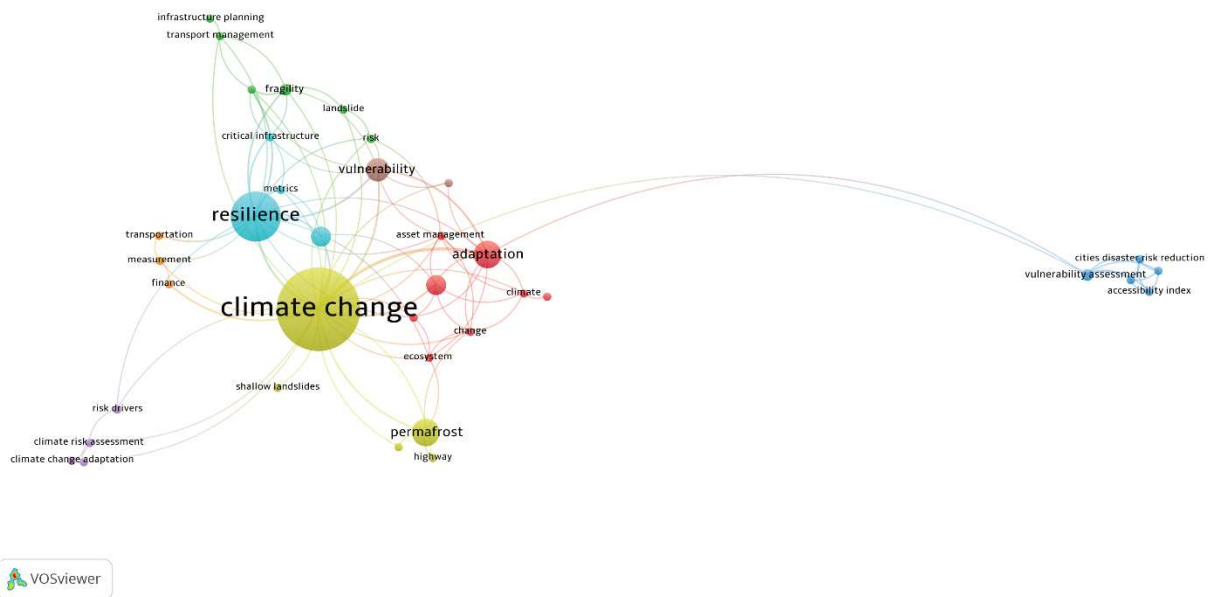


Figure 3 Bibliometric network of the studied field and data in this work

### 2.3. LAND MOVEMENT AND CLIMATE CHANGE

Land movement, driven by geological processes and exacerbated by climate change, poses critical challenges to transport infrastructure. Natural phenomena such as tectonic shifts, soil erosion, and permafrost thaw can destabilize roads, bridges, and railways, leading to increased maintenance costs and safety hazards. Climate change further complicates this issue by intensifying extreme weather events, such as heavy rainfall and flooding, which can accelerate erosion and trigger landslides. Research indicates that regions vulnerable to these geological shifts face heightened risks to their transport networks, which are essential for economic stability and community connectivity. For instance, studies show that the rising frequency of extreme weather events has led to a marked increase in infrastructure failures, necessitating urgent adaptation measures. Understanding the interplay between land movement and climate dynamics is crucial for developing resilient transport systems. This includes incorporating predictive modelling, engineering innovations, and sustainable planning practices that consider both current vulnerabilities and future climate scenarios.

Ensuring the reliability of transport networks in an era of rapid environmental change has been a challenge lately. The anticipated rise in the frequency and intensity of extreme weather events due to climate change is a concern addressed by [7] year after year. Hereby, the International Panel on Climate Change (IPCC) in its latest report has urged on shedding light on the rise in climate extremes leading to some irreversible impacts. This relates to the natural and human systems which are being pushed beyond their ability to adapt. The more acting on this issue, the fewer options will be available and the worse the climate impacts would be. In Europe, projections and models suggest that significant challenges related to climate change are on the horizon, including extreme heat, water shortages, forest fires, rising sea levels, storm surges, flooding, and landslides. In response, the European Union has developed an adaptation strategy designed to bolster preparedness and resilience. This strategy emphasizes enhanced coordination and information exchange among member countries while ensuring that climate adaptation is integrated into all pertinent EU policies. As recorded by [41], the climate change committee addressed that the current adaptation measures are not working and the need for change is urged. As

noticed in Fig. 4 [48], from the most imminent global risks lie failure of climate policies and extreme weather conditions contributing to a significant impact on the environment.

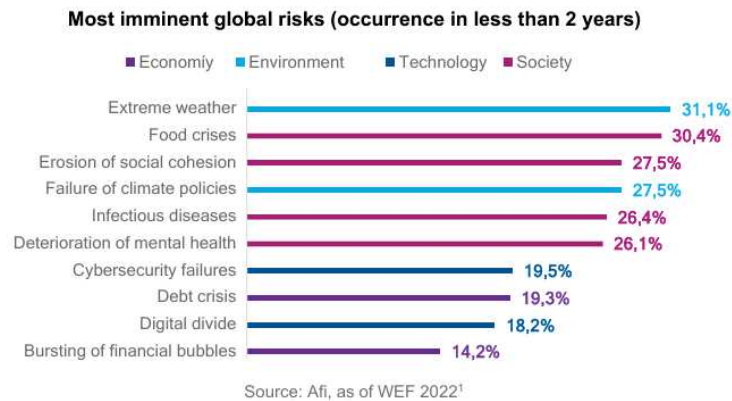


Figure 4 An outlook into the most prominent global risks in the current decade

Climate related extreme events have been a constant variation from 1980 till 2022 in Europe and are continuing year after year with the development of the climate change. As per records shown in Fig. 5 below, the climate-related extremes have not only held significant social and environmental impacts but also consumed a fine economic loss estimated around EUR 650 billion (2022 prices). Meteorological hazards (precipitation events) and mass movements solely contributed to around 29% of the total. This expenditure is subject to significant variation year after year especially in asset development of vulnerable areas with potential reporting biases over time[49]. Transport infrastructure hold a significant of being affected by their functionality and contribute to economic losses directly on asset functionality level or on economic use level for transport and trade.

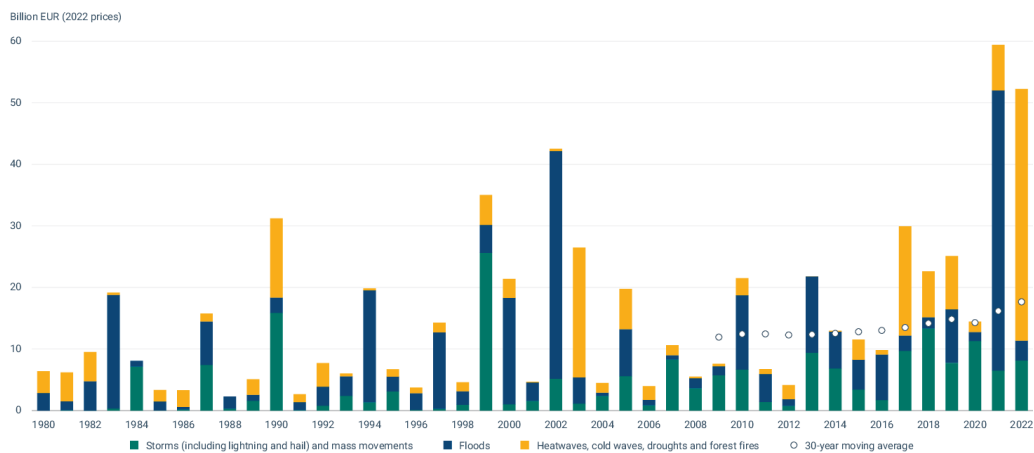


Figure 5 Climate Extremes losses Euro in Europe yearly

Looking on some numbers in Table 1 below and considering a sample of the countries affected by climate related extremes such as landslides and others, the visualization of the losses tends to be significant [49]. This emphasises on the need for intervention and solutions that can reduce the impacts of such situations.

Table 1 Comparison among countries on expenditure on climate related extremes

Country	Total losses (Million €)	Losses per sq.km €	Losses per capita €	Insured losses (Million €)	Insured losses (%)	Fatalities
Italy	111110	367817	1918	5081	5	21758
Germany	167299	467879	2065	50391	30	101334
Portugal	15042	163099	1470	535	4	10339
Norway	4965	12912	1073	3551	72	41
Spain	83782	165582	1977	3990	5	18954
Switzerland	18743	453957	2542	6690	36	2281

Considering different contexts, the 2022 edition of the "Global Risks" report by the World Economic Forum [48] and [50] identify extreme weather events as one of the most urgent and impactful risks. Highlight the efforts of public and private entities in Spain to mitigate the immediate effects of disasters through insurance, compensation, repairs, and reconstruction. These measures aim to enhance Spain's preparedness for minimizing the effects of natural disasters but still need effort to reduce the catastrophe costs shown in Fig. 6. Landslides, in particular, severely disrupt ground transport systems, causing prolonged downtimes and costly repairs and contribute to a significant portion of expense.

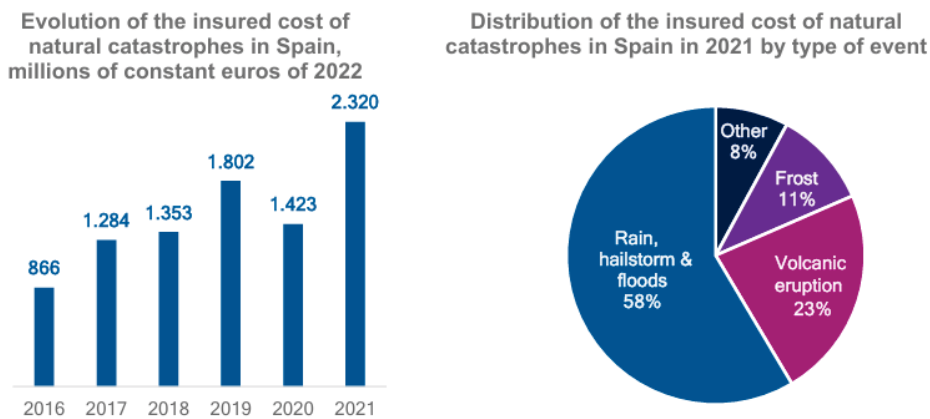


Figure 6 Specific Expenditure in Europe

The consequences of traffic disruptions are also significant, as demonstrated by the closure of the Rhine Valley railway from August 13 to October 2, 2017. This interruption, caused by mass movements at the Rastatt Tunnel construction site, led to substantial delays and increased costs, especially for freight transport. This vital north-south transport corridor typically accommodates up to 350 trains daily, connecting Italian ports with those in Rotterdam, Hamburg, Bremerhaven, and Basel to the container port in Duisburg. The closure at Rastatt caused severe congestion of freight trains along the route due to the lack of alternative transport lines, engines, and railroad engineers. Besides direct economic damage, indirect costs such as noise disturbance, air pollution from increased cargo train and heavy goods vehicle traffic on alternative routes, and longer travel times for commuters and travellers are also significant. According to the IPCC latest report and several studies, the future climate projections accompanied with broad environmental changes indicate the potential of increasing the occurrence of rapid disaster risks especially rainfall induced landslides [51], [7], [52]. Over the next few decades, it is anticipated that alterations in the frequency and intensity changes of precipitation patterns by the end of the twenty-first century will determine areas at risk of landslides. This will lead to significant influence

on the evolution of the land and resource degradation, societal dynamics, and economic factors within human communities as shown in Fig. 7 [7].

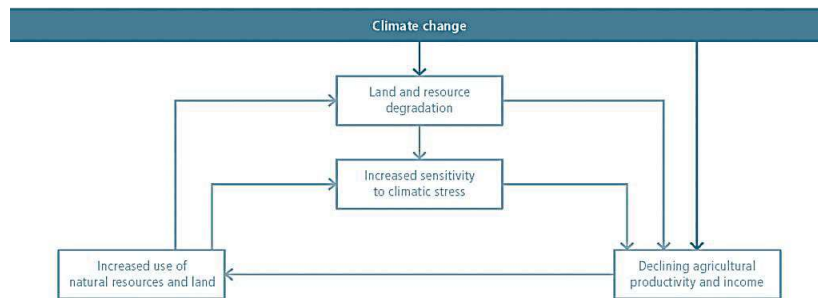


Figure 7 Schematic representation of links between climate change, land management and socio-economic conditions.

According to [53], areas susceptible to landslide occurrences include the Alpine, Pannonian, and Mediterranean regions. The effect of precipitation on the was analysed using CMIP5 global climate simulations and has shown that the region is prone to two main types of landslides: shallow and deep-seated landslides.

However, although climate change is exacerbating is influencing several disasters occurring globally, land degradation remains critical especially in predicting the future consequences and the land use changes determine with consideration of cc and without. To a very large extent, combining scenarios of climate change with land degradation models can help facilitate the knowledge on the strategies necessary to avoid, reduce and adapt to the future consequences. Landslides are often caused by several reasons as shown in Fig. 8 below:

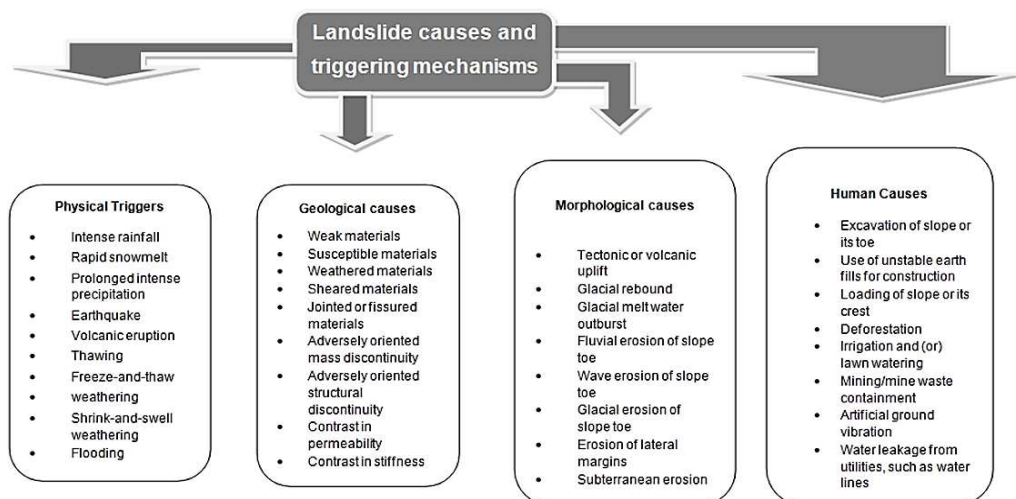


Figure 8 Possible causes of landslides [54]

To better understand the context of landslides and referring to the research definitions, [55], [56], [57] the major types shown in Fig. 9 below and includes:

- **Rotational avalanche:** Usually occurred on concave shaped slipping planes recognized through the surface morphology, shape of the deposit like a ladder visual. It often occurs in hilly areas and characterized by slowly to very quick mass movement.

- **Shallow translational/sub-translational landslide:** usually occurred on geomorphic erosive steep hillsides triggered by high-intensity and/ or persistent precipitation events and can cause deposits of volumes ranging from a few to hundred cubic meters. Shallow landslides are very common are known to speed up land deterioration with the high-speed soil erosion.
- **Avalanche flow:** usually considered of flow-type landslides with the most destructive behaviour. This is related to its rapid nature of movement and the water saturation combination causing mud and slope deposit consequences.

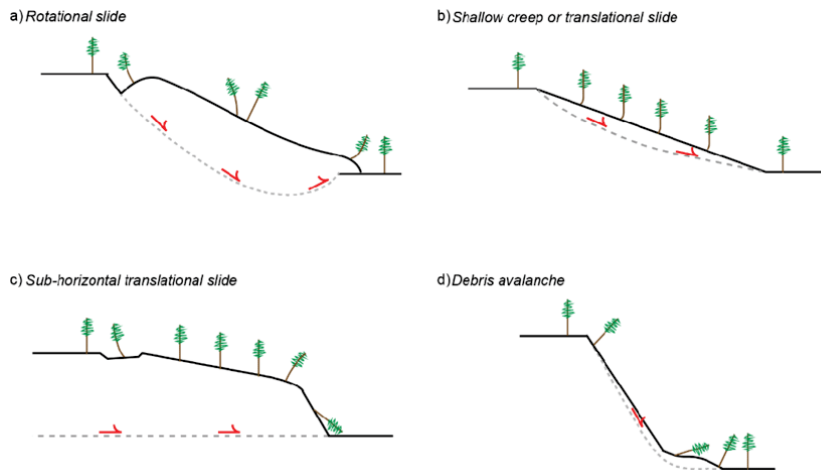


Figure 9 Landslide types and failure areas

Assessing future risks of climate-induced land degradation involves two main uncertainties. The first, with relatively lower uncertainty, includes changes in agents like precipitation erosivity, heat stress, and drought. The second, with higher uncertainty, concerns ecological changes due to shifting climate variables such as rainfall patterns, temperature, and CO<sub>2</sub> levels. Vegetation cover is essential for erosion control, and changes in rainfall patterns are likely to increase land degradation risks. Although there is theoretical support for increased landslide activity due to intensified rainfall, empirical evidence linking climate change to landslides is still limited, with human disturbance potentially being a more significant future trigger. Shallow landslides, common in grass-covered and steep areas, account for a significant portion of global landslide events and are particularly triggered by high-intensity or prolonged precipitation. Studies indicate that variations in landslide hazard trends are associated with different vulnerability factors.

Traditionally, dealing with landslides has been heavily dependent on data-driven predictive solutions. The basis was to assess geographically the potential of a landscape to have landslides another considering that the spatial characteristics remain constant over time or to approach early warning systems with probabilities of working varies across different locations and periods. Up to this day, there is a growing urgency to have reliable, accurate and feasible solutions for Early Warning Systems or solutions to mitigate the effects of landslides and help communities that are threatened with the possibility of harm to lives, cities and infrastructure. Some of these solutions are shown in Fig. 10 below. In any way, physically based and data-driven methods are primarily constrained to site-scale applications or huge databases demanding a significant amount of data requirements. Conversely, data-driven methods can be extended to regional and global scales using open-access datasets but on the local conventional basis, this information applied to critical infrastructure is deemed challenging to deal with.

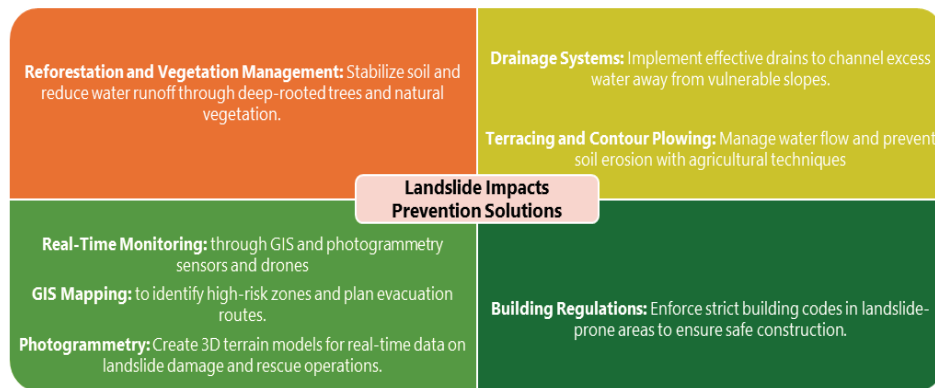


Figure 10 Landslide Impacts prevention solutions examples

According to [55], [57] the risk of landslides is an interrelation between the intensity and frequency of the precipitation events but also the quantity of people, assets, and infrastructure exposed to the consequences. Using the landslide risk index (LRI), it is possible to compare the danger, exposure, and physical vulnerability of buildings in different municipalities and to order them by each of the landslide risk factors. These three risk dimensions are conceptualized as follows: three key landslide risk drivers, each standardized between 0 and 1 (very high). Disaster risk reduction is a systematic practical approach to identify or recognize, assess and reduce the risks posed by disaster events. The goal is to reduce socioeconomic vulnerabilities to disasters and deal with environmental and other hazards that cause vulnerability.

## 2.4. DECISION MAKING

Climate change, economic fluctuations, rapid urbanization are from the risks currently present a lot in the built environment. Assessing how infrastructure projects address climate resilience, sustainability, and equitable development focuses on how infrastructure designs and operations minimize carbon footprints, integrate renewable energy sources, and adapt to changing climate conditions and impact communities, including their accessibility, safety, and benefits.

Governance involves ensuring that infrastructure projects adhere to transparent practices, regulatory compliance, and ethical standards, with robust oversight and stakeholder engagement and guide the creation of infrastructure that is both resilient to climate impacts. While risk assessments and targeted mitigation measures remain crucial, the inevitability of emerging pressures and unforeseeable events needs a broader perspective[58]. Questions arise when encompassing our current practices and potential avenues for action. There is a lack of agreement on the optimal practices or guidance for integrating resilience assessments into the transportation planning process, particularly in the areas where these decisions are formulated. As project objectives take shape in the early stages, it is crucial for stakeholders to be adequately represented, and seamless communication within the entire team is essential to outline how the project will meet overall performance requirements, including design, operations, and maintenance goals [59], [60].

Assets, defined as items with significant service or financial value, are termed critical assets. Transport infrastructure is one of its significant examples. The distribution of responsibilities for managing these assets varies among countries, with some being overseen locally and others falling under national jurisdiction. Essential services like water and sanitation, solid waste management, and road maintenance are typically within the purview of local authorities. Critical assets, encompassing those with substantial service or financial worth, may entail differing management responsibilities across countries. While some critical assets are managed locally, others are overseen nationally. Generally, local authorities are tasked with overseeing essential services such as water and sanitation, solid waste management, and road maintenance [61]. In preparing for the future, it is important that an inherent mechanism is developed

to evaluate whether their developmental trajectories will enhance or undermine resilience, a particularly pertinent concern for rapidly growing cities in developing nations. This emphasis is essential to prevent significant losses in terms of both life and property resulting from climate-related risks [28][58].

To foster resilience, stakeholders such as governments, donors, investors, policy makers, and the private sector must comprehend the factors contributing positively or negatively to resilience at a context and national scale understanding the interactions of the different components amidst a disaster. Identifying strategic areas for action and investment becomes paramount. This underscores the immediate necessity for governments, businesses, and communities to gain a deeper understanding of how susceptible their assets are to distinct types of extreme weather and to develop more effective plans in response [38],[58] [20]. Additionally, understanding the dynamic networks of control and influence that extend beyond administrative boundaries is essential for informed decision-making and the ability to take effective, appropriate action [58][4]. A significant factor contributing to the insufficient scale and intensity of investment in climate adaptation is the lack of a comprehensive understanding coordination and leadership among government departments, private investors, and the public regarding the benefits of adaptation actions nor the need for preserving resilience.

Consequently, there is a lack of motivation to increase investment in this area [62]. Barriers impede the sharing of best practices or institutional insights, hindering communication and collaboration between different infrastructure sectors. This limitation undermines the overall efficiency of the infrastructure system, making it challenging to identify and leverage synergies. In certain instances, it can even escalate the costs associated with constructing, maintaining, and decommissioning infrastructure assets [1].

The impact of CC is compelling national and local administrations to reassess their operational methods, encompassing the planning, design, construction, and maintenance of infrastructure. Additionally, climate change alters service delivery, affecting the quality of services rendered and the associated costs and risks. Transportation systems, buildings, water management systems, marine infrastructure, and natural assets like parks and forests bear the brunt of these effects. Specifying the requirements for post-disaster event rehabilitation and allocating relevant resources ensures swift recovery and restoration following climate-related events. The rationale behind this lies in the fact that prioritizing disaster-resilient asset management facilitates efficient recovery, minimizing disruptions and enhancing the overall resilience of infrastructure systems[63], [64].

Delving into IPCC projections, boundary conditions, and the quantification of impacts establishes a foundation to start from. This opens doors for using the concept of the impact chain where it helps to present the reality of asset resilience and interdependency and thus forecast a dynamic nature where risks tend to be acting. Identifying the specific challenges and opportunities inherent in each case study can help stakeholders gain deeper insights into the intricate dynamics at play within diverse contexts [14], [27]. This nuanced understanding is crucial for devising effective strategies and interventions that are tailored to the unique circumstances of each scenario. Also, ensuring that the scenarios accurately reflect not only the local conditions but also the different stakeholder concerns help to confirm that the framework reflects diverse perspectives and priorities. This also underscores the importance of integrating Climate Change (CC) adaptation into various policies and funding instruments[15].

Given the enduring, extensive, and socially embedded nature of infrastructure, heightened participation of stakeholders and local end-users can trigger self-adjustment mechanisms in response to disruptive shocks, specifically through the implementation of adaptation policies aimed at effecting change and adjustment to new conditions. This initiative-taking involvement facilitates the minimization of service provision recovery time following adverse events, inherently contributing to an enhancement of overall resilience [65], [66] According to [31], there is a lack of sufficient understanding regarding the long-term effectiveness, economic costs, and potential trade-offs associated with various adaptation options. Additionally, the scarcity of research examining the intricate interactions between climate change,

urbanization patterns, and socio-environmental factors presents a notable gap in current knowledge. Furthermore, effective, and context-specific adaptation strategies are hindered by a lack of collaboration among stakeholders. According to [67], Eighty-one percent of respondents believe that a rating system dedicated to resilience is necessary. Many indicated that there is currently a moderate demand for such a certification system. Seventy-six percent of respondents think that current guidance on resilience design for the built environment falls short of their requirements, highlighting a widespread industry need for a deeper understanding of and better strategies for managing climate risks. Resilience was identified as a key factor driving investment decisions among all respondents.

Table 2 Analysing existing strategies towards climate change adaptation

Name	Description	Challenges Highlighted
<b>The Research for Community Access Partnership (ReCAP)</b>	Regional guidance on adaptation of rural access roads to climate change	<ul style="list-style-type: none"> <li>- Diverse rural settings with varying climatic conditions require localized solutions.</li> <li>- Limited funding and resources in rural areas can hinder implementation.</li> <li>- Ensuring community engagement and local knowledge integration.</li> </ul>
<b>FHWA Framework</b> [68]	Manual for transportation organizations to assess road infrastructure vulnerability to extreme weather and climate impacts	<ul style="list-style-type: none"> <li>- Accurately predicting the impacts of diverse climate scenarios.</li> <li>- Integrating new vulnerability assessments into existing management systems.</li> <li>- Coordinating across various agencies and stakeholders.</li> </ul>
<b>ROADAPT</b> [69]	Common method for risk analysis and management for roads considering climate change with practical application	<ul style="list-style-type: none"> <li>-Standardizing methods across different European regions with unique climates and infrastructure.</li> <li>- Translating risk assessments into actionable plans.</li> <li>- Ensuring continuous updates and relevance of risk data.</li> </ul>
<b>German Strategy for Strengthening Resilience to Disasters</b> [70]	Strategy to increase resilience of federal transport infrastructure against climate change and extreme weather	<ul style="list-style-type: none"> <li>- Implementing findings across diverse federal infrastructure.</li> <li>-Addressing the complexity of extreme weather events with varying impacts.</li> <li>-Balancing short-term costs with long-term resilience benefits.</li> </ul>
<b>Working Towards a resilient infrastructure in the Netherlands</b> [71]	Holistic approach for future climate conditions effect identification, risk assessment, and adaptation strategy development	<ul style="list-style-type: none"> <li>- Adapting findings to real-world applications across different infrastructure.</li> <li>- Managing public perception and gaining political support.</li> </ul>

<b>Plan for Resilience of Infrastructures to Climate Change (PRIAC), Portugal</b> [72]	Managing road and rail infrastructures to understand risks and assess climate change impacts	<ul style="list-style-type: none"> <li>- Coordinating efforts across multiple types of infrastructure.</li> <li>- Integrating varied datasets and methodologies for holistic assessment.</li> <li>- Coping with not having a significant historical register of occurrences in the telematics caused by climate events</li> </ul>
<b>European Union Adaptation Strategy</b> [13]	Strategy for a climate-resilient EU by 2050 with objectives for smarter, swifter, systemic adaptation and international action	<ul style="list-style-type: none"> <li>- Achieving coherence and commitment among member states with diverse priorities and capabilities.</li> <li>- Monitoring and enforcing compliance across the EU.</li> </ul>
<b>HTV Asia Applied Research Programme – State of Knowledge Report</b> [73]	Transport research to improve safety, affordability, and inclusivity in low-income countries	<ul style="list-style-type: none"> <li>- Addressing diverse transport needs with limited resources.</li> <li>- Ensuring research findings are actionable and tailored to local contexts.</li> <li>- Overcoming infrastructural and political barriers in low-income countries.</li> </ul>
<b>ADB 2011 “Guidelines for Climate Proofing Investment in the Transport Sector”</b> [74]	Methodological approach to incorporate climate change adaptation in transport sector projects	<ul style="list-style-type: none"> <li>- Ensuring guidelines are flexible enough to accommodate diverse projects.</li> <li>- Aligning project-level adaptation with broader policy and planning frameworks.</li> <li>- Securing stakeholder buy-in and consistent implementation.</li> </ul>
<b>FORESEE Project</b> [45]	Toolkit for improving road and rail asset management schemes for resilience to disruptive events	<ul style="list-style-type: none"> <li>- Adapting tools and guidelines for practical use by various authorities and operators.</li> <li>- Ensuring interoperability and compatibility with existing systems.</li> <li>- Maintaining up-to-date and comprehensive data for resilience planning.</li> </ul>
<b>LARIMIT</b> [55]	Development and implementation of smart monitoring technologies to enhance road infrastructure resilience against climate impacts	<ul style="list-style-type: none"> <li>- Integrating data from multiple sources into a cohesive monitoring system.</li> <li>- Overcoming technical and logistical barriers in deploying and maintaining new monitoring infrastructure.</li> </ul>

<b>D4 RUNOFF</b> [75]	A current project aims to create a novel framework for identifying, monitoring, and mitigating contaminants in stormwater using Nature-Based Solutions (NBS) and advanced technologies	-Poor characterization and monitoring of urban water pollutants -Limited data on pollution sources and impacts, which hinders the design and implementation of effective mitigation strategies
<b>ICARUS</b> [27]	ICARUS aims to provide a robust and adaptable framework for enhancing the climate resilience of road infrastructure across Europe.	-Adapting methods and strategies to diverse climatic and geographical conditions across different regions. -Integrating new resilience measures into existing road management and planning frameworks. -Securing continuous funding and stakeholder engagement for long-term resilience initiatives.

After analysing existing strategies towards climate change adaptation in Table 2 above, it is noticed that in tackling prevailing and emerging systemic vulnerabilities in infrastructure, a primary challenge lies in the absence of a comprehensive systems thinking approach [1]. While several frameworks have tried to make progress in easing the process of climate change implementation, many stakeholders and organizations still experience a noticeable gap between strategy definition and implementation. This is because of how the defined targets often remain theoretical inaccessible and siloed, hindering the scaled implementation. The significant challenge of adapting broad and varied climate resilience strategies to localized contexts with unique environmental, infrastructural, and socio-economic conditions. Each initiative, while well-intentioned, faces hurdles in practical implementation such as diverse climatic conditions, limited resources, and the need for continuous data updates. For example, some must develop localized solutions for different rural areas, while others struggle with integrating new vulnerability assessments into existing management systems. Additionally, several efforts must standardize methods across diverse regions and ensure the ongoing relevance of risk data. The gaps highlighted include the need for consistent stakeholder engagement, overcoming financial constraints, integrating new data seamlessly into current frameworks, and achieving coherent policies among diverse stakeholders. This highlights a critical difficulty in translating high-level strategies into actionable and sustainable local practices. This claims that with an approach starting with generic interpretations and definitions fully tailored to the organizations core business to leverage end-customer can simultaneously unlock positive systemic benefits [76] and develop further in the next stages. Optimistically, it can be better understood that a systemic transformation cannot be realised in isolation but only by building deep and meaningful industry coalitions.

The next major challenge will be to systematically transfer knowledge across the wider organization. It is important that each stakeholder must not only change behaviour but develop a clear attitude towards resilience and sustainability. To decide on choosing the right adaptation option, the needs should be compared to the steering mechanism used by in the Decision-Context. In most cases the cost benefit ratio is the decision maker, although not always positive yet is a still a policy-based steering mechanism facilitating investment [17]. One significant limitation is that adaptation valuation methods aim to capture intangible benefits that typically do not have a clear valuation which associates with significant

uncertainty diminishing the potential of inclusion in effective decision making [78]. The challenge remains on how to conceptualize the generation of the vulnerability and choose the proper indicators such that local planners and decision makers can realize the vulnerabilities to climate change threats [79]. Despite these weaknesses, there are opportunities to enhance resilience through autonomous risk mitigation behaviours and practical sustainability metrics. To effectively navigate these dynamics, it is crucial to find more practical ways to integrate climate change impact drivers into decision frameworks and quantify infrastructure preparedness comprehensively paving the way for resilient infrastructure development in the face of escalating climate challenges.

Examining sectors provides insight into the regions and industries that might need significant efforts to enhance the resilience of existing and planned critical infrastructures to future climate conditions. For example, considering the shortage of practical vulnerability assessment tools and techniques for infrastructure management, the use of methods like Problem Tree Analysis, and Participatory Rural Appraisal, Bayesian Networks, Multiple Criteria Analysis (MCA), Impact Matrix, Cost Benefit (CB) can be valid however a concern remains in how these different tools can be deemed suitable best when used in different stages of the assessment thus an integrated approach of the different tools could create a potential for a more effective assessment tool [47].

Analysing the literature done in this field, the combination of CBA and MCA is clearly a topic being looked and considered for its potential [80]. Several cases and frameworks proposed a variety of ways to integrate those two methods where it is also a well-defined approach in the state of practice [78]. Yet, although the CBA is favoured among several studies, the sum of all the costs and benefits shall be brought to the present value through Net present Value (NPV); by applying a certain discount rate, the opportunity cost in investing in a certain adaptation measure can be graded. However, this does not allocate the funds to other activities that could be more profitable thus resulting in long term operational difficulties and links to construction data costs and records that are not easily obtained. Most co-benefits are intangible with no standard no market price and is another main restriction to the use of such methods. While methods of quantification are present, most of the time they do not consider the full value of environmental and social services limiting the value to their attributes or functions. This also presents underestimating the benefits of an adaptation measure and yielding poor decision making. On the other hand, the selection of a suitable discount rate is another challenge for the NPV at varying time spans. In cases where a high the discount rate used is, a low NPV can be interpreted for a consequence happening in the future. For example, for investments returning positive benefits after in the distant future 30+ years, it will not be profitable according to the CBA and this hinders effective implementation of solutions and prevention of hazardous impacts on the infrastructure [81]. Addressing climate change adaptation is a complex interrelationship of different concerns and different fields of needs. Thus, there can be different ways to reach a justification of solutions, but the effectiveness is what varies and what is concerning.

## **2.5. RESILIENCE OF INFRASTRUCTURES**

Resilience is characterized as the community's capacity to endure an extreme event and promptly recover from it [82]. Resilience, encompassing both adaptation and robustness, plays a pivotal role in the functioning and influencing sustainability outcomes. It is commonly assessed within the time from the onset of a hazard event to the point at which recovery is finalized. In contrast, sustainability encompasses the entire lifespan of the asset, extending beyond the completion of recovery [83], [84]. Creating a connection between resilience, adaptation, evolution, and sustainability may initially appear straightforward. However, an examination of the extended historical narrative within archaeological records reveals a nuanced perspective. The long-term history of human-environment interactions illustrates instances where certain human responses and adaptive strategies, seemingly beneficial in enhancing short-term resilience or over a few generations, ultimately contributed to a substantial

erosion of resilience in the extended duration. This erosion, in turn, precipitated the collapse of both environmental and social systems [46].

A relevant example from Lebanon is the historical exploitation of cedar forests. Cedars have long been a symbol of Lebanon's natural heritage and cultural identity. However, over centuries of human activity, including logging for timber and clearing land for agriculture and urbanization, Lebanon's cedar forests faced significant depletion. While the exploitation of cedar trees may have provided short-term economic gains and met the immediate needs of societies, it led to long-term environmental degradation and loss of biodiversity. The decline of cedar forests resulted in soil erosion, habitat loss for various plant and animal species, and disruption of ecosystem services such as water regulation and carbon sequestration. Additionally, the loss of cedar forests diminished Lebanon's natural resilience to environmental challenges, including climate change, as these forests play a crucial role in mitigating climate impacts through their ability to store carbon and regulate local climate conditions. The response of these long-lived tree species inhabiting mountainous terrain to impending climate changes, particularly within a semi-arid region of the Middle East, remains an unresolved question. Multiple global climate models project a temperature increase of approximately 4 degrees Celsius and a precipitation decrease of about 20% by the close of the 21st century[85].

Another example is related to the Bay of Biscay, Spain with its rugged coastline and proximity to the Atlantic Ocean increasing its vulnerability to climate-related hazards such as storm surges, coastal erosion, and flooding. Historically, coastal communities have adapted to periodic storm events through various measures, including the construction of seawalls, breakwaters, and coastal defences which may have appeared beneficial in enhancing short-term resilience by protecting coastal communities and infrastructure from the immediate impacts of storms [86]. However, as climate change exacerbates the frequency and intensity of coastal storms, the effectiveness of traditional engineering solutions may diminish, leading to increased vulnerability of coastal communities and infrastructure. contributing to the erosion of resilience in several ways [2], [4], [87]. For example, seawalls and other hard coastal defences can disrupt natural coastal processes, such as sediment transport and beach dynamics, leading to accelerated erosion in adjacent areas and the loss of valuable coastal habitats. Additionally, reliance on engineering solutions alone created a false sense of security and discouraged consideration of more sustainable and adaptive approaches to coastal management. Short-term adaptive strategies may provide immediate protection and serve the needs at a certain time however it is crucial to consider that they can contribute to the erosion of resilience over the long term, especially in the face of changing environmental conditions[19], [47], [88], [89].

Climate resilient infrastructure encompasses infrastructure whose planning, design, building, and functioning are geared towards anticipating, getting ready for, and adjusting to changing climate circumstances. It can withstand and manage the repercussions of severe weather, recovering rapidly after a disaster to guarantee that climate adaptation remains an ongoing process throughout the entire lifespan of the infrastructure. This in return enhances the dependability of infrastructure services, prolongs the effective lifespan of infrastructure, and safeguards the envisioned utility of the infrastructure[28][32]. The importance of integrating CC considerations at the planning stage of infrastructure development is crucial. This involves incorporating resilient technologies and materials, as well as implementing climate-sensitive design and planning practices and the revision of building codes and regulations, as well as strategically planning evacuation routes to withstand projected climate impacts. Topography also emerges as a critical consideration for national road authorities, especially in the effective management of excess surface water runoff during flood events. Soil and geology take centre stage in areas prone to landslides and flood risks. Additionally, the accessibility of geographical locations, coupled with transportation links, becomes a crucial factor influenced by climatic variables, including extreme weather events and flooding. In essence, these considerations underscore the importance of a nuanced, location-specific approach to adapting to CC.

Amidst temperature fluctuations such as permafrost, which contribute to road instability through permafrost thawing, an initiative-taking strategy entails attentive monitoring to pinpoint potential problem areas, determine cause-and-effect relationships among the assets, co-assets and the source of damage imposed. Also, maintaining comprehensive construction and maintenance documentation tailored to diverse pavement compositions like bituminous, concrete, and semi-rigid surfaces, spanning the entire road network can be a meticulous approach to not only aid in early detection and mitigation of issues but also facilitate informed decision-making for long-term infrastructure resilience [90], [91], [92], [93]. The underlying principle behind this suggestion is that incorporating climate considerations early in the planning phase results in infrastructure better prepared to cope with extreme weather events, thereby decreasing vulnerability [43]. Amidst this period of considerable uncertainty, where decisions cannot rely on such unpredictable models, several authors agree that there is a critical need for more adaptable solutions to bolster the resilience of our infrastructure [38], [60], [94].

In the Table 3 below, a summary of the possible impacts on the infrastructure provides an insight about the different levels affected when a disruption of an asset occurs [43], [47], [74], [95], [96], [97], [98]. This disruption does not only affect the resilience of the infrastructure but also on the social, environmental and economic related aspects thus impacting the sustainability.

Table 3 Possible Examples of climate change consequences on linear infrastructures

<b>Linear Infrastructure</b>	<b>CC Impact</b>	<b>Consequences on Functionality</b>	<b>Consequences for Material</b>	<b>Consequences for Safety</b>
<b>Roads</b>	<b>Increased precipitation</b>	Disruption of traffic flow, road closures. Increased travel time, detours	Rutting, Cracking, Erosion, Settlement	Increased risk of accidents, hydroplaning.
	<b>Extreme temperatures</b>	Reduced road capacity, increased maintenance costs.	Rutting, Cracking	Uneven road surface, reduced friction.
	<b>Sea level rise</b>	Permanent road closures, loss of coastal connectivity.	Erosion, Settlement	Coastal flooding, road submersion.
<b>Railways</b>	<b>Heavy rainfall</b>	Train delays, service disruptions. Track closures, reduced train speeds.	Track misalignment, increased maintenance. Washouts	Increased risk of derailments.
	<b>Thawing permafrost</b>	Track misalignment, increased maintenance. Track deformation, speed restrictions.	Settlement	Uneven tracks, increased risk of derailments.
	<b>Storm surges</b>	Track damage, service disruptions.	Erosion, Settlement	Coastal flooding, track instability.
<b>Pipelines</b>	<b>Thawing permafrost</b>	Pipeline displacement, service interruptions.	Deformation, Rupture	Increased risk of leaks, spills.

	<b>Increased temperatures</b>	Increased inspection and maintenance, traffic rerouting.	Corrosion, Leakage	Pipeline exposure, risk of damage.
	<b>Extreme weather events</b>	Pipeline ruptures, hazardous material spills.	Damage, Breakage	Increased risk of accidents, explosions.
<b>Power Lines</b>	<b>High winds</b>	Power outages, traffic congestion.	Sagging, Collapse	Fallen power lines, electrocution risk.
	<b>Heavy snowfall</b>	Reduced clearance, risk of contact with vehicles.	Sagging, Collapse	Reduced visibility, icing on lines.
	<b>Lightning strikes</b>	Equipment failure, service interruptions.	Damage, Outages	Increased risk of electrical accidents.
<b>Waterways</b>	<b>Increased precipitation</b>	Navigation restrictions, increased dredging. Reduced channel depth, increased dredging costs.	Build-up, Navigation Hazards	Reduced visibility, increased risk of collisions.
	<b>Sea level rise</b>	Changes in waterway salinity, habitat loss. Port closures, disrupted maritime transportation.	Corrosion, Deterioration	Increased risk of vessel accidents.
	<b>Extreme weather events</b>	Navigation hazards, increased dredging. Increased risk of vessel collisions, navigation restrictions.	Erosion, Scouring	Increased risk of capsizing, accidents.

Moreover, many infrastructure systems are interconnected and reliant on one another. Consequently, the failure of one system can trigger a domino effect, potentially leading to the failure of others. For instance, flooding may overwhelm storm and sanitary drainage systems, contaminating local water sources and dispersing waste from landfill sites into streets, lakes, and rivers. This poses health risks to communities and threatens the natural environment [61].

In navigating the current landscape of climate change adaptation, the first step involves understanding our present position and methodologies. Questions arise, encompassing our current practices and potential avenues for action. Delving into IPCC projections, boundary conditions, and the quantification of impacts using Impact Chains establishes a foundation. The Resilience level and hazard classification, based on both damage and resilience, further guide the decision-making process. The procedure should be completed by monitoring Key Performance Indicators (KPIs) and identifying opportunities for adaptation options. The linkages with decision making ensures continuous improvement of infrastructure management approaches[27]. Infrastructure assets, whether to a greater or lesser extent, are interconnected and not independent entities. However, a fragmented methodology is prevalent within the sector. Although there is a clear understanding of vulnerabilities and risk management

strategies for individual assets, the appreciation and comprehension of system resilience and the interconnectedness among infrastructure assets are less pronounced. Neglecting to account for climate change during the design or renovation of assets diminishes their anticipated lifespan from the outset [32].

## 2.6. IMPACT CHAIN

Resilience in the context of CC, as expressed by the Intergovernmental Panel on Climate Change (IPCC), refers to the capability of systems to absorb and rebound from disturbances induced by climate variations while maintaining functionality. This encompasses the capacity to withstand sudden shocks, such as extreme weather events, as well as the flexibility to adjust to longer-term shifts in climate patterns. Not only but also resilience extends beyond physical infrastructure, encompassing social, economic, and institutional dimensions. This emphasizes the importance of proactive measures aimed at reducing the infrastructure vulnerability to CC impacts, enhancing its adaptability, and fostering sustainable development throughout its response [7], [39], [99], [100]. According to [99], vulnerability and restoration analyses indicate that Transport infrastructures are the most sensitive to operational disruptions especially those associated with the largest restoration areas, due to the extended time required for repairs and prolonged loss of transport route functionality. Consequently, this results in indirect losses that are significant for example in the case of bridges and assets with longer detour lengths highlighting the socio-economic impact of these indirect losses. It was observed that the speed of restoring functionality strongly depends on the likelihood of significant damage and the bridge's proximity to conflict areas, reflecting the increase in resilience during restoration efforts.

In navigating the current landscape of climate change adaptation, the first step involves understanding our present position and methodologies. After analysing existing literature in Fig. 11, the conflicts in the landscape of decision-making in infrastructure development and climate resilience reveals a complex interplay of challenges in quantifying collective benefits, and a significant lack of stakeholder engagement. These factors hinder swift interventions despite escalating climate change projections. Furthermore, existing infrastructure shows inflexibility against dynamic land use patterns, exacerbating exposure risks. Uncertainties in scientific data further complicate decision-making processes, exacerbated by a lack of standardized data and inefficient operational integration strategies [11], [62], [78], [100], [101], [102].

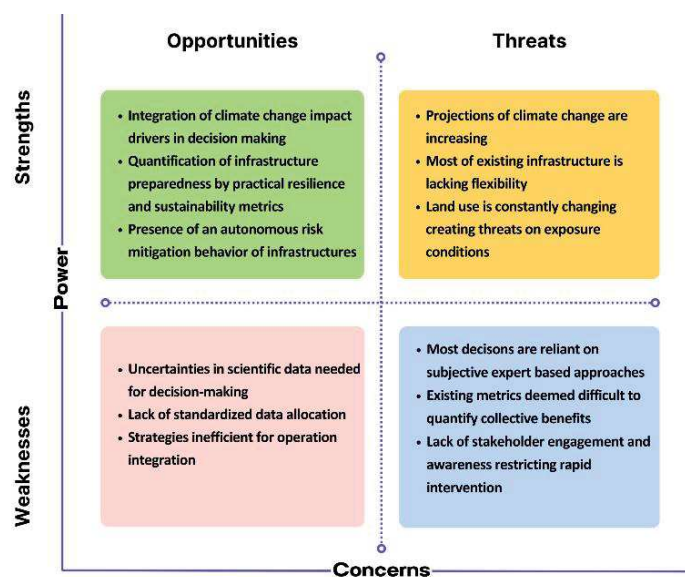


Figure 11 Analysis of current situation in climate resilience infrastructure adaptation

The analytical framework of impact chains (ICs) stands as a sophisticated tool, meticulously designed to enhance our understanding, organization, and prioritization of factors influencing climate-related risks within specific systems. It serves as a fundamental pillar for conducting operational climate risk assessments, offering a structured approach to unravelling intricate interrelationships. Initially conceived by EURAC Research for probing climate vulnerability in the Alps, this concept underwent rigorous refinement during Germany's national climate vulnerability assessment. Further adaptation took place within the GIZ Vulnerability Sourcebook, focusing on climate vulnerability assessment in international cooperation contexts [103]. Subsequently, the IC concept harmonized with the IPCC AR5's climate risk framework, garnering widespread endorsement for its application in climate risk assessments within the domain of Ecosystem-Based Adaptation. Over time, ICs have evolved into a widely adopted method for climate risk assessment, revered for their effectiveness in analysing and communicating the complex cause-and-effect relationships associated with climate change impacts and risks [5], [10], [104].

At its core, impact chains serve as a tailored conceptual model aimed at dissecting specific climate risks, delineating risk components based on the IPCC AR5 framework (hazard, exposure, vulnerability), and their respective underlying factors. The structure of an impact chain encapsulates primary cause-and-effect sequences, where a climate signal, such as a heavy rain event, initiates a cascade of intermediate impacts, such as upstream erosion contributing to downstream flooding. These intermediate impacts, when coupled with the vulnerability of exposed elements within the social-ecological system, ultimately converge to determine one or multiple risks. In the realm of operational risk assessment, impact chains serve as a pivotal foundation for selecting pertinent indicators and act as the structural backbone for aggregating indicators into composite risk indicators. Their utility lies not only in dissecting and understanding complex risk dynamics but also in guiding decision-making processes aimed at building resilience and adapting to the challenges posed by climate change.

The evolving understanding of impact chains within Intergovernmental Panel on Climate Change (IPCC) assessments constitutes a pivotal element in comprehending the intricate dynamics of climate change impacts. The latest framework of impact chains developed by the (IPCC) holds significant potential for enhancing the resilience of specific transport infrastructures, such as roads, railways, pipelines, and transmission lines. Through a systematic approach, this framework enables the identification of exposure and vulnerability points along transport infrastructures, facilitating targeted interventions to strengthen critical segments. Moreover, by tracing impact chains, as shown in Fig. 12 below allows for comprehensive assessments of climate hazards and associated risks can be conducted, informing informed decision-making processes regarding infrastructure design, maintenance, and management.

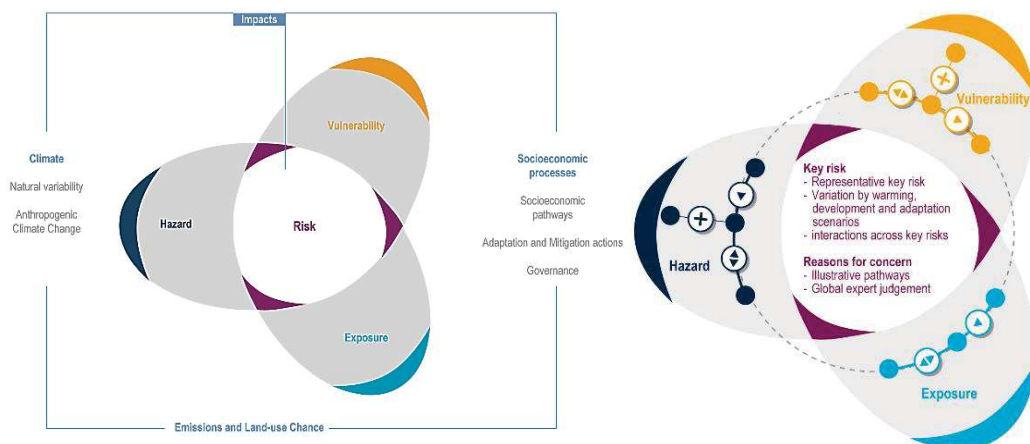


Figure 12 IPCC report 5 & 6 [105]

These impact chains delineate the sequential pathways through which climate change influences diverse systems, sectors, and regions, thereby enhancing the grasp of the underlying mechanisms driving such

impacts[27]. Furthermore, impact chains serve as a foundation for informed policy decisions, offering valuable insights into the potential consequences of different climate policies and mitigation efforts.

Incorporating the framework into infrastructure practices allows for the integration of climate resilience considerations from the outset, fostering adaptive management strategies that involve regular monitoring, updating of risk assessments, and adjustment of infrastructure management practices. However, it is important that this occurs from planning stage of infrastructure development through incorporating resilient technologies and materials, as well as implementing climate-sensitive design and planning practices and the revision of codes and regulations. While it is deemed very challenging to change the building codes and regulations instantly planning evacuation routes to withstand projected climate impacts such that the infrastructure better prepared to cope with extreme weather events, thereby decreasing vulnerability [43]. Amidst this period of considerable uncertainty, where decisions cannot rely on such unpredictable models, several authors agree that there is a critical need for more adaptable solutions to bolster the resilience of our infrastructure [38], [60], [94].

Examined individually, hazard quantification and vulnerability assessment do not offer a comprehensive depiction of risk. A realistic portrayal of risk necessitates integrating measures of hazard intensity with the vulnerability of assets affected by actions impacting their structure. According to several research studies, the perception of risk does not solely hinge on recognizing hazards or threats; instead, it encompasses the probability of an event occurring, the response it gives and the resulting consequences as shown in Fig. 13. Events are delineated in terms of probability or certainty through quantifying hazards specific to a location. To distinguish between assets most susceptible to damage and those less so, quantifying the vulnerability of assets becomes imperative, thus necessitating fragility functions[34], [64], [106]. Accordingly, the consideration of both the intensity of hazards at a site where assets are situated and the vulnerability of those assets to such events yields insights into the likelihood of specific damage occurring to the assets under consideration[28], [32], [34].

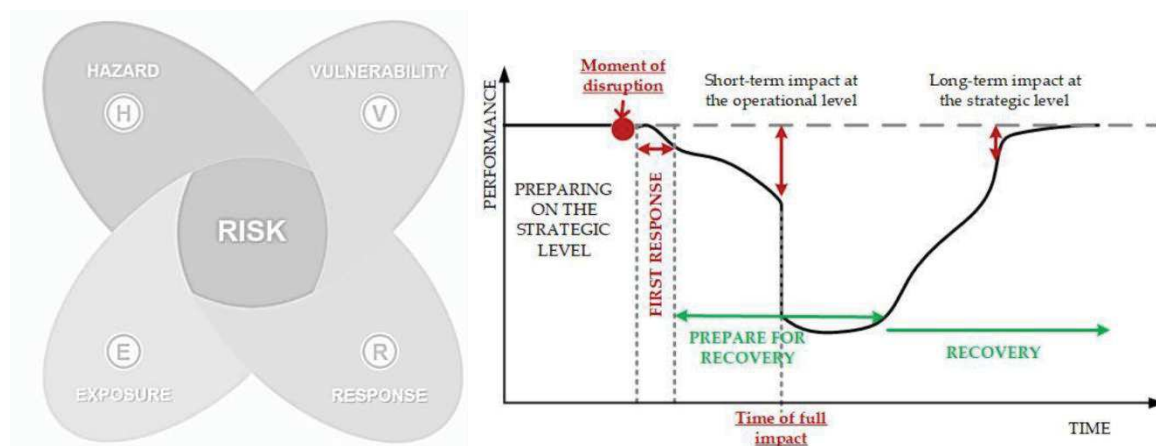


Figure 13 The phases of the disturbance occurrence[107]

The incorporation of impact chains into assessments also fosters cross-sectoral integration, enabling stakeholders to develop holistic responses that address the interconnected nature of climate change impacts across various domains. Ultimately, the elucidation of impact chains within IPCC assessments contributes to a more robust framework for understanding, managing, and responding to the multifaceted challenges posed by climate change. By integrating impact chains into assessments, scientists and policymakers can conduct more comprehensive evaluations of vulnerability and adaptation strategies, facilitating the targeted allocation of resources to mitigate risks and enhance resilience[5], [7], [10], [14], [104]. The evolution of IPCC impact chain framework represents a significant advancement in understanding and addressing the complexities of climate change impacts. Over time,

the IPCC has refined its approach to impact chains by incorporating advancements in scientific research, modelling techniques, and stakeholder engagement as shown in Table 4 [7].

Table 4 Improvements to the impact chain concept throughout history of IPCC Reports.

<b>ASSESSMENT REPORT</b>	<b>WEAKNESSES</b>	<b>IMPROVEMENTS</b>
<b>First Assessment Report (FAR) (1990)</b>	Lack of systematic framework for analysing impact chains, limited understanding of causal pathways due to qualitative assessments and insufficient consideration of socioeconomic factors	Introduction of more structured methodologies and data-driven approaches; enhanced understanding of climate drivers and availability of observational data
<b>Second Assessment Report (SAR) (1995)</b>	Relatively qualitative representation of impact chains, limited quantification of relationships and interactions between climate change and various systems, and challenges in integrating socioeconomic factors	Introduction of rigorous modelling techniques and scenario-based assessments to enhance quantification; improved computational capabilities and advancements in climate modelling
<b>Third Assessment Report (TAR) (2001)</b>	Insufficient consideration of feedback loops and non-linear interactions within impact chains, leading to an incomplete understanding of complexity, and limited integration of uncertainty analysis and cross-disciplinary approaches	Incorporation of advancements in systems thinking and complexity science to address feedback loops and non-linear dynamics; integration of uncertainty analysis and adoption of cross-disciplinary approaches
<b>Fourth Assessment Report (AR4) (2007)</b>	Challenges in integrating cross-sectoral interactions and addressing uncertainties, limiting the robustness of impact chain analyses, and insufficient consideration of adaptation strategies and cultural factors	Introduction of comprehensive vulnerability assessments and probabilistic approaches to uncertainty analysis; enhanced stakeholder engagement and refinement of modelling methodologies; improved consideration of adaptation strategies and recognition of cultural factors influencing vulnerability
<b>Fifth Assessment Report (AR5) (2014)</b>	Difficulty in effectively communicating the complexity of impact chains and their implications for decision-making, and limited integration of socioeconomic factors and improved scenario analysis techniques	Employment of enhanced visualization techniques and scenario-based storytelling to improve communication; integration of socioeconomic factors and improved scenario analysis techniques

<b>Sixth Assessment Report (AR6) (2021)</b>	Difficulties in integrating local and Indigenous knowledge into impact chain assessments, potentially overlooking important nuances and perspectives, and challenges in recognizing and addressing cultural factors influencing vulnerability	Prioritization of integration of local and Indigenous knowledge through participatory processes and co-production of knowledge; enhanced consideration of adaptation strategies and recognition of cultural factors influencing vulnerability
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It is vivid that the IPCC should target its efforts towards delivering more actionable and solution-oriented climate information steering its role towards providing enhanced guidance on implementation and monitoring. This includes offering recommendations for managing and mitigating climate-related risks and advice on integrating these strategies with mitigation efforts, disaster risk reduction, and the Sustainable Development Goals (SDGs). Although the IPCC is primarily focused on informing policy rather than directing it, there is a need for clearer delineation of responsibilities for implementing its insights, along with a better understanding of the potential benefits and risks for stakeholders such as industry, civil society, communities, and individuals [108], [109], [110], [111].

Yet, its improvement can be attributed to several key factors: Firstly, increased availability of data and improved computational capabilities have enabled more comprehensive and accurate assessments of climate change impacts, allowing for a more detailed delineation of impact pathways and their interactions. Secondly, advancements in interdisciplinary research have facilitated a more integrated understanding of the interconnectedness between climate drivers, socio-economic systems, and ecosystems, leading to a more nuanced representation of impact chains. Additionally, enhanced stakeholder engagement and collaboration have ensured that the impact chain framework reflects diverse perspectives and incorporates local knowledge, making it more relevant and applicable across different regions and sectors [5], [14], [27], [104]. Overall, the continual improvement of the IPCC impact chain framework underscores the organization's commitment to providing robust and actionable insights into the complex dynamics of climate change impacts, thereby enhancing global efforts to mitigate and adapt to climate change.

Furthermore, understanding impact chains provides opportunities to enhance connectivity and redundancy within infrastructure networks, thereby increasing system robustness in the face of climate-related disruptions. Engaging stakeholders and communities in resilience-building efforts is also facilitated by this framework, promoting collaborative approaches to addressing climate risks. In essence, the IPCC's latest framework of impact chains offers a structured methodology for identifying vulnerabilities, assessing risks, integrating resilience into infrastructure practices, implementing adaptive strategies, enhancing connectivity, and engaging stakeholders to enhance the resilience of specific transport infrastructures [28][43], [112],[94],[4],[7]. A more dynamic approach to risk assessment for transport infrastructure could be adopted, integrating real-time monitoring data, advanced modelling techniques, and scenario-based analysis to assess emerging risks and adaptively manage infrastructure resilience over time. Also, fostering cross-sectoral collaboration and coordination is paramount, emphasizing multi-sectoral partnerships and integrated planning approaches that consider the interdependencies between different infrastructure systems and incorporate climate resilience considerations into design, operation, and maintenance practices [28][43][83][113][83].

Various case studies within the realm of climate risk assessment and adaptation planning, which are paramount in addressing the multifaceted challenges posed by climate change. The authors of [14] which is related to the project (UNCHAIN) Unpacking Climate Impact Chains research case studies

investigate the suitability of Impact Chain-based Climate Risk and Vulnerability Assessments (CRVAs) in addressing transboundary climate risks and propose integrating macroeconomic models to account for potential future socioeconomic exposure[6]. Their research illustrates that the modular design of Impact Chain-based CRVAs facilitates the incorporation of diverse methodological enhancements shown in Table 5. They conclude that further improvements are feasible to evaluate intricate climate risks and enhance decision-making processes regarding adaptation strategies more effectively.

Table 5 Impact Chain challenges as addressed in (UNCHAIN)

<b>CASE STUDY NAME</b>	<b>CHALLENGE/OPPORTUNITY</b>	<b>INNOVATION AREA</b>
<b>The Mannheim #1</b> [114], [115]	Rebuilding Impact Chains from scratch results in redundant efforts and potential inconsistencies across various studies.	Elaborating the existing modules
<b>The Mannheim #2</b> [104]	The existing approach caters to policymaking and hasn't been utilized to identify risks and adaptation strategies for industrial stakeholders.	Improving the stakeholder interface
<b>The Salzburg Case</b> [5]	Impact Chains represent connections between drivers and risk impacts yet fail to acknowledge dynamic feedback.	Elaborating the existing modules
<b>The Paris Case</b> [116], [117]	The use of arithmetic aggregation may lead to the cancellation of risk indicators with varying values, potentially resulting in an underestimation of risk.	Elaborating the existing modules
<b>The Upper Rhine Case</b> [25]	Stakeholders hold diverse perspectives and "worldviews" regarding system functioning, which the current method doesn't accommodate.	Improving the stakeholder interface
<b>The Halmstad Case</b> [118], [119], [120], [121]	There's a lack of understanding regarding the social groups impacted by disruptions across essential societal functions and critical infrastructures, as well as the driving factors of vulnerability.	Improving the stakeholder interface
<b>The Balearic Islands Case</b> [122]	The current IC approach lacks a method to address uncertainties associated with selected indicators and their assigned weights.	Uncertainty management
<b>The Netherlands Case</b> [123]	The current methodology hasn't undergone testing to assess its compatibility with financial investment portfolios.	Improving the stakeholder interface
<b>The Germany/Transboundary Case</b> [14]	The existing method is tailored for evaluating domestic climate risks. However, for regions with high adaptive capacity and low exposure, transboundary climate risks	Modelling socio-economic scenarios

	can significantly contribute to overall climate risk.	
<b>The Germany Case</b> [14]	While Impact Chains depict relationships between risk drivers and impacts, they fail to account for future societal exposure and uncertainties.	Modelling socio-economic scenarios
<b>The Klepp Case</b> [124]	The current method is designed to evaluate on-site and local climate risks, whereas transboundary climate risks, typically assessed at the national level, are interconnected with these assessments.	Examining transboundary climate risks
<b>The Nordland Case</b> [14]	Although the current approach assesses on-site and local climate risks, industry risk is often influenced by transboundary climate risks, which aren't adequately addressed.	Examining transboundary climate risks

It is true to be noticed that systemic adaptation necessitates moving beyond technical and climatic factors to consider the varying adaptive capacities of regions and citizens to manage the impacts of climate change. However, there are gaps in effectively incorporating these considerations into adaptation strategies, which may result in inadequate responses to climate-related challenges. Nevertheless, there exist gaps in effectively engaging the different stakeholders, which may impede progress in adaptation initiatives.

Identifying the specific challenges and opportunities inherent in each case study can help stakeholders gain deeper insights into the intricate dynamics at play within diverse geographical and socio-economic contexts. This nuanced understanding is crucial for devising effective strategies and interventions that are tailored to the unique circumstances of each scenario. Also, accounting for transboundary climate risks is imperative to develop responses that comprehensively manage the full spectrum of climate risks facing society in a globalized world. Also, there are gaps in adequately addressing these transboundary risks, which may hinder the effectiveness of adaptation efforts. Failing to acknowledge the transboundary aspect of climate change results in underestimating the extent of risk exposure, overlooking relevant climate risks and vulnerable stakeholders, and failing to incentivize essential investments and cooperation in adaptation efforts noting that it is crucial to have collaborative, iterative process is essential to co-develop climate information and solutions, accelerating adaptation efforts.

Consequently, adopting a "reflect-then-act" approach becomes paramount, especially under uncertain conditions, as opposed to the conventional "predict-then-act" approach which may be limiting in action. On the other side, projects encounter distinct planning obstacles by managing underlying works among the different infrastructure assets [59]. When putting all these concerns together as in Fig. 14 if the development starts from improving the existing solutions, it is possible to work towards the bigger scope reaching not only local risks but also the transboundary risks. This improvement done to the impact chain can be a pathway to build on for addressing and effectively communicating uncertainties is crucial in this stage to ensure decision-making grounded in cutting-edge science and model outputs, yet there are gaps in recognizing and managing scientific limitations.

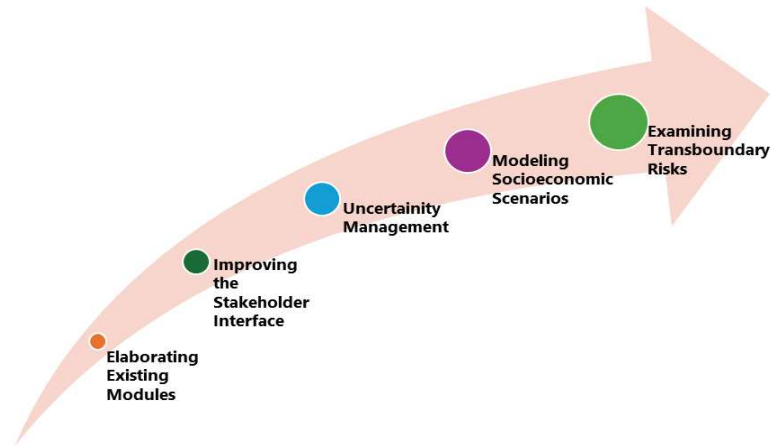


Figure 14 Route towards improving the existing impact chains

## 2.7. SUSTAINABILITY IN INFRASTRUCTURE

Sustainable infrastructure is comprised of constructed or natural systems that ensure economic, financial, social, environmental, and institutional sustainability, in accordance with the Sustainable Development Goals and throughout the entire infrastructure lifecycle from strategic planning to decommissioning and repurposing. This includes resources and services such as energy, water, transportation, communications, and flood protection. Investing in sustainable and high-quality infrastructure, facilitated by suitable delivery methods, and efficiently managed throughout its lifecycle, fosters socioeconomic development and reduces impacts on the environment [17], [66], [96], [102], [125]. The consideration of sustainability serves optimizing resource utilization, minimize environmental impacts, and enhance societal well-being while maintaining or improving technical performance and economic viability. The growing frequency of extreme weather events is exerting strain on worldwide infrastructure [28]. Thus, the utilization of sustainable practices in contemporary construction methods is evolving as the vision and future direction for the upcoming development of structures. As it has a vital role in enhancing life for the public, fostering resilience against extreme weather and recurring disasters, and ensuring sound economic development. Hence, the construction of infrastructure with capability of resisting impacts of CC is of utmost significance, as it can significantly mitigate the harm inflicted upon human society by climate disasters. Infrastructure systems are presently facing numerous challenges, ranging from the impacts of CC to growing population needs and economic constraints [43], [112].

Looking back to the business guide to sustainability shown in Fig. 15 below [67], there are several ways, tools, techniques and overall efforts have been put into action over the past decade to try to deliver efficient life cycle management. This entails the adoption of innovative design, construction, and operational practices that prioritize resilience, adaptability, and longevity. Every approach is important to ensure the effectiveness of infrastructure assets in the face of evolving challenges, including climate change, urbanization, and resource constraints.



Figure 15 Different Life Cycle Management Options

Yet, to go beyond the mere functionality of structures and systems; it is important to consider the broader implications of the design life and context on the environment, society, and future generations and put the mindset of understanding what is really hindering the use of all these valuable resources.

Life Cycle Assessment (LCA) for example conducted on transport infrastructures have revealed a deficiency in standardized methods concerning functional units, system limits, network impacts, and the potential for burden offsetting[113]. This challenge is exacerbated by the fact that current assessment approaches are predominantly product-oriented and do not adequately capture the life-cycle characteristics unique to infrastructure networks. In the context of recovery interventions following hazardous events like floods, landslides, earthquakes, etc., product based LCA may still be applicable, provided that the temporal focus is restricted to the commissioning of the restored asset [83][113]. Also, according to the authors ongoing research, there have been scarce publications offering a cohesive framework integrating sustainability and resilience, particularly in terms of correlation metrics at both asset and network levels and encompassing climate resilience for transportation assets [83].The examination of CC impacts on sustainability and resilience indexes reveals that different climate projections can adversely affect the effectiveness of optimal solutions. In all scenarios considered, prioritizing solutions that enhance sustainability and reduce greenhouse gas emissions proves to be the most advantageous approach when considering both resilience and cost.

Currently, the pressing need for resilient infrastructure and sustainable development is underscored by several critical challenges that intersect with the Sustainable Development Goals (SDGs). With the escalating impacts of climate change, as highlighted by SDG 13, Climate Action, infrastructure resilience has become increasingly urgent [12] [20], [58], [82], [96], [98]. Extreme weather events, such as floods, storms, and heatwaves, are intensifying, placing infrastructure systems at greater risk of damage and disruption. This necessitates a proactive approach to adapt existing infrastructure and build new infrastructure that can withstand and recover from these climate-related shocks and stresses. Furthermore, the rapid pace of urbanization, as emphasized by SDG 11, Sustainable Cities and Communities, presents challenges related to the development of inclusive, safe, and resilient urban environments. In many cities, inadequate infrastructure, particularly in marginalized communities, exacerbates vulnerabilities to climate change impacts and compromises the well-being of residents. However, challenges such as energy infrastructure gaps, technological barriers, and policy constraints hinder progress towards achieving universal access to affordable, reliable solutions. Sustainability

encapsulates the systematic integration of environmental, social, and economic considerations throughout the lifecycle of infrastructure projects and systems as shown in Fig. 16 below.

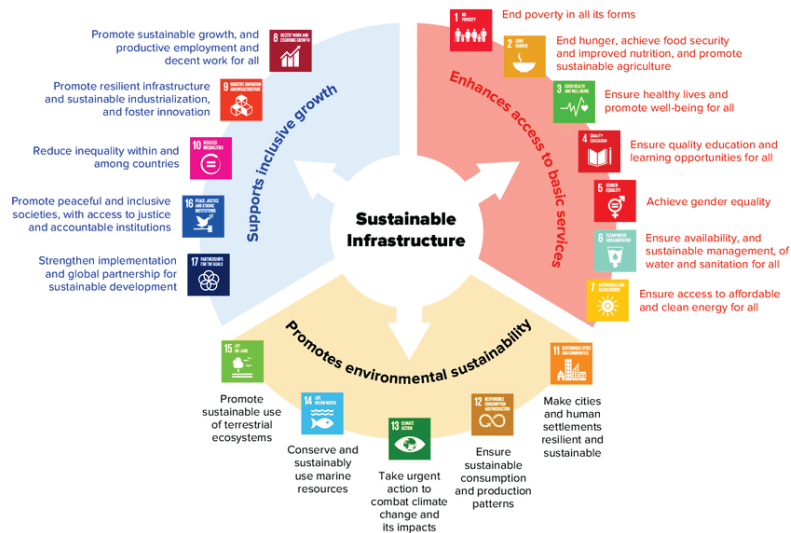


Figure 16 Sustainable Infrastructure interrelation with Sustainable Development Goals [126]

Multiple methodologies and frameworks are employed varying in planning, process, indications and scope of decisions [7]. However, the absence of standardized methods to measure these climate change impacts coupled with limited understanding of a project's societal and environmental effects often hinders the attainment of sustainability goals [67], [76], [127][59]. This is not unexpected due to the different expertise involved in attaining the sustainability goals from an infrastructure and often it is a challenge to understand whose responsibility is to take care of, how a certain issue is important and why should it be considered by stakeholders who do not acknowledge this importance to its ambiguity.

A concern urges the need to understand why most of the current methods primarily rely on qualitative techniques and index systems [32] while there is a need for complimentary validation methods to reduce the uncertainties following climate change. Yet those KPIs and their measurability shows that the subjective methods for decision making are still not sufficient and there is an increasing demand to look for evidenced-based decision making and interpret the real impacts. In this context, the choice of the KPIs becomes increasingly important [127][128].

Simultaneously, the individual assets or components conform to building codes with extended lifespans, meaning that various existing elements were not originally intended to withstand the continually rising external pressures [94][4]. Within the myriads of critical areas related to CC adaptation, strengthening the climate resilience of infrastructure stands out as particularly crucial [7][28][43]. In the past few years, there has been a notable increase in the importance of studying bridges, roads, and railways, with a strong emphasis on enhancing how safe, efficient, and sustainable transport infrastructures can be throughout their life cycle. This emphasis has led to the adoption of a variety of methodologies and technologies aimed at improving the planning and management of diverse types of transport projects. As a result, there has been a significant optimization of resources and time allocation, ultimately leading to improved outcomes and performance within the infrastructure sector [17], [59], [82], [102], [129].

The breakdown or interruption of a single critical infrastructure system when subject to different hazards including climate change induced ones may result in extensive repercussions. This impacts various sectors, locations, communities and occasionally, on a global scale [130]. Due to the considerable interconnectedness of infrastructures, promoting a cross-sectoral approach to strategies for CC

adaptation and resilience is strongly encouraged [15]. As the decision making is the key player in implementing effective strategies, the current policies should start focusing on the resilience of critical infrastructure which must contend with a variety of intricate shock events, increasingly interconnected systems, and the rapid advancements in infrastructure sectors [130]. Also, considering the aging nature of infrastructures further compounds the policy challenge, necessitating thoughtful consideration and strategic responses in solutions that compensate vulnerabilities with age. A structured methodology bringing together climate risk and vulnerability assessment can assist in identifying suitable actions for implementing adaptation measures. This connection can be illustrated in the impact chain, providing additional information on possible advantages for both climate change mitigation and urban planning, particularly when examining it from the perspective of NbS [29].

This discussion on transport infrastructure and its influence on urban environments is fundamentally linked to sustainability. Transport infrastructure plays a significant role in urban development, affecting all aspects of sustainability including environmental, social, and economic dimensions [17], [43], [66], [102], [131]. From an environmental perspective, the materials used in transport infrastructure construction and their impacts on urban temperatures contribute to climate change and urban heat island effects, highlighting the importance of sustainable construction practices and materials choices. Moreover, transport infrastructure's efficient design and management can reduce energy consumption and greenhouse gas emissions associated with transportation and utility services, contributing to environmental sustainability goals. Socially, well-planned transport infrastructure can enhance accessibility, connectivity, and equity within cities, promoting social sustainability by improving mobility and access to essential services for all residents. Additionally, economically sustainable transport infrastructure investments can lead to cost savings over the long term and support economic development [26], [45].

When it comes to creating long-lasting infrastructure and supporting the UN Sustainable Development Goals (SDGs), it's important to have a consistent method for evaluating sustainability at the project level and sharing sustainability information at the organizational level. However, there are significant challenges when it comes to integrating sustainability frameworks across both the organizational and project levels, due to several reasons however one of great concern is the synergy between infrastructure rating tools and the UN SDGs [102]. Considering that, an efficient and optimal recovery of Transport infrastructures post a hazard occurrence necessitates a preliminary evaluation of direct and indirect losses, as well as sustainability and resilience metrics. This thorough assessment is essential for effective planning, prioritization, and decision-making [99]. Based on the existing literature, it is true that this state of insufficient process for establishing qualitative connections presents an unprecedented obstacle towards decarbonization. Development that is rapid, inclusive, and considers climate factors, incorporating sustainable infrastructure, has the potential to avert most short-term effects. Concurrently, the prompt implementation of policies aimed at reducing emissions can effectively mitigate the long-term consequences of climate change [126]. This justifies that the lack of integrated approaches at a strategic, tactical, operation levels that combine UN-SDGs delivery with sustainability evaluation hinder the possibility for implementing and reporting at the organizational level and development of effective policies. Given these escalating challenges, a data-driven, empirical approach to environmental policymaking is more crucial than ever. Well-designed metrics enable policymakers and other stakeholders to monitor trends, pinpoint effective policy measures, exchange best practices, and optimize the return on environmental investments [39]. Assessing the sustainability of transport infrastructure remains challenging due to a lack of standardized evaluation methods, complicating the development of comprehensive analytical frameworks [111]. While social and environmental factors are typically considered during construction and operation phases, aspects like communication, collaboration, design objectives, and regulatory frameworks are highlighted as critical parameters. Despite the research efforts aimed at quantifying sustainable variables in transport projects still face

challenges in linking risk management, where trust and transparency are emphasized for conflict resolution, particularly regarding land acquisition, environmental impacts, and route selection.

Nevertheless, sustainability and resilience can either align, function independently, or come into direct competition as design targets [17]. Moreover, the development of better models to accurately capture the positive returns arising from reduced lifetime costs associated with sustainability such as enhanced resilience, decreased operational expenditures, and minimized carbon emissions can significantly enhance the attractiveness of such investments[126]. Given these considerations, the authors of this study agree that there is an imperative need for a framework integrating projecting how can both aspects be addressed in a simplified way such that the potential for further contributions can be put into action[102]. This framework will aid infrastructure managers in aligning their contributions to UN-SDGs targets and understanding the decision-making process in this complex area of implementation.

The growing frequency of extreme weather events is exerting strain on worldwide infrastructure [28]. Thus, the utilization of sustainable practices in contemporary construction methods is evolving as the vision and future direction for the upcoming development of structures. Sustainable infrastructure plays a vital role in enhancing life for the public, fostering resilience against extreme weather and recurring disasters, and ensuring sound economic development. Hence, the construction of infrastructure with capability of resisting impacts of CC is of utmost significance, as it can significantly mitigate the harm inflicted upon human society by climate disasters. Infrastructure systems are presently facing numerous challenges, ranging from the impacts of CC to growing population needs and economic constraints [43], [112]. Simultaneously, the individual assets or components conform to building codes with extended lifespans, meaning that many existing elements were not originally intended to withstand the continually rising external pressures [94][4]. Within the myriads of critical areas related to CC adaptation, strengthening the climate resilience of infrastructure stands out as particularly crucial [7][28][43].

Given that similar functions can be achieved through different configurations and structures, it becomes evident that transformative rather than conservative policies are necessary to embody resilience in response to changes [43]. This underscores the imperative of embracing resilience strategies that facilitate adaptations and transformations, thereby aligning with sustainability principles in developmental patterns. Also, it's crucial to recognize that adapting to climate change is an ongoing process, necessitating continuous monitoring, evaluation, and updates to strategies[34], [45], [55], [132]. Proactively addressing the impacts of CC on projects and mainly in maintenance programs to ensure that these systems are resilient and capable of meeting society's needs both in the present and the future.

## **2.8. NATURE-BASED SOLUTIONS**

Nature Based Solutions (NbS) have a potential understanding for being a solution capable of encompassing the use of nature itself to target the environmental, social, and economic challenges addressing sustainability [20][3], [19], [20], [21], [22], [133]. According to existing studies, empirical evidence highlights that the adoption of solutions that consider the aspects of sustainability through its materials, strategies, and practices, can result in a remarkable up to 50% enhancement in the infrastructure impacts on the context of its implementation[17]. This hereby encourages imperative investments in nature-based solutions. The reason behind that is that this integration of regenerative adaptation strategies within transport infrastructure is noted to have a pronounced difference in the way the infrastructure copes with the hazard induced impacts. NbS is therefore a way to address climate change impacts on Transport infrastructure while enhancing socio-economic benefits. Accordingly, the integration climate-resilient and nature-based design principles aids in adapting to the changing conditions while offering a range of benefits showcasing their position as a valuable approach to enhance the resilience and sustainability[19], [20], [21], [22]. Some of the potential obtained by nature-based solutions are shown in Table 6 below.

Table 6 List of NBS approaches and ecosystem services adopted from [134]

NBS Approach		NBS Challenge to be Solved/SDGs	
<ul style="list-style-type: none"> <li>• Climate adaptation approaches</li> <li>• Ecosystem based management</li> <li>• Ecosystem based disaster risk reduction</li> <li>• Ecological engineering</li> <li>• Ecological restoration</li> </ul>		<ul style="list-style-type: none"> <li>• Climate mitigation and adaptation</li> <li>• Water management</li> <li>• Participatory planning and governance</li> <li>• Public health and well-being</li> <li>• Potential of economic opportunities and green jobs</li> </ul>	
Ecosystem services provided			
Provisioning services		Regulation and Maintenance	
<ul style="list-style-type: none"> <li>• Raw (biotic) materials</li> <li>• Water for non-drinking purposes</li> </ul>		<ul style="list-style-type: none"> <li>• Carbon sequestration</li> <li>• Local climate regulation</li> <li>• Water purification</li> <li>• Erosion prevention</li> <li>• Flood protection</li> <li>• Maintaining populations and habitats</li> <li>• Soil formation and composition</li> </ul>	
Cultural			
<ul style="list-style-type: none"> <li>• Recreation</li> <li>• Aesthetic appreciation</li> <li>• Spiritual and symbolic appreciation</li> </ul>			

NbS represent a form of resilient infrastructure, offering multifaceted approaches. These solutions not only tackle diverse urban challenges, including those stemming from climate change, but also foster sustainable development [20]. The implementation of NbS has become increasingly significant as a comprehensive strategy to address CC for their capability to operate effectively in both facets of climate action, encompassing mitigation and adaptation. This dual impact helps minimize trade-offs and foster synergies [80], [135]. Consequently, NbS play a crucial role in the context of Climate Resilient Development. There is a growing body of evidence indicating that NbS can function as a supportive and effective alternative to grey infrastructure for achieving climate adaptation and enhancing resilience [80] [7], [21], [22] and emerges as a vital life support system, embodying a spatial approach to implement ecosystem services. This approach has earned increasing attention as an effective and synergistic solution for mitigating and adapting to CC [28].

Furthermore, nature-based solutions, such as green infrastructure and natural drainage systems shown in Fig. 17 below, offer promising avenues for enhancing transportation infrastructure resilience by mitigating climate change impacts, such as the urban heat island effect and flooding. The integration of these solutions serves to cool urban environments, reduce energy consumption, and fortify transportation infrastructure against the adverse effects of extreme weather events [3], [19], [20], [21], [22].



Figure 17 Nature Based Solutions tailored examples

Recognizing and comprehending the environmental and social context is vital to ensure the effectiveness and longevity of nature-based solutions. Prioritizing and highlighting key environmental functions and connections in the landscape enables us to optimize and bolster the implementation and preservation of these solutions. This approach fosters an understanding of the necessary conditions for successfully pursuing nature-based solutions[3], [21], [22], [136].The integration of NbS enhances not only the Urban context but also helps in developing long term infrastructure resilience contributing to an efficient sustainability manner as shown in the Fig 18 illustrated.

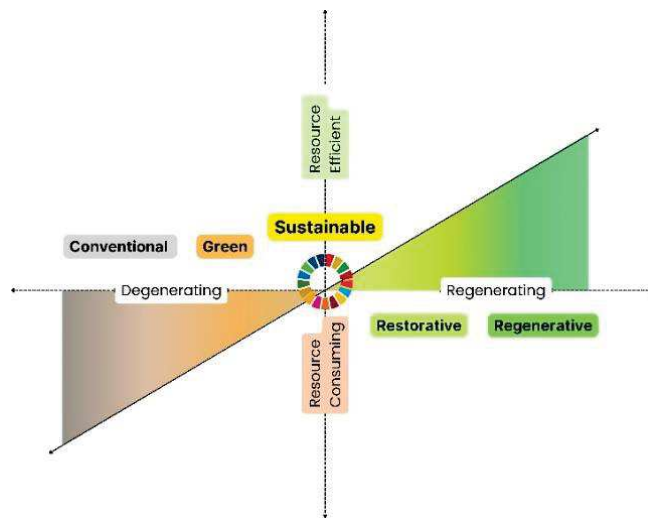


Figure 18 Different choice for adaptation solutions and their consequences

To advance infrastructure development with a focus on sustainability and resilience, it is essential to integrate nature-led design principles that emulate and enhance natural systems. This involves leveraging evolutionary design principles accumulated over billion years to create place-based strategies that respond to and work with site-specific features, fostering systemic health and planetary resilience. A systemic approach requires a deep understanding of material and resource flows to develop interconnected ecosystems, utilizing regenerative practices and circular infrastructure to maintain the continuity of resource cycles. Furthermore, equitable development mandates a shift towards a biosphere

economy that prioritizes planetary health and promotes social justice through fair distribution and inclusivity. This includes contextual stewardship, which involves co-creating with local communities and recognizing nature as an integral stakeholder. Yet, all this still is yet to be verified and ensured that the transition is working, solving the risks and not causing a negative impact and thus resource consumption to make up.

These approaches effectively tackle social and economic challenges while promoting social well-being and biodiversity benefits. The applicability of NBS extends across various spatial scales and settings within and around urban areas[20]. For instance, activities like wetland restoration or watercourse re-meandering can enhance the landscape's ability to retain water naturally. However, it's crucial to consider both environmental and social aspects of the landscape when designing such solutions. Without this information, there's a risk of failing to achieve the intended ecosystem services. In the worst-case scenario, poorly designed interventions may exacerbate the situation instead of improving it [46], [47], [104], [137] [138]. The depiction should encompass the distinctive biodiversity prevalent in the region alongside the ecosystem services it offers. Additionally, it should outline the current utilization of the area or terrain, detailing the stakeholders involved, their impact, reliance, and management oversight. It is crucial to grasp the area's inherent values encompassing its ecological significance, environmental roles, recreational amenities, and productive capacities, as well as its utilization patterns. Reference to ongoing initiatives such as plans aimed at conserving high nature-value areas, comprehensive master plans, land acquisition strategies, and management blueprints should be incorporated to provide direction in this regard[19], [20], [22][138]

Since up to the author's knowledge, no market price exists for these broader social and environmental benefits, specialized non-market valuation techniques, such as contingent valuation and benefit transfer, may be employed for their estimation[78]. This shows how can the utilization of a certain adaptation measure's capability to reduce the deterioration levels providing optimized sustainability and resilience performance as shown in Fig.19 below. Grey solutions or carbon-intensive restoration tasks following the hazard occurrence tend to have an underscored impactful influence on the overall carbon footprint of the asset limiting the decarbonization potentials which is urgently needed nowadays towards mitigating climate change effects[22]. Research indicates that transitioning to low-carbon infrastructure could elevate investment requirements by as little as 5%. However, the heightened initial capital expenses might be entirely compensated for by decreased operational costs, such as those stemming from diminished fuel consumption[126]. Nonetheless, it is important to emphasize that the resilience of the asset demonstrated minimal impact at lower hazard intensities, as it is predominantly contingent on task duration, which exhibits considerable overlap across most restoration scenarios. The lower intensity of the hazard because resilience mainly depends on the duration of the tasks, which overlap in most restoration scenarios[17]. This is prevalent in the 2024 EPI Framework where 58 indicators into 11 issue categories and three policy objectives, with weights shown at each level as a percentage of the total score. [39].

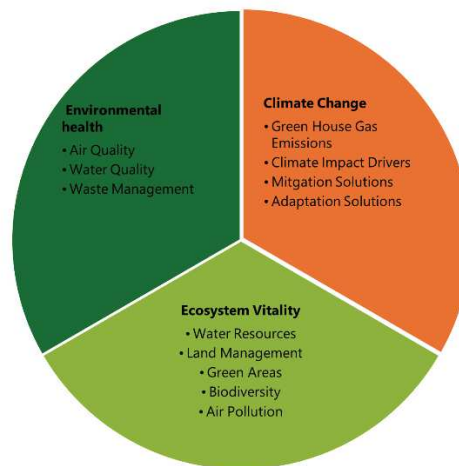


Figure 19 Nature Based Solutions Contributions

Notably, they were acknowledged in a COP 27 decisions for the first time. The decision underscores the importance of safeguarding, preserving, and restoring nature and ecosystems to meet the temperature goal outlined in the Paris Agreement [7][58]. This involves leveraging forests and other terrestrial and marine ecosystems as sinks and reservoirs of greenhouse gases, as well as protecting biodiversity. The decision also emphasizes the need for incorporating social and environmental safeguards in these efforts [1]. Considering predictions about CC that emphasize growing threats to cities and infrastructures, it is crucial to enhance the resilience of urban areas and ecosystems to better endure climate-related challenges. This transformation can be realized by embracing adaptation strategies rooted in urban ecosystems as the favoured model for urban planning and development. To optimize the effectiveness of ecosystems in bolstering resilience, the core of urban planning processes should prioritize the ecosystem approach. This approach should be guided by climate risk data, ecosystem evaluations, and participatory vulnerability analyses [22]. Yet, major barriers remain due to the lack of financial and personnel resources information and data related to the infrastructure and climate change scenarios, the organisational engagement. Also, a gap is identified in the lack of longer-term planning when considering climate change adaptation making it difficult to pave the way for adaptation contradicting the short-term decisions.

Spatial planning has a well-established tradition of creating engineered grey infrastructure solutions, such as impermeable protective embankments and culverted water courses for managing climate-related challenges like flooding or erosion. This means that these types of solutions are often documented, evaluated, and widely known and therefore often take precedence during planning. Nature-based solutions, in turn, are a new concept that often lack comprehensive, systematic evaluations of their effects on a larger scale. This lack of comprehensive evaluations means that nature-based solutions feature a higher degree of uncertainty and risk being opted out of when different solutions must be prioritised. Clarifying the multifunctionality and range of benefits a well-planned nature-based solution can offer can be critical for prioritising this type of solution over a grey solution[138].

According to a study made by [28], where 2429 publications have been analysed, 9 clusters of cited documents could be structured reflecting the development of knowledge in the field of climate resilient infrastructure as seen in Fig.20. The basis with the biggest clusters is the driver for constructing and

improving it with contribute to the improvement of the overall urban resilience and potential of having strong capacity to adjust to the CC impacts. To achieve that, adaptation and mitigation of the disaster impacts associated the relation of the urban ecosystem services and enhanced infrastructure facilitate reduction of impacts [3], [20], [21], [22].

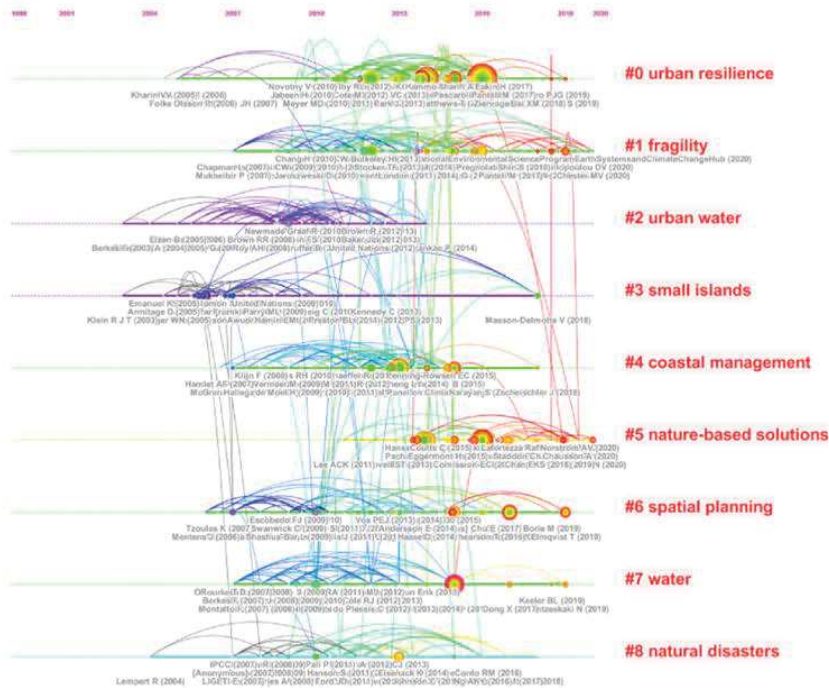


Figure 20 clustering of co-cited documents[28]

From the gaps existing according to [21] is having a comprehensive synthesis of existing studies to further examine the strength and assess the impact of NbS on biodiversity and ecosystem health metrics. This serves to enhance the understanding of their capacity to support biodiversity conservation goals. According to [31] there is a pressing need for more comprehensive studies focusing on urban resilience and the implementation of ecosystem-based approaches. Research on coping with the CC impacts has shifted from solely dealing with natural disasters and extreme weather conditions to analysing the intercity elements[19], [22], [56], [88]. Simultaneously, such a synthesis on ecological outcomes is essential to evaluate the long-term effectiveness and sustainability of NbS. It is crucial that NbS are designed in accordance with ecological principles to provide solutions resilient to future climate changes. The potential of NbS to support adaptive capacity in the long run can be compromised by a reduction in ecological resilience. For example, the rapid reduction of soil erosion and increased fodder for livestock achieved by using fast-growing, exotic vegetation may come at the cost of undermining ecological functions that sustain water flows, thereby reducing ecosystem stability and resilience [21][75]. Also, knowledge gaps exist regarding the design, implementation, and maintenance of Nature-Based Solutions (NBS), along with the quantification of their benefits and co-benefits, and the monitoring and assessment of their effectiveness. There is a notable lack of conclusive evidence supporting the efficacy of ecosystem-based approaches to address climate change[134]. To overcome the various challenges faced by NBS, several strategies can be applied: fostering targeted collaboration among stakeholders, encouraging strategic citizen involvement, providing information dissemination and advisory services for NBS implementation, promoting collaboration across different departments, and integrating NBS science into planning regulations. Also, in many countries, NbS alternatives are often overlooked due to the absence of policies that promote their development over traditional infrastructure options. Even when NbS are considered, insufficient legislative support presents a significant barrier to their implementation as discussed by[134]. Additionally, communication and social

obstacles emerge from the lack of a common language among stakeholders, who come from diverse backgrounds and possess varying levels of expertise. This multidisciplinary landscape complicates collaboration and hinders the effective advancement of NbS initiatives.

A similar consequence exists for designing and implementing NbS to alleviate coastal vulnerability to CC as it becomes more challenging in the absence of context-specific evidence. This difficulty is heightened by the strong influence of contextual elements, such as geomorphology, on the effectiveness of these solutions. Also, it has been acknowledged that forests in temperate regions have been the subject of most studies, with a notable scarcity of research on the effectiveness of nature-based interventions in grasslands, coastal ecosystems, and freshwater wetlands. This imbalance in the evidence base is evident in current NbS policies and commitments, which predominantly emphasize the role of nature, particularly afforestation and reforestation, in contributing to greenhouse gas (GHG) reduction objectives [9]. While interventions in forest ecosystems offer the potential to address various climate impacts, it is crucial not to divert attention from other ecosystems that play a vital role in providing adaptation and mitigation benefits in diverse regions worldwide. Efforts should be made to broaden the focus beyond forests and acknowledge the significance of various ecosystems in the overall effectiveness of nature-based strategies.

## PROPOSAL OF A NEW METHODOLOGY

### 3.1. GENERAL OVERVIEW

Integrating considerations of CC into decision-making processes and translating existing research into practical applications is a challenge for organizations handling, managing, and operating road infrastructure. Seeking to manage the disruptive effects of increasingly extreme weather hazards on current road infrastructure and developing an adaptation functionality, ultimately contributes to the establishment of safer, and more resilient infrastructure and opens the doors to contribute to improving the sustainability. The work aims to analyse the existing the adaptation guidelines and climate change frameworks and move towards a simplified practical toolset capable of assessing the resilience of transport infrastructure systems towards climate change hazards, selecting, and validating the appropriate sustainable and resilient adaptation measures in a simplified approach. The impact chain concept will be the basis of analysis, improvement, and development of adaptation strategies from the early stages through linking the climate data, vulnerability risks and assessment and adaptation/mitigation measures.

A part and major concern of planning lies in reflecting diverse perspectives, priorities possibilities and challenges in the decision making. This thereby leads to complications when moving from the strategic to the tactical level due to the complexity of understanding the various needs and concerns. Following that, the works highlights another major scope from the literature analysed, that is standardizing the way decisions are taken throughout this guideline such that a common language is present to develop and validate the possible options. This is according to common base key Performance indicators tailored specifically for paving a way for sustainability and resilience of transport infrastructure systems to be present in solutions that cope with consequences of different hazardous events improving resilience of infrastructure assets and combatting the various impacts of climate change (CC). On this motivation, the developed work shall target the following in Fig. 21.

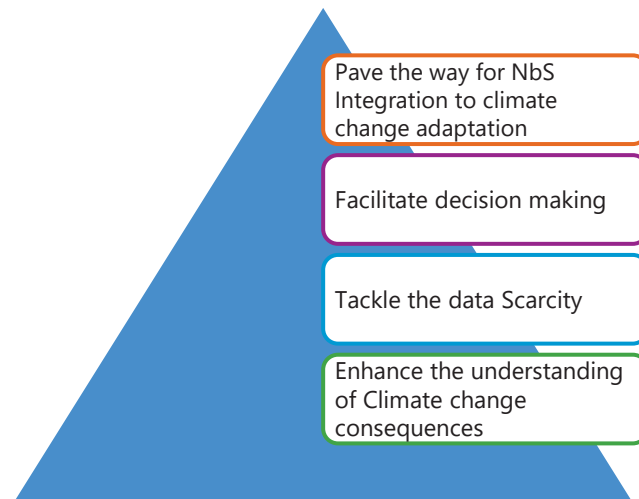


Figure 21 Scope of the Methodology

The methodology for addressing climate change disruptions on transport infrastructures is a meticulously structured process that seamlessly integrates strategic, tactical, and operational levels to build a resilient adaptation framework. It starts with the resolution to tackle climate change, setting a foundational policy and regulatory framework essential for all subsequent steps. This resolution must be translated into a comprehensive long-term strategic plan, incorporating extensive forecasting and scenario planning to anticipate future climate conditions. This stage is critical as it ensures a multi-disciplinary approach, integrating insights from climate science, engineering, and urban planning to prepare for a wide range of possible future scenarios.

Following this, the development of an impact context understanding is crucial. This involves sophisticated modelling and simulations that leverage big data and machine learning to predict how various climate variables, such as temperature increases, sea-level rise, and extreme weather events, might affect different infrastructure components. Establishing threshold development acceptance is the next pivotal step, which involves setting resilience benchmarks that infrastructures must meet to be deemed sustainable under future climate scenarios. These benchmarks need to be grounded in rigorous scientific research and stakeholder consensus, ensuring their credibility and practicality. Shifting to the tactical level, choosing key performance indicators (KPIs) is paramount. These KPIs must be carefully selected to measure infrastructure resilience under stress conditions, including metrics like structural integrity, service continuity, and recovery time. Ensuring these KPIs are directly correlated with specific climate impacts is validated through empirical studies and stakeholder engagement. This validation is essential to ensure that the chosen KPIs are robust indicators of resilience.

Next, defining criteria for decision-making involves establishing clear, evidence-based criteria to guide the selection and implementation of adaptation measures. This step requires a transparent decision-making framework that incorporates input from engineers, climate scientists, policymakers, and affected communities. Resource allocation must be strategically planned to support both the immediate implementation of adaptation measures and their long-term sustainability, encompassing financial resources, technical expertise, and institutional capacity.

A comprehensive resilience level assessment is then conducted to evaluate the current infrastructure resilience using the established KPIs. This involves rigorous inspections, stress tests, and resilience scoring to identify areas that need improvement. The findings from this assessment inform the development of mitigation solutions, which must be cost-effective, scalable, and context-specific, addressing the unique vulnerabilities identified. During the preliminary adaptation measure selection phase, a detailed vulnerability assessment is carried out to gain an in-depth understanding of

infrastructure weaknesses. This assessment includes both structural and non-structural aspects, providing a comprehensive picture of the vulnerabilities. The response assessment evaluates the effectiveness of different response strategies under various climate scenarios, ensuring flexibility and robustness. Following this, the specific risks to the structural function of the infrastructure are defined and quantified, leading to the development of an adaptation plan outlining the necessary adaptation measures and their implementation timelines.

In the detailed adaptation measure selection phase, the criteria for adaptation are translated into co-benefits, ensuring that the adaptation measures provide additional benefits such as improved public health, economic savings, and enhanced biodiversity. The formulation of a decision matrix guides the selection of adaptation measures, ensuring they are based on comprehensive decision analysis. This analysis involves evaluating different adaptation options and conducting sensitivity analyses to understand the implications of various decisions. Based on this analysis, adaptation solutions are identified and ranked according to their effectiveness, feasibility, and co-benefits.

These chosen adaptation measures are then validated through pilot testing, peer reviews, and iterative feedback to ensure their effectiveness and practicality. A detailed assessment of outcomes is conducted using the established KPIs, ensuring that the adaptation measures meet their intended objectives. Evaluation of outcomes provides insights into the effectiveness of the adaptation plan, informing future iterations of the adaptation process. This cyclical process of continuous adaptation ensures that infrastructure remains resilient in the face of changing climate conditions.

Optimized adaptation implementation involves the actual implementation of the chosen adaptation measures, requiring coordination among stakeholders, adequate funding, and monitoring mechanisms. Continuous monitoring of key metrics ensures the adaptation measures perform as expected, with ongoing engagement of relevant stakeholders to maintain alignment and address any challenges that arise. Regular reconsideration of the decision context ensures the adaptation measures remain relevant and effective, leading to a successful completion of the adaptation cycle. This integrated approach ensures that strategic goals are translated into actionable plans and effective operational measures, fostering a dynamic and resilient infrastructure system capable of withstanding the impacts of climate change. The full methodological structure and is then presented in Fig. 22.

### 3.2. METHODOLOGY FLOWCHART

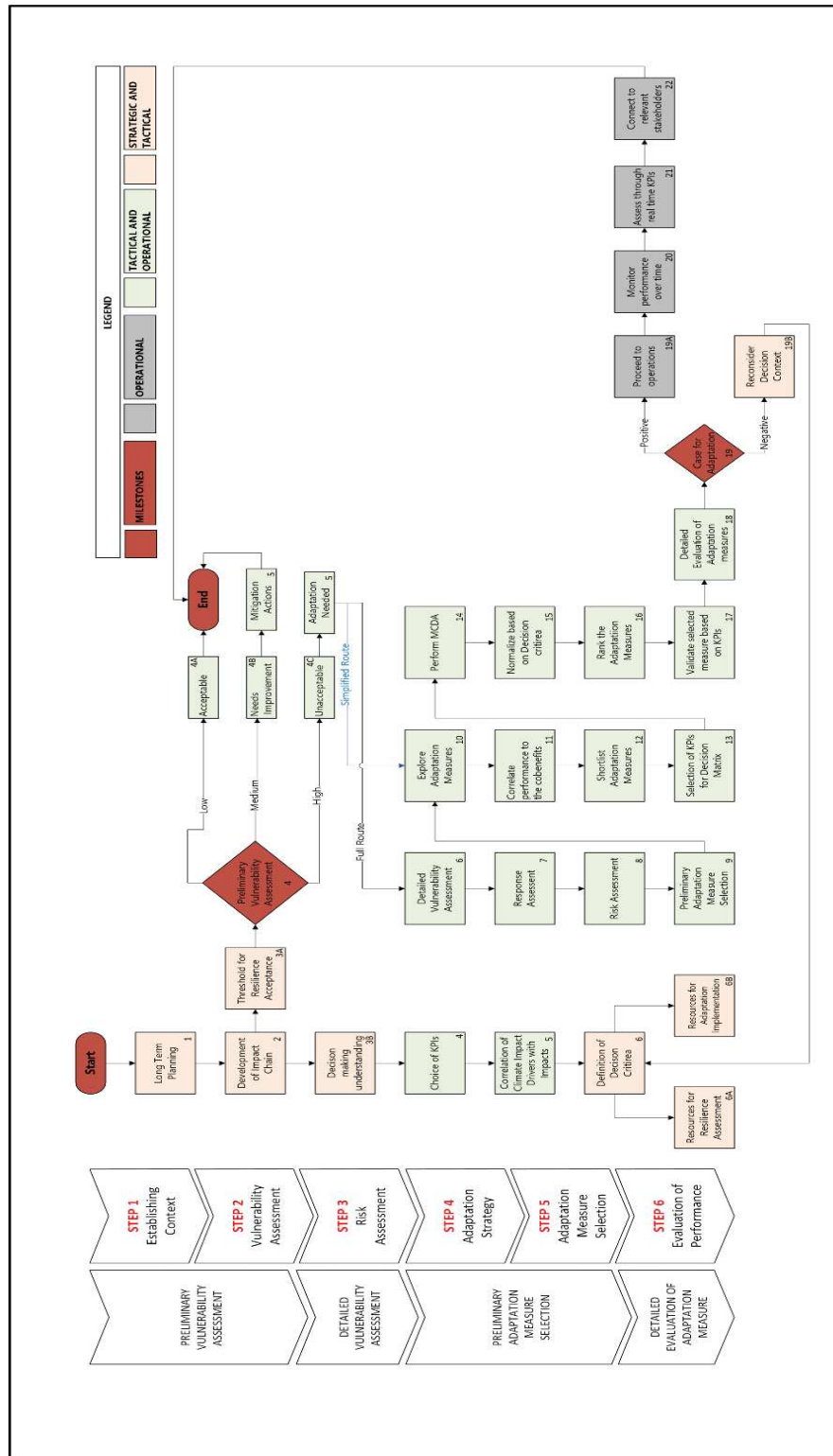


Figure 22 Methodological Flowchart

### 3.3. DECISION FRAMEWORK

- Starting from the exhaustive review of relevant literature and existing frameworks, a robust conceptual foundation can be established to draw improvements and fulfil the attainable gaps and updates towards the development of a comprehensive conceptual framework. Data collection and analysis represent critical stages in the methodology. Based on the data, the **realization of climate change** can be made. The initial phase of the methodology involved crafting a vision for the area, which served as the foundation for the project and helped local stakeholders reach a consensus while addressing various challenges that emerged during implementation. To formulate this vision, it was crucial to identify the environmental and ecological issues affecting the region, allowing for a comprehensive approach to address these challenges in a way that would enhance the area's value and resilience. Engaging local stakeholders and decision-makers was essential for turning this vision into reality.
- After establishing the vision, the next steps included securing funding and conducting baseline studies required for environmental assessment, as well as gathering the necessary data for designing alternative solutions. For example, in our specific case, a flood protection study entailed the following baseline assessments.
- To ease **decision context understanding**, the generation of **the impact chain** is implemented. When linking the different parameters of hazard, vulnerability and exposure conditions, the visualization of the context can be understood towards the impacts expected and the risks withheld. This process requires the integration of climate projections, land-use change scenarios, and socio-economic trends to generate realistic and context-specific scenarios and consider all possible risks resulting from affecting the infrastructure asset.
- The **data needed** include the characteristics of transport infrastructure systems, geological and geomorphological factors contributing to hazard susceptibility, historical disaster events, and the socio-economic context of the affected areas. The impact chain is then expanded to a **qualitative index spreadsheet** quantifying the levels of risks associated with its different interrelated components.
- According to the initial vulnerability assessment results from the impact chain, the basis is set for a **detailed resilience assessment**. With the use of the qualitative data subjected to thematic analysis and serving in the identification of the recurring themes and patterns, the plausible future scenarios are developed to simulate various hazardous events and assess their potential impacts on transport infrastructure systems. Accordingly, an analysis of the existing situation and condition can be made to validate if resilience enhancement is needed, then justify the need for adaptation options. In case of no data available, the qualitative assessment can also pave the way for tackling adaptation solutions.
- **Case of adaptation** is the final decision made where the measure is based on analysing the results and verifying through the validation criteria. This includes important aspects such as sustainability, reliability, scalability, and stakeholder acceptance. At this stage it is important to create standardized criteria decision making such that climatic events are tackled on all aspects in the chosen the key performance indicators. Unless that happens, the understanding of the climate change effects on the transport infrastructures will not be possible. Under this condition, the interpretation of the KPIs will underline a temporary resilience manner and an unnoticeable highlight of the performance change though adaptation Cobenefits.
- The **performance metrics through the KPIs** are crucial for analysing the climate adaptation solutions as they open the doors for translating the benefits and Co-Benefits into quantifiable metrics. These metrics results are then compared according to a minimum threshold set justifying

the need for climate adaptation solution to be implemented. If after the evaluation, the decision is deemed unacceptable, the criteria should be redefined, and the decision made is reconsidered.

A detailed explanation of the process is summed up in a structured procedure proposed here and composed on 2 main stages: Vulnerability Assessment and Adaptation Selection, each accompanied with a preliminary and detailed analysis as shown in Table 7 below.

Table 7 Methodology Description and Steps

<b>PRELIMINARY VULNERABILITY ASSESSMENT</b>	<b>DETAILED VULNERABILITY EVALUATION</b>	<b>PRELIMINARY ADAPTATION MEASURE SELECTION</b>	<b>DETAILED ADAPTATION MEASURE EVALUATION</b>
<ul style="list-style-type: none"> <li>➤ Impact chain flowchart</li> <li>➤ Impact chain spreadsheet</li> </ul>	<ul style="list-style-type: none"> <li>➤ Fragility curves</li> <li>➤ Vulnerability curves</li> </ul>	<ul style="list-style-type: none"> <li>➤ Multicriteria decision analysis (MCDA)</li> <li>➤ TOPSIS ranking</li> </ul>	<ul style="list-style-type: none"> <li>➤ Validation through KPIs</li> </ul>

While this is the detailed methodology, a simplified procedure can be taken as shown in Fig. 23. The importance is that the difference varies with the application stage and thus for decision making, the preliminary steps are key.

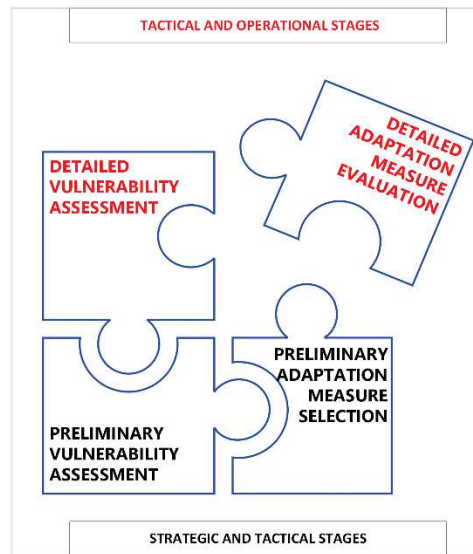


Figure 23 Full or Simplified methodology possibilities

Examined individually, hazard quantification and vulnerability assessment do not offer a comprehensive depiction of risk. A realistic portrayal of risk necessitates integrating measures of hazard intensity with the vulnerability of assets affected by actions impacting their structure. According to several research studies, the perception of risk does not solely hinge on recognizing hazards or threats; instead, it encompasses the probability of an event occurring and the resulting consequences. Events are delineated in terms of probability or certainty through quantifying hazards specific to a location. According to several studies, to be able to distinguish between assets most susceptible to damage and those less so, quantifying the vulnerability of assets in a detailed assessment becomes imperative, thus necessitating fragility calculations[34], [64], [106]. Yet, this process tends to be limited to data availability, resources for assessment, or complex simulations. With the variation in the vulnerability data parameters and their weighing criteria makes adds an extra challenge to develop a common vulnerability index

perspective [139]. Accordingly, the consideration of a way to put forward a correlation between the hazard intensities of hazards and the vulnerability in a simplified way can yields insights into the likelihood of specific damage occurring to the assets under consideration[28], [32], [34] and facilitate decision-making. Also, according to a study made by [28], where 2429 publications have been analysed reflecting the development of knowledge in the field of climate resilient infrastructure, the basis with the biggest clusters is the driver for construction of climate resilient infrastructure, improving it with contribute to the improvement of the overall urban resilience. To achieve that, adaptation and mitigation of the disaster impacts associated the relation of the urban context opens the potential of having strong capacity to adjust to the CC impacts. Also, to decrease vulnerability, the connection between cities and their natural surroundings must be re-evaluated [20].

Climate risk and vulnerability assessment aid in resource allocation and provide input for post-implementation follow-up. Various analysis and assessment methods are available, with selection dependent on project specifics. Documenting the assessment is crucial, irrespective of legal requirements, ensuring transparency and accessibility of the risk evaluation process for all stakeholders. This includes clear justification and reporting of methodology, underlying data, calculation parameters, assessments, and assumptions, allowing for transparency and comprehension by all involved parties. At the end of the cycle the process could be represented referring to the Fig. 24 [7].

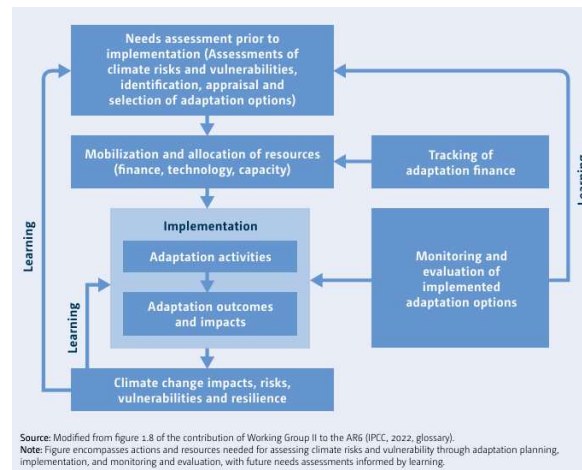


Figure 24 Assessing climate risks through adaptive planning

### 3.4. PRELIMINARY VULNERABILITY ASSESSMENT

The first stage is composed of a preliminary assessment of transport infrastructure studied, its context, possible correlation to climate change and visualization of the whole context using impact chain concept. It is aimed to address the definition of the project aim, issues, effects and thresholds considering the existing solutions, site requirements and settings and this is performed through developing the key components of the impact chain as shown in Fig. 25 below.

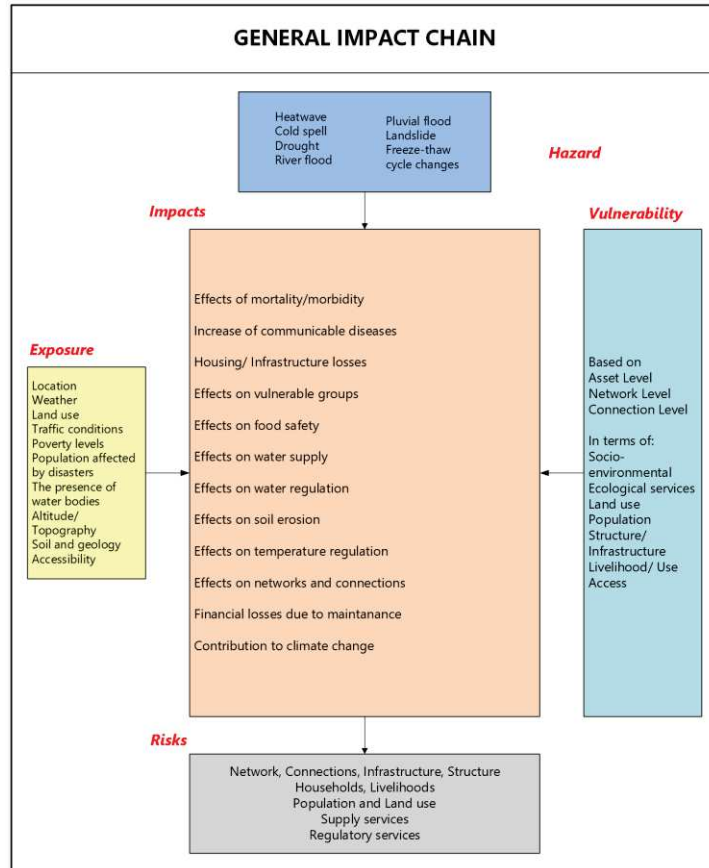


Figure 25 Component categories considered in the development of the impact chain

The phase one is preliminary vulnerability assessment or the screening. The stage gives an empirical estimate of current and expect resilience change imposed on the structure when correlated with climate change. The significance of this stage is that it deals with minimum data requirements and facilitates performance evaluation. The aim of this stage is to put forward the adaptive behaviour present and try to understand how the resilience can be improved and answer the performance questions as shown in Fig. 26.

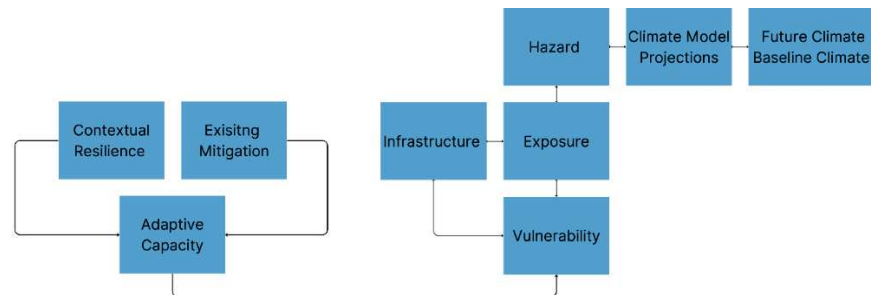


Figure 26 Preliminary Vulnerability Analysis

3.4.1. GROUND PREPARATION FOR CLIMATE ADAPTATION:

The concept of Climatic Impact-Drivers (CIDs) is introduced in the IPCC Sixth Assessment Report (AR6). CIDs refer to various physical conditions within the climate system, such as means, events, or extremes, that exert an influence on elements of society or ecosystems. CIDs tend to be very irreversible and variable through timescale. Key characteristics of (CIDs) include time of occurrence, composition and elements affected. According to the risk framework described in the IPCC (AR5), it was understood that

the hazard may exist at any given time  $t$  and therefore, the baseline also carried with it its own set of risks. The projected change uses the assumption of baseline hazard = 0. which is equivalent to assuming that there is zero risk [42]. Given the fact that this assumption was seen as unrealistic. Accordingly considering the contexts of interest, the following information is important to analyse:

The design and operation of transport infrastructure is complex by nature and is typically performed according to technical standards and standardized procedures which can be assimilated to the impact models and linked to the climate conditions and highway design and operation. To create a way for addressing the impact models in decision making, the integration of climatic data should be a part of the starting process as the proposed cycle in Fig. 27 can be followed:

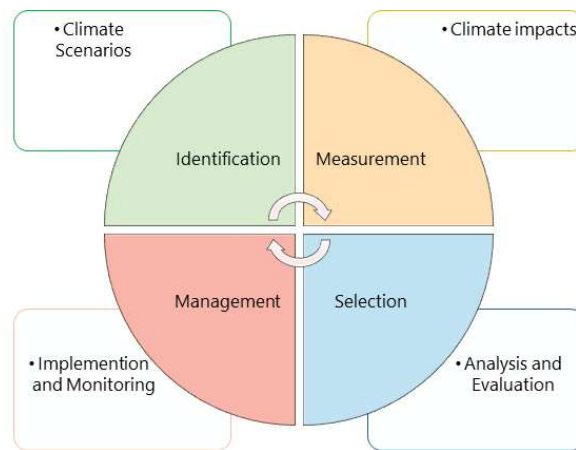


Figure 27 Climate change-based decision-making strategy briefing for adaptation measures implementation

Historical climate data is usually the type of data used for decision making; however recent studies propose to also consider climate projections to aid a more robust result. Unfortunately, due to the diverse, intricate, and context-dependent nature of CC, to the latest of the authors' knowledge there is no single approach to transform raw climate information into practical information addressing CC induced hazards [27]. The most common approach used for that at local level is the "top-down" or "science drive approach". This involves a combination of tasks that provide a consideration of different climate forcing or emission scenarios and generate an ensemble of global climate model (GCMs). This hereby combines regional climate models nested to the GCMs, statistically downscale and/or bias corrected and then facilitate climate change projections with hazard models [29]. The sources and type of climate data of interest for climate risk assessment is summarized in Table 8 [27].

Yet, despite these advantages, there are notable limitations. Accessibility remains a challenge for non-experts, as significant expertise is often required to fully utilize the resources. While user-friendly formats are provided, the reliance on complex data formats requiring special expertise can still pose barriers. The integration of diverse climate models and observations demands substantial effort and expertise, complicating comprehensive analysis. Addressing these issues is essential to enhance the usability and impact of these vital climate tools in transport infrastructure resilience[26].

Table 8 Services to obtain climate data of interest risk assessment.

NATIONAL CLIMATE SCENARIOS AND PORTALS	COPERNICUS CLIMATE CHANGE SERVICE	GLOBAL CLIMATE ATLAS
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<ul style="list-style-type: none"> <li>• CORDEX derived simulations (regional models) complemented with new simulations of high-resolution models (DMI, 2014) increased spatial resolution and bias correction through combining model outputs with local observations.</li> </ul>	<ul style="list-style-type: none"> <li>• A huge growing catalogue of climate data covering historic climate data and their projections (CMIP6, CORDEX, etc.), reanalysis, gridded observations, seasonal forecast, sectorial impact data (projections of river flow, sea level rise, wind energy potential, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>• IPCC AR6 WGI Interactive Atlas is highlighted for its inclusion of an important and updated catalogue of data (CMIP5, CMIP6, CORDEX, observations, reanalyse, etc.),</li> <li>• Combination of RCP/SSP and temporal horizons (e.g., Medium Term, 2041-2060) considering the SSP2-RCP4.5 pathways) are also included.</li> </ul>
<ul style="list-style-type: none"> <li>• Data is available in formats that usually are more accessible than the outcomes of the models (e.g., txt or csv vs netCDF or GRIB respectively)</li> </ul>	<ul style="list-style-type: none"> <li>• Climate projections (outcomes from climate models) data can be found. Yet, Limitation of access is present for non-trained personnel.</li> </ul>	<ul style="list-style-type: none"> <li>• Functionality access for non-expert users and possibility of consulting data using two types of scenarios: degrees above the preindustrial era (and other baselines)</li> </ul>
<ul style="list-style-type: none"> <li>• Not only, but also includes the integration of the time series for generating climate indexes, synthetic information, etc and facilitating atlas-based visualization.</li> </ul>	<ul style="list-style-type: none"> <li>• Provides impact data elaborated with different simulation chains such as river flow projections (C3Sb and C3Sc), soil erosion indicators (C3Sd),</li> <li>• Due to the increasing demand of risk evaluations under an uncertain climate, the data acquired can be deemed beneficial for probabilistic analysis of climate scenarios, damage functions, etc.</li> </ul>	<ul style="list-style-type: none"> <li>• The Interactive Atlas combines outputs from climate data with other sources to provide different information about risks focusing on providing a score, evaluation more than on the provision of quantitative values of the variables.</li> </ul>

Evaluating the climate risk of different components of road assets requires the consideration of a defined set of scenarios. To generate coherent results, it is interesting to define a time horizon that allows the evaluation along the life span of the infrastructure. This necessitates going beyond the RCP2.6 scenario rather to RCP8.5 scenario considering significant climate change projections. Understanding how to integrate climate data from GCM and RCM for example remains a concern. This is because most documentation of climate data is tailored specifically for the climate modelling experts and restricts access to those with limited knowledge on this field. An ideal workflow in the existing literature for climate data is proposed in Fig. 28 based on [26], [29], [140]

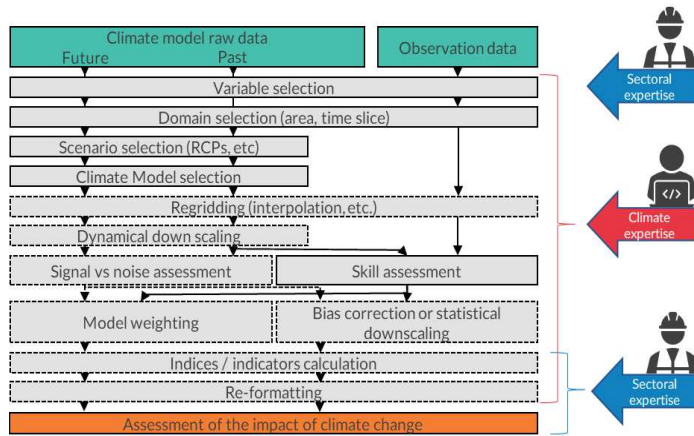


Figure 28 A workflow diagram for climate model data use

The significance of this workflow is in the way some actions can be made to pave the way for resolution generation coherent for the specific application/user and less bias in climate models outcomes. This then highlights the importance of using of observation data. Knowledge of what variables will drive impact and risk is required at the start of the process and, for the final calculations. The conclusion implies the connection of this data to impact models, expert judgment, qualitative risk assessment, design considering climate parameters, etc.) These steps also allow for transforming the outcomes of the climate models into actionable information for climate risk assessment. Variables such as temperature, precipitation, etc. can be applied to create a time series generated by climate models and facilitate creation of indices assess the impact of concern on the infrastructure. As an example, extreme temperatures can be evaluated for a 50-year return period and the maximum temperature. This then can be an index for thermal actions identification as shown in Fig. 29 below [27]:

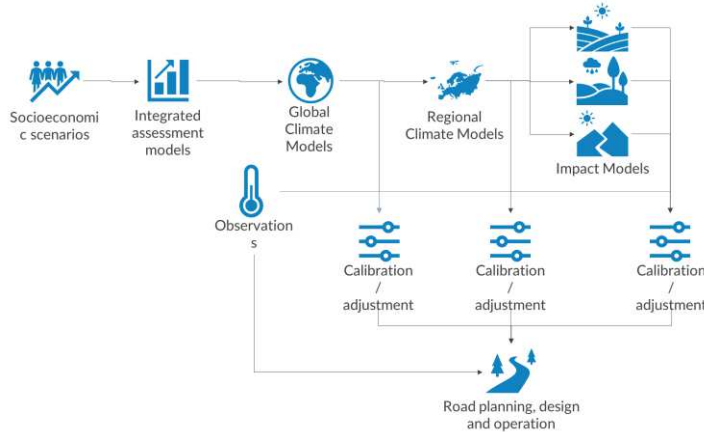


Figure 29 Climate data and their transformation into useful information for road adaptation and resilience

However, there still exist climate variables and processes that their simulation is not correctly addressed by global and regional climate models. Considering hydrological cycles for example, even though climate models perform a simplified simulation, the resolution of outcomes cannot be used to evaluate the evolution of water resources, floods, etc. This is because evaluations through additional impact models should be run using the outcomes of climate models.

### 3.4.2. CLIMATE DATA INTEGRATION IN DECISION MAKING

Assessing the future impacts of CC involves significant uncertainty due to the modelling chain used for local scale changes and the techniques and scenarios assumed. Impact modelers typically dictate the approach for CC-related hazard assessments, which poses challenges for decision-makers in interpreting the results of ensemble experiments and converting the uncertainty into actionable information [27][7]. Assessing the climate vulnerability of various elements of road infrastructure necessitates examining a predetermined range of scenarios. To ensure consistency in results and facilitate meaningful comparisons, employing this set of scenarios to gauge the risk across all assets and encompassing all potential hazards proves valuable. Establishing a time frame that enables the assessment of the lifespan of all assets further serves in enhancing the evaluation process. The source of this data is based on Climate model-based scenarios which involve utilizing data outputs from either Global Climate Models (GCM) or Regional Climate Models (RCM). These scenarios are typically created by modifying a baseline climate, often derived from regional climate observations over a reference period, through adjustments based on the absolute or proportional differences between simulated present and future climates. In any case, uncertainty is intrinsic to the climate impact modelling chain. The use of climate projections and scenarios to plan, design and operate transport infrastructures implies that it should be considered and managed. Climate Adapt [29] proposes different approaches for dealing with this uncertainty. At this stage of the project, the next approaches are considered of interest are present in Table 9 below [98] [3]:

Table 9 Approaches for tackling uncertainty in decision making

<b>SCENARIO PLANNING</b>	<b>ADAPTIVE MANAGEMENT</b>	<b>ROBUST STRATEGIES</b>	<b>OPTIMIZATION OF BENEFITS</b>
Compare effectiveness of alternative designs and decisions under future conditions	Select strategies that can be modified to adapt climate changes.	Identify a range of possible future circumstances expected through historic situation analysis.	Include different regret level measures.
Provide a useful description of uncertainty and scenarios	Propose adaptive design approach for infrastructure planning and design.	Shortlist strategies reasonably deemed effective to cope with future scenario.	Consider a wide inclusion of benefits, soft strategies, reversibility, flexibility, and safety margins, etc.
Improve the clarity regarding the trade-offs made within the decision-making process.		Ensure presence of an effective robust strategy over very wide range of alternative futures.	

Evaluating the climate risk of different components of road assets requires the consideration of a defined set of scenarios. To generate coherent results, it is interesting to define a time horizon that allows the evaluation along the life span of the infrastructure. This necessitates going beyond the RCP2.6 scenario rather to RCP8.5 scenario considering significant CC projections. Understanding how to integrate climate data from regional climate models (RCMs) driven by global climate models (GCMs) for example remains a concern. This is because most documentation of climate data is tailored specifically for the climate modelling experts and restricts access to those with limited knowledge on this field. The significance of this workflow is in the way some actions can be made to pave the way for resolution

generation coherent for the specific application/user and less bias in climate models outcomes. This then highlights the importance of using of observation data. Knowledge of what variables will drive impact and risk is required at the start of the process and, for the final calculations.

The conclusion implies the connection of this data to impact models, expert judgment, qualitative risk assessment, design considering climate parameters, etc. These steps also allow for transforming the outcomes of the climate models into actionable information for climate risk assessment. Variables such as temperature, precipitation, etc. can be applied to create a time series generated by climate models and facilitate creation of indices assess the impact of concern on the infrastructure [27]. As an example, extreme temperatures can be evaluated for a 50-year return period like the maximum temperature. However, there still are climate variables and processes which simulation is not correctly addressed by global and regional climate models. Considering hydrological cycles for example, even though climate models perform a simplified simulation, the resolution of outcomes cannot be used to evaluate the evolution of water resources, floods, etc. This is because evaluations through additional impact models should be run using the outcomes of climate models.

Reviewing existing hazard maps is an important step in the process of this works as it helps in considering historic, present, and projected future conditions that are triggered by the climate impact drivers. Tools for hazard data can be found on different national databases and inventories can provide this information. From there, the most important data to identify is the event name, type, location, intensity, and date of occurrence. Accordingly, a record can be made and identification of count of occurrences can be deduced giving an idea not only on the susceptibility of this location to hazards but also on the possibility of a certain climate impact driver being the reason behind such hazards through the climate hazard correlations which is shown in the Fig. 30 below.

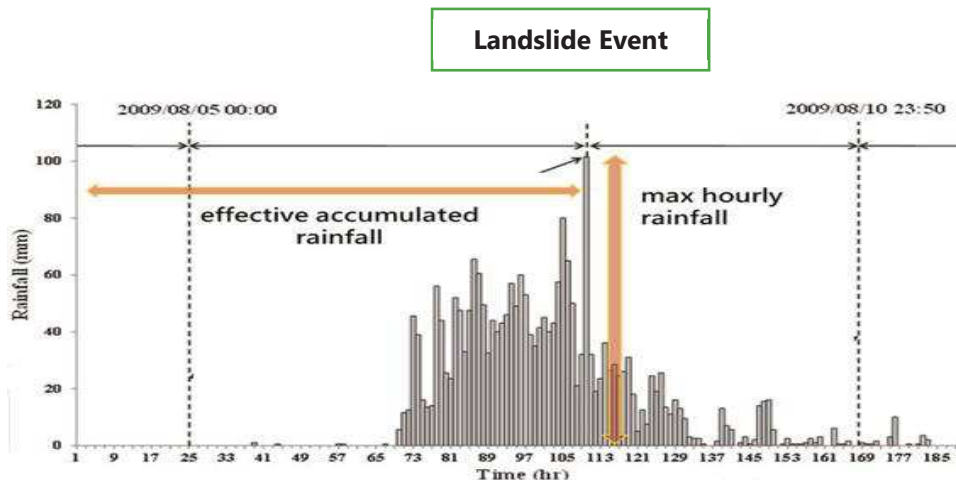


Figure 30 Correlation of landslides and precipitation events

## EXPOSURE

In the context of risk assessment, several exposure conditions are involved in the spatial relation between an asset and a potentially damaging event plays a crucial role. This includes population growth, migration, urbanization, and economic development which are factors that lead to the concentration of people and assets in hazard-exposed areas. While it is impossible to completely avoid exposure to events, land use planning and location decisions should be complemented by mitigation measures to prevent or mitigate risk contingent on reliable early warning systems and effective preparedness planning and adaptation measures to facilitate better coping and regenerative mechanisms in the area. Exposure is comprised of the geographical aspects as the location factors affecting the infrastructure

and social aspects including the existence of individuals; means of subsistence; varieties of life forms or ecological systems; environmental operations, amenities, and facilities.

To prepare adaptation measures for any infrastructure asset, there are some crucial factors influencing strategies and customized approaches that can be used to have an efficient adaptation strategy to climate change based on diverse geographical factors. Coastal regions, characterized by the presence of water bodies, accentuate an increased concern for sea-level rise, while inland areas may prioritize various aspects. Higher elevations face distinctive challenges, with altitude playing a pivotal role in dealing with extreme weather events like high wind speeds and augmented precipitation linked to climate change-induced storms. Variances in land-use, distinguishing between urban and rural settings, dictate specific concerns; urbanized locales concentrate on infrastructure damage, whereas rural areas grapple with issues related to access and dependence on road structures [141].

### **VULNERABILITY**

Vulnerability according is derived as Sensitivity x Exposure where these two indicators can be evaluated in detail, separately, or combined. This analysis is done based on the characteristics of the infrastructure components and their location in 2 stages. In a detailed case study, using a GIS database to describe landslide areas can be utilized to help in developing the fragility curve model. However, to simplify the case these indices were looked up through literature and put in a grading scale where the severity level can be identified and put with the rest of the parameters building the vulnerability study [142] [27]. The purpose of the vulnerability assessment is to understand when considering a certain climatic phenomenon to which are context components putting the infrastructure and its service at risk. This is based on the inherent characteristics of the components, the service parameters the location and the current situation of the infrastructure. In this way, it is determined which threats and which components present a significant vulnerability and, therefore, require analysis in a more detailed subsequent risk assessment phase.

- **Physical Vulnerability:** This assessment targets infrastructure components, including factors such as age, material composition, structural types, and design standards.
- **Functional Vulnerability:** This assessment targets the functional characteristics of the infrastructure highlighting the network, such as its capacity, efficiency, and resilience to disruptions. The combination of vulnerabilities tends to impact the asset, connection and network levels and increase susceptibility to hazards.

This step opens doors to 3 approaches: the first approach if the vulnerability assessment concludes that the infrastructure is not vulnerable to any climate event, and that conclusion is justified, the subsequent risk assessment for that non-vulnerable component will not need to be carried out. in this case the vulnerability is low, thus risk is low, and the path can end here.

The second approach is when the vulnerability is medium or high but there are no sufficient resources for implementation of a detailed vulnerability analysis. This is the case where data cannot be easily obtained, is not accessible, dependable or even found which is mostly the case in a lot of data scarce countries. Then the detailed vulnerability analysis can be bypassed and proceeding to the selection of the adaptation measures is made. The reason why this is an important step is because in most cases, the path towards reaching decision-making stops from the beginning due to these limitations and the intervention made tend to be responsive and during the event occurrence without prior planning. This hinders effective implementation and does not open doors for further investigation highlighting the criticality of improving this process. For that reason, it will assume that the vulnerability level is justified to put forward the next steps and show the process that should be done instead. In the case of this study, this is the approach taken due to some encountered difficulties that will be elaborated later. The development of the impact chain plays the main role in grasping information about the expected risks amended within each infrastructure and prepare for climate adaptation. The main components of the impact chain include the hazard, exposure, vulnerability, and impacts. Considering a focus in this case

study on transport infrastructures in specific roads influenced by landslides, the information needed for the preliminary vulnerability assessment would be as shown in Fig. 31 [26]:

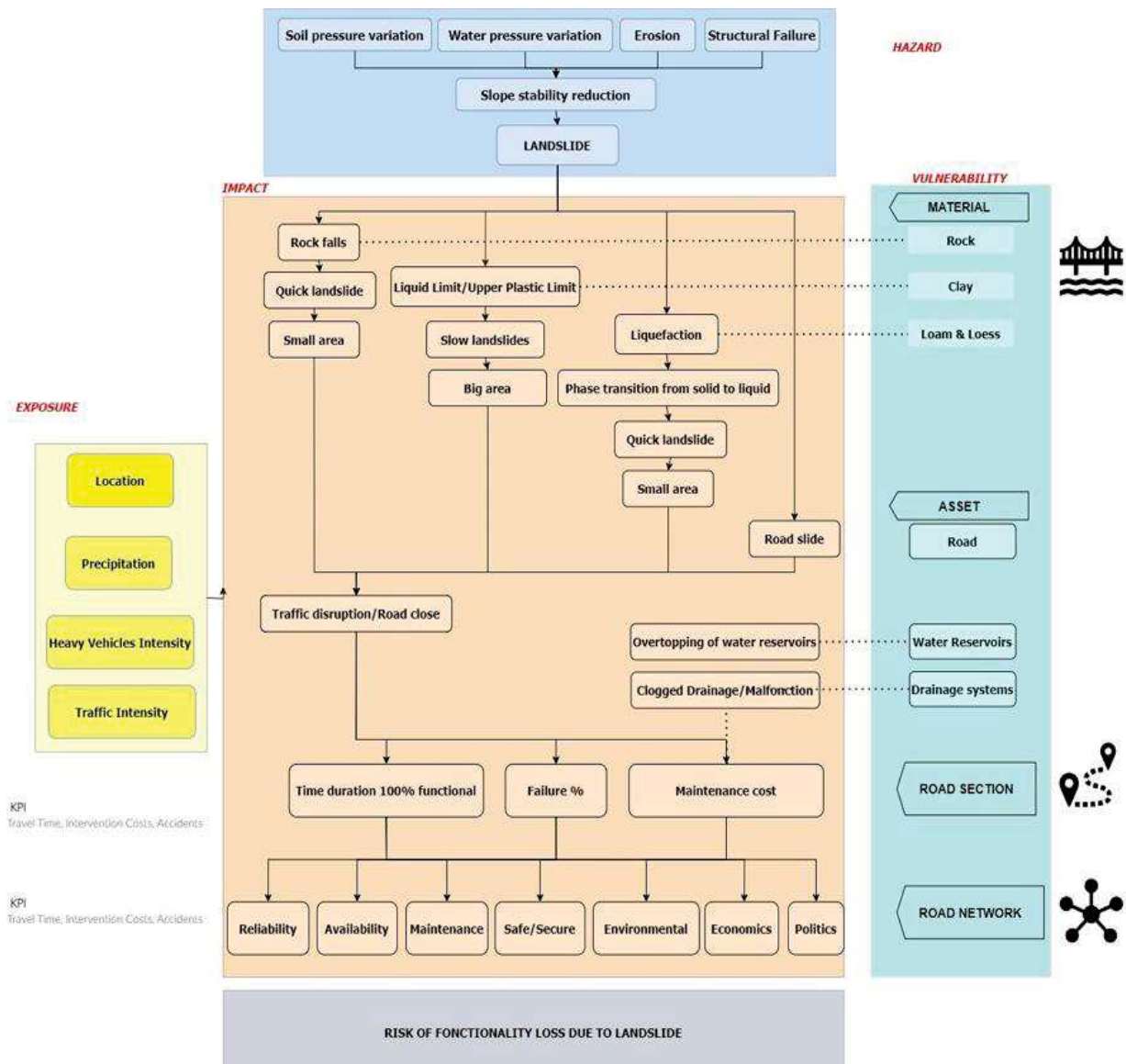


Figure 31 Impact Chain Base Example for Landslide Hazards, Referenced from ICARUS

Those factors are the building blocks of the vulnerability assessment frameworks for the asset covering its not only its structure, connection, and network levels but also the elements linked to this asset. The data collected will be structured below in subsections as follows: The use of these parameters will aid in building for the detailed vulnerability assessment with the addition of the response parameter will be a contribution made to showcase a more in-depth analysis.

### 3.4.3. IMPACT CHAIN DEVELOPMENT

To facilitate a preliminary vulnerability evaluation the impact chain components have been elaborated into different parameters that can be quantified with the minimum data requirements in a tool sheet. The sources of information are obtained based on a combination of existing tool recommendation, possible available data, and linkage of the most parameters critical when climate change impacts happen. The toolset creates a link between the inherent characteristics of the infrastructure and the

functionality. Considering the resilience should cover a combination of both and the impact score will be the sum of both. Applying this based on the existing literature and the available data, it can be estimated the risk level on the studied infrastructure. The resources building up this tool are obtained from the following sources: [55], [142], [143] The elaboration of the impact chain will be considered in this project for landslides induced by different factors. For that, a global perspective of the interrelations within has been done in ICARUS and will be the baseline to build on and narrow down for case specific approaches. Analysing the situation in 2024, although there is a noticeable improvement in the way climate adaptation in transport infrastructure is addressed yet still the complexity of applying is present. For that, first step is creating a basis methodology covering the existing extensive research work done by expertise and use it as a preliminary tool to characterize the road network and analyse the vulnerabilities based on a pre-established typology of impacts, as can be seen in Table 10 below.

Table 10 Parameters to consider and explanations

<b>HAZARD PARAMETERS</b>	<b>EXPOSURE PARAMETERS</b>	<b>VULNERABILITY PARAMETERS</b>
The intensity measures responsible for triggering landslide occurrences.	The presence of water bodies, Altitude, Land-use, Topography, Soil and geology, Accessibility	The combination of sensitivity and adaptive capacity.
Include maximum hourly rainfall mm/time and maximum cumulative rainfall intensity in a continuous rainfall event	Slope aspect (A): the slope aspect represents the vulnerable directions of occurring landslide when given a known topography.  Landslide area (LA): observing the landslide distribution through image classification results can obtain the information about the land cover change.  Vegetation index (N): vegetation indices employ to quantify the density of plant growth on the earth	The chosen parameters can cover Embankment Height, Soil Type, Number of Lanes, infrastructure quality

Next is to characterise the level of the impact (low, moderate or high) of the current climate conditions on each of the sections defined, using a predefined scale. The level of the impact is determined not only by the climate change aspects but also by the inherent infrastructure characteristics like its age, design criteria, construction methods and maintenance. Accordingly, it can be inferred if the transport infrastructure sections are or not affected by any future extreme events. This realization emphasizes the need for a detailed intervention and resilience assessment and puts the validation concern in decision-making. According to the basis of the impact chain, the data for creating a scale of each parameter has been retrieved from different extensive studies forming different useful tools targeting vulnerability assessment. The combination of them together in this tool signifies the benefits of using the impact chain to build a relationship and a common language between the different projects serving similar purposes. The spreadsheet holds the basic details needed to understand a context of a landslide susceptible to climate change. The more details fed into this spreadsheet, the more accurate the interpretation could be. However, the information currently present can be sufficient as a starting point to know how vulnerable this infrastructure is, how the climate change affects it and decide accordingly either to proceed with a detailed analysis or no depending on the overall impact and risks on functionality. The screening process will rely on rating methods utilizing indices and expected damage

for hazards. These indices describe structural and network vulnerabilities alongside hazard intensity. Rating based on expected damage employs fragility functions and estimates economic losses for given hazard levels. This facilitates the potential of prioritizing efforts in areas of importance, deficiencies, remaining useful life, and other socio-economic considerations. This criterion emphasizes the need to improve understanding and knowledge regarding asset data. It involves identifying high-risk locations, defining existing vulnerabilities, and recognizing interdependencies within asset components and subcomponents identified as critical aspects in resilient infrastructure design. This final stage will highlight the choice of adaptation measures that help the infrastructure to accommodate additional stresses caused by climate change. It involves designing for extremes and multiple hazards within the context of resilience-based design principles.

1 to 5 scale for offering a standardized and easily interpretable method for assessing risk. This combination of quantitative measures with qualitative descriptors facilitates a nuanced understanding of risk levels, which is crucial for prioritizing actions based on both the potential severity and probability of events. The clarity and simplicity of these scales make them accessible to a wide range of stakeholders, from engineers and planners to policymakers and community leaders, thus enhancing the framework's utility in diverse contexts. A key strength of the framework lies in its distinction between prevention and adaptation strategies. Prevention focuses on immediate measures to avert landslides, such as engineering interventions, which are critical in high-risk scenarios. On the other hand, adaptation addresses the long-term adjustments needed in infrastructure and management practices, recognizing that not all risks can be entirely mitigated, particularly in the context of chronic conditions. This dual strategy reflects a realistic understanding of risk management, acknowledging that while some issues can be addressed through direct action, others require a sustained and flexible response over time.

To start the rating, the completion of all the indicators is needed for the structure of the impact chain. To ease the process the typology of the infrastructure, the highway in the first case and include the parameters accessible for the preliminary study [144] The aim is to have a global idea on the current conditions the highway is set in. Climate Related Hazard existing, the type of solution that should be considered can be interpreted. For instance, considering acute events, in most cases the uncertainty underlying is difficult to interpret and in the case of the dynamic climate change, it is a challenge. For that in such cases the adaptation to the consequences expected in the long term and having solutions that provide persistent performance of time would be a good option to consider and would be shown in this methodology through the various steps.

	Temperature related	Wind related	Water related	Solid mass related
Chronic	Changing temperature (air, freshwater, marine water)	Changing wind patterns	Changing precipitation patterns and types (rain, hail, snow/ice)	Coastal erosion
	Heat stress		Precipitation and/or hydrological variability	Soil degradation
	Temperature variability	Permafrost thawing	Ocean acidification	Soil erosion
			Saline intrusion	Solifluction
Acute	Heat wave	Cyclone, hurricane, typhoon	Drought	Avalanche
	Cold wave / frost	Storm (blizzards/dust / sandstorms)	Heavy precipitation (rain/hail/snow/ice)	Landslide
	Wildfire *	Tornado	Flood (coastal, fluvial, pluvial, groundwater)	Subsidence
			Glacial lake outburst	

The list of climate-related hazards in this table is non-exhaustive, and constitutes only an indicative list of the most widespread hazards that are to be taken into account as a minimum in the climate risk and vulnerability assessment.

Figure 32 EU Taxonomy Table 5 – Classification of climate-related hazards

However, in the cases of events that are triggered by chronic climate related hazards, as shown in the Fig. 32 above the likelihood of occurrence in the future is interpreted by the projections of climate change ex, RCP 8.5. In this case the impact is more global and governing regardless of the measures implemented or the adaptive capacity present. For this type of events, the methodology would not be efficient to be applied and thus mitigation should be considered to try as much as possible limit the possibility of reaching to critical impacts [18], [145]. Some examples of the climate conditions are present in the Table 11 below and the climate conditions in relation to landslides impact level in Table 12.

Table 11 Climate conditions in relation to landslides

<b>LANDSLIDE TYPE</b>	<b>CLIMATE CONDITION</b>	<b>IMPACT SCALE</b>	<b>LIKELIHOOD SCALE</b>	<b>PRIMARY APPROACH</b>
<b>Precipitation-Driven Landslides</b>	Acute (heavy rainfall)	1 (Minimal) to 5 (Severe)	1 (Rare) to 5 (Very Likely)	Prevention
	Chronic (prolonged rainfall)	1 (Minimal) to 5 (Severe)	1 (Rare) to 5 (Very Likely)	Adaptation
<b>Permafrost-Driven Landslides</b>	Acute (rapid thawing)	1 (Stable) to 5 (Unstable)	1 (Rare) to 5 (Very Likely)	Prevention
	Chronic (gradual thawing)	1 (Low) to 5 (High)	1 (Rare) to 5 (Very Likely)	Adaptation

Table 12 Climate conditions in relation to landslides impact level

<b>IMPACT SCALE</b>	<b>PRECIPITATION-DRIVEN LANDSLIDES</b>	<b>PERMAFROST-DRIVEN LANDSLIDES (ACUTE)</b>	<b>PERMAFROST-DRIVEN LANDSLIDES (CHRONIC)</b>
<b>1</b>	Minimal: Little to no damage	Stable: No significant impact	Low: Minimal impact
<b>2</b>	Minor: Small-scale damage	Slightly Unstable: Minor instabilities	Moderate-Low: Small impact
<b>3</b>	Moderate: Noticeable damage	Moderately Unstable: Noticeable instabilities	Moderate: Noticeable impact
<b>4</b>	Major: Extensive damage	Unstable: Significant instabilities	High: Significant impact
<b>5</b>	Severe: Catastrophic damage	Highly Unstable: Severe instabilities	Very High: Severe impact

The categorization into precipitation-driven and permafrost-driven landslides, further divided into acute and chronic conditions, effectively captures the primary triggers of landslides. This distinction is critical as it not only reflects real-world conditions but also allows for tailored interventions. Acute events like heavy rainfall or rapid permafrost thawing require immediate action, while chronic processes such as prolonged rainfall or gradual thawing necessitate long-term strategies. This dual approach ensures that stakeholders is to differentiate between immediate, short-term threats and long-term, gradual changes, thus enabling more targeted and effective intervention strategies. The descriptions are shown in Table 13 below.

Table 13 Approach Descriptions

<b>PRIMARY APPROACH</b>	<b>DESCRIPTION</b>
<b>Prevention</b>	Implement measures to prevent landslides, such as building retaining walls, improving drainage, etc.
<b>Adaptation</b>	Adapt infrastructure and management practices to mitigate long-term impacts of gradual climatic changes.

This step enables stakeholders to prioritize areas for intervention based on quantifiable data, ensuring that resources are allocated effectively to mitigate the most significant risks. For acute precipitation-driven landslides, where high impact and likelihood scores are identified, immediate preventive actions are necessary. These include traditional engineering solutions such as building retaining walls, improving drainage systems, and reinforcing slopes etc. High impact and likelihood scores in acute scenarios necessitate immediate preventive measures, while chronic conditions call for sustainable, long-term adaptation solutions like NBS. Integrating NBS offers co-benefits such as enhancing biodiversity, improving water quality, and sequestering carbon, making them a sustainable approach to managing risks associated with chronic climate conditions. These solutions should be resilient and flexible, capable of being adjusted and scaled over time to adapt to changing climatic conditions. For acute conditions, particularly rapid permafrost thawing, technological interventions like real-time monitoring systems and ground insulation are essential [4], [93]. Additionally, monitoring rainfall patterns and deploying early warning systems play a crucial role in mitigating risks. In contrast, chronic precipitation necessitates long-term adaptation strategies. Nature-based solutions (NBS), such as reforestation, wetland restoration, and green infrastructure, offer sustainable means to manage water flow and stabilize slopes over time. These solutions enhance ecosystem resilience, reduce runoff, and improve soil stability, thereby mitigating the risk of landslides. For permafrost-driven landslides, rapid thawing, which results in high impact and likelihood scores, demands immediate preventive measures. Technological interventions such as temperature monitoring systems and ground insulation are critical to preventing rapid thaw-induced landslides. These measures help maintain permafrost integrity and provide early warnings of instability. On the other hand, gradual permafrost thawing requires long-term adaptation strategies. Implementing monitoring systems to track permafrost temperature and integrating climate-resilient infrastructure designs are crucial. Additionally, NBS such as re-vegetation and controlling surface water flow can help manage the impacts of gradual thawing, promoting soil stability and reducing landslide risks [35], [90], [146]. The inclusion of detailed baseline climate data and specific hazard parameters, such as the rate of movement and material characteristics, ensures that the assessment is grounded in current environmental conditions. This comprehensive data collection allows for precise risk analysis and helps in understanding the interaction between natural and anthropogenic factors, such as land use and infrastructure characteristics, which influence landslide vulnerability. The following tables of grading obtained to build up this process are shown in Tables 14-26 respectively.

Table 14 Baseline Information

<b>CLIMATE IMPACT DRIVERS</b> [45]	<b>UNIT</b>
Annual mean temperature	°C
Annual mean precipitation	mm
Consecutive dry days	days/year
Very heavy rainfall days	days/year
Summer days	days/year

Tropical nights	days/year
River flooding frequency	Return period (years)
Coastal flooding frequency	Return period (years)
Days with Fire Danger	days/year

Table 15 Soil Basic Characteristics

<b>MATERIAL [55]</b>	<b>WATER CONTENT</b>	<b>ASSOCIATED NATURAL HAZARD</b>
Rock	Dry	Fall
Soil	Moist	Topple
Debris	Wet Earth	Slide
	Very wet Debris	Spread
	Frozen	Flow

Table 16 Rate of Movement:

<b>LANDSLIDE RATE [55]</b>	<b>VELOCITY</b>	<b>RESPONSE NEEDED</b>
Extremely rapid	$V > 5 \times 10^{-3}$	Prevention
Very rapid		
Rapid		
Moderate	$5 \times 10^{-6} \leq V \leq 5 \times 10^{-3}$	Evacuation
Slow	$5 \times 10^{-8} \leq V \leq 5 \times 10^{-6}$	Maintenance
Very slow		
Extremely slow		

Table 17 Probability Level and Score

<b>PROBABILITY LEVEL [55]</b>	<b>DESCRIPTION</b>	<b>FREQUENCY</b>	<b>SCORE</b>	<b>PROBABILITY OF OCCURANCE/YEAR [137]</b>
<b>Rare, Very Unlikely</b>	The impact on the infrastructure is zero or very unlikely.	$\leq 1$ time every 10 years	1	5%
<b>Unlikely</b>	The impact on the infrastructure is unlikely.	$\leq 1$ time every 5 years	2	20%

<b>Moderate, Possible</b>	The impact on the infrastructure is possible.	≤ 1 time every 3 years	3	50%
<b>Likely</b>	The impact on the infrastructure is probable.	≤ once a year	4	80%
<b>Almost Certain, Very Likely</b>	The impact on the infrastructure is very likely.	Several times a year	5	95%

By integrating exposure and vulnerability indicators, such as social consequences embankment height, soil type, and the number of lanes, the decision moves beyond the physical infrastructure, to incorporating the social dimensions of risk which is essential for comprehensive risk management, ensuring that the needs and vulnerabilities of affected communities are considered alongside technical aspects.

Table 18 Slope grade

<b>SLOPE HEIGHT/LENGTH [147]</b>	<b>&lt;50</b>	<b>50-100</b>	<b>100-250</b>	<b>250-500</b>	<b>&gt;500</b>
1->10	1	2	3	4	5
10->20	2	3	4	5	5
20->30	3	4	4	5	5
30->50	4	5	5	5	5
>50	5	5	5	5	5

Table 19 Land Use

<b>LAND USE [147]</b>	<b>REALLY CLOSE</b>	<b>NEXT</b>	<b>LITTLE CLOSE</b>	<b>AWAY</b>	<b>FAR AWAY</b>
Residential Area	5	4	3	2	1
Industrial area	5	4	3	2	1
forest	2	2	1	1	1
farm	3	3	2	1	1
Road infrastructure	4	4	3	2	1
port infrastructure	4	4	3	2	1
water resource	3	3	2	1	1

Table 20 Climate Change Potential

<b>CLIMATE IMPACT DRIVERS</b> [137]	
Current Climate	Low
Future Climate	Medium
Highest Score (current and future)	Medium

Table 21 Social Consequences Impact

<b>SOCIAL CONSEQUENCES IMPACT</b> [137]		
Insignificant	1	No impact on Society
Minor	2	Localized Temporary social impacts
Moderate	3	Long term Localized impacts
Major	4	Failure of vulnerable group protection, long term impact
Catastrophic	5	Loss of social license for operation

Table 22 Road Conditions

<b>ROADWAY PARAMETERS</b>	<b>EMBANKMENT HEIGHT</b>	<b>SOIL TYPE</b>	<b>NUMBER OF LANES</b>
Low	H>8m	Type D	<2
Moderate	5m<H≤8m	Type C	2
High	2m<H≤5	Type B	>2

### Resilience Impact Score

To differentiate a resilient system from no resilient, it important to consider the basis of its definition which withholds Rapidity, Robustness, redundancy, and resourcefulness. To achieve resilience, standard level of performance or Level of Service should be attained and that is linked the speed that defines the system recovery. For that, it is important to achieve the following characteristics while maintaining a minimal probability of failure, improvement of safety, reduced impact on both the economy and society and capability of finding quick and clever ways to overcome disruptions or failures[148], [149], [150]. The resilience impact score is one way to have an indication how the hazard will impact the resilience of the infrastructure. The higher is the score, the greater is the loss of service and vice versa. This can be a way to correlate the functional aspect of service loss with the damage scale of hazard impact. behaviour in a simple way and gain the insights needed for further preparation. This creates a shift from an object to connection, to network level. To be able to proceed with to the classification Hazards/Impacts effects on the Resilience of transport infrastructure, it is prominently important to use the resilience Impact Score which is calculated based on the impact of the hazard or event on the asset[26]. The higher the score, the greater the impact on the asset, and the greater the loss of service or disruption and thus higher vulnerability [26] According to the study of [149], the service loss can be determined through the calculation of the resilience triangle area:

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

$$Resilience\ Impact\ Score = \frac{1}{2}(t_E + t_R) \cdot$$

Where:  $t_0$  is the time of the event  
 $t_1$  is the normal functionality restoration time  
 $\Delta Q$  is the functionality change prevent and post event

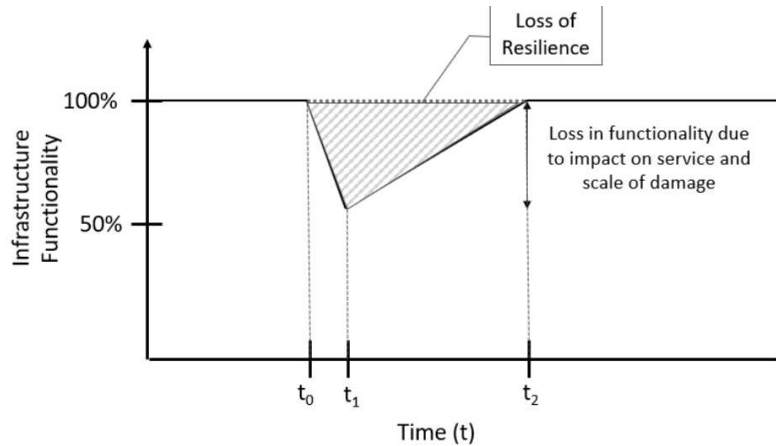


Figure 33 The resilience triangle area

The inclusion of the Resilience Impact Score links the physical damage caused by landslides to the loss of service and system functionality. The loss of resilience is function of the infrastructure functionality and time as shown in Fig.33. This metric not only quantifies the impact on infrastructure but also provides insights into recovery times and overall system resilience. The use of the historic data by the decision-makers helps them evaluate the effectiveness of existing infrastructure situation and plan necessary upgrades or adaptations. It not only shows the impact on the resilience but also the expected recovery time. As this is difficult to predict, this method facilitates obtaining this. The information needed for the resilience impact score rely on the historic events that have occurred in the study area. For example, when the resilience impact score is very high, that means the damage is more critical and would necessitate the intervention of adaptation measures since the infrastructure itself with its current conditions is not able to withstand the CC impacts.

Table 23 Social Consequences Impact

CALCULATION		FUNCTIONAL RESILIENCE IMPACT SCALE [27]			
Type of Asset	Event	CID Duration (t1-t0)	Recovery Time (t2-t1)	Impact due to Damage Qd	Scale of Impact I
Event CID	Landslide	0: Instant	0: None	0: No impact	1: Object
Event Type	Extreme	1: <6 hours	1: <1 day	1: Small	2: Connection
A- CID Duration (t1-t0)	TBA	2: <1 day	2: <1 week	2: Medium	3: Network

<b>B-Recovery Time (t2-t1)</b>	TBA	<b>3:</b> >1 day	<b>3:</b> <month	<b>3:</b> Large
<b>C-Impact due to Damage Qd</b>	TBA	<b>4:</b> >1 month		
<b>D- Scale of Impact I</b>	TBA			
<b>RS-Resilience Impact Score</b>	TBA			
$RS = \frac{1}{2}(A + B) \cdot (C * D)$				

Table 24 Overall impact scale Average sum of all the building blocks of the impact chain:

<b>OVERALL IMPACT SCALE IS BASED ON THE AVERAGE IMPACT<sup>[147]</sup></b>	<b>VERY LOW</b>	<b>LOW</b>	<b>MEDIUM</b>	<b>HIGH</b>	<b>VERY HIGH</b>
Level	1	2	3	4	5

Table 25 Functionality Risks

<b>RESILIENCE IMPACT SCORE</b>	<b>GRADE</b>	<b>INTERPRETATION</b>
<b>x &lt; 10</b>	Low	Low loss of system functionality
<b>10 &lt; x &lt; 20</b>	Medium	Moderate loss of functionality/ Mitigation can be beneficial
<b>x &gt; 20</b>	High	Adaptation options should be considered to increase the resilience of the infrastructure to climate change.

Finally, the emphasis on Nature-Based Solutions (NBS) underscores its forward-looking approach to risk management. While they are recognized for providing sustainable and cost-effective solutions to environmental challenges, it is important to recognize if they are applicable in the study context recognizing that the solutions would contribute positively to the environment.

Table 26 Potential for NbS

<b>NBS, NATURE BASED SOLUTIONS</b>	<b>CONSTRAINTS</b>
Vegetative measures	Slope < 50%
Bio-engineering techniques	Slope ≥ 50%
Restoration of terraces	Location of terraces

The combination put together in the spreadsheet result is shown in Table 27 below.

Table 27 Preliminary Assessment Decision Spreadsheet result

HAZARD	EXPOSURE	VULNERABILITY	IMPACTS	RISKS	ADAPTATION
Rate of Movement	Slope Height/Length	Embankment Height	Functional Resilience Impact Scale	Resilience Impact Score	Possibility of NBS
Probability of Occurrence	Land use Climate change potential Social Community	Soil Type Number of Lanes	Overall Impact		

### 3.5. DETAILED VULNERABILITY ASSESSMENT

Based on this resilient impact score preliminary judgement, the target now is to correlate the response of the infrastructure over time with the climate impact driver posing the hazard. This stage is done through the fragility assessment and development of the fragility curves. Knowing this facilitates estimating the probability of reaching a certain damage state, the time needed for recovery, estimate the resources needed and build up for the case of improvement. This step is crucial for the choice of the adaptation measure needed. This introduces analysing the Response. The second stage is dependent on the results of the impact chain or the preliminary analysis where the adaptive capacity is now analysed through detailed vulnerability assessment. The ideal case where there are sufficient resources to consider improving the current situation at intermediate levels or at high vulnerability level where a detailed vulnerability analysis should be performed. According to existing studies and work, most of the time vulnerability analysis requires performing simulations, extensive data. Due to the acknowledgement of the complexity of obtaining the data, a trial proposal was made to rely on existing literature and develop a literature-based fragility curve opening doors to vulnerability assessment. The steps that should be taken are explained below and the data needed is also identified. The currently used concept of the impact chain is also proposed to present the reality of asset resilience and interdependency and thus forecast a dynamic nature where risks tend to be acting. In this thesis work, the impact chain used will be updated to incorporate a new concept, Fragility, as shown above in Fig. 34.

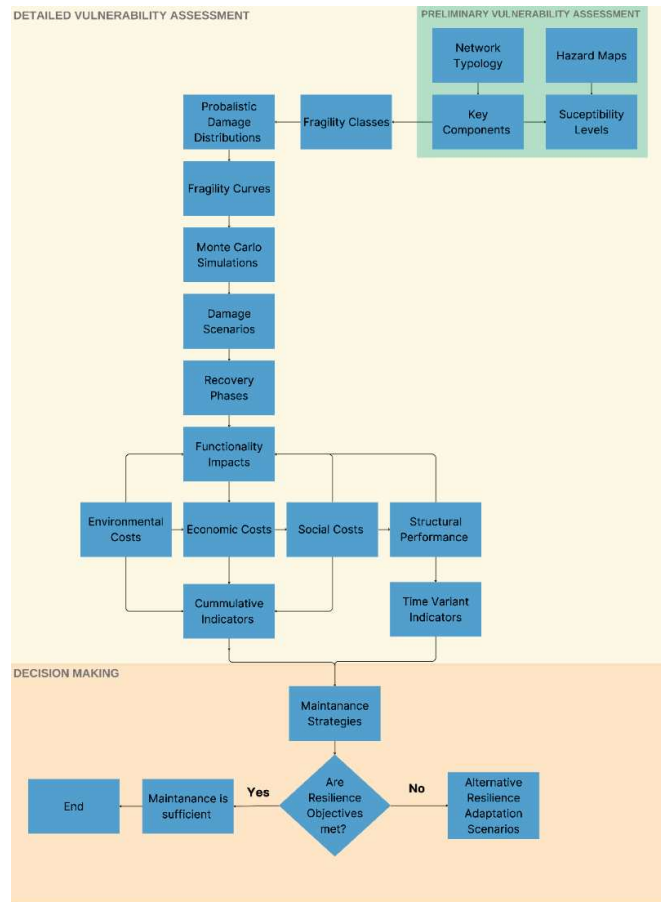


Figure 34 Detailed Vulnerability Assessment Flowchart

### 3.5.1. FRAGILITY ASSESSMENT

Previous research primarily concentrated on assessing the physical vulnerability of individual components, such as the built environment, roadway systems, or governmental infrastructure. However, there is a need to integrate these diverse criteria as these assets function as an interconnected system during any hazardous events occurring. Additionally, there is a scarcity of studies that combine asset damage, functionality, accessibility to essential services, and network performance compared to those focusing on hazard vulnerability alone. The fragility criterion will not only help in implementing measures for contingency planning, but also it will highlight areas emergent for rapid repair and rerouting of traffic in response to emergencies or disruptions. As this stage is strongly correlated with data availability, the maintenance stage will not be considered in the analysis but rather directly towards adaptation measures. Integrating fragility assessments into impact chains can highlight an improvement in the assessment of climate change impacts and the resilience of infrastructure systems. Through their quantitative representation of the vulnerability of infrastructure assets to specific climate hazards and facilitating the possibility of quantifying the likelihood and severity of infrastructure damage or failure at different stages and different components of the infrastructure along the impact pathway. This can be a noticeable improvement to the accuracy and granularity of impact assessments, allowing for more precise identification of high-risk areas and critical infrastructure components. Up to the author's interpretation, a quantification through fragility assessment could be the completion needed for a more accurate perception of vulnerability. Also, the components needed in the detailed evaluation can be seen in Table 28 below.

Table 28 Components needed in the detailed evaluation

<b>CATEGORY</b>	<b>ATTRIBUTE</b>	<b>CATEGORY</b>	<b>COMPONENTS</b>	<b>CATEGORY</b>	<b>CRITERIA</b>
<b>Hazard Level</b>	The intensity or severity of the hazard being considered (e.g., earthquake magnitude, flood depth, wind speed).	<b>Data Collection</b>	Gathering relevant data on the system or structure under consideration, including its physical characteristics, material properties, and past performance during hazard events.	<b>Accuracy</b>	The degree to which the fragility curve accurately represents the vulnerability of the system or structure.
<b>Damage Level</b>	The extent of damage experienced by the system or structure at various levels of the hazard.	<b>Modelling</b>	Developing mathematical or computational models to simulate the response of the system or structure to different hazard scenarios.	<b>Precision</b>	The level of detail and resolution provided by the fragility curve in quantifying the relationship between hazard intensity and damage.
<b>Probability</b>	The likelihood of experiencing a certain level of damage given a specific hazard level.	<b>Analysis</b>	Evaluating the performance of the system or structure based on the generated data and models to derive fragility relationships.	<b>Applicability</b>	The extent to which the fragility curve can be applied to different scenarios, structures, or hazard types.
<b>Uncertainty</b>	The degree of confidence or variability associated with the predicted damage levels.	<b>Validation</b>	Comparing the predicted fragility curves with observed damage data from real-world events to assess the accuracy and reliability of the models.	<b>Sensitivity</b>	The ability of the fragility curve to capture changes in vulnerability due to variations in hazard intensity, system characteristics, or other factors.

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<b>Interpretability</b>	The ease with which the fragility curve can be understood and used by stakeholders, such as engineers, policymakers, and emergency managers.
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In most cases, the evaluation of the effects and interconnected risks within infrastructure systems is not highlighted resulting in an inefficient quantification of the risk extent. In real cases, disruptions in one part of the system can propagate and amplify throughout the network, infrastructure components and sectors. Thus, a nuanced understanding of the critical points of failure is needed to ensure the development of targeted resilience strategies and mitigate the potential for cascading impacts and analyse the response. This can be done by complimenting the impact chain results and using the concept of fragility curves where combine the fragility curves with probabilistic risk assessment techniques, and decision-making to make the way for assessing the effectiveness in terms of resilience and sustainability trade-offs of various adaptation options and prioritize investments where they are most needed.

Previous works have identified several types of analysis for fragility function assessment, including displacement-based assessment, non-transport static analysis, and non-transport dynamic analysis. Non-transport static and dynamic analyses, including incremental dynamic analysis (IDA), typically require Finite Element (FE) models. Both approaches tend to be quite complex and difficult to apply since using FE models for a large set of assets would demand substantial computational effort and time[34], [45], [131], [151], [152], [153]. Literature-based fragility curves on the other side are also explored to perform detailed vulnerability assessments applicable to large infrastructure systems such as bridges, roads, and tunnels. Thus, utilizing them as a basis can be deemed acceptable and can be verified through the detailed approaches to validate that the analysis of the critical asset is gateway for finding solutions that can facilitate a faster recovery. coherent and simulates its actual behaviour as shown in Fig. 35 below:

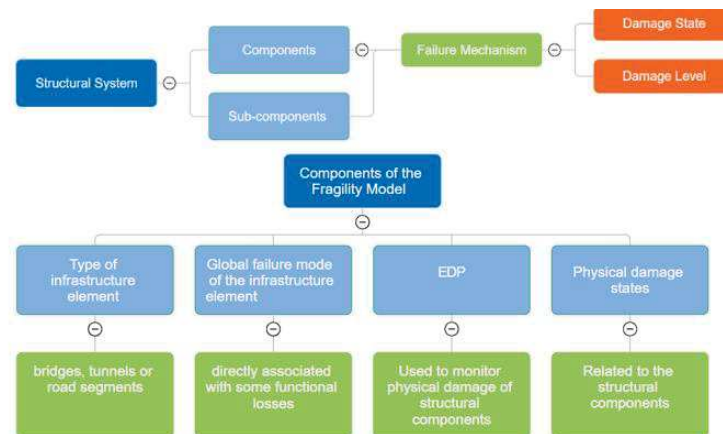


Figure 35 Setting Fragility assessment in steps

Also, fragility functions can be developed through various analyses, from simplified methods using existing databases or literature to detailed approaches like Finite Element models. Despite the analysis type, the core methodology remains consistent and the prerequisites of developing a fragility function are shown in Table 29 below.

Table 29 Prerequisites of Fragility Function

PREREQUISITE	DESCRIPTION
<b>Intensity Measure (IM)</b>	This parameter represents the hazard loading applied to the structure at a period of study.
<b>EDP (Engineering Demand Parameter)</b>	This parameter covers the structural response and provides the quantities used to predict a certain damage the structural and functional components of an asset.
<b>Damage State (DS)</b>	The damage states are bounded by different limit states or damage levels, corresponding to a given level of potential values for the engineering demand parameter (EDP).
<b>Functional Form (FF)</b>	This parameter links the probability of reaching or exceeding a damage state (DS) as a function of the selected (IM).

To start developing a fragility function relies on a set of prerequisites. The first step is to identify the global damage states corresponding to configurations of component damages. The second step is to assessment component fragility curves and obtain probabilities at system levels. Following that, a matrix-based reliability model shall be created to derive the system fragility function from the individual components. For every category of infrastructure component, various potential failure modes are suggested, followed by the identification of specific damage mechanisms at the component level corresponding to each type of hazard. This in return builds up for the creation of the fragility matrix which will be later used to develop the fragility curve as shown in Fig. 36 below.

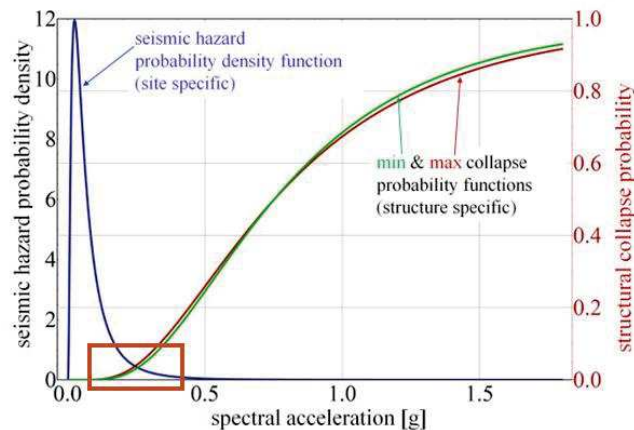


Figure 36 Sample Fragility Curve Example, highlighting the probability area for damage

This matrix leads to the presence of all the necessary tools to quantify the distributed (IM)s at the susceptible sites of the infrastructure system helping in the preparation for the subsequent steps of infrastructure risk analysis and later estimation of the system performance depending on the disruption of each of the individual elements. Using the aggregated failure modes of the elements from physical damage mechanisms to specific structural components develops the global failure modes consistent in terms of functional losses or repair duration. the area where the capacity and hazard are intersected identifies the vulnerability of the asset, the higher it is the probability of reaching a certain damage state and the higher disruption on functionality. This criterion emphasizes the need to improve understanding and knowledge regarding asset data. It involves identifying high-risk locations, defining existing vulnerabilities, and recognizing interdependencies within asset components and subcomponents identified as critical aspects in resilient infrastructure design.

According to the fragility curve, a clear idea can be present on the expected behaviour of the structure when subject to a certain hazard. The response of the structure and the severity of it provides a strengthening background for resilience preparedness of the structure to cope with the design strategy needed or the maintenance or adaptation response. Also, the fact of dissecting the asset into its components gives an idea on where the most critical aspect of deterioration is and how this contributes to the reduction of the infrastructure resilience behaviour when exposed to a certain hazard and how it affects its functionality. Considering that for different hazard, the hazard curve describing for example the probable rainfall at a particular point within a catchment is not sufficient. A reconstruction of how this rainfall translates into runoff over the asset is needed or how this rainfall changes the level of groundwater in case of landslides. The inclusion of the fragility curve gives a strong background from the generation of the scenarios expected to happen leading to a better understanding of the traffic impact, service reduction and a better estimation of the cost values needed for maintenance based on the levels of damage and the secondary impacts resulting from it as applied in the FORESEE Project [45] and can be simply represented as the Table 30 below:

Table 30 Example of Results

DAMAGE STATE	TIME RECOVERY	EXPECTED COSTS	INTERVENTION TYPE	AFFECTED
High	1 month	48900€	Slope Stability	Asset and Service

This can be set as a main risk generator leading to the occurrence of several other risks. The inclusion of the fragility curve gives a strong background from the generation of the scenarios expected to happen leading to a better understanding of the traffic impact, service reduction and a better estimation of the cost values needed for maintenance based on the levels of damage and the secondary impacts resulting from it. It can also be set as a main risk generator leading to the occurrence of several other risks as shown in Fig. 37 and Fig. 38 [125].

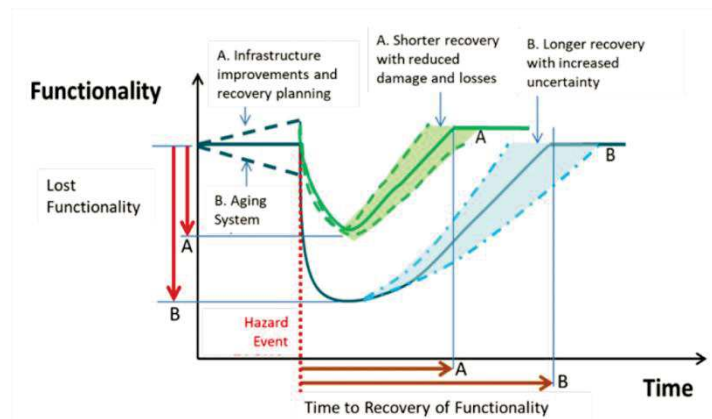


Figure 37 Effects of functionality and recovery time on system resilience

Going back to the basic definition of the system resilience is interpreted as the level of functionality over time.[154] The impact of however is characterized by the extent of effect on the total functionality loss and the required time needed to recover post a disruptive event. [44] When analysing the figure below, at the time of the event, which is the most critical in terms of impact, the highest drop in functionality occurs. According to that, as the resilience decreases, the loss of functionality increases and the more time it will take for the infrastructure to recover. Based on this hypothesis, it can be concluded that it is possible to include the way the asset is going to behave when it is subject to these impacts. Then this leads to have an estimation of how much time it would take to return to its original functionality state.

To know this, we must do a monitoring or prediction analysis of how the behaviour of the structure will be and what is its probability of reaching certain damage states. This can be generated through Fragility assessment and Fragility functions.

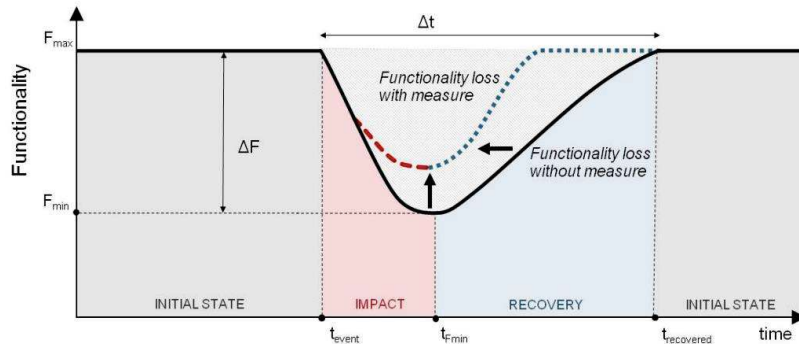


Figure 38 Phases of functionality throughout time [44]

### 3.5.2. CLIMATE-RELATED RISKS AND VULNERABILITIES

The gradual changes in average temperature or annual rainfall for example can significantly impact the frequency and severity of extreme weather events. These alterations prompt the use of various climate scenarios to identify potential impacts and describe the associated climate-related risks. The Copernicus [155] platform offers a comprehensive array of climate analyses, serving as an excellent starting point for this endeavour. By examining different climate indicators, like annual average rainfall, within diverse climate scenarios, insights into the anticipated future climate can be obtained [138].

Risk assessment becomes pivotal because it's determined by both probability and consequence. In any planning process, the likelihood of an impact occurring must be considered alongside its potential consequences. If an impact is deemed to have significant consequences, it becomes crucial to include scenarios that involve continued high emissions of greenhouse gases. By utilizing the gathered information on current conditions, risk assessment methodologies, and evaluated probability-consequence pairs, the understanding of the risks warrant the highest priority and unveil the root causes of identified risks. Once the climate impacts and associated risks are investigated and prioritized, this data serves as supporting documentation for subsequent steps in selecting appropriate measures

The steps for developing the fragility curve include:

- Identify the Asset characteristics, location and hazard description expected.
- Create a simulation technique to understand the structure's behaviour. This can be done through several ways including Digital twin, Structural modelling simulation, or structural health monitoring
- showcase the state of structural integrity based on the expected conditions based on the information obtained
- Develop from the data obtained a relationship between the hazard characteristic and the damage state of the structure.
- The projection of this relationships contributes to obtaining the probability of exceeding the damage limit state which is the fragility curve.
- Accordingly, the linkage of the fragility curve will pave the way for the resilience control strategy and map of maintenance activities, costs, intervention and time and allows judgement and decision making.

#### Step 1: Intensity measure Definition

1. Total Number of Load Intensities Analyzed	11
2. Intensity Label	Max Precipitation in 24 hrs
3. Intensity Unit	mm

Intensity No.	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Max Precipitation in 24 hrs (mm)	114.3	54.1	73.5	53.6	88.5	78	71.3	81.6	64.9	60.2	85.8

**Step 2:** Obtain the literature data, historic event database. Some information needed may include the following:

**Step 3: List the engineering demand parameters defining the damage states**

5. Number of Analysis Performed in Each Intensity	1
6. Engineering Demand Parameter (EDP) Considered	Rockfall Magnitude
7. EDP Unit	m3
8. Total Number of Performance Levels Considered	5

**Step 4: Develop a performance level table:**

Performance Level	1	2	3	4	5
Rockfall Magnitude Limit (m3)	1	5	50	500	5000

10. Minimum Intensity in the Fragility Function	0
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11. Maximum Intensity in the Fragility Function	5000
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**Step 5: Develop a correlation between IM and EPD adding the historic events that have happened at the time of occurrence of the intensity measure**

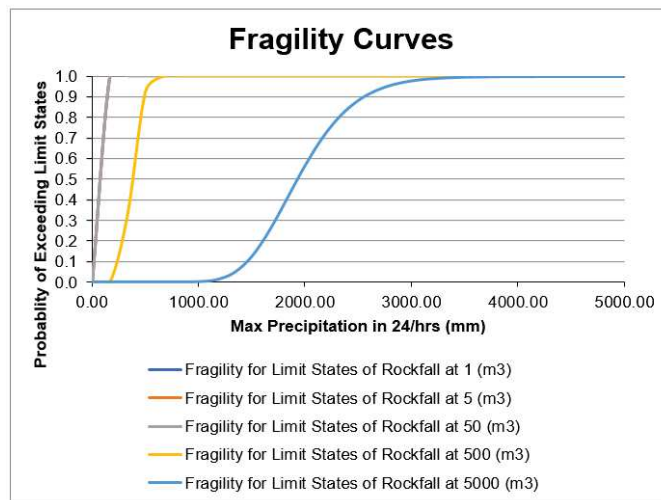
Max Precipitation in 24/hrs (mm)	Rockfall (m3)	Ln(Rockfall)
114.3	95	4.553876892
54.1	35	3.555348061
73.5	55	4.007333185
53.6	34.5	3.540959324
88.5	70	4.248495242
78	60	4.094344562
71.3	50	3.912023005
81.6	65	4.17438727
64.9	45	3.80666249
60.2	40	3.688879454
85.8	68	4.219507705

Standard Deviation                      17.2548951  
 Ln of Std. Dev                            0.301941771

Max Precipitation in 24/hrs	Fragility for Limit States of Rockfall at				
	1 (m3)	5 (m3)	50 (m3)	500 (m3)	5000 (m3)
0.0100	0.0000	0.0000	0.0000	0.0000	0.0000
166.6667	1.0000	1.0000	1.0000	0.0001	0.0000
333.3333	1.0000	1.0000	1.0000	0.3316	0.0000
500.0000	1.0000	1.0000	1.0000	0.9232	0.0000
666.6667	1.0000	1.0000	1.0000	0.9970	0.0000
833.3333	1.0000	1.0000	1.0000	0.9999	0.0001
1000.0000	1.0000	1.0000	1.0000	1.0000	0.0013
1166.6667	1.0000	1.0000	1.0000	1.0000	0.0105
1333.3333	1.0000	1.0000	1.0000	1.0000	0.0452
1500.0000	1.0000	1.0000	1.0000	1.0000	0.1247
1666.6667	1.0000	1.0000	1.0000	1.0000	0.2522
1833.3333	1.0000	1.0000	1.0000	1.0000	0.4091
2000.0000	1.0000	1.0000	1.0000	1.0000	0.5875
2166.6667	1.0000	1.0000	1.0000	1.0000	0.7046
2333.3333	1.0000	1.0000	1.0000	1.0000	0.8100
2500.0000	1.0000	1.0000	1.0000	1.0000	0.8840
2666.6667	1.0000	1.0000	1.0000	1.0000	0.9321
2833.3333	1.0000	1.0000	1.0000	1.0000	0.9616
3000.0000	1.0000	1.0000	1.0000	1.0000	0.9790
3166.6667	1.0000	1.0000	1.0000	1.0000	0.9887
3333.3333	1.0000	1.0000	1.0000	1.0000	0.9941
3500.0000	1.0000	1.0000	1.0000	1.0000	0.9969
3666.6667	1.0000	1.0000	1.0000	1.0000	0.9984
3833.3333	1.0000	1.0000	1.0000	1.0000	0.9992
4000.0000	1.0000	1.0000	1.0000	1.0000	0.9996
4166.6667	1.0000	1.0000	1.0000	1.0000	0.9998
4333.3333	1.0000	1.0000	1.0000	1.0000	0.9999
4500.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4666.6667	1.0000	1.0000	1.0000	1.0000	1.0000
4833.3333	1.0000	1.0000	1.0000	1.0000	1.0000
5000.0000	1.0000	1.0000	1.0000	1.0000	1.0000

**Step 6: Development of the Fragility Curve:**

The curve is developed based on a log-normal cumulative probability distribution which defines what is the probability of exceedance a certain limit state for a given intensity measure.



The fragility curves for example in this case indicates that smaller rockfalls are more probable with lower precipitation levels, while larger rockfalls require significantly higher precipitation to occur. This is a sample graph just for illustration on a fictive example. The right graph reinforces this by showing a strong positive correlation between precipitation and rockfall magnitude, suggesting that as rainfall intensity increases, so does the likelihood and size of rockfalls. This combined information can be crucial for infrastructure planning and management of the risks associated with varying rainfall levels

This enables more efficient allocation of resources by building an improvement management system. the concept of fragility curves will be used in control strategy for the global failure modes consistent in terms of functional losses or repair duration and paves the way for the control of time and losses. Based on the fragility curve, a clear idea can be present on the expected behaviour of the structure when subject to a certain hazard. The response of the structure and the severity of it provides a strengthening background for resilience preparedness of the structure to cope with the design strategy needed or the maintenance or adaptation response. Also, the fact of dissecting the asset into its components gives an idea of where the most critical aspect of deterioration is and how this contributes to the reduction of the infrastructure resilience behaviour when exposed to a certain hazard. The inclusion of the fragility curve gives a strong background from the generation of the scenarios expected to happen leading to a better understanding of the traffic impact, service reduction and a better estimation of the cost values needed for maintenance based on the levels of damage and the secondary impacts resulting from it. This can be set as a main risk generator leading to the occurrence of several other risks. Accordingly, the interpretation needed for recovery and from this approach, the general data of interest needed for this project to develop the fragility curves in Table 31, some of the following information are needed will be limited to:

Table 31 Components of the fragility assessment

COMPONENT	FACTOR	INDICATOR	UNIT
Hazard	Climate Impact	Intensity, distribution, and	Unit/time
	Drivers	Duration during Event	
		Intensity distribution and	Unit/week
		duration over continuous	
		duration	(D° M' S"), (D° M' S")

		Location of climate station with respect to hazardous event location	
		Hazard Type	Name
		Area Affected by Event	km <sup>2</sup>
		Frequency of events/year	Unit/year
		Severity of event, magnitude	Scale (low, medium, high)
		Rate of movement	Scale (low, medium, high)
<b>Exposure</b>	Location	Altitude	m above mean sea level
		Number of events < 50 years	Unit/50 years
		Land use	Type
		Green Landcover	% Of km <sup>2</sup>
	Traffic	Percentage of heavy vehicles	% trucks/day
		Traffic intensity measure	Vah/day/km
	Infrastructure	Variable in importance	% exposure/day
	Specific Factors	according to type of infrastructure	

### 3.6. PRELIMINARY ADAPTATION MEASURE SELECTION

Starting from the risk acknowledgment and the definition of the types of impacts on the studied infrastructure, the aim now is to identify a certain adaptation measure that would fit a good solution. To be able to differentiate among the different options, the selection of the KPIs is important. KPIs are Key performance indicators are targets that are set to achieve a certain objective and capable of being quantified and compared as shown in Fig.39.

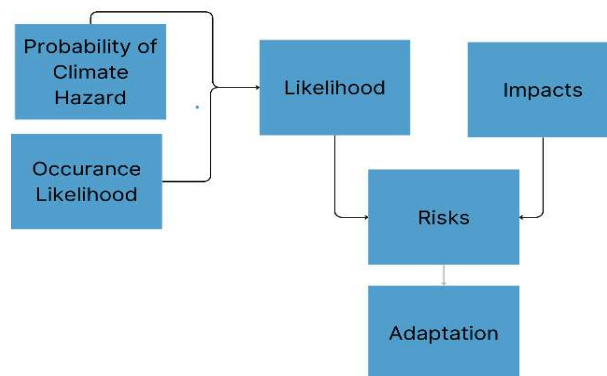


Figure 39 Stages leading to current

The role of KPIs in this project then will take place into 2 stages: **Shortlisting, Evaluation, and Monitoring.**

**Shortlisting:** The first stage to shortlist the different criteria used to define the KPIs in the analysed studies. Based on the collective base criteria for selection depending on the priorities, try to prioritize a general arrangement for all. This in gives the building blocks for the different assessments methods for quantifying the performance change in future assessment data and ensures the integration of the sustainability and resilience aspects in the decision making. Through Multicriteria decision making, the qualitative assessment can provide preliminary expectations for the different possible adaptation measures but also, facilitate the choice of the best option at this stage.

**Evaluation:** At this stage the base criteria will be narrow down to allow selection of project/context specific (KPIs) to hold a crucial task of allowing measurement and tracking of performance across various domains, and availability of data and resources for evaluation. The quantitative evaluation prepares for the progress toward analysing areas for improvement.

**Monitoring:** Following the KPIs, during the operation phase, infrastructure managers can proactively anticipate challenges and adjust their strategies accordingly. This enables them to track trends over time, including changes in disruptions or incidents, infrastructure conditions, and traffic volume, thereby empowering them to adjust their strategies in response. This plays a crucial role in making informed decisions regarding resource allocation, including budget, equipment, and personnel distribution enabling tasks prioritization.

### 3.6.1. KEY PERFORMANCE INDICATORS

Multi Criteria Analysis (MCA) is the baseline for the identification of adaptation measures creating a systematic approach. Firstly, criteria deemed relevant for evaluating these measures are identified. These criteria encompass factors such as effectiveness in vulnerability reduction, feasibility of implementation, environmental and social impacts and stakeholder acceptance. Subsequently, weighting is assigned to each criterion, reflecting its relative importance in the decision-making process. Alternatives in the form of adaptation measures are then identified, ranging from infrastructure upgrades to policy interventions. These measures are evaluated against the established criteria, utilizing both qualitative and quantitative indicators where applicable. Through this evaluation, adaptation measures are ranked and prioritized based on their performance against the weighted criteria. Sensitivity analysis is conducted to assess the robustness of the results and identify key decision drivers. For quantification purposes, a weighted mean will be deployed where each data point value will be multiplied by its assigned weight, summing these products, and then dividing by the total sum of weights. This method provides a more descriptive representation than a simple mean as it accounts for the relative importance of each observation. Finally, the outcomes of the MCA are communicated to stakeholders, providing support for informed decision-making regarding adaptation strategies. Regardless of which method is chosen, the analysis will likely have to include some form of multi-criteria analysis for comparing different solutions. This analysis is often used as an alternative or complement to a cost-benefit analysis establishes a basis for comparison between different solutions. A multi-criteria analysis can be a semi-quantitative method of analysis in which the outcome or function of a solution is weighted against several predetermined criteria. The criteria that are set can be advantageously linked to the risks. In the analysis, compliance with environmental, social, and environmental criteria should be evaluated. This translates into besides successfully managing the hazard risk, perhaps is possible to present some Cobenefits such as to promoting biodiversity and creating a recreational space. The question is then how well does the solution meet these requirements? In this way, the criteria help to set the requirements while enabling the of nature-based solutions and grey solutions. The weighted criteria are then used to rank action proposals. The valuation should be based on the expertise and views of the stakeholders. The criteria for fulfilment can have different weightings depending on the context and challenge. In this work, the MCDA done by different studies are considered and the synergy among the different solutions captures the advantages and disadvantages of the solution alternatives. The target result is summed up in the structure of the work figure 40 below and is based on the impact chain developed for the studied case.

- Consider the sustainability and social benefits of the various solutions as well as resilience.
- Consider the long-term costs of care and maintenance and the benefits of evaluating different solutions – nature-based solutions can be more expensive in the short term but highly cost-effective in the long run.
- Include the risk management in the decision-making

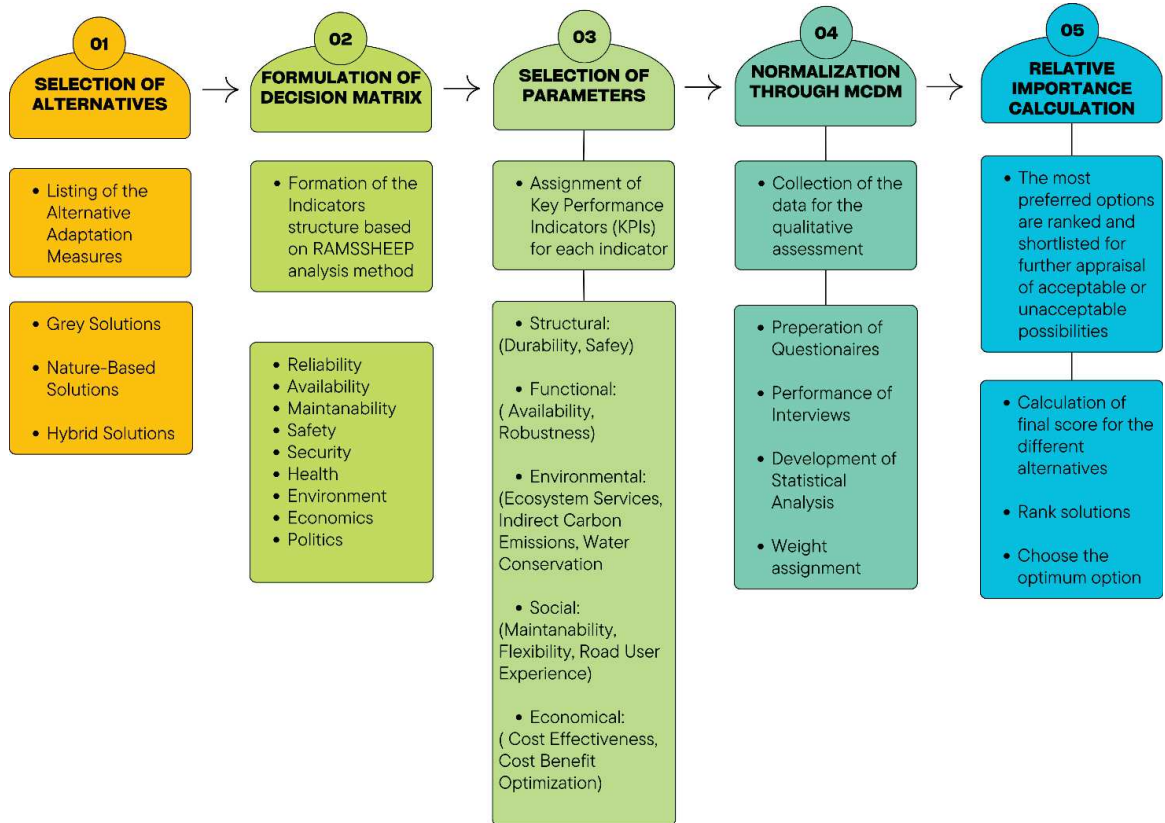


Figure 40 Multicriteria Analysis Development Process

Determining the optimal level of adaptation involves complex considerations, thus it needs to explore the delicate balance between the different KPIs in climate change adaptation. The main obstacle of evaluation is working with absolute certainty how much change will occur or the exact consequences. For that, the inherent uncertainty in climate projections should be considered and the adaptation plans should be robust enough to accommodate potential variations. As a result, identifying the “ideal” level of adaptation becomes a nuanced task. [156]This differs in the stakeholder’s willingness to accept risk. Some advocate for proactive adaptation, recognizing the urgency of addressing climate risks. Others may be more risk-averse, preferring a cautious approach. High-risk scenarios demand more robust adaptation measures, while low-risk situations may allow for a more measured response. If costs are minimal but risks remain high (e.g., early warning systems for extreme weather events), adaptation becomes a clear imperative. Situations with minimal costs and low climate risks offer flexibility. Adaptation decisions here have fewer downsides.

Validation can be made according to the basis of this study that revolves around resilience and sustainability. In regards of climate change adaptation and road resilience, some KPIs have been chosen to facilitate the stages of decision making and assessment. These metrics can help measure the efficiency and effectiveness of the measures. Prior developing an extensive literature review aiming to understand the criteria used for selecting and prioritizing Adaptation solutions for resilience and sustainability, the

reference data provided by ICARUS was used. According to the extensive database created, the adaptation measures are evaluated on the base reference of RAMSHEEP[157].

The evaluation in ICARUS considered the availability, cost and safety parameters of evaluation in a cost benefit analysis and chosen based on a multicriteria analysis facilitating a coherent and efficient comparison of alternatives. To use multicriteria analysis, it is necessary to define the existing alternatives, the attributes that define these alternatives, the objectives to be achieved with said attributes, the goal of the alternatives and the criteria that give relevance to the different attributes, objectives and goals.

The involvement of stakeholders from various backgrounds—ranging from municipal and regional experts to landowners, interest groups, and residents—brings a diverse array of perspectives, expertise, and concerns to the forefront. This engagement facilitate decision making throughout the planning, implementation, and maintenance phases of adaptation measures. According to ICARUS and the expert input provided, the level of change is the most addressed way of analysing the alternatives. The full grading and the alternatives are presented in the Annex. Considering the landslide event scenario, the following table is developed analysing different possible options. While most of these criterions are interrelated to a valuation of cost, this will be analysed separately in the evaluation. After analysing several studies on climate change and vulnerability in the transport sector, it was noticed that most of the used KPIs used are similar or belong to the same criteria. From here the motivation of sorting them together into a base standard. This also has raised a question of how the choice of KPIs could move from being industry- and business-specific KPIs to standardized selection help in finding a common language for all the varying concerns and reduce the frustration during implementation and decision making.

After analysing selected recent projects addressing climate change adaptation, it was noted that most of them have a common basis in common in terms of choice of key performance indicators. While [75]and [88] were focusing on prioritizing nature-based solutions, [55] and [45] are tackling resilience response and preparation for adaptation, [26] showcased a combination of both. In [55], the procedure follows an analytic hierarchy process (AHP) to identify the most suitable landslide risk mitigation measures based on user inputs and expert ratings of various candidate measures not only type of movement and the physical conditions at the site, as but also ratings of the technical, economic, and environmental suitability of the mitigation measures. Besides its potential, this still needs further validation and possible refinement of the ranking criteria.

Another project is FORESEE, [102] discussed that one major difficulty in measuring infrastructure sustainability lies in its numerous attributes, each requiring different units because of the varied dimensions and their corresponding units where it was suggested to have a management by employing conversion relationships to a probabilistic scale to achieve a performance target. ASCE, American Society of Civil Engineers, for instance, defines sustainability as maintaining and improving society's quality of life indefinitely without depleting natural, economic, and social resources, while sustainable development involves enhancing safety, welfare, and quality of life through these resources[96]. This closely aligns with the UN (SDGs), United Nations Sustainable Development Goals, which similarly aim to achieve a sustainable future through inclusive economic growth, environmental protection, and social well-being. Both frameworks emphasize the importance of balancing and integrating economic, environmental, and social dimensions to ensure long-term sustainability and quality of life for all. While in Following the framework developed [45], the vulnerabilities that should be addressed on network and asset level for any selected segment. The key performance indicators (KPIs) chosen will be used to monitor the evolution of these KPIs along the segment over time will facilitate a well-informed assessment of financial and technical risks, aiding in the decision-making process for infrastructure managers to select the most effective mitigation actions based on current and predicted KPI values. Meanwhile, at the operational level, maintenance activities are guided by risk analysis studies encompassing technical, financial, and governance risks.

In the case of this work, the evaluation is going to be made differently focusing more on a decision weighing all the Cobenefits instead tilting more the decision-making process towards the cost perspective. After understanding the position of the benefits in this scenario, it was observed that the underlying basis links sustainability and resilience together. Afterwards, the frameworks in Table 32 below were chosen according to their extensive key performance indicators choices to be considered. This hereby led to the understanding that regardless of how the names are, the basis is still the same as a different language of interpretation.

Table 32 List of Attributes for Comparison

<b>BASE [88]</b>	<b>[75] D4RUNOFF</b>	<b>[135]ICARUS</b>	<b>[45]FORESEE</b>	<b>[55] LARIMIT</b>	<b>[140]ROADAPT</b>
<b>Technical Feasibility</b>	-Construction Operational and End-of-Life Costs -Sewer System Cost	- Maintainability -Availability -Robustness for future	-Frequency of monitoring	-Feasibility and manageability -Economic Suitability	-Availability -Direct Cost -Reputation
<b>Risk Reduction</b>	-Expertise -Flood mitigation -Land Use optimization	-Impact on Safety -Flexibility -Durability -Impact on Health	-Design resistance to hazard -Condition state of bridge	-Functional Suitability - Reliability	-Safety -Impact on network -General Management
<b>Environment &amp; Ecosystem</b>	-Runoff Water Quality (Conventional) and (Emerging Pollutants) -CO2 Capture -Groundwater quality -Biodiversity	-Water quality -Ecosystem services -Embodied carbon	-Quality of emergency plan	-Environmental Suitability	-Climate Change and Energy -Ecology /Biodiversity -Physical resources

<b>Society</b>	<ul style="list-style-type: none"> <li>-Social Engagement</li> <li>-Aesthetic Values</li> <li>-Recreational Value</li> <li>-Cultural and educational Values</li> </ul>	<ul style="list-style-type: none"> <li>-Impact on Reputation or Politics</li> <li>-Road user experience</li> </ul>	<ul style="list-style-type: none"> <li>-Regulatory framework</li> </ul>	<ul style="list-style-type: none"> <li>-Time required for implementation</li> </ul>	<ul style="list-style-type: none"> <li>-Quality of Life</li> <li>-Safety, Health &amp; Equity</li> <li>-People and Communities</li> </ul>
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### 3.6.2. PROPOSAL OF ALTERNATIVES

The involvement of stakeholders from various backgrounds ranging from municipal and regional experts to landowners, interest groups, and residents—brings a diverse array of perspectives, expertise, and concerns to the forefront. This engagement facilitate decision making throughout the planning, implementation, and maintenance phases of adaptation measures. According to [132] and the expert input provided, the level of change is the most addressed way of analysing the alternatives. Accordingly, and considering the landslide event scenario, the following tables below were developed shown in Fig. 41 and 42 analysing different possible options. While most of these criteria are interrelated to a valuation of cost, this will be analysed separately in the evaluation.

Once the infrastructure vulnerability assessment has been completed, it will be necessary to propose specific adaptation measures. These measures should allow combatting the risks identified and reduce the overall risk levels on the infrastructure. After choosing the case studies to be evaluated by this methodology, a detailed understanding of the possible adaptive measures has been done where each measure had some of its main benefits highlighted, its suitability and ways of measurement to facilitate the evaluation in the next stages. The database focused on solutions for 3 main consequences: erosion, landslides and permafrost. The references for the data [27] [147] [55] [140] are found in Table 33.

Example	Consequence	Benefit	Effect or Expected Outcome	Parameter for Assessing Magnitude of Effect	Possible Means of Measurement	Possible Means of Valuation	Type of Solution
<b>Wall composed of micropiles</b>	Landslide	Safety	Increased slope stability and reduced landslide risk	Frequency and severity of landslides	Landslide monitoring data	Cost savings from fewer landslide incidents	Grey
	Landslide	Durability	Enhanced structural stability of slopes	Maintenance and repair frequency	Maintenance records and costs	Long-term cost savings and infrastructure longevity	Grey
	Landslide	Accessibility	Maintained road accessibility during adverse conditions	Road closure frequency	Number of road closures avoided	Economic benefits from reduced travel disruption	Grey
<b>Riprap buttresses</b>	Erosion Control	Safety	Prevention of riverbank erosion and flooding	Incidence of erosion and flood events	Number of erosion incidents and flood events	Economic savings from avoided flood damage	Hybrid
	Erosion Control	Durability	Stabilized riverbanks and reduced erosion	Erosion rate measurements	Erosion rate monitoring data	Cost savings from reduced erosion impacts	Hybrid
	Erosion Control	Ecosystem Services	Enhanced aquatic and riparian habitats	Biodiversity and habitat quality metrics	Biodiversity surveys and habitat assessments	Environmental value of improved habitats	Hybrid
<b>Mesh anchored by bolts</b>	Landslide	Safety	Prevention of rockfall incidents	Frequency and severity of rockfalls	Rockfall monitoring data	Cost savings from avoided accidents and repairs	Grey
	Landslide	Durability	Enhanced road safety and stability	Maintenance and repair frequency	Maintenance records and costs	Long-term cost savings and infrastructure longevity	Grey
	Landslide	Accessibility	Maintained road accessibility during adverse conditions	Road closure frequency	Number of road closures avoided	Economic benefits from reduced travel disruption	Grey
<b>Monitoring to detect potential problem areas</b>	Permafrost Thawing	Improved Durability and structural integrity	Reduction in frequency and level of Replacement/upgrading needed	Hours worked, units of material, fuel machine hours	Wages, hours of service loss, machinery and materials needed	Infrastructure durability, level of change number of distresses and/or failures	Grey
	Permafrost Thawing	Contribution to climate change positively	LOC in the air quality	Variation in volume of greenhouse gasses released to the atmosphere / temperature change record	Atmospheric observations	Identification of the total Global Warming Potential (GWP) change	Grey
<b>Maintain specific construction and maintenance records</b>	Erosion Control	Durability	Changes in emergency maintenance costs, frequency of road failure, and effectiveness of resource allocation	Material savings, labour needed, machinery, time	Costs of material, wages, degree of intervention	Condition of infrastructure, time of recovery, period of loss of service	Grey
	Erosion Control	Availability and accessibility	Change in time needed for decision making and intervention	LOS, travel time, change of traffic flow	Serviceability of network, LOS change	Condition of infrastructure, time of recovery, time of loss of service	Grey
	Erosion Control	Safety	Maintain an acceptable level of safety	Identifying patterns, high-risk areas, and common causes of incidents	Conduct regular safety audits and assessments of the road infrastructure	Incident data analysis	Grey

Figure 41 Table of Adaptation Measures Descriptions 1

Example	Consequence	Benefit	Effect or Expected Outcome	Parameter for Assessing Magnitude of Effect	Possible Means of Measurement	Possible Means of Valuation	Type of Solution
Erosion Control	Erosion Control	Job Opportunities	Creation of demand for specialists in forest and land management and timber harvesting investments	Quantity of jobs created, availability of business lines, potential for forest products from ongoing management	Statistical observation data from government labour statistics, industry reports, or job market platforms	Periodic updates on employment status fulfilled	Nature-based
Erosion Control	Erosion Control	Safety	Reduction of flooding events on nearby infrastructure	Risks associated with infrastructure use	Number of affected users, frequency of flood accidents	Value of statistical life	Nature-based
Erosion Control	Erosion Control	Climate Change	Carbon sequestration and prevention of uncontrolled wildfires	Measure changes in greenhouse gases (GHGs) periodically	Remote sensing measurements to monitor the effects of forest disturbances and changes in land cover	Quantity of carbon sequestered in both vegetation and soils, emissions and removals of GHGs	Nature-based
<b>Cutting slopes to shallower angle</b>	Landslide	Safety	Reducing risks related to slope dynamics accidents or connection blockage	Detect LOC of probability of slope failures or landslides, LOC of number of risks encountered	Costs of maintenance or reconstruction	Potential savings or avoidance of costs associated with slope failures or maintenance	Grey
Landslide	Landslide	Accessibility	Improved accessibility for pedestrians, cyclists, and other vulnerable road users	Number of users	Visual means and observations	User feedback and satisfaction	Grey
Landslide	Landslide	Durability	Feasibility of solution for road maintenance	Level of effort needed for maintenance	Cost of construction of a shallow reconstruction costs ratio	Cost savings	Grey
<b>Protection of wind-exposed road sections with planted forests and other vegetation</b>	Erosion Control	Climate Change	Improved air quality and reduced temperature	Temperature change, carbon sequestration	Delta temperature, metric tons of carbon stored per area	Value of improved climatic conditions	Nature-based
Erosion Control	Erosion Control	Safety	Reduction in the frequency and severity of accidents and damages	Reduction in the occurrence and severity of accidents	Quantifying changes in the number of accidents, types of accidents, and severity levels	Quality of travel	Nature-based
Erosion Control	Erosion Control	Accessibility	Enhanced connectivity and ease of travel	Travel time, road closures, ease of transportation	Expenses associated with changes in the efficiency of travel and reduced delays, duration of road closures	Transportation costs, potential business losses	Nature-based
Erosion Control	Erosion Control	Ecosystem Services	Enhancement of local ecosystems	Ecological health of the ecosystem	Biodiversity surveys, soil health assessments, ecological monitoring	Quality of biodiversity and ecological health of the land	Nature-based
<b>Interseasonal Heat Transfer</b>	Permafrost Thawing	Safety	Elimination of snow and ice danger effects	Occurrence and severity of accidents	Number and scale of accidents	Quality of life and properties	Grey
Permafrost Thawing	Permafrost Thawing	Durability	Improved road quality and life	Extension of life span variation before and after, unit of material and maintenance costs	Costs and expenses for maintenance	Resurfacing costs, repair expenses, and overall infrastructure investment	Grey

Figure 42 Table of Adaptation Measures Descriptions 2

Metrics		Availability	Direct Cost	Reputation	Safety	Impact on network	General Management	Climate Change and Energy	Ecology / Biodiversity	Physical resources	People and Communities	Quality of Life	Safety, Health & Equity
A. M. 1	Assess the risk of landslides based on pore pressure	-3	-2	-1	-1	0	0	0	0	0	1	0	0
A. M. 2	Avoid deforestation on slopes	3	-1	2	1	0	0	0	3	0	3	2	2
A. M. 3	Carriageway cross-over	-2	-2	2	-1	0	1	2	1	1	1	1	2
A. M. 4	Carrying out risk assessment of identified areas	1	-2	-2	2	1	1	0	0	0	0	0	0
A. M. 5	Continuously measure the pore pressure in the slope	3	-2	0	1	0	0	0	0	0	0	0	0
A. M. 6	Cover slope with rock blanket	2	2	2	3	1	-1	-3	0	0	-3	0	0
A. M. 7	Cover slope with vegetation	3	-1	1	1	0	0	2	0	0	1	0	0
A. M. 8	Cutting back the slope to a shallower angle	1	-1	0	2	-1	0	0	-1	0	0	0	0
A. M. 9	Develop plans and routines for the priority of securing areas prone to landslides	1	-2	0	2	-1	0	0	0	0	0	0	0
A. M. 10	Implement a system of geotechnical risk management	2	1	-1	1	0	0	0	0	0	0	0	0
A. M. 11	Inspect and clean watercourses regularly	3	1	0	2	0	0	0	1	0	0	0	0
A. M. 12	Install erosion barriers soon after the wildfire	3	1	1	2	0	0	0	1	0	1	0	0
A. M. 13	Lane closure	-2	-2	2	-3	0	1	2	1	1	1	1	2
A. M. 14	Make strategies for temporary rerouting	3	-1	2	1	2	-2	-1	0	0	0	-1	0
A. M. 15	Mapping areas prone to landslides	2	0	1	1	0	0	0	0	0	0	0	0
A. M. 16	Mapping sites of occurred landslides	0	0	0	0	0	0	0	0	0	0	0	0
A. M. 17	Rebuild stretches of the road on safe ground	1	-1	-2	1	-1	-2	-2	-2	0	-2	0	0
A. M. 18	Resize drainage systems to meet threats	3	-1	2	1	-1	0	2	-1	0	-1	0	0
A. M. 19	Spread mulch over the soil to protect it	3	0	1	1	0	0	0	2	0	1	1	0
A. M. 20	Stabilize the surrounding area	2	1	1	2	1	0	0	-1	0	-1	0	0
A. M. 21	Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides	1	-2	0	1	0	0	0	0	0	0	0	0
A. M. 22	Support the slope with a retaining structure	3	-2	0	0	0	0	0	0	0	0	0	0

Table 33 The weighing table of the different possible solutions

### 3.6.3. STANDARDIZATION OF ATTRIBUTES

Then, the data present has been evaluated for 5 chosen adaptation options obtained and compared based on 2 different criteria, environmental and political to understand how the different perspectives would affect the choice of measure. It can be noticed that the choice is extremely affected depending on the perspective of the person in charge of choice; however, it is a strong point to state that regardless of the priority, there is always a NbS that could be a candidate for evaluation. Yet, the scores should be also updated to reflect their situation more accurately depending on the decision maker's perspective and this is performed in Table 34.

Table 34 Standardization of Attributes based on Different Priorities

<b>Attributes</b>	Risk Reduction	Technical Feasibility	Environment & Ecosystem	Society
Criteria/Priorities	C1, C2, C3	C7, C8, C9	C4, C5, C6	C10, C11, C12
<b>Neutral</b>	3	3	3	3
<b>Technical</b>	5	4	3	1
<b>Political</b>	2	3	2	5
<b>Environmental</b>	3	2	5	4
<b>Average</b>	3.3	3	3.3	3.3

According to the selected perspective, 5 chosen adaptation measures are ranked using the TOPSIS method and the best is evaluated in the next stage. The last stage is to structure a list of KPIs possible for evaluation and choose at least 1 category specific KPIs to evaluate the chosen adaptation measure for level of change. In this project, the data used is obtained from a previously conducted multi-criteria analysis; data source results obtained from the ICARUS project. A proposal is made to create a standardized base category highlighting the common aspects among all the studied frameworks. Following that, a weighing will be made not for the alternatives but rather for the priorities, which is the key difference between the frameworks and in practice. This depends on the accuracy of the evaluation and the aim of the project, making the number of indicators dynamic, adapting to the needs of the project. To be able to facilitate this, the indicators have been normalized according to the gradings proposed by the base project [88].

This consideration has been made and analysed by the TOPSIS method, which is Technique for Order of Preference by Similarity to Ideal Solution, is a MCDA method; it is based on the concept that the chosen alternative must have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution [75]. The ranking of the alternatives has been done following the TOPSIS method. TOPSIS is a compensatory aggregation method that evaluates a set of alternatives by normalizing scores for each criterion considered in MCDA and calculating the geometric distance between each alternative and an ideal solution, maximizing the benefit criteria and minimizing the cost criteria, while the anti-ideal solution, which would be the cheapest option; this method is chosen as it fully utilizes attribute information, provides a cardinal ranking of alternatives, and does not require independent attribute preferences. It aids decision-makers in organizing problems, analysing, comparing, and ranking alternatives, thus facilitating the selection of the most suitable option. This is shown in the Fig. 43 below.

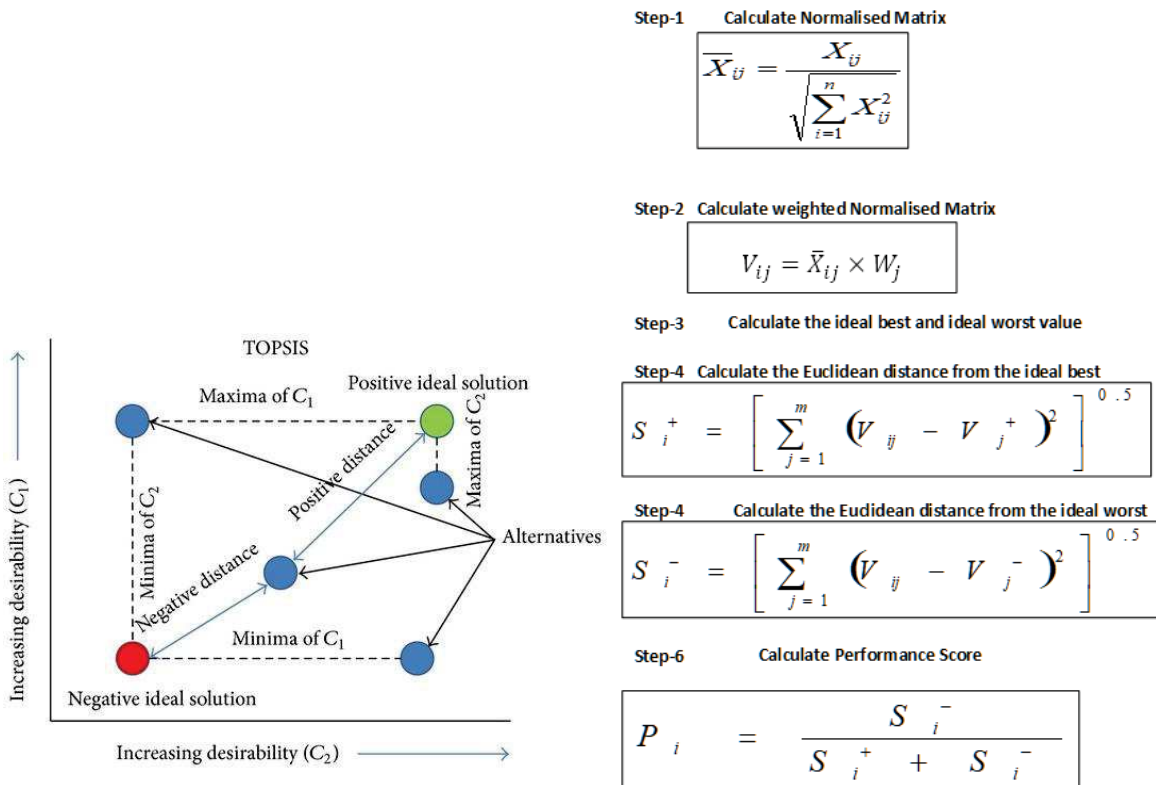


Figure 43 TOPSIS Method and Equations

### 3.6.4. STANDARDIZED WEIGHING OF ALTERNATIVES

The first trial made was to try to weigh the data presented from ICARUS in terms of objective evaluation methods such as the Entropy Weight Method (EWM) [75]. The aim was to use this approach to evaluate the significance of each response without considering biased preferences. It is employed to determine the weight of a specific issue based on the data from the decision matrix, essentially the performance scores of various alternatives concerning each criterion and/or attribute and operates on the principle that information from higher-weight indicators is more valuable than that from lower-weight indicators. It is true that this method has proven effectiveness in several studies including [75] however due to the nature state of the stakeholder input data used in this project, the application of this method was not possible due to the binary and negative quantification values restricting the formula application. It is recommended by the author to redo this method and compare the results with the final chosen method in this study to understand how close the interpretation has been when considering unbiased weighing criteria. The second approach was to consider reinterviewing stakeholders in request of changing the scale of grading and obtaining more bold evaluations, however this approach was also limited due to the time restrictions for data collection. The 3<sup>rd</sup> method was to create a baseline weighting method, highlighting the different priorities, standardizing the criteria into fixed categories and ranking the alternatives on this basis. This evaluation created a considerable method for not only reaching bolder results but also reducing the radius of ambiguity in realizing how the prioritization of certain alternatives has been made. This resolves the gap of finding the same adaptation option valued the same but different in each case study but rather fixes the choice based on the priorities keeping the nature of the solution fixed in terms of its own performance. The best criteria to follow in this case was following a study [88] that has created an extensive database of KPIs covering all the aspects needed for evaluation and using a reliable stakeholder input for analysing the different priorities in terms of Technical, Environmental, Economic, Political or Average no priority. The factors involved in the analysis of 3

frameworks supported the structure defined because they fall majorly within these attributes and can a common basis among all.

Standardizing the attributes of the climate change adaptation measures for transport infrastructure according to a base category chosen enhances the robustness of decision-making by improving comparability, consistency, and comprehensiveness across multiple stakeholder priorities which is a key obstacle addressed in this research [88]. This is because when aligning all attributes to a unified base, the analysis ensures that various adaptation measures are evaluated on a consistent scale thus facilitating precise comparisons of their resilience effectiveness and sustainability contributions. Consequently, this approach enables more informed decision-making that considers the diverse priorities of stakeholders, enhances strategic planning by providing a clearer picture of trade-offs, and improves the communication of results to various audiences, ultimately leading to more effective and balanced adaptation strategies. Also, standardization can mitigate divergences ensuring that technical, economic, environmental, and social factors are uniformly assessed and covers. After the main decision has been made, it opens door for comprehensive case specific evaluation. This process of integrating then the diverse different dimensions can help in addressing the multifaceted impacts of climate change. This procedure can be applied to all the projects listed below for comparison however as ICARUS has been the basis of this work, the first approach was to try to apply the standard weighing on its values, however it was not possible due to the form of weighing. The benefits and co-benefits developed were evaluated according to binary positive, negative or no change effects compared to the current situation. Thus, the same adaptation measures were looked up in a different database, the [147] and used to complete the study with a more comprehensive way of weighing suitable for the type of study proposed. Accordingly, the approach is mentioned in below in steps towards ranking and proceeding with weighing. The Criteria for KPIs and applying on the Cobenefits is obtained from ICARUS and shown in Table 35.

Table 35 Criteria for KPIs and applying on the Cobenefits

<b>C 1</b>	-Safety	<b>C 7</b>	-Reputation
<b>C 2</b>	-Impact on network	<b>C 8</b>	-Availability
<b>C 3</b>	-General Management	<b>C 9</b>	-Direct Cost
<b>C 4</b>	-Climate Change and Energy	<b>C 10</b>	-Safety, Health & Equity
<b>C 5</b>	-Ecology /Biodiversity	<b>C 11</b>	-People and Communities
<b>C 6</b>	-Physical resources	<b>C 12</b>	-Quality of Life

### Effective climate change adaptation requires finding the right equilibrium as shown in Table 36:

Table 36 Description of adaptation conditions

<b>Too Little Adaptation</b>	can be through ignoring climate risks which then can lead to severe consequences, including loss of life, economic damage, and ecosystem disruption.
<b>Over-Adaptation</b>	can be through investing excessively in adaptation measures where risks are low may divert resources from other critical areas.
<b>Optimal Adaptation</b>	can be balancing risk, cost, and uncertainty ensures a pragmatic approach. It involves prioritizing actions that yield the greatest benefits relative to their cost

Adaptation measures revolve around several fields of implementation all serving almost the same goal, disaster reduction. However, the difference from conventional/grey solutions reaching regenerative is huge. This difference is mainly present throughout its lifecycle and with its presence as a new element in the urban context with its own impacts and risks. Besides serving the main purpose of protecting the infrastructure asset from the climate change impacts, it is a priority to make sure that itself is not contributing as a catalyst of climate change. This is present in planning towards regenerative solutions and opens doors for seeking nature-based solutions.

### 3.7. DETAILED ANALYSIS OF THE ALTERNATIVES

#### 3.7.1. ADAPTATION MEASURE EVALUATION

The final stage of the methodology is the detailed evaluation. Climate change is dynamic and there is no certainty over how much time would be expected until the next hazard encounter. For that it is important that the solution implemented gives an added value to the urban context it has been put in and provide benefits in the way it is constructed, maintained or altered in the location where it was set.

Uncertainty is an element that cannot be avoided in the process of valuation and analysis of the effectiveness of the adaptation option. After identifying climate-related risks and mapping environmental and social conditions, the next step involves identifying and evaluating potential solutions in collaboration with stakeholders. Typically, there are multiple options available for addressing a specific climate challenge, including nature-based solutions, grey solutions, or a combination of both. In some cases, the optimal solution may entail implementing a measure in a different geographical location from the problem area itself. Thus, adopting a landscape perspective becomes crucial for assessing potential solutions based on geographical conditions. The compiled list should encompass all potential solutions, whether traditional grey or nature-based, and provide a comprehensive overview of their direct and indirect advantages and disadvantages as shown in Fig. 44 below

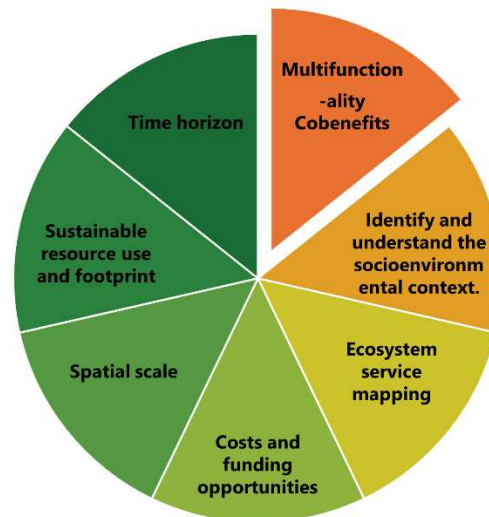


Figure 44 Evaluation Criteria for selection of adaptation solution

. Long-term functionality, resource use, testing, and funding must also be addressed for aiding a comprehensive solution evaluation. Some key aspects to look for include:

### **Spatial scale**

Various climate-related risks may necessitate management at different spatial scales. Moreover, a measure may have implications for surrounding land areas and environments. Thus, adopting a comprehensive landscape perspective is advisable to encompass all effects of a measure effectively.

### **Multifunctionality- Identifying Cobenefits**

Each proposed measure should be accompanied by a list of its benefits, including those pertaining to other societal challenges. The primary advantage of nature-based solutions for example lies in their potential for multifunctionality when designed meticulously where they should not detrimentally impact biodiversity but instead augment it. Thus, it is imperative to outline the benefits, including added value, at this stage to form a basic understanding of the various potential solutions. This step involves identifying and documenting any disadvantages and risks associated with each measure.

### **Time horizon**

Understanding the advantages and disadvantages of both short and long-term implications is essential. Implementing an adaptation solution often requires time to realize its full impact, distinguishing it from traditional grey solutions. The time factor is also significant from a maintenance standpoint. Various solutions necessitate different maintenance approaches, with nature-based solutions typically requiring continuous management, while engineered solutions may entail longer service intervals, spanning several years. It's prudent to consider not only the costs but also the responsibility for managing the solution.

### **Sustainable resource use and footprint**

A measure designed to adapt communities to climate change should not exacerbate greenhouse gas emissions. Therefore, it's crucial to scrutinize material usage and potential carbon footprints. This entails evaluating the materials required for the measure and assessing whether the processes involved are energy intensive and the impact of the materials used. Additionally, it's pertinent to consider the long-term sustainability of the measure and the requisite management and maintenance needs.

### **Costs and funding opportunities**

Including the total costs over time is advisable, as a sustainable measure should remain functional well into the future. Considering the time horizon reveals that significant upfront costs, such as those for compensation or land acquisition, can be offset by low maintenance expenses. Essentially, nature-based solutions demonstrate substantial potential for cost-effectiveness because, when appropriately designed, they contribute to economic, environmental, and social sustainability.

To be able to put all these considerations into practice and validate the best-chosen method, an evaluation can be made based on the 4 main criteria following at least 1 KPI each. This step is case specific depending on the context, available data, possibility of application and priority of choice which gives back the involved stakeholder the freedom of choice to decide

### **Identify and understand the socioenvironmental context.**

Understanding biodiversity and ecosystem services is paramount for effectively enhancing landscape climate adaptation addressing several critical inquiries to inform decision-making processes comprehensively. Examining the area's environmental and social characteristics, including habitat types and topographical features are pivotal in determining adaptation strategies. Also, the current land use patterns and demographics to discern utilization and ecosystem service provision. On the other hand, identifying key stakeholders, such as landowners, residents, and interest groups, is crucial for fostering

a user-based support and integration developing tailored and effective approaches to climate adaptation that prioritize biodiversity conservation and ecosystem resilience.

### Ecosystem service mapping

Given that ecosystems typically provide a multitude of services, it's crucial to underscore the presence of other ecosystem services that exist and influence the overall outcome. The natural conditions prevalent in the area serve as a crucial determinant and framework for devising climate adaptation measures, whether through nature-based solutions, grey infrastructure solutions, or a blend of both. Once the ecosystem services have been mapped, the subsequent step involves analysing and visualizing the values they generate through an ecosystem service analysis. This analysis establishes a link between how ecosystem services contribute to societal well-being and how these values can be impacted by various alternative measures. The outcome of this process furnishes decision-making insights, delineating existing values in the area, how they can be positively impacted by a measure, and what considerations can be taken to mitigate negative impacts.

#### 3.7.2. PRIORITISE A SOLUTION

The solution should be viewed as part of a whole, meaning part of an overall strategy for climate adaptation. Based on the initial assessment of possible measures developed, in-depth analyses like cost-benefit analyses or multi-criteria analyses are done in this step to prioritise the different options. The analyses also help to determine whether a measure is justified from a sustainability perspective and can be used for both nature-based and engineered measures. To compare engineered and nature-based solutions, it is vital to weigh and evaluate even the less visible benefits of a measure, multifunctionality: The main benefits that nature-based solutions can offer to address climate challenges in different sectors, as well as the additional co-benefits that are created. The division of the analysis will be through choosing at least 1 parameter representing or contributing to the overall criteria shown in Fig.45.



Figure 45 Stages towards selection summed up

#### 3.7.3. OPERATION OF SOLUTION

##### Management plan

Planning for maintenance and management of nature-based and grey solutions should be addressed early in the process. After a preliminary assessment, a detailed management plan should be developed, specifying tasks, responsibilities, and financing. Stakeholders' roles should be clear, and funding sources identified. Monitoring and evaluation mechanisms must be established, with contingency plans in place. Regular reviews are essential to ensure ongoing effectiveness.

##### Follow-up and evaluation

Monitoring and assessing the selected solution are crucial due to the current limited understanding and systematic evaluations of their full potential, particularly for large-scale applications and their long-term performance. Without this, there is a risk for example that nature-based solutions may be overlooked in favour of traditional grey infrastructure, which is better understood in case of, inherently reliant on dynamic and complex ecosystem functions, introduce a degree of uncertainty. Consequently, ongoing monitoring and evaluation are vital to facilitate necessary modifications and adaptations over time, embodying an adaptive management approach.

## PRECIPITATION INDUCED LANDSLIDES

### 4.1. GENERAL OVERVIEW

#### 4.1.1. CONTEXT DESCRIPTION

GI-627 Road in Fig. 46 is located in Gipuzkoa, a province in the Basque Country, northern Spain, with hilly and forested areas (around 43°N, 2°W). Slopes with lengths varying from 100 to 600 meters, with gradients often exceeding 20 degrees. It has predominantly a large scale of mountainous terrain with dense forests; limited agricultural activity and significant areas designated as natural parks and reserves.



Figure 46 GI-627 Landslide incident in 2021[158]

Among the GI-627, in Eskoriatza and Aretxabaleta, there are three roundabout-type discontinuities in the section between Arlabán and the Goroeta junction. Also, in Arrasate there is a roundabout at the junction with the AP-1 and the GI-2630, the access road to Oñati. In the municipal area of Bergara there is a roundabout-type discontinuity, between the Engiozar junction and the Elgeta junction. The Average Annual Daily Traffic (AADT) is around 4,000 vehicles, with a significant proportion being heavy goods vehicles (approximately 15%).

According to the historical statistics in Gipuzkoa, the basic network, the GI-627 characterized among the greatest number of accident concentration sections, with three sections of concentration of accidents with recurrence in the periods in the last period decade. Landslides events have increased due to

precipitation and soil saturation lead to frequent landslides, particularly on steep slopes. This caused Steep gradients and heavy rainfall accelerate erosion, undermining road foundations and affecting road stability and safety. Changes in the frequency and intensity of the precipitation events are expected in 2050 as shown in Fig. 47 and Fig. 48 thus, the risks associated with landslides and flooding are predicted to rise by 50%-70 Effective engineering solutions, though necessary, pose economic challenges due to high costs. Table 37 presents the following resources for climate and hazard data used.

Table 37 databases used and analysed from the following resources for climate and hazard data:



#### 4.1.2. CASE DESCRIPTION

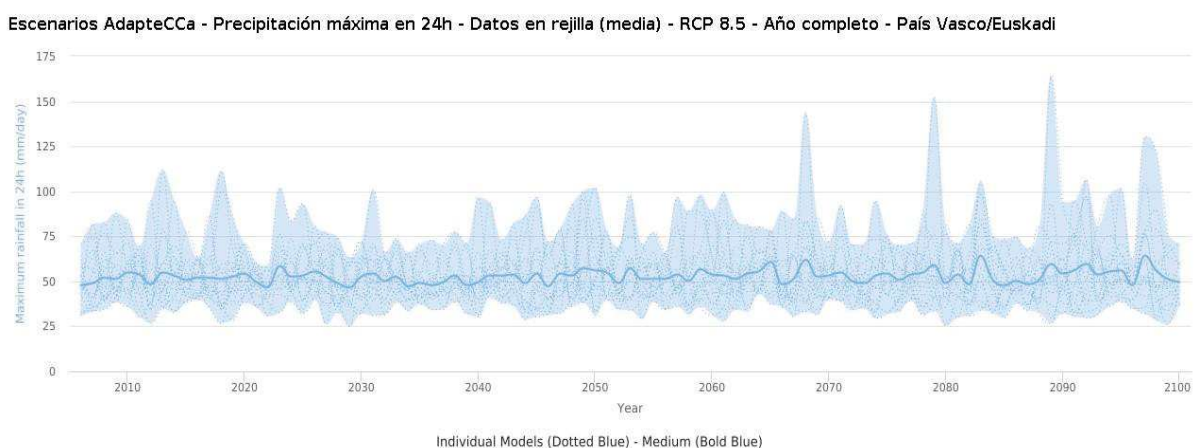
<b>Infrastructure Name</b>	GI-627
<b>Location</b>	Gipuzkoa, Basque Country, Spain
<b>Network Direction</b>	FROM VITORIA TO EIBAR
<b>Typology</b>	Road
<b>Full length</b>	38.24 km
<b>Nodes Affected</b>	kilometre points 22,855 and 22,965
<b>Hazard Imposed</b>	Landslide
<b>Most probable climate impact driver</b>	Precipitation, Slope instability
<b>Latest Event Date</b>	13 January 2022, Between Eibar and Soraluze
<b>Number of Unstable Nodes/totals</b>	Numerous; specific data required
<b>Latest Event Description</b>	Very Fast
<b>Affected Components</b>	55m long longitudinal wall constructed from 1991 Pavement surface and Pedestrian Lane signs of Instability and deformation Transport Function: Limitation of traffic / Cycling route affected
<b>Existing Adaptation Measures</b>	Installation Retaining walls of Micro-piles
<b>Economic Expenditure for Maintenance</b>	0.8 Mi Euros for Road Surface Repair Land Repair: Slope Stabilization cost of 1,453,071€
<b>Execution Time</b>	5 Months; Full Repair
<b>References:</b>	[37], [159], [160], [161], [162]

## 4.2. PRELIMINARY VULNERABILITY ASSESSMENT

### 4.2.1. GROUND PREPARATION FOR CLIMATE ADAPTATION:

#### Historic Climate Data:

Table 38 presents Historic Data in Gipuzkoa up to 2021. The IPCC report indicates with high confidence that climate change will lead to more intense and frequent precipitation in the Mediterranean region, with the largest increases in extreme precipitation expected in the western and northern areas. In Europe, most sources suggest a general trend of rising precipitation intensities, consistent with the IPCC's findings, though variations in these trends are also present. Yet, to consider the effect of a hazard being induced by precipitation, the study should be limited to a specific geographic location at the local level. This is needed to draw more comprehensive conclusions about the correlations. Therefore, it would be valuable in future research to apply the methodology from this work to representative rainfall series.



Fuente: <http://escenarios.adaptecca.es>

Figure 47 Maximum precipitation in 24hrs mm/day in Basque country under RCP 8.5 [155]

Table 38 Historic Data in Gipuzkoa According to the [37], the following data have been recorded in Gipuzkoa up to 2021.

Year	Average Annual Precipitation (mm)	Number of Rainy Days	Maximum Precipitation in 24 Hours (mm)	Maximum Number of Consecutive Wet Days	Number of Days with $\geq$ 20 mm Precipitation	Maximum Accumulated Precipitation in 5 Days (mm)
2010	1411	186.5	68.6	9	14	220.6
2011	1277	165	114.3	10	16	149
2012	1328	188	54.1	13	18	188.5
2013	2050	210	73.5	12	22	136.3
2014	1578	213	53.6	11	19	175.6
2015	1503	185.8	88.5	13	21	131.8
2016	1448	198	78	19	19	155.6

<b>2017</b>	1478	185	71.3	18	21	147.8
<b>2018</b>	1597	211	81.6	11	19	153.3
<b>2019</b>	1652	143	64.9	18	-	124.5
<b>2020</b>	1424	187	60.2	8	-	211.4
<b>2021</b>	1489	177	85.8	-	20	-

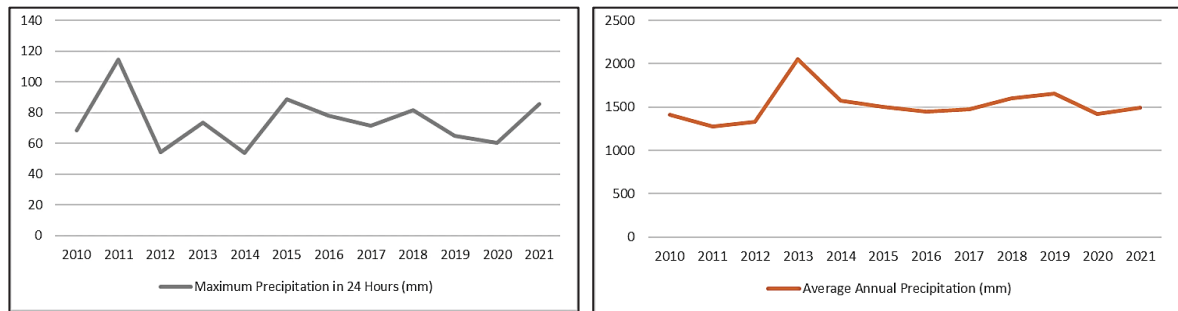


Figure 48 The trend of rainfall in Gipuzkoa, the case study location

It can be noticed that when comparing the historical events with the projections, there is no significant trend that proves that the precipitation would increase nor the opposite. According to this, it is difficult to interpret how the situation would be in the future scenarios as it is very dynamic and carries an uncertain trend. Also, when analysing the possibility of having a sudden precipitation event after the drought, the impact on the soil conditions would result in a rapid quick generation of landslide causing a critical risk on the infrastructure. For that reason, it is important to keep in the mind the realization that the solution designed should be covering consistent precipitation events or sudden. After analysing the climate information, the next step is to understand the time of event occurrences and try to find the underlying trend happening when correlating the precipitation with the landslide generation.

In the study made on the Gipuzkoa region, the basic landslide instabilities governed by water pressure variations. In both types of landslides mass landslides and flow-type instabilities, the triggering factor considered is precipitation, in the form of continuous precipitation with significant accumulations in the case of mass landslides (projections of accumulated precipitation in 5 days), or in the form of short but intense rainfall in the case of flow instabilities (projections of maximum daily rainfall as studied). Yet, this analysis has been only expressed qualitatively concluding that the susceptibility in general is low to moderate, with moderate to very high susceptibility zones concentrated in the mountainous areas [37].

Trying to bridge this hypothesis with realistic data, a reliance on a risk assessment developed in the study [160] where the risk assessment process evaluated the probability of failure of the road network overseen by the Gipuzkoa Regional Council. Addressing various slope instabilities such as rockfalls, retaining wall failures, slow-moving landslides analysis was informed by extensive field data collection, which was then integrated with assessments of the expected consequences associated with each hazard [160].

The correlation between the risk assessment and vulnerability assessment can provide a stronger view towards the limitations of the current solutions and opens doors to the potential for choosing the right adaptation measure. Some insights on the current situation can be also shown in Fig. 49 and Fig. 50.

The translation below refers to natural disasters in the Gipuzkoa region of Euskadi, focusing on flooding, Tempestades Ciclónicas Atípicas (TCA), and the impact of sea surges (embate de mar). These are common risks in the area, with previous reports detailing the extremity.

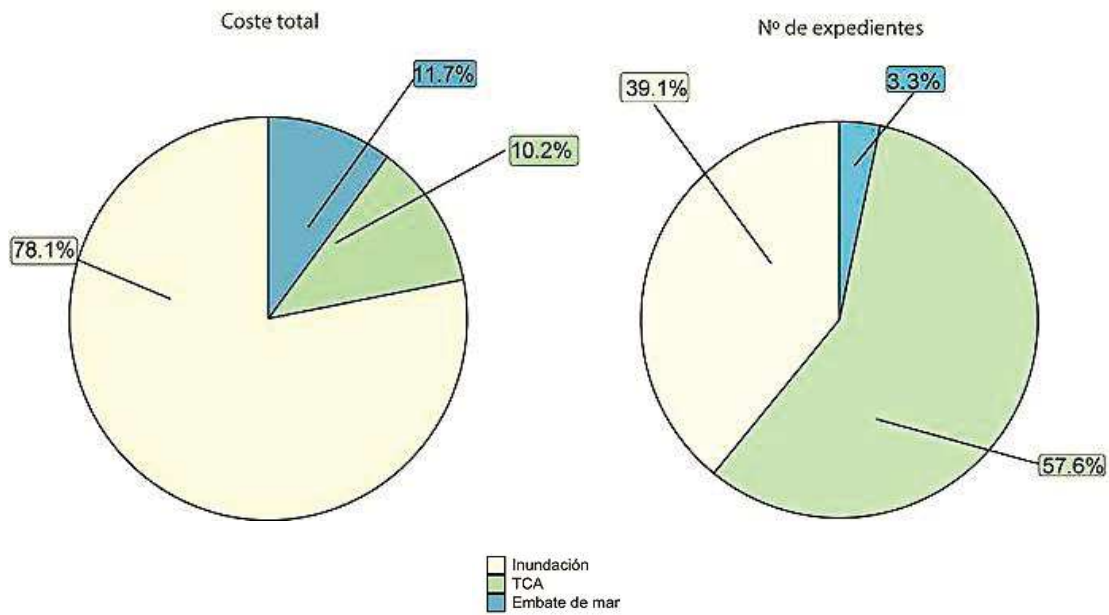


Figure 49 Damage caused through landslides

Figure 50 Cause of occurrence

The study area is focused on the Gipuzkoa Road Authority, in the Basque Country, Spain especially transport infrastructures and narrowing down to road networks This is due to the importance of their capacity and functionality being the connecting corridors in that region. The layout of the road networks has been spatially constrained by its characteristically strong morphological reinforcement [164]. Fig. 51 below showcases a map revealing the notably high susceptibility to landslides in the Basque Country and throughout the Cantabrian Mountain range. This observation is unsurprising given the topography of the Basque Country, characterized by steep slopes (with more than 90% of Gipuzkoa's historical territory, 75% of Bizkaia, and 50% of Araba/Alava featuring slopes exceeding 15%) and high levels of rainfall. These conditions fundamentally promote the occurrence of landslides by facilitating the dislodging of loose materials or stones in the region. Thus, a theoretical increase in landslides is expected due to the increase in extreme rainfall due to global warming and human influence [165] [37]. The conditions existing such as land occupation and soil sealing stand out as prominent threats to soil conservation. The development of "grey" infrastructure on land surfaces to resolve the landslide susceptibility in the area not only diminishes the organic contributions but also contribute to a decline in soil organic carbon levels. This, in turn, impedes the soil's capacity to capture CO<sub>2</sub>, consequently affecting the viability of life in these regions. Addressing such, it is the driver to look up solutions with less impacts while solving the consequences of climate change.

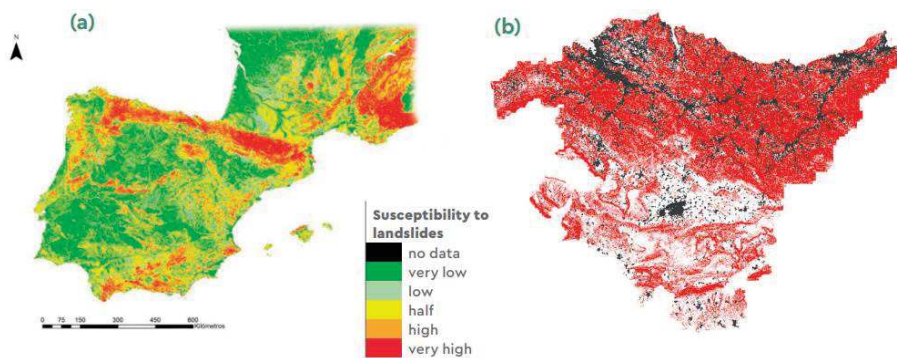


Figure 51 Map of landslide susceptibility in Spain [42] (b) Map of slopes in the Basque Country areas most prone to the landslide genesis marked in red (slope > 15 %)

As mentioned by [166], in 2018, a local collaboration was made among transport stakeholders to perform a study aiming to identify the most vulnerable inland transport infrastructure network needing consideration and attention due to the dynamic climate change yet as it was deemed difficult to obtain all the needed asset data covering information on the sensitivity to the different hazards, construction and maintenance details, and previous events occurrence thus it was qualitative assessment was then held by interviewing experts and personnel. When trying to analyse the situation in 2024, it is true that the difficulty in obtaining the data is still present and needs to be tackled. For that reason, the validation will be based on the qualitative assessment opening doors for a detailed verification in the future if data was obtained. According to a qualitative risk analysis in Table 39 of elements exposed covering the area of study and in climate change scenario (RCP scenario 8.5 for the period 2011-2040) [159], the following results were obtained on the infrastructure risks to climate change consequences as shown in Fig. 52 and Fig. 53 below: The results overall imply that the area and its 97% of the road infrastructure is subject to a moderate to very high risk thus, adaptation is needed in this area. The torrential rains over the past years have caused significant damage to Gipuzkoa's road network. Minor landslides have also occurred elsewhere in the region, leading to localized disruptions and pavement cleaning operations and it becomes particularly challenging due to persistent rainfall making rapid response and user safety quite critical. There is a constant need for having a thorough assessment and to deploy all available resources to restore normalcy as quickly as possible. This in return helps in responding swiftly and performing emergency repairs at all affected sites to minimize the impact on road users and reopen the entire network promptly. From the most affected roads is the GI-627[161].

Table 39 Road Infrastructure analysed in the study area under risk of climate vulnerable area[159]

<b>BASIC</b>	<b>REGIONAL</b>	<b>PREFERRED INTEREST NETWORK</b>
GI-627	GI-2631	N-638
GI-638	GI-2634	AP-8
GI-40	GI-2634	AP-1
N-629	GI-2636	
GI-631		
GI-3452		
GI-41		

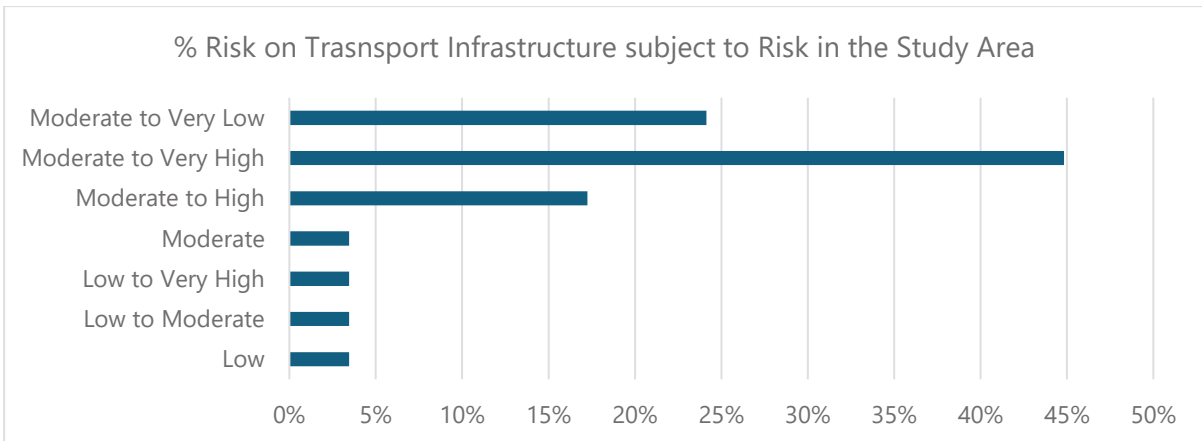


Figure 52 The percentage of risks in the study area on the different Infrastructure by grades

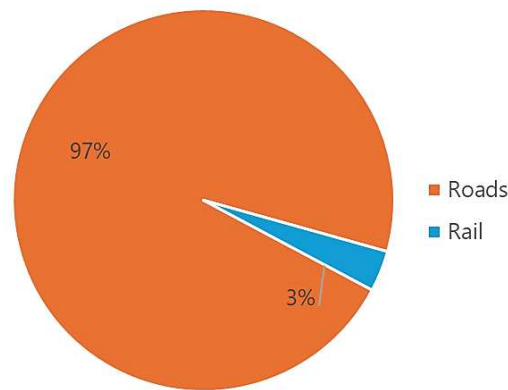


Figure 53 Count of infrastructure types prone to risks of landslides

When analysing 3 sources of data [167], it was noticed that there could be high uncertainties in the interpretation due to the lack of a more complete landslide inventory which also has been supported by previously done studies[160], [161]. Another aspect is being unable of creating definitive landslide susceptibility map for the studied area as this is beyond the scope of this study. Table 40 below shows the different information obtained for the studied area.

Table 40 Location and Details on Event occurrence

NAME	EVENT LOCATION	DATE	(Y, X) COORDINATES		COINCIDES WITH PRECIPITATION EVENT
GI-627	Between Eibar and Soraluze, Gipuzkoa	1/13/2022	43.19	-2.43	Yes
GI-627	Arlaban, Gipuzkoa	12/10/2021	42.96	-2.59	Yes
GI-627	Bergara, Gipuzkoa	12/24/2018	43.13	-2.42	Yes
GI-627	Arlaban, Gipuzkoa	2/5/2018	42.96	-2.59	Yes

<b>AP-1</b>	Lessari Tunnel, Bergara, Gipuzkoa	11/11/2022	43.13	-2.42	No
<b>NA-1300</b>	Navarre	6/22/2017	43.07	-2.01	Yes
<b>N-1</b>	Between Itsasondo and Legorreta Gipuzkoa	4/12/2018	43.08	-2.16	Yes
<b>N-634</b>	Zarautz and Getaria Gipuzkoa,	4/12/2018	43.29	-2.19	Yes
<b>GI-627</b>	Gipuzkoa	4/12/2018	43.07	-2.47	Yes
<b>GI-2630</b>	Udana, Gipuzkoa	4/12/2018	43.02	-2.36	Yes
<b>GI-2634</b>	Azkarate, Gipuzkoa	4/12/2018	43.04	-2.01	Yes
<b>GI-3452</b>	Gipuzkoa	2/16/2016	43.32	-1.80	Yes
<b>A-8</b>	Behobia, Bilbao	6/14/1988	43.34	-1.76	Yes

As climate change progresses, there is a probability of increase in the occurrence of intense and more frequent heavy rainfall. This saturation of soils on slopes, elevating the likelihood of shallow to medium-sized landslides and debris flows as shown in Fig. 54 below.

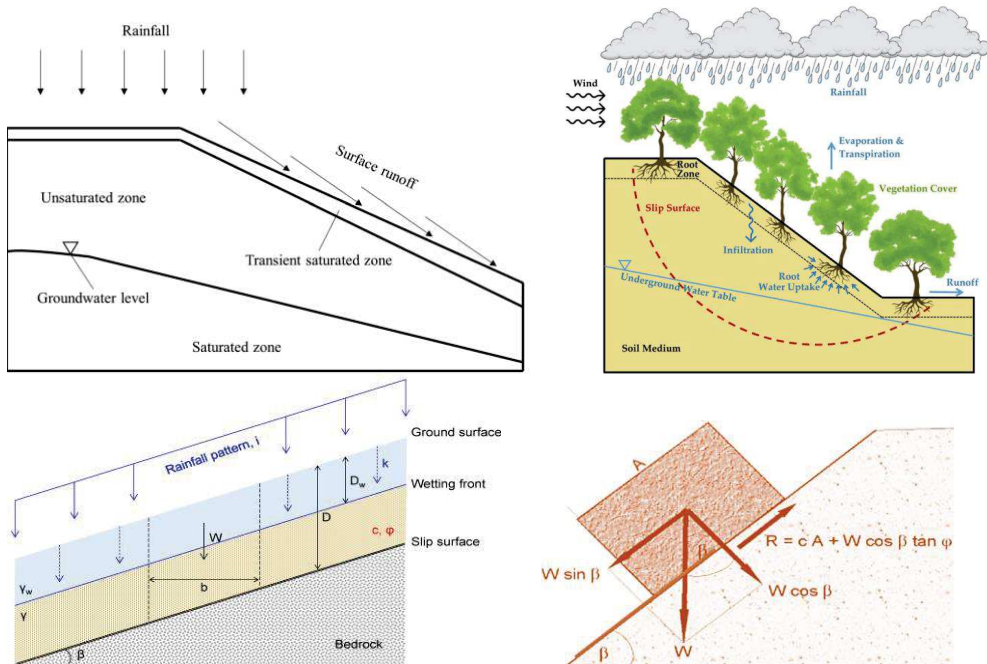


Figure 54 Visualization of the landslide dynamic action [51], [57]

To quantify the extent of it, the correlation of all these parameters can be deduced in the equation of USLE (Unified Soil Loss Equation). The USLE method is an equation-based quantitative approach used for indirectly assessing soil loss resulting from water erosion processes. This widely adopted method relies on modelling the natural soil system's response to rainfall to estimate erosion rates, supplying insights into erosion patterns and aiding soil conservation efforts worldwide. It determines the annual soil loss per hectare by integrating various factors such as rainfall intensity, soil properties, slope gradient, and land use practices as in Fig.55 below. This equation format facilitates systematic evaluation, allowing for a comprehensive assessment of soil loss dynamics and informing effective erosion control strategies.

$$A = R \times K \times L \times S \times C \times P$$

Where, A is average annual soil loss rate (t/ha/yr.), R is rainfall erosivity factor (MJ-mm/ha/h/yr.), K is soil erodibility factor (t-hah/ha/MJ/mm), LS is topographic factor, C is crop management factor and P is conservation supporting practice factor. The following parameters can be deduced from the graphs below derived from the soil susceptibility map for the Basque country [168].

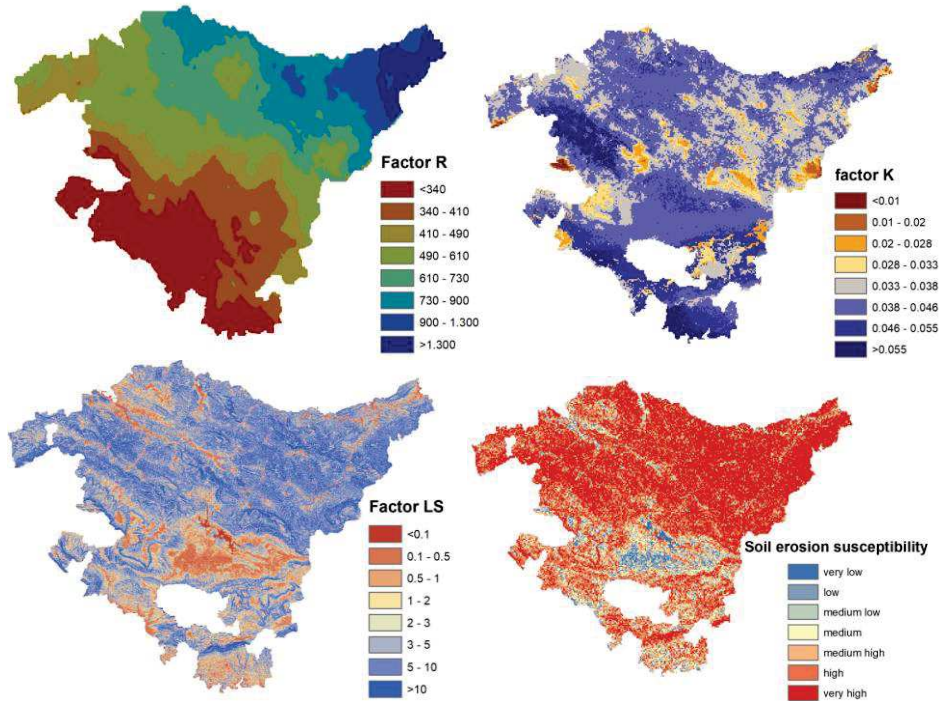


Figure 55 Input layers for the USLE Mode

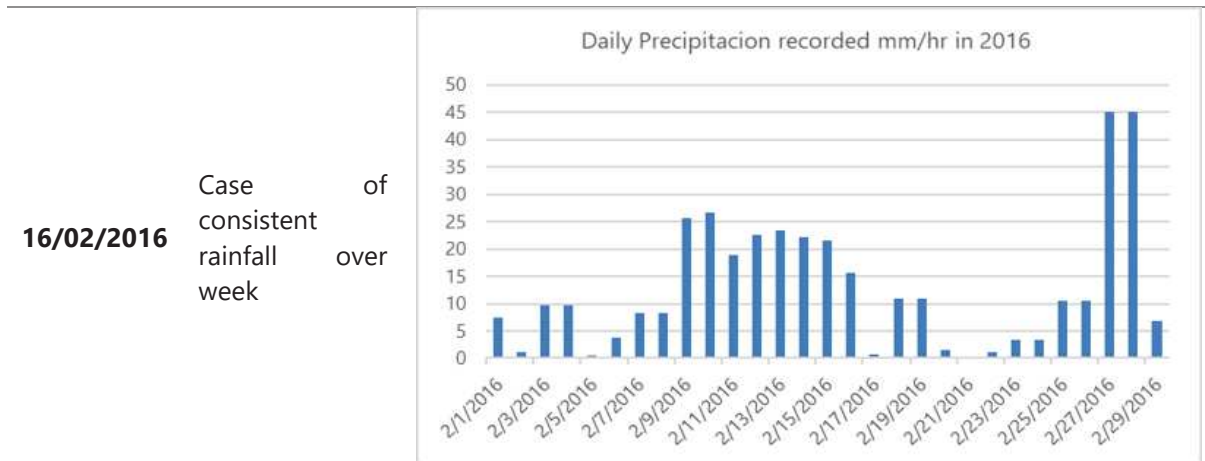
#### 4.2.2. CLIMATE DATA INTEGRATION

Analysing the rainfall events that have occurred during this period, the following results can be interpreted: Most of the events occur in 2 cases, when the rainfall event exceeds 35 mm/hr or when a consistent rainfall event persists close to a week with average rainfall of 20 mm/ hr. Also, it was noted that sometimes the event occurrence takes place either the same day or within the week after the rainfall event. The most severe year of landslides according to this sample is in 2018. The recorded daily rainfall data happening on the dates when the GI-267 road has been exposed to landslides are obtained from ERA5-Land Hourly Data from 1950 to Present can be shown in the graphs in Table 41 below:

Table 41 Interpretation of Climate events

LANDSLIDE ON GI-627	DESCRIPTION [167]	[159], MONTHLY METEOROLOGICAL RECORDS FROM [169]
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<p><b>13/01/2022</b></p> <p>Case of intense and consistent rainfall over week</p>	<p>Daily Precipitation recorded mm/hr in 2022</p> <table border="1"> <caption>Daily Precipitation recorded mm/hr in 2022</caption> <thead> <tr> <th>Date</th> <th>Precipitation (mm/hr)</th> </tr> </thead> <tbody> <tr><td>1/1/2022</td><td>0</td></tr> <tr><td>1/2/2022</td><td>0</td></tr> <tr><td>1/3/2022</td><td>15</td></tr> <tr><td>1/4/2022</td><td>16</td></tr> <tr><td>1/5/2022</td><td>6</td></tr> <tr><td>1/6/2022</td><td>9</td></tr> <tr><td>1/7/2022</td><td>9</td></tr> <tr><td>1/8/2022</td><td>36</td></tr> <tr><td>1/9/2022</td><td>37</td></tr> <tr><td>1/10/2022</td><td>23</td></tr> <tr><td>1/11/2022</td><td>5</td></tr> <tr><td>1/12/2022</td><td>0</td></tr> <tr><td>1/13/2022</td><td>0</td></tr> <tr><td>1/14/2022</td><td>0</td></tr> <tr><td>1/15/2022</td><td>0</td></tr> <tr><td>1/16/2022</td><td>0</td></tr> <tr><td>1/17/2022</td><td>0</td></tr> <tr><td>1/18/2022</td><td>0</td></tr> <tr><td>1/19/2022</td><td>0</td></tr> <tr><td>1/20/2022</td><td>4</td></tr> <tr><td>1/21/2022</td><td>4</td></tr> <tr><td>1/22/2022</td><td>1</td></tr> <tr><td>1/23/2022</td><td>0</td></tr> <tr><td>1/24/2022</td><td>0</td></tr> <tr><td>1/25/2022</td><td>0</td></tr> <tr><td>1/26/2022</td><td>0</td></tr> <tr><td>1/27/2022</td><td>0</td></tr> <tr><td>1/28/2022</td><td>0</td></tr> <tr><td>1/29/2022</td><td>0</td></tr> <tr><td>1/30/2022</td><td>0</td></tr> <tr><td>1/31/2022</td><td>5</td></tr> </tbody> </table>	Date	Precipitation (mm/hr)	1/1/2022	0	1/2/2022	0	1/3/2022	15	1/4/2022	16	1/5/2022	6	1/6/2022	9	1/7/2022	9	1/8/2022	36	1/9/2022	37	1/10/2022	23	1/11/2022	5	1/12/2022	0	1/13/2022	0	1/14/2022	0	1/15/2022	0	1/16/2022	0	1/17/2022	0	1/18/2022	0	1/19/2022	0	1/20/2022	4	1/21/2022	4	1/22/2022	1	1/23/2022	0	1/24/2022	0	1/25/2022	0	1/26/2022	0	1/27/2022	0	1/28/2022	0	1/29/2022	0	1/30/2022	0	1/31/2022	5
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As recorded by [37], December 9 and 10, 2021, numerous consequences impacting the transport network such as road closures because of rainfall induced floods and landslides. this event occurred after 10 days of intense rainfall ( $Pr > 1$  mm/day), in which more than 200 mm accumulated at the stations. The average daily total precipitation at the territory's meteorological stations was greater than 70 mm to 100 mm. Accumulation of precipitation, greatly exceeding the average accumulated precipitation values recorded during this century, this has created a social impact on the availability of the network and the accessibility to the main services as health centres, schools, or industrial areas. To mitigate the effects of interannual variability and ensure representative results, the analysis spans three 30-year periods in the future (2011-2040, 2041-2071, and 2071-2100) is recommended and present in Table 42. It is assumed that the climate variables remain stationary within each period. These selected timeframes offer adequate coverage across the century and provide a reasonable estimation of end-of-century impacts as shown in Table 43.

Table 42 National Level Climate Projections:

INDICATOR	2011-2040	2041-2070	2071-2100
N° Rainy Days	-1 ± 5%	-6 ± 4%	-14 ± 5%

Table 43 The noticeable trend of rainfall during the years is the prolonged rainfall

INFRASTRUCTURE	IMPACT TYPE	SEVERITY (1 TO 5)	EXISTING DATA	ACTION NEEDED
GI-627	Chronic prolonged rainfall)	3 (Moderate)	Limited	Adaptation

Following the data provided on climate change projections, the historical data and the event occurrences it can be considered that there is no fixed trend that shows when the landslide is expected to happen, how will the future be or claim that the situation would worsen or not. One way to try to resolve that is to be able to monitor the trend of precipitation causing the landslide occurrence, a correlation of all the landslide events occurred during rainfall events over history should be plotted refining this equation and showcasing at which peak level, the trigger occurs and causes the instability. Accordingly, planning to manage the rainfall volumes can be done ahead This correlation would help in identifying, which is the critical season, what is the critical time span of rainfall, what is the level of rainfall that triggers landslides and how to cope with its consequences making way for a better adaptation in the next years coping with the climate change dynamics. This was proposed and put to create a correlation between the events that have occurred on the GI-627 only in Fig.56.

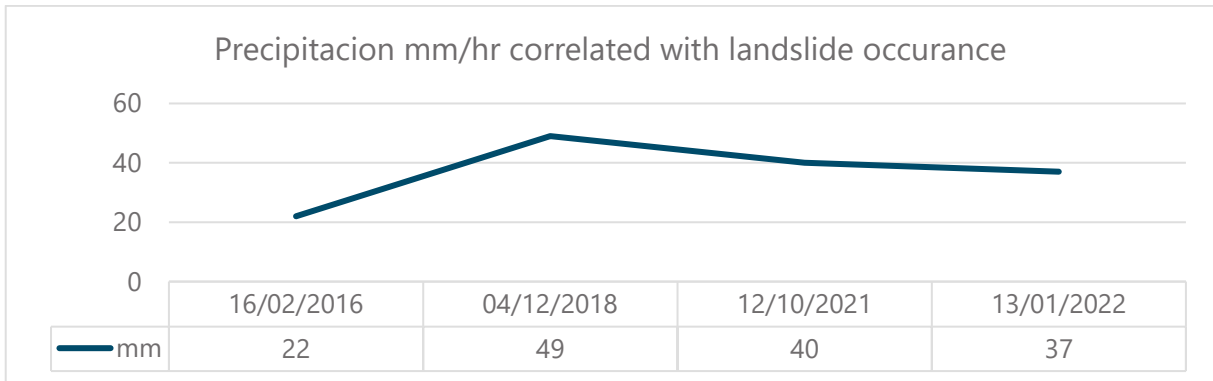


Figure 56 Correlating landslide events with precipitation occurrence

As noticed in the graph above, a trend was starting to become present in the period between (2018-2022) but still due to the limited information and small scale of analysis it was difficult to create a conclusion. It is recommended that the full events that have occurred in study on the infrastructure are correlated with the event data and a creation of a full graph is made. This verifies a common behaviour on the different infrastructure, confirm this interpretation and put forward less uncertainty when trying to propose an action. Also, the verification of the peak rainfall volume would put on the table solutions for drainage or coping with the water through long term adaptation solutions that would reduce the impacts resulting if climate change impacts worsen in the future. This theory of dealing with uncertainty with uncertainty may yield a positive solution when better interpreted and this is what is proposed at this stage. To proceed with the solutions, the following data interpretation will be considered, and the next step will be selecting adaptation measures that deal with the water retention and slope stability.

#### 4.2.3. IMPACT CHAIN DEVELOPMENT

According to the impact chain, the joint combination of the hazard, exposure and vulnerability yields the full picture showcasing what the risks are and facilitates a way to correlate them and find the suitable adaptation measure. In this case, the main problem relies from the impact of the landslide in this area on the infrastructure clear in Fig. 57.

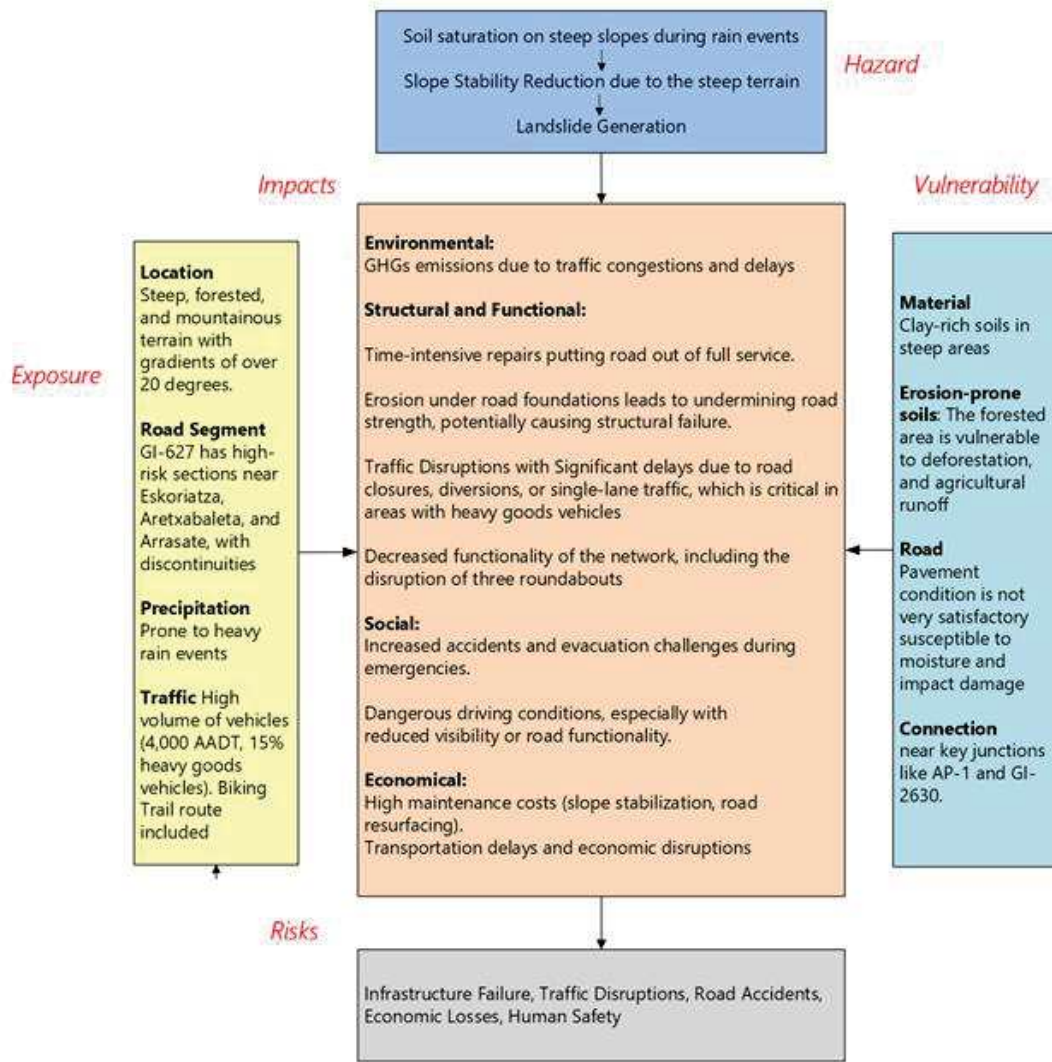


Figure 57 Impact chain for rainfall induced landslides on GI-627

According to the preliminary vulnerability assessment, overall risk is high on this studied infrastructure as shown in Table 44.

Table 44 Impact Chain Spreadsheet development depending on the impact chain analysis

HAZARD	EXPOSURE	VULNERABILITY	IMPACTS	RISKS	ADAPTATION
Rate of Movement High (3)	Slope Height/Length High (3)	Embankment Height High (2)	Functional Resilience Impact Scale High (3)	Resilience Impact Score High (22.5) Adaptation needed	Possibility of NBS Medium (2)
Probability of Occurrence High (3)	Land use Medium (1) Climate change potential High (3)	Soil Type High (3) Number of Lanes High	Overall Impact High (3)		

	Social Community High (3)				
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### 4.3. DETAILED VULNERABILITY ASSESSMENT

Besides the significance of the fragility curve approach discussed in the methodology and its potential, trying to fill the gap of data integration was not possible for this case study and the data correlation was not sufficient to obtain reliable results. For that reason, this part will remain a part of this methodology however will not be considered in the application due to the lack of data, time and resources available to complete this motivation. The brainstorming is shown in Fig. 58 below.

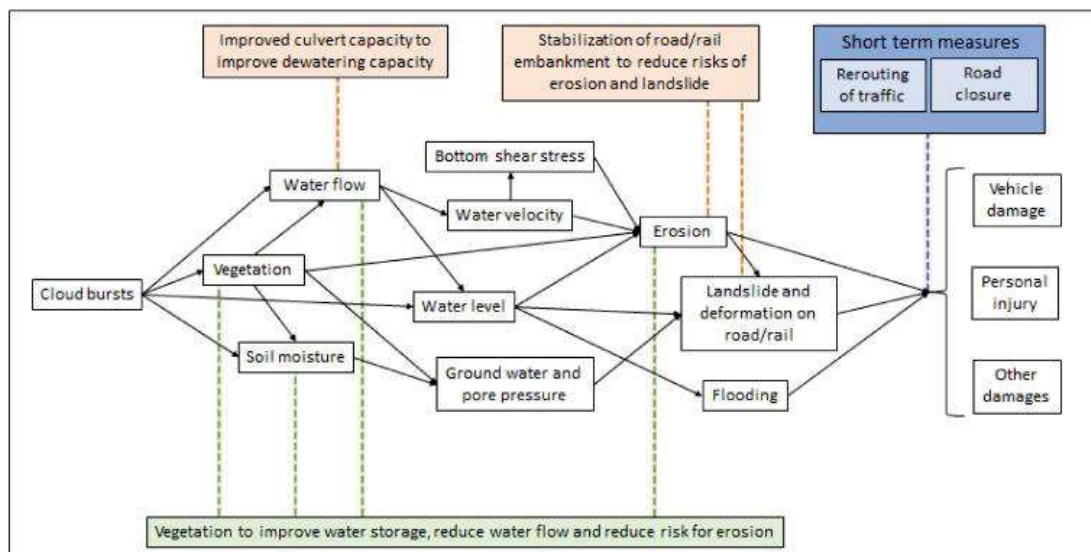


Figure 58 Brainstorming for interpretation of the existing solutions [40]

#### 4.3.1. FRAGILITY ASSESSMENT

The analysis of the physical damage due to landslide events has been carried out based on 'generic' damage curves from the available data in the [160] and the correlation of the climate impact drivers in the specialized bibliography[37] to showcase the percentage of damage it could cause to the infrastructure in Fig. 59. According to the fragility curve for precipitation-induced landslides in Gipuzkoa and the insights into the relationship between slope stability and the annual probability of failure, the curve categorizes slopes based on their Hazard Index (HI) and Factor of Safety (FoS). For instance, Category I slopes (HI < 1.45) have an annual failure probability ranging from  $10^{-6}$  to  $10^{-5}$  indicating high stability. Conversely, Category IV slopes (HI > 2.6) show a probability exceeding  $10^{-3}$  highlighting critical instability.

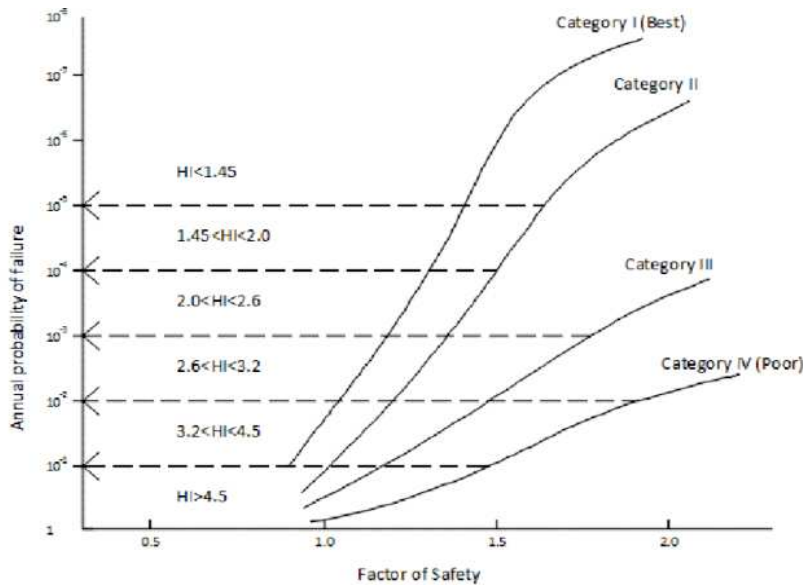


Figure 59 Classification of the engineered slopes and relation to the annual probability of failure[160]

The slope of the GI-627 road in Gipuzkoa, when analysed for landslide susceptibility reveals significant risks of failure under precipitation-induced landslides according to existing studies shows different levels of the Hazard Index (HI) correspond to varying annual probabilities of failure. For example, areas with an HI less than 1.45 have a low probability of failure (around  $10^{-7}$ ), while areas with an HI greater than 4.5 have a much higher probability (around  $10^{-3}$ ). The slope's stability is assessed using the Factor of Safety (FS), which is a measure of the slope's ability to resist failure. An FS below 1.0 indicates an imminent risk of failure, whereas an FS above 1.5 is generally considered stable. The fragility curve demonstrates that as the FS decreases, the annual probability of failure increases exponentially. This asserts the need for adaptation to tackle this uncertainty and work on improving the slopes stability in the places of event occurrence mainly and on along the whole.

#### 4.3.2. CLIMATE-RELATED RISKS AND VULNERABILITIES

For that, the risk assessment integrated as a basis of this work is based on a study [160] evaluating the probability of failure and the potential consequences at 84 specific risk points across the entirety of the road network administered by the Gipuzkoa Provincial Council. The analysis focused on various types of slope instabilities, including rockfalls, failures of retaining walls, and slow-moving landslides while also performing the expected road damage assessment for each hazard level in terms of a fixed unit cost (UC). In climate change studies, long-term perspectives, like 30-year weather averages, are common. Time frames are key in risk analysis, typically considering three perspectives: current impact, 2050 projection, and 2100 projection. Beyond 2100, if needed, can be explored. Impact assessment follows, categorizing effects as very small, small, medium, or large. Probability assessment relies on estimated return periods exceeding predefined thresholds. It's prudent to conduct this across various climate scenarios to capture potential differences [138]. Investigation related to the direct losses thus taking the indirect losses into consideration would be the complimentary interpretation. This context builds up the strategy in need for finding the suitable adaptation measure that could serve further in reducing the severity if the consequences compared to the current situation.

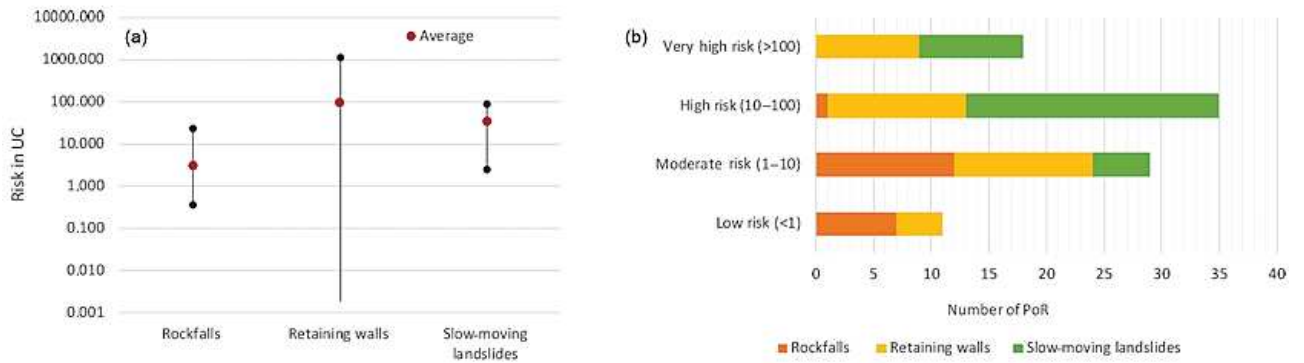


Figure 60 (a) Risk Assessment for each hazard type; (b) number of (PoR) points of risk per hazard type in each risk class

The correlation between the climate impact drivers causing those risks showcases the different consequence classification and the actions needed for service restoration of the roadways. The consequences involve expenses linked to the elimination of debris, repairing, or substituting the pavement, removal of loose non-detached rock or debris, and stabilizing the slopes. These costs are assessed as multiples of a unit cost (UC), which is fixed at EUR 1000 in Fig. 60. As quoted, the work presented is only limited to the risk of landslides which is highly probable as seen in Fig. 61 below.

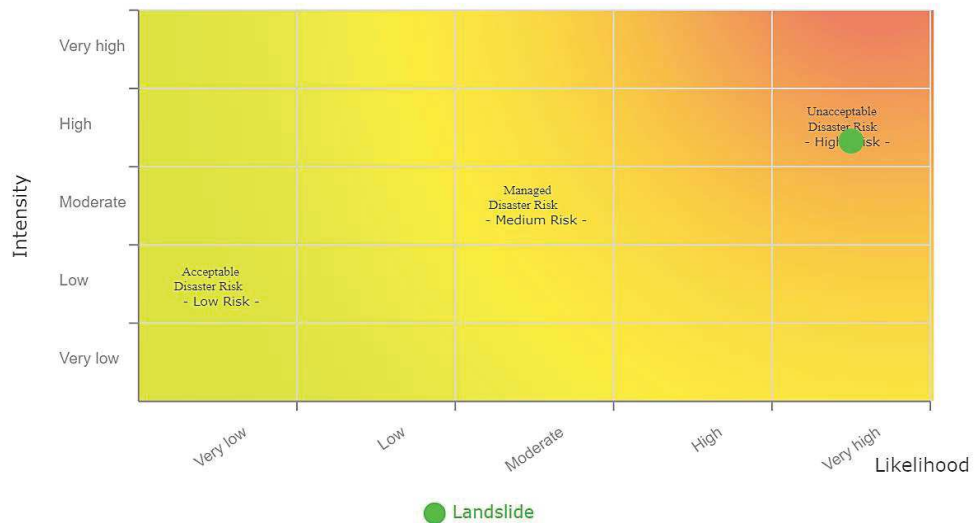


Figure 61 Potential for Landslide impacts in the next 25 years starting 2019 [160]

#### 4.4. PRELIMINARY ADAPTATION MEASURE SELECTION

##### 4.4.1. KEY PERFORMANCE INDICATORS

The key performance indicators chosen were related to the criteria in Table 45 below

Table 45 Criteria of measurement and KPIs

Availability	Safety	Climate Change and Energy	People and Communities
--------------	--------	---------------------------	------------------------

Direct Cost	Impact on network	Ecology / Biodiversity	Quality of Life
Reputation	General Management	Physical resources	Safety, Health & Equity

The metrics chosen are narrowed down then to the following shown in Table 46 for this case study.

Table 46 Key performance indicators chosen metrics

Criteria	Direct Cost	General Management	Climate Change and Energy	Quality of Life
KPI	€/year	Level of change $\Delta\%$	m <sup>3</sup> of retained water	Kg of CO <sub>2</sub> Absorbed

#### 4.4.2. PROPOSAL OF ALTERNATIVES

From the extensive database prepared in the ICARUS project referred in [135], the adaptation measures covering prevention techniques were selected. This choice has been due to the large uncertainties present where the best intervention could be preventing the impacts from taking place. Referring to the table presented earlier, the description of the alternatives was analysed helping select the most appropriate alternatives for this study limited to the best 5 alternatives. Then, the following alternatives were looked up in the weighting table that has been obtained from a previously conducted multi-criteria analysis data source results obtained from the ROADAPT guidelines on adaptation which includes specific insights into potential adaptation strategies concerning geotechnics, drainage, pavements, and mobility services correlating with the goals of this project and coinciding with ICARUS as it is one of its references [140]. The use of those guidelines was important in this project because they provided a sample of data that can be used and helps in creating a baseline to start from. The table below shows the adaptation measures facilitating a prevention behaviour for landslide events.

Table 47 Table of Selected adaptation measures from ICARUS Project

CODE	ADAPTATION MEASURE	FUNCTION
<b>S1</b>	Support the slope with a retaining structure	Prevention
<b>S2</b>	Spread mulch over the soil to protect it	Prevention
<b>S3</b>	Cover slope with rock blanket	Prevention
<b>S4</b>	Cover slope with vegetation	Prevention
<b>S5</b>	Cutting back the slope to a shallower angle	Prevention

#### 4.4.3. SELECTION OF ATTRIBUTES

The criteria and rating system for evaluating the performance and sustainability of adaptation measures for case study are based on a comprehensive risk evaluation study done by [140]. This framework emphasizes the current climate and existing road construction practices, posing the critical question of the potential impact the measures were to be implemented. The evaluation encompasses several key aspects, including availability, safety, the effects on surrounding road networks, direct technical costs, and the reputation of the motorway operator, all of which are assessed using a scoring system that ranges from -3 to +3. Negative scores indicate detrimental impacts, such as catastrophic disruptions to traffic availability or extreme hazards to user safety, while positive scores reflect beneficial outcomes,

such as significant improvements in safety and operational efficiency. Additionally, the assessment of surrounding network impacts considers the degree of traffic disruption resulting from each measure, and direct technical costs account for the financial implications of implementation. The reputation criterion evaluates how well the road operates and is perceived in terms of preparedness for extreme weather events, with lower scores associated with severe reputational damage and higher scores indicating notable improvements. Sustainability criteria draw on established systems and address climate change impacts, social implications, ecological preservation, resource management, quality of life, and health and safety considerations. Each sustainability metric is similarly rated, enabling a holistic view of the trade-offs and implications of various adaptation measures shown in Table 48. This integrated framework allows road authorities to make informed decisions to enhance infrastructure resilience while balancing performance and sustainability in the face of climate change.

Table 48 Evaluation of Slope Stabilization Strategies Based on Multiple Metrics

METRICS	S3	S4	S5	S2	S1
	Cover slope with rock blanket	Cover slope with vegetation	Cutting back the slope to a shallower angle	Spread mulch over the soil to protect it	Support the slope with a retaining structure
Availability	2	3	1	3	3
Direct Cost	2	-1	-1	0	-2
Reputation	2	1	0	1	0
Average	2	1	0	1/3	1/3
Safety	3	1	2	1	0
Impact on network	1	0	-1	0	0
General Management	-1	0	0	0	0
Average	1	1/3	1/3	1/3	0
Climate Change and Energy	-3	2	0	0	0
Ecology / Biodiversity	0	0	-1	2	0
Physical resources	0	0	0	0	0
Average	-1	2/3	- 1/3	2/3	0
People and Communities	-3	1	0	1	0
Quality of Life	0	0	0	1	0
Safety, Health & Equity	0	0	0	0	0
Average	-1	1/3	0	2/3	0

#### 4.4.4. STANDARDIZED WEIGHING OF ALTERNATIVES

According to the selected perspective, 5 chosen adaptation measures are ranked using the TOPSIS method with the data used is obtained from a previously conducted multi-criteria analysis data source results obtained from the [147]. The importance of this step lies in its ability to systematically evaluate and rank adaptation measures to address a particular issue in this case, slope stability in the context of landslide occurrence. The normalization process in this analysis is critical for ranking the selected adaptation measures using the TOPSIS method, which facilitates systematic evaluation of options related to slope stability and landslide occurrence. By normalizing the data obtained from a previously conducted multi-criteria analysis, we can ensure that each criterion is measured on a comparable scale, allowing for a fair assessment of each adaptation measure's performance. Normalization transforms the various metrics—such as technical feasibility, risk reduction, environmental impact, and social implications—into a uniform range, which is essential for unbiased comparisons.

The importance of this step lies in its ability to provide an objective framework for decision-making. By evaluating each adaptation measure against an ideal solution, normalization helps reduce bias and subjectivity that can arise from differing scales and units of measurement. This systematic approach allows for a balanced consideration of multiple criteria, ensuring that no single factor, such as economic judgment, unduly influences the overall assessment.

In the provided data shown in Table 49, different adaptation measures are listed along with their normalized scores across the specified criteria. For instance, the measure "Cover slope with rock blanket" has scores reflecting low technical feasibility and societal impact, while "Cover slope with vegetation" shows a more balanced performance across various criteria. Based on the normalized scores, it is possible to highlight the most effective solutions that address slope stability comprehensively, considering not only their technical aspects but also their environmental and social implications. This thorough evaluation process supports the identification of optimal adaptation measures for enhancing slope stability, aligning with the broader goals of sustainable infrastructure management.

Table 49 Listing of different alternatives after normalization

Code	Adaptation Measures	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society
S3	Cover slope with rock blanket	2	1	-1	-1
S4	Cover slope with vegetation	1	1/3	2/3	1/3
S5	Cutting back the slope to a shallower angle	0	1/3	- 1/3	0
S2	Spread mulch over the soil to protect it	1 1/3	1/3	2/3	2/3
S1	Support the slope with a retaining structure	1/3	0	0	0

Using the TOPSIS method ensures objective decision-making by comparing each adaptation measure against an ideal solution, thereby reducing bias and subjectivity. This approach incorporates a multi-criteria analysis, which is essential because it considers various factors such as technical feasibility, risk assessment, environmental impact, and social implications. Accordingly, the process is grounded in

established research, ensuring reliability and relevance. The ranking of adaptation measures and allow for a comprehensive evaluation, highlighting the most effective solutions based on a balanced consideration of multiple criteria compared to the common norm focusing on economic judgement solely.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a widely used multi-criteria decision-making method that helps identify the best option among a set of alternatives by comparing each one against an ideal solution. The method operates on the principle that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution. This dual comparison effectively highlights options that not only meet the desired criteria but also stand out in terms of performance across multiple dimensions. Using TOPSIS is crucial for several reasons. First, it ensures objective decision-making by systematically comparing adaptation measures based on a variety of criteria, thus reducing bias and subjectivity that can often skew results. Traditional methods that focus solely on economic judgments may overlook critical factors such as technical feasibility, risk assessment, environmental impact, and social implications.

Moreover, the method is grounded in established research, which enhances its reliability and relevance in real-world applications. It allows decision-makers to rank adaptation measures comprehensively, ensuring that the most effective solutions are identified based on a balanced consideration of multiple criteria. This comprehensive evaluation is particularly important in contexts like slope stability and landslide risk management, where the implications of decisions can significantly affect safety, environmental sustainability, and community well-being. In summary, TOPSIS not only facilitates a structured approach to decision-making but also empowers stakeholders to make informed choices that reflect a broader range of impacts, ultimately leading to more effective and sustainable adaptation strategies.

After performing the TOPSIS ranking depending on the political and environmental perspectives, some conclusions were made. In the environmental perspective, the weightages prioritize environmental benefits (5) and social benefits (4) significantly higher than technical feasibility (2). This weighting reflects a strong emphasis on long-term ecological sustainability and societal impact. The political perspective, however, places greater emphasis on social benefits (5) and risk reduction (2), reflecting a more balanced approach between immediate risk mitigation and long-term societal gains. Technical feasibility remains a lower priority in both perspectives, indicating a consensus that while challenging, it is a surmountable barrier if the benefits are significant. The rankings differ notably between the two perspectives. For instance, in the environmental perspective, adaptation measure S2 (covering the slope with vegetation) ranks first, highlighting its perceived superior environmental benefits and social impact despite potential technical challenges. Conversely, the political perspective ranks S2 highest as well but shows a closer competition with S4 (spreading mulch over the soil), reflecting its balanced consideration of risk reduction and social benefits. Adaptation measure S3 (cutting back the slope to a shallower angle) ranks lowest in both perspectives, emphasizing its perceived ineffectiveness across environmental and political criteria. This consensus suggests a need for re-evaluating its inclusion as a viable solution. This comparison underscores the nuanced differences in prioritizing adaptation measures based on the lens through which they are viewed. The environmental perspective emphasizes long-term ecological and social benefits, while the political perspective balances immediate risk mitigation with social impact. These are shown in Tables 50 and 51 below.

Table 50 Ranking NbS using TOPSIS Method considering environmental perspective

Weightage	Criteria		Environmental		S1+	S1-	Pi	Rank
	Non-Benefit	Benefits	Benefits	Benefit				
	2	3	5	4				
	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society				
S1	0.33333333	0	0	0				
S2	1.33333333	0.333333	0.66666667	0.666667				
S3	2	1	-1	-1				
S4	1	0.333333	0.66666667	0.333333				
S5	0	0.333333	-0.33333333	0				

	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society
S1	0.12700013	0	0	0
S2	0.50800051	0.288675	0.471404521	0.534522
S3	0.76200076	0.866025	-0.707106781	-0.80178
S4	0.38100038	0.288675	0.471404521	0.267261
S5	0	0.288675	-0.23570226	0

	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society	S1+	S1-	Pi	Rank
S1	0.25400025	0	0	0	4.116	4.9395	0.5455	3
S2	1.01600102	0.866025	2.357022604	2.13809	2.008	8.0188	0.7997	1
S3	1.52400152	2.598076	-3.535533906	-3.20713	8.1004	2.5981	0.2428	5
S4	0.76200076	0.866025	2.357022604	1.069045	2.1734	7.3715	0.7723	2
S5	0	0.866025	-1.178511302	0	4.4801	4.349	0.4926	4

V+	0	2.598076	2.357022604	2.13809
V-	1.52400152	0	-3.535533906	-3.20713

Table 51 Ranking NbS using TOPSIS Method considering political perspective

Weightage	Criteria		Political		S1+	S1-	Pi	Rank
	Non-Benefit	Benefits	Benefits	Benefit				
	3	2	2	5				
	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society				
S1	0.33333333	0	0	0				
S2	1.33333333	0.333333	0.66666667	0.666667				
S3	2	1	-1	-1				
S4	1	0.333333	0.66666667	0.333333				
S5	0	0.333333	-0.33333333	0				

	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society
S1	0.12700013	0	0	0
S2	0.50800051	0.288675	0.471404521	0.534522
S3	0.76200076	0.866025	-0.707106781	-0.80178
S4	0.38100038	0.288675	0.471404521	0.267261
S5	0	0.288675	-0.23570226	0

	Technical Feasibility	Risk Reduction	Environment & Ecosystem	Society	S1+	S1-	Pi	Rank
S1	0.38100038	0	0	0	3.3432	4.6584	0.5822	4
S2	1.52400152	0.57735	0.942809042	2.672612	1.912	7.1493	0.789	1
S3	2.28600229	1.732051	-1.414213562	-4.00892	7.4447	1.7321	0.1887	5
S4	1.14300114	0.57735	0.942809042	1.336306	2.1037	5.9805	0.7398	2
S5	0	0.57735	-0.471404521	0	3.2367	4.7455	0.5945	3

V+	0	1.732051	0.942809042	2.672612
V-	2.28600229	0	-1.414213562	-4.00892

## 4.5. DETAILED EVALUATION OF THE ALTERNATIVES

### 4.5.1. ADAPTATION MEASURE EVALUATION

The differences in ranking adaptation measures between these two perspectives illustrate how prioritization criteria shape strategic decisions. For example, while both perspectives rank S3 (cutting back the slope to a shallower angle) lowest, the environmental perspective's emphasis on long-term benefits might lead to investing in research and innovation to improve this measure's feasibility. In contrast, the political perspective's balanced approach may prioritize readily implementable solutions with immediate social and risk-reduction benefits, potentially side-lining longer-term but more challenging measures. The vegetation cover S2 was an intermediate option which both perspectives agreed on so it will be considered for evaluation. Using this simple evaluation process, which incorporates technical, environmental, and social KPIs, is highly beneficial in the context of the thesis because it aligns with the multifaceted approach required for addressing slope stabilization challenges in a sustainable way. In earlier discussions and sections of the thesis, emphasis was placed on the need for solutions that go beyond just technical feasibility. The context of landslides and slope stability in vulnerable areas requires that solutions not only mitigate immediate risks but also provide long-term environmental, economic and social benefits.

Considering general management and quality of life allows the analysis to integrate community well-being, which was also a significant focus earlier and shows how such interventions can enhance or detract from societal value. This KPI-driven analysis method also addresses the concerns raised earlier about avoiding the conventional focus solely on economic costs, thus allowing for a broader, more sustainable framework that fits within the thesis's overall goals. This is particularly crucial when recommending adaptation measures that are intended to provide co-benefits, such as the forestation cover solution, which not only stabilizes the slope but also enhances environmental and social systems over time. To compare with existing solution, 3 sub-criteria have been selected covering the technical expertise and the sustainability aspects in the Table 52 below.

Table 52 Criteria selected KPIs

DESCRIPTION	CRITERIA	DIRECT COST	GENERAL MANAGEMENT	QUALITY OF LIFE	CLIMATE CHANGE AND ENERGY
Scoring	KPIs	€/year	Level of change Δ%	Kg of CO <sub>2</sub> Absorbed	m <sup>3</sup> of retained water

### 4.5.2. PRIORITISE A SOLUTION

Table 53 Cost information based on existing construction project in Spain year 2024

Cost Information	Concrete C30/37	Formwork	Formwork exterior	Water proofing
Cost per cubic meter	€107.19	€26.83	€31.99	€7.40

**Micro-piles Solution (Existing): All the values are assumed to due lack of the actual construction data obtained from Table 53.**

#### Implementation Cost

- Assuming a retaining wall supported by micro-pile of a diameter of 0.4 m and a length of 25 m
- $V_{pile} = \pi(0.4)^2 \times 25$
- $V_{pile} = 3.14m^3$

- For a 110m x metric unit wall, assuming 74 micro-piles are needed
- The total concrete volume,  $V_{total} = 3.14 \times 74$
- $V_{total} = 232.36 \text{ m}^3$
- Total Concrete Cost =  $232.36 \text{ m}^3 \times \frac{€107.19}{\text{m}^3}$
- Total Concrete Cost = € 24,901
- For the  $110 \text{ m}^2$  section, considering formwork and waterproofing to be around €8400, the total will be approximately €33,300

#### **Maintenance Cost:**

- Given that the total Stabilization cost of €1,453,071 including pavement repair €0.8 Mi
- This is divided to annual Inspection cost: €8,500
- Minor Repairs (every 5 years): €42,500

Total Maintenance Cost would be approximately =  $(20 \times €8,500) + (4 \times €42,500) = €340,000$

Narrowing down to the  $110 \text{ m}^2$  segment studied:

- Annual Inspection cost = €93.50 per year.
- Minor repairs (every 5 years) = €468.50
- Total Maintenance Cost would be approximately =  $(20 \times €93.50) + (4 \times €468.50) = €3774$

#### **Environmental Impact:**

- Air Purification: Neutral ( $0 \text{ m}^3$  of  $\text{CO}_2$  absorption) on the contrary the maintenance rather negative.
- Water Retention: Neutral ( $0 \text{ m}^3$  of additional water retained)

#### **Forestation Cover Solution (Proposed): All the values are assumed to due lack of the actual construction data.**

##### **Implementation Cost:**

- Initial Planting Cost: €4.5 per square meter (local cost estimate)
- Total Cost:  $110 \text{ m}^2 \times \left( \frac{€4.5}{\text{m}^2} \right) = € 495$

##### **Maintenance Costs:**

- Annual Maintenance (watering, pruning, etc.): €46.75
- Replanting (every 10 years): €187
- Total Maintenance Cost over 20 Years:  $(20 \times €46.75) + (10 \times €187) = €1,309$

##### **Environmental Impact:**

- Air Purification: According to [170], 15 mature trees per  $100 \text{ m}^2$ , each absorbing 22 kg of  $\text{CO}_2$  per year
- Number of trees =  $110 \text{ m}^2 \times \frac{15 \text{ trees}}{100 \text{ m}^2} = 16.5 \text{ trees}$
- Total  $\text{CO}_2$  Absorption =  $17 \text{ trees} \times 22 \text{ kg of } \frac{\text{CO}_2}{\text{tree}}/\text{year} \times 20 \text{ years}$
- Total  $\text{CO}_2$  Absorption =  $7480 \text{ kg}$

- Water Retention: Improved infiltration by 20% of annual rainfall (average annual rainfall: 1,200 mm)
- Total Water Retention=  $110m^2 \times 0.2 \times 1.2m$
- Total Water Retention =  $26.4m^3/year$

To protect road users and infrastructure against soil–rock mass movements and inherent instability, it is necessary to conduct soil infills or excavations as well as important construction such as retaining walls. The anchored walls make up a considerable proportion of the retaining wall. Those have been the applied measures previously and will be the basis for comparison and improvement [164]. To evaluate consequences, it's valuable to examine past events. For instance, if the assessment predicts increased torrential rains in the future, analysing previous events can provide insights. Then, one can speculate on potential consequences if such events occur midway through this century or at the start of the next.

When comparing the 2 solutions in Table 54, Table 55 and Table 56, an understanding can be drawn on how future climate changes will redefine terms like torrential or extreme rains is also crucial. After fixing the base attributes and performing the ranking covering 2 different perspectives the political and environmental approaches, the retaining wall still tend to have the least benefits contribution due to its sole purpose of providing structural support against the event occurrence. Accordingly, the other two measures are going to be evaluated and compared in terms of co-benefits generation.

Table 54 Comparison of the 2 solutions according to the evaluation results

DESCRIPTION	CRITERIA	DIRECT COST	GENERAL MANAGEMENT	QUALITY OF LIFE	CLIMATE CHANGE AND ENERGY
Scoring	KPIs	€/year	Level of change Δ%	Kg of CO <sub>2</sub> Absorbed	m <sup>3</sup> of retained water
<b>Existing</b>	Retaining walls using micro-piles	€3774	50%	Negative	None
<b>Proposed</b>	Forestation Cover	€1309	30%	7480 kg of CO <sub>2</sub> absorption	26.4 m <sup>3</sup> /year

When considering the 2 alternatives, the hybrid solution, which combines micro-piles for immediate structural support with vegetation cover for long-term environmental resilience, is a strategically superior approach to slope stabilization. This method balances immediate risk reduction with the benefits of ecosystem services, such as air purification and water retention, which are essential in a sustainable, climate-resilient framework with also using the existing solution present in favour of the adaptation strategy. The hybrid solution not only provides the urgent, highly effective stabilization needed in areas prone to landslides but also enhances long-term resilience by strengthening the slope naturally through vegetation.

Table 55 Recommended Criteria Cobenefits Comparison

<b>CRITERIA</b>	<b>SUB-CRITERIA</b>	<b>MICRO-PILES (EXISTING)</b>	<b>VEGETATION COVER (PROPOSED)</b>	<b>HYBRID SOLUTION</b>
<b>Risk Reduction</b>	Slope Stability	Immediate, highly effective, requires engineering expertise	Delayed effectiveness, moderately effective, requires environmental expertise	Strengthening the vegetation upslope to enhance micro-piles wall resilience
<b>Society</b>	Air Purification	Neutral impact on air quality	Positive impact on air quality, highly socially accepted	
<b>Environmental &amp; Ecosystem</b>	Water Retention	Minimal impact on water retention	High impact on water retention, supports biodiversity	
<b>Technical Feasibility</b>	Maintenance Costs	High initial cost, moderate maintenance costs	Moderate initial cost, low maintenance costs	

#### 4.5.3. OPERATION OF SOLUTION

The best solution is then evaluated in the last stage by structuring a list of KPIs possible for evaluation and choosing at least one category-specific KPI to assess the chosen adaptation measure for the level of change. In the case of this study, using trees as part of the vegetation solution is expected to have a positive result in supporting the existing micro-piles and improving the overall context. This improvement is achieved by reducing the stresses on the slope, minimizing deflection, and absorbing a portion of the landslide's energy, resulting in a significantly less severe occurrence. For this adaptation measure to perform effectively, the time span between landslide events should be highlighted, ensuring that it is long enough for the tree roots to grow and develop resilience in preparation for the next event. In areas prone to frequent landslides, with events occurring almost annually, a hybrid solution becomes essential. This hybrid approach allows the slope to withstand immediate events through the use of micro-piles while simultaneously building long-term resilience through vegetation that takes time to fully develop its mitigating potential.

Vegetation can enhance landslide risk mitigation by reinforcing slope stability and contributing to an increase in the factor of safety by up to 34%, as analyzed by several studies. The effectiveness of vegetation tends to increase when coverage is uniform and provided by mixed species. However, its efficacy is inversely proportional to the slope angle. Furthermore, forests play an effective role in reducing landslides when crown coverage exceeds 30%, with no gaps greater than 25 meters in length. The protective effects of forests also rely on having a stem density higher than 15%, the number of stems per hectare, and sufficient surface roughness to be impactful. Forest density has a significant influence on landslide mitigation, especially when the tree class has a mean diameter ranging from 1 cm to 15 cm at breast height. Importantly, small trees appear to be particularly crucial within the first 200 meters of the landslide path, helping to reduce speed and limit the volume of landslides or rockfalls [133]. This highlights the necessity of strategically combining engineered solutions with ecological methods for robust, long-term resilience against slope instability.

Table 56 Estimation of the performance along the lifetime of the infrastructure

YEAR 0-5	YEAR 5-15	YEAR 15-30
Micro piles offer immediate stability, reducing landslide risk in the short term.	Growth of deep-rooted tree species, significantly increasing soil cohesion and shear strength.	Mature forest provides maximum soil reinforcement, with roots increasing soil shear strength by up to 100% (additional cohesion of 20-60 kPa).
The Rapid establishment of pioneer species then provides initial soil cover and reducing erosion.	Reduction in the need for maintenance of engineered structures as the forest matures.	Long-term reduction in landslide frequency and severity, enhancing road safety and reducing maintenance costs.

The performance estimation of the proposed solution over its lifetime highlights the dynamic interplay between micro-piles and vegetation in stabilizing slopes. The forest strength development is modelled using an exponential growth function, reflecting the increasing soil stability provided by growing tree roots while the micro-pile strength seduction is modelled using an exponential decay function, indicating the gradual reduction in structural integrity of engineered solutions over time.

Considering a sample example, in the initial years (0-5), micro-piles provide immediate stability, significantly reducing landslide risk in the short term. During this period, deep-rooted tree species are established, which markedly enhance soil cohesion and shear strength as shown in Fig. 62. As the trees grow (years 5-15), their roots contribute to increased soil stability, while pioneer species offer initial cover that mitigates erosion. By the time the forest matures (years 15-30), the reinforced soil, supported by tree roots, can increase shear strength by up to 100%, providing additional cohesion of 20-60 kPa. This maturation not only reduces the need for maintenance of engineered structures but also leads to a long-term decrease in landslide frequency and severity, thereby enhancing road safety and lowering maintenance costs. The relationship between the strength development of the forest and the gradual reduction in effectiveness of micro-piles illustrates a crucial synergy, where both systems ultimately converge to optimize slope stability over time.

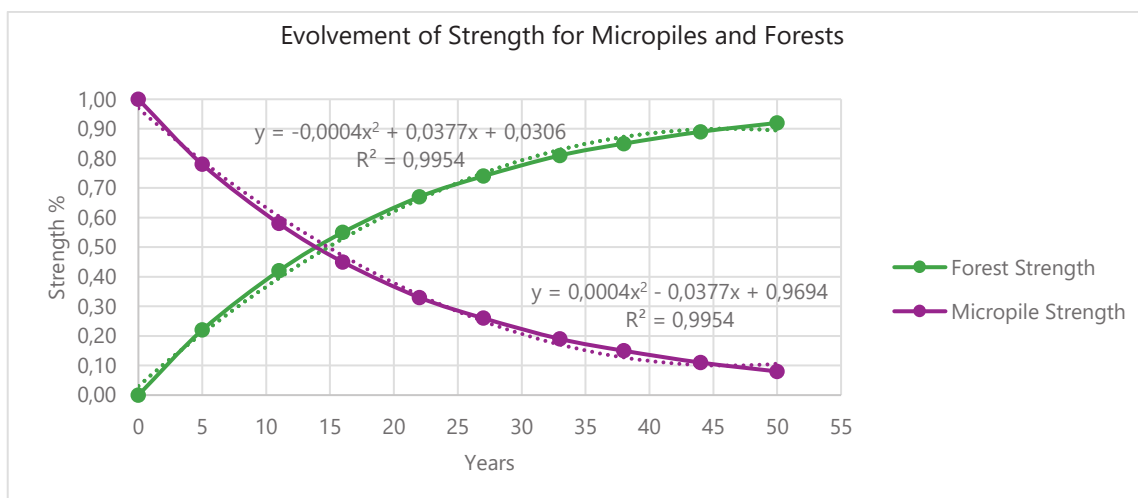


Figure 62 Hybrid Solution Example for Visualization

## PERMAFROST INDUCED LANDSLIDES

### 5.1. GENERAL OVERVIEW

#### 5.1.1. CONTEXT DESCRIPTION

The European Route E6 is a critical north-south highway in Norway, spanning from the southern border at Svinesund to the northern border near Kirkenes. The segment in Nordland County, particularly around Saltfjellet and the Svartisen glacier, is of particular concern due to its vulnerability to permafrost thawing and landslides area (approximately 66°N, 14°E) shown in Fig. 63 below. This route includes segments with slopes of lengths varying from 200 to 1,000 meters, with gradients often exceeding 30 degrees. It is a predominantly mountainous terrain with sparse vegetation; limited agricultural activity and significant areas designated as natural reserves. The Average Annual Daily Traffic (AADT) is around 2,500 vehicles, with a significant proportion being heavy goods vehicles (approximately 20%).



Figure 63 Landslide on the E6 highway in Norway[171]

According to the climate change projections, the damage posed on transport infrastructure is expected to increase from 60%–80% with the climate warming. This is due to their high vulnerability to being affected by the degrading permafrost where almost 70% of the infrastructure currently in use is in areas of high permafrost increasing risks of developing thaws near the surface by 2050 as shown in Fig. 64 below [172].

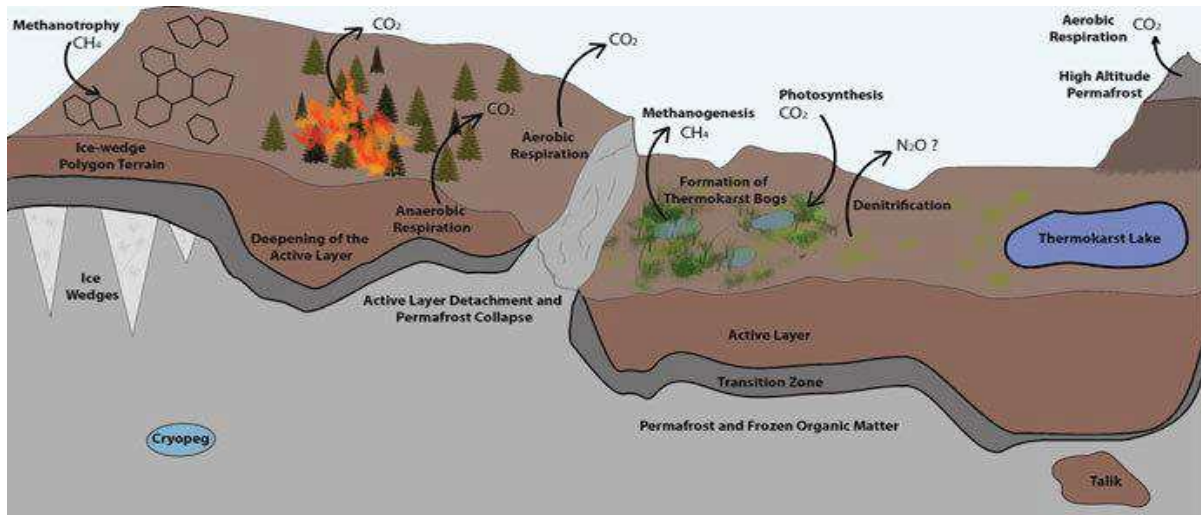


Figure 64 Schematic diagram of permafrost landslide consequence

Mitigating the detrimental impacts and occurrence of permafrost-related infrastructure failure is demanding great efforts to minimize the effects of the degrading permafrost. Yet, the main obstacle is that engineering solutions of high effectiveness are not economically feasible. A similar incident has occurred in another part of Norway, in Longyearbyen. A huge population had to be evacuated from landslides potential due to an active layer being partially refrozen and possibly triggered by precipitation events. However, no data was readily accessible to demonstrate this during the occurrence.

Modelled ground temperatures indicate that near-surface permafrost in coastal and low-altitude areas is projected to thaw before the end of the century under emission scenario RCP8.5. Increases in the active layer thickness and permafrost temperature will speed up slope processes controlled by permafrost, with a marked increase in slope instability[173]. Present and future permafrost warming, and degradation will affect coastal erosion processes, especially where the coastline consists only of sediments[90], [91].

Permafrost is defined by its temperature, remaining at or below 0 °C (32 °F) for at least two years. It can include ice content of over 30 percent in various layers and lenses. Annually, the upper portion of permafrost undergoes thawing and freezing cycles, with the maximum depth of seasonal thawing known as the active layer. Identifying the location and extent of permafrost can be challenging, as ground temperature does not always mirror average air temperature above it. Even if the average annual air temperature is below freezing, permafrost might not be present, and vice versa. Seasonal snow cover can insulate the ground, resulting in warmer ground temperatures in regions with continuous permafrost. Conversely, in areas with discontinuous or sporadic permafrost, the lack of snow cover can facilitate permafrost formation by allowing the ground to cool more effectively. Thus, adaptation solutions must account for these uncertainties.

Although there are efforts in place in Norway to handle those occurrences, according to[174], there is still a lack of systematic and coordinated follow-up after landslide events, as well as inadequate preparation of event inventories. Consequently, landslide occurrences are not consistently documented or monitored. While forecasters utilize a “verified landslide dataset” for warning performance analysis, this verified information does not always align with the data in the existing database. Also, rainfall plays a role in causing landslides in addition to permafrost however addressing the challenges posed by the increasing frequency of heavy rain showers in Norway requires the development of reliable regional thresholds for short, intense rainfalls. The current lack of long-term hourly rainfall records hinders effective monitoring and preparedness. Therefore, establishing comprehensive data collection and analysis practices will be essential for enhancing the understanding of rainfall patterns and improving

response strategies to mitigate potential impacts. Without sufficient information, proposed solutions might be ineffective. Nature-based solutions, like vegetation, face limitations due to growth challenges and maintenance needs, making them neither sustainably nor resiliently effective.

#### 5.1.2. CASE DESCRIPTION

<b>Infrastructure Name</b>	<b>European Route E6</b>
<b>Location</b>	Norway
<b>Network Direction</b>	North-South
<b>Typology</b>	Highway
<b>Full length</b>	2,628 km (stretching from the southern tip at Trelleborg, Sweden, through Norway to Kirkenes in the north)
<b>Nodes Affected</b>	Kvænangen (Troms og Finnmark) Saltfjellet (Nordland)
<b>Hazard Imposed</b>	Landslide
<b>Most probable climate impact driver</b>	Permafrost Melting, soil warming
<b>Latest Event Date</b>	landslide in Kvænangen in January 2023
<b>Number of Unstable Nodes/totals</b>	Numerous; specific data required
<b>Latest Event Description</b>	A significant landslide caused by heavy rainfall and thawing permafrost led to the closure of the E6. Emergency crews were deployed to clear debris and reinforce the affected sections.
<b>Affected Components</b>	Road surface Underlying soil and permafrost layers Adjacent slopes and embankments Drainage systems
<b>Existing Adaptation Measures</b>	Installation of advanced warning systems for landslides Reinforcement of roadbeds and embankments Improved drainage systems to manage heavy rainfall Regular monitoring of permafrost conditions
<b>Economic Expenditure for Maintenance</b>	the Norwegian Public Roads Administration allocated around 200 million NOK for maintenance and improvements on vulnerable sections of the E6 in northern Norway in 2023.
<b>Execution Time</b>	Ongoing
<b>References:</b>	[54], [174]

## 5.2. PRELIMINARY VULNERABILITY ASSESSMENT

### 5.2.1. GROUND PREPARATION FOR CLIMATE ADAPTATION:

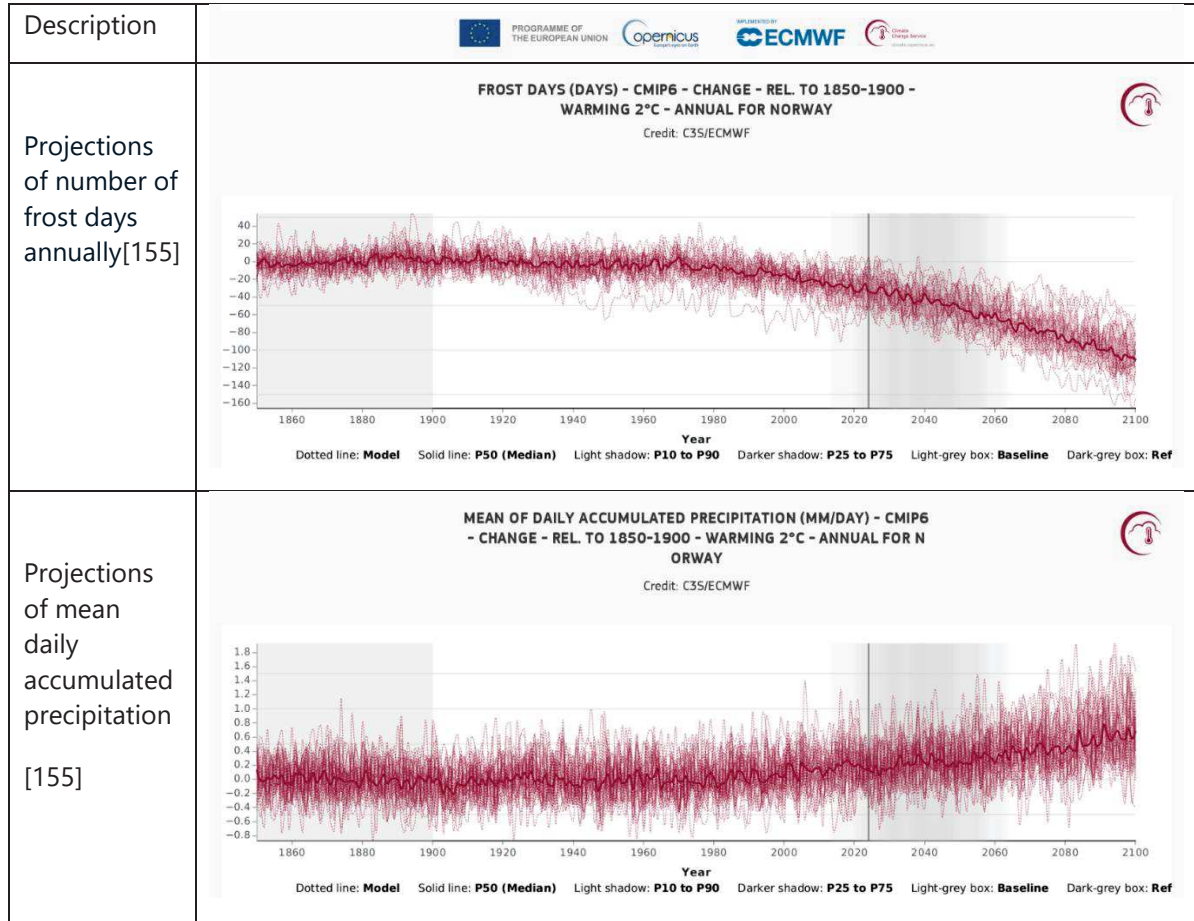
Given the region's subarctic climate, characterized by cold winters and mild summers, and the projected increase in both temperature and precipitation under RCP 8.5, the risks associated with permafrost degradation are significant as shown in Table 57 and Table 58. Subarctic, with cold winters (average

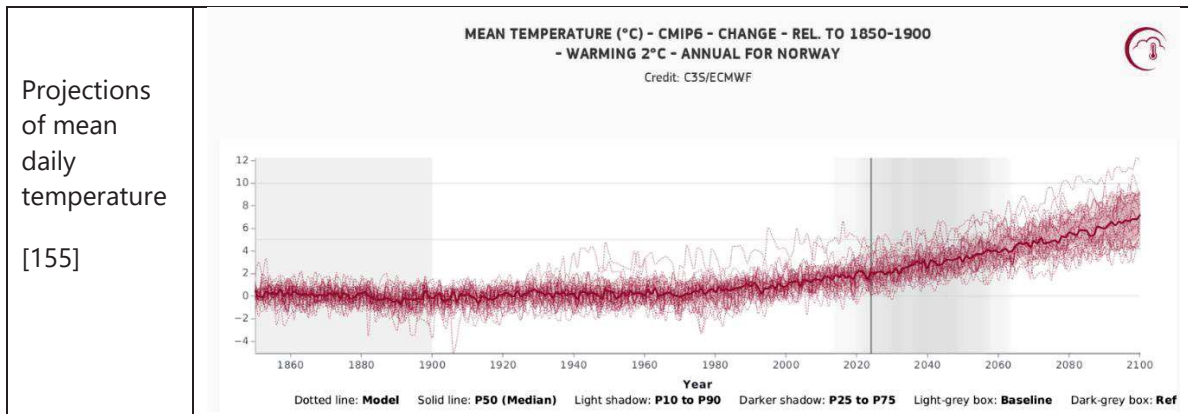
temperatures around -10°C) and mild summers (average temperatures around 10-15°C). Annual precipitation is approximately 1,500-2,000 mm, with the majority falling in autumn and winter. RCP Projections: Under RCP 8.5, average temperatures in the region could increase by 3-5°C by 2100. Precipitation is expected to increase by 10-20%, with more frequent and intense rainfall events.

Table 57 National Level Climate Projections

RCP Projections	2011-2040	2041-2070	2071-2100
<b>Average Temperature</b>	+1.0°C to +2.0°C	+2.0°C to +3.5°C	+ 3% +5%
<b>Precipitation</b>	+5% to +10%	+10% to +15%	10%-20%

Table 58 Interpretation of Climate Trends





5.2.2. CLIMATE DATA INTEGRATION

When analysing the climate projection on this infrastructure, the primary concern is the vulnerability of permafrost thawing and landslides development. The highway's infrastructure, including the road surface, underlying soil, and adjacent slopes, is already experiencing increased instability due to the warming climate. This is evidenced by recent events, which were triggered by a combination of heavy rainfall and thawing permafrost. To effectively assess and verify the occurrence and extent of landslides during that combination of events, it is imperative to develop a thorough overview of their spatial and temporal distribution, alongside an analysis of their number, type, and dimensions. A well-structured event inventory is vital; it should comprehensively document all landslides triggered by specific weather events. This approach not only facilitates the evaluation of the accuracy of warnings issued as the appropriateness of the warning level and area but also serves as a foundational tool for long-term improvements in landslide thresholds. Without such systematic documentation and analysis, efforts to enhance predictive capabilities and mitigate risks will remain inadequate, limiting the ability to respond effectively to future events.

The critical issue as supported also by Table 59 here is the active layer's increased depth and higher temperatures, leading to more frequent freeze-thaw cycles and solifluction a process where the thawing upper layer of permafrost causes soil and sediment to move downslope. These processes are exacerbated by the steep gradients of the terrain, which exceed 30 degrees in many areas, increasing the likelihood of large rockslides and other slope instabilities.

Table 59 The noticeable trend of permafrost driven landslides

LANDSLIDE TYPE	CLIMATE CONDITION	IMPACT SCALE	LIKELIHOOD SCALE	PRIMARY APPROACH
Permafrost-Driven Landslides	Acute (Rapid Thawing)	4 (High)	4 (Likely)	Prevention

While NbS and broader adaptation strategies have their place in enhancing long-term resilience, they are not sufficiently responsive to the acute and dynamic nature of the hazards faced in this region. Therefore, investing in targeted mitigation efforts is both the most resilient and sustainable approach to safeguarding the E6 infrastructure and the people who rely on it. Moreover, the uncertainty surrounding permafrost behaviour, particularly the discrepancies between ground and air temperatures, further complicates the situation. The presence or absence of permafrost is not solely determined by average air temperatures, making it challenging to predict where permafrost may thaw or persist. This uncertainty

underscores the necessity for robust, immediate, and technically reliable mitigation measures, as opposed to more experimental or slower-acting adaptation strategies.

5.2.3. IMPACT CHAIN DEVELOPMENT

Given these circumstances, the emphasis to deal with this uncertainty must either be based on a critical detailed analysis on permafrost itself or be on mitigation solutions rather than adaptation or Nature-Based Solutions (NbS). Mitigation in this context involves preventing or minimizing the immediate impacts of permafrost degradation on the infrastructure. This approach is necessary because the rapid changes in permafrost conditions can trigger landslides with little warning, necessitating real-time monitoring and responsive interventions to protect both the infrastructure and the safety of its users and restrict the trigger for release of the GHGs within which is neither a sustainable act nor a resilient solution to add following this methodology. To facilitate an understanding of the situation, the impact chain is shown in the Fig. 65 below:

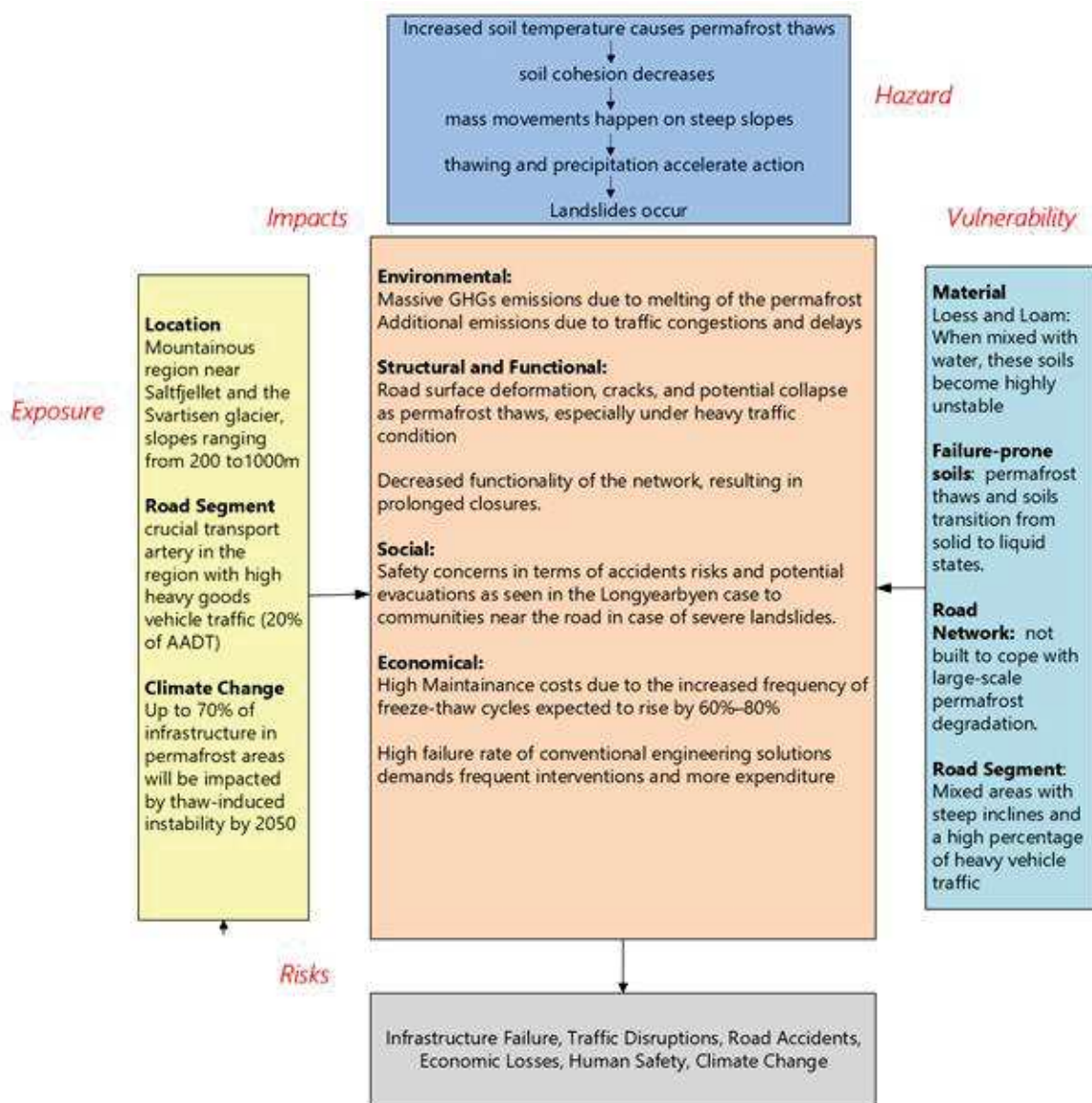


Figure 65 Impact chain for Permafrost induced landslides on E6

### 5.3. MITIGATION ACTIONS

#### 5.3.1. SOLUTIONS TO IMPROVE CURRENT SITUATION

The need for proactive investments in permafrost monitoring and engineering solutions is significant in cold climate regions. In Norway, annual expenditure on monitoring permafrost conditions and installing early warning systems, which include permafrost temperature sensors and ground stability measurements, has cost around 10 million NOK (approximately 860,000 EUR) almost a decade ago [175]. These systems provide critical real-time data that allow for early detection of permafrost thaw and slope instability, facilitating timely interventions to mitigate road failures and landslides. As a result of rising temperatures, these investments are essential in safeguarding critical transport infrastructure, such as the European Route E6, from permafrost-induced damage [176].

In addition to monitoring efforts, substantial financial investments are required to implement engineering solutions. Reinforcing roadbeds, constructing retaining walls, and improving drainage systems are commonly used to prevent the damaging effects of permafrost thaw and heavy precipitation. These interventions can cost around millions of euros for large-scale projects. Such solutions are highly effective in addressing the immediate risks posed by degrading permafrost; however, their costliness often makes them economically challenging for long-term sustainability.

#### 5.3.2. MITIGATION MEASURES FOR PERMAFROST THAW-INDUCED RISKS

Investing in advanced monitoring systems, such as ground temperature and deformation sensors, is considered an adequate mitigation measure for infrastructure resilience. Early detection allows for rapid interventions, including road reinforcement, to minimize the impact of permafrost thaw. Studies highlight that combining these engineering solutions with drainage improvements can handle the increased risks from both thawing and heavy precipitation. Timely mitigation efforts not only extend the lifespan of infrastructure but also reduce the frequency of closures and disruptions caused by landslides.

While nature-based solutions (NbS) such as reforestation and soil restoration provide long-term ecological benefits, their immediate effectiveness in permafrost regions is limited. NbS improve slope stability and contribute to carbon sequestration over time, but they are often too slow to respond to the rapid thawing of permafrost [177]. Reforestation projects in areas like Nordland, where sparse vegetation and natural reserves predominate, face challenges due to slow vegetation growth in cold environments. Moreover, the economic feasibility of large-scale NbS projects is limited when compared to engineering solutions that can more effectively mitigate immediate risks. Permafrost-affected infrastructure indicates that while NbS are valuable for enhancing overall ecosystem resilience, they do not provide the immediate stability required to safeguard roads and other transport networks [178], [179]. Engineering solutions, particularly roadbed reinforcement, retaining walls, and improved drainage systems, remain more appropriate for dealing with the urgent infrastructure challenges in these regions. However, NbS can play a complementary role by enhancing the long-term sustainability and environmental health of permafrost regions once critical infrastructure has been secure.

# 6

## DISCUSSION

### **Data is an effective a barrier to effective implementation of this framework.**

Despite the growing availability of data and tools, there remains a significant gap in using this information effectively to support decision-making processes and urban planning. This gap underscores the ongoing need to enhance capacity for translating information into actionable outcomes. It is essential for data to be open source and accessible, utilizing innovative tools that integrate geospatial data with other datasets to offer a more comprehensive perspective on climate risks. AI has significant potential to aggregate these datasets and create future risk scenarios, thereby enhancing the understanding of these risks. In the field of process towards climate adaptation, several stakeholders are involved, and the ones facilitating decision making are not necessarily climate scientists nor data analysts thus choosing the data needed, project scenario and presentation would be a difficult decision to make. For that a suggestion would be to perform to put forward a platform designed for the infrastructure and geological sector, putting the most convenient climate data for infrastructure and an explanation of how the different type of data would yield an expected change in results and when should this type of data be used but still with emphasis on limiting the database scale into a smaller specific one with only the data usually needed.

This methodology can be a useful roadmap for risk assessment in similarly challenging environment since the approach is flexible and can address similar needs in data-rich countries or data-poor countries because it helps to create quick preliminary evaluations without extensive data collection. Also, this methodological approach is iterative rather than strictly theoretical, incorporating a series of stages which enables the integration of vulnerability dynamics into decision-making processes by generating, communicating, and providing pertinent and actionable information.

### **There is a need to start having databases that correlate climate events with hazard occurrences.**

The first type of uncertainty is here considered by using 2-3 emission scenarios wherever available. The second and third types of uncertain ties are to some degree considered by giving intervals based on ensembles of several model calculations. However, these span only a part of the total uncertainty. Thus, it cannot be ruled out that future climate changes could fall outside the intervals. Thus, to be able to use climate projections in research and management, it's recommended that relevant scientific expertise help simplifying the in the interpretations of the results and to gain information on new knowledge.

In this study, several research has addressed that once the climatic event occurs, the response in terms of a hazard event takes place. It is true that each of these data sources provides a valuable source of information, however what the implementation actions are missing is the combination of them all. It is important to note that this process is still quite uncertain but improving the way data is structured gives rise to chances for reducing the level of uncertainty and lack of understanding currently present. The

information is basically just informative which means that up to the author's knowledge there was no data source claiming that in the date of the rainfall occurrence with a certain intensity, the hazard took place. The landslide susceptibility on transport infrastructures can be interpreted as caused by a climate impact driven, human intervention consequence, land use change or seismic action. For example, establishing thresholds on the specific rainfall characteristics obtained from the trends that relate to landslides triggering can build rainfall intensity-duration thresholds, where the probability of a landslide to occur in each area. Thus, to be able to create a conclusion of the most probable reason causing this consequence, the data should be available in a structured, well recorded way covering all the possible details such that when a correlation is needed to be made, the pattern of which factors coincide with the landslide activity and a firm conclusion can be detected. In Table 60 is a recommendation of how the data can be organized and presented in future national database.

Table 60 Sample Climate Event Data Organization

DATE	PRECIPITATION ACCUMULATIONS REGISTERED	GENERAL DESCRIPTION	RISK TO PEOPLE	DAMAGE TO BUILDINGS	DISRUPTION OF TRANSPORT	OTHERS OR COMMENTS
22-23 October 2019	119 mm/24 hours 81 mm/12 hours 60 mm/1 hour	Hazard Event causing widespread flooding in the community, extent level (high) speed high	2 people were trapped inside their vehicles. They had to be rescued by authorities	Underground parking lots and lower floors were flooded within 1 km from location	Main roads x and y had to be closed due to surface flooding for 30 mins	140 calls to the 112 around noon. Most of the localised flooding and rescue activities

Also, the climate data analysed in this study is mostly covering months or annual or seasonal but does not easily fasciculate accessing daily data at the time of the event. The importance of that is not only in the ease of process making but also because the uncertainties in analysing what could have been the trigger for a certain hazard remains very high. Proving to have a trend or pattern especially in areas like the Basque Country where constantly landslide hazard occurs would help in emphasizing the considerations for adaptation for simulations or for analysing the probability of damage taking place with the climate change projected scenarios. This is because it proves that when the rainfall intensity for example reaches a certain level, the soil starts to lose its cohesion and the forces are strong enough to cause a landslide or maybe not, if there is no consistent trend it might also prove that the rainfall was not the main cause. However, at this stage all this remains still unclear due to the lack of correlation.

**Not all hazard events are registered in the existing databases for that it was deemed difficult to decide about the selected area.**

After analysing 3 sources of data looking hazard event descriptions in Gipuzkoa, Basque Country, Spain, the process effectiveness was hindered by the lack of detailed event descriptions, unclear methodology for risk assessment, incomplete coverage of events, and infrequent updates. While the national geographic database provides valuable information on significant landslide events, including detailed characteristics such as type, speed, magnitude, and estimated occurrence dates, concerns arise regarding the database's omission of recent events and uncertainties about the frequency and consistency of data updates.

Another data source provides a conclusion of the infrastructure risk to climate change but with not specifying further details on how this has been interpreted, what events prove that what existing

measures were put forward. This raises questions about its current relevance and reliability for informing real-time decision-making and risk mitigation strategies. Also, informative reports emerge as with specific event details, including locations, dates, times, proposed solutions, lane closures, and infrastructure functionality status, that could be helpful through putting these details in a collective database. An improvement can be made when all those 3 sources are put together giving rise to a data source, specifying 1 area containing a certain number of transport infrastructure, where these infrastructures vulnerability condition is graded as high, low, medium risk justified by existing event occurrences, the date, time and location of nodes affected as what was deemed difficult is to find the needed data in the needed area. Then, this data can link the hazard characteristics such as speed or severity, causalities, solutions proposed and effectiveness state.

Creating such a database can make interpretation easier, clearer, highlight which are the mostly affected by a certain hazard, how are the existing solutions contributing and how to rapidly intervene to reduce future impacts with the climate change. This does not only affect the decision-making process for resilience improvement but also the sustainability of the infrastructure. A lot of decisions made due to uncertainties have resulted in waste of materials and energy especially in areas where reliance is mostly on grey solutions. Also, understanding the severity of the situation helps early warning systems to reduce functional losses on a certain infrastructure when an intensity measure such as rainfall occurs leading to rerouting and reduction of traffic reducing congestion in case a hazard takes place. This reduces the indirect GHG, greenhouse gas emissions generated due to traffic jamming.

**The selection of the KPIs is still subjective to a high extent thus there is a need for standardization**

After reviewing numerous studies on adaptation solutions and their corresponding Key Performance Indicators (KPIs), it has become apparent that while many studies employ similar priorities, the interpretation of these priorities varies. Although the underlying focus on resilience and sustainability is consistent, the subjective nature of KPI evaluation leads to differing interpretations and weightings. This variability results in inconsistent decisions, as the same KPI might be assessed differently depending on its perceived importance. This inconsistency creates confusion, weakens the basis for decision-making, and undermines the reliability of the studies. To mitigate these issues, it is advisable to establish a standardized set of KPIs that address core aspects of resilience and sustainability, applicable across various adaptation solutions and implementation contexts. This standardization would facilitate a more streamlined and objective evaluation process, ensuring that all solutions are assessed against a consistent benchmark, thereby improving the likelihood of achieving basic performance standards. Once potential solutions are narrowed down using these standardized KPIs, a more subjective assessment can be applied to tailor the evaluation to specific contexts and expert judgments. This approach also allows for a more focused use of KPIs in later stages of implementation and operation, enhancing the effectiveness of adaptation measures by concentrating on key performance metrics relevant to ongoing monitoring and adjustment.

Another critical issue is the insufficient visibility of sustainability considerations in the creation of KPIs. Often, the integration of sustainability attributes into decision-making processes is limited, resulting in an underemphasis on the co-benefits of solutions and the potential of regenerative approaches. Typically, functional and economic values are prioritized, while social, environmental, and economic sustainability aspects are either minimally considered or treated merely as ancillary benefits. This traditional approach fails to address the comprehensive impacts of climate change and its effects on infrastructure and its broader context, including the environment and society. To effectively respond to climate change, decision-making processes must evolve. This requires a holistic evaluation that incorporates all relevant dimensions—structural, environmental, and societal—ensuring that sustainability metrics are prominently featured and play a significant role in guiding decisions.

**This methodology is not designed to replace the complex analysis of infrastructure resilience however, it is created to facilitate a simplified approach for decision making and consideration for the different stakeholders involved in infrastructure management.**

The central insight from this work is the shift from the reactive mindset of “what is the worst thing that could happen if nothing is done?” to an initiative-taking approach that integrates broader sustainability principles into core strategies. This transformation is essential for fundamentally altering how the industry creates value and aligns with environmental considerations. It emphasizes that managing and measuring responsibilities towards environmental, social, and economic values should not solely focus on financial gains, but should also prioritize environmental conservation, emission control, and community improvements. In this study, the approach to assessing resilience and sustainability performance was outlined as follows: Resilience was planned to be evaluated using literature or historical fragility curves, which involve analysing existing patterns of events impacting structures, correlating them with hazard occurrences, and predicting the likelihood of reaching certain damage states. Although such projections do not immediately warrant solution implementation, they justify the urgency of action, the time required for renovation, and aid in selecting appropriate improvement or adaptation measures.

From an engineering perspective, any proposed solution, regardless of its theoretical support, should be validated through simulations, modelling, or monitoring. This process provides insights into functionality, behaviour, and the expected outcomes when structures are subjected to various loads. However, this work does not aim to overhaul engineering practices. Although updating standards to address climate change impacts is crucial, literature suggests that such changes take considerable time. Instead, the focus is on facilitating a faster, more comprehensive decision-making process that provides clear expectations and viable solutions.

It is acknowledged that while nature-based solutions are frequently regarded as the most sustainable adaptation measures for climate resilience, their effectiveness is dependent on factors such as rooting depth and the time required for stabilization in the soil. This process not only enhances their efficiency but also strengthens the soil, improving its capacity to withstand forces from events such as rainfall or permafrost.

When models or calculations are performed, it should be considered that nature-based solutions alone are unlikely to provide adequate resistance. In many cases, a hybrid approach is required. Existing structures, which have been found insufficient to resist landslides as demonstrated in case studies, highlight the necessity of such hybrid solutions. By integrating nature-based solutions, it is anticipated that structural resistance will improve progressively over time. As conventional structures approach the end of their service life, the strength of nature-based solutions is expected to increase, compensating for the diminishing strength of traditional structures. This dynamic contributes to enhancing overall resilience.

From fragility curves, probabilities and recovery times associated with various damage states can be determined. As monitoring and implementation occur, reductions in the likelihood of reaching a damaged state or improvements in recovery times can be assessed. This data enables the efficiency of hybrid solutions to be evaluated and prior predictions to be evaluated. Thus, the study is intended to serve as a foundational reference, allowing comparisons and validations of interpretations. It also facilitates the future implementation of innovative solutions by providing essential data and supporting the assessment of new, less-established approaches within the industry.

**The uncertainties will be always high whenever considering simplified approaches; thus, verification is always desirable and recommended before implementation especially in critical projects.**

When implementing sustainability measures, the environmental impacts of proposed solutions are assessed, focusing on aspects such as temperature regulation, urban context, and water runoff reduction. This evaluation aims to predict how nature-based solutions will affect soil structure and overall environmental behaviour. Such analyses provide insights into the potential future functionality and benefits of these solutions. Through visualization and comparison, improvements in social and environmental contexts can be identified. Although this preliminary approach offers valuable projections, its accuracy will be validated through practical implementation and monitoring techniques. The use of tools like ENVI-met is essential due to its compatibility with lifecycle assessment software such as Open LCA, which allows for a comprehensive evaluation of the solutions' long-term impacts on the urban environment throughout their lifecycle. Furthermore, while tools like ENVI-met and lifecycle assessment software like Open LCA are crucial for comprehensive evaluation, their utility is diminished without the data required to validate projections and monitor real-world impacts over time. Analysing adaptive measures without data is challenging because it is impossible to accurately assess environmental impacts such as temperature regulation, urban context, and water runoff reduction. Without data, predicting how nature-based solutions will influence soil structure and overall environmental also behaviour becomes speculative. Visualization and comparison of potential improvements in social and environmental contexts cannot be effectively conducted without empirical evidence and undermines the ability to provide reliable insights into the future functionality and benefits. For that, it is recommended that the methodology developed in future research with all the necessary data addressed to validate its practicality and usefulness in real case contexts.

**Tackling this framework provides insights on the possibility of nature-based solutions being an adequate solely or complimentary solution for tackling the impacts of climate change.**

Traditional methods are often reflected upon, leading to conventional solutions that may fall short in terms of sustainability. However, integrating new approaches and persuading stakeholders to adopt them can be challenging without a well-established framework. The importance of this framework is highlighted by its aim to establish a preliminary standard incorporating sustainability considerations and their evaluation. Regardless of how the approach is perceived or the priorities established, it is evident that at least one nature-based solution is always found to be viable.

This framework ensures that nature-based solutions are not only implemented but also evaluated, with valuable data on their functionality and co-benefits being provided. It emphasizes that these solutions are not merely alternatives but essential strategies for addressing current environmental challenges. An objective methodology for assessing various solutions suitable for the specific hazard under investigation is established during the initial phase of the study. By refining the options, nature-based solutions with potential effectiveness are identified, which can then be validated and analysed for their impact and improvements.

Significant measures, such as reforestation, have been demonstrated to yield meaningful enhancements and offer economic benefits, as evidenced by the ICARUS study. A robust foundation for future research is thereby provided, allowing the same nature-based solutions to be re-evaluated with different priorities and compared to current approaches.

**Although the analysis focuses on the impacts on a certain hazard occurrence, the reality is that the impacts are due to an integrate package of multi-hazard impacts and other triggers that are not only related to the climate change but mainly to the exposure conditions and vulnerability behaviour of the asset itself.**

The uncertainties in decision-making were addressed due to the recognition that their origin often stems from factors beyond climate change alone. Through the impact chain, it was visualized and acknowledged that climate impact drivers might not always be the primary or sole cause. Efforts were made to verify this by correlating events with potential climate impact drivers to assess the future

significance of these impacts. For example, uncertainties in projections are influenced by future human-caused emissions, natural climate variations, and evolving climate models. It was observed that climate data, whether from Gipuzkoa or Kvænangen did not reveal a consistent trend, as a clear increase or decrease in impact drivers such as temperature or precipitation could not be demonstrated. Furthermore, in regions near the marginal ice zone, such as Kvænangen additional uncertainty was introduced by systematic biases in the initial sea ice extent, as changes could influence projections over much longer periods than a few decades.

Future recommendations involve addressing all potential triggers for impact and determining which ones have the most significant effect. This approach is expected to reduce uncertainties and provide a clearer understanding of the context. The study was constrained to the evaluation of the impact of a single hazard trigger due to the complexity of gathering comprehensive data. Nevertheless, it is essential that all possible factors behind infrastructure risks be correlated and that a solution be developed to identify the most impactful triggers and the most likely causes of hazard occurrences.

# 7

## CONCLUSIONS

Tackling climate change adaptation in transport infrastructure remains an unformidable challenge facing the world and carrying huge amounts of uncertainties. While not only influencing the resilience behaviour of the infrastructure but also hindering the implementation of sustainable solutions.

The present and the future of the built environment demand planners, engineers, architects, contractors, and all stakeholders involved in updating the way infrastructure construction, design and management is done. The climate change escalation is surely a necessity that no longer needs only mitigation but also adaptation to ensure coping with its inevitable consequences. While climate resilient projects are the highlight of the current research, it remains a concern that the interpretation of the consequences is performed in way that can be put into decision making. Efforts to create huge databases of climatic data is noticeable around the world however the complexity of climate interpretation by nonexperts hinders their potential.

In the process of effectively tackling is climate change impacts, several research projects have been proposing different ways that can address the context for decision making and rapid intervention. However, the process towards analysing the risks in the practical context remains heavily reliant of extensive data, different expertise and economic expenditure which hinders the effectiveness of response.

This dissertation intended to propose a methodology based on a critical analysis the existing works on climate change adaptation for transport infrastructure. The challenge was to understand what is contributing to the limitation of applying effective solutions and contribute to simplifying the track towards implementation. The research has tried to tackle enhancing the understanding of climate change consequences on transport infrastructure, tackling the data Scarcity, facilitating decision making and paving the way for NbS Integration to climate change adaptation

The basis started from the ICARUS project which proposed the concept of the impact chain to visualize the vulnerability assessment process towards risk development on the infrastructure. This was then used to create a qualitative analysis grading putting the elements of the impact chain from concept into values that yield a preliminary level of vulnerability based on the existing studies covering to create a decision of intervention. This decision is simplified, not heavy reliant on data, verified by several studies and economically feasible when compared to the detailed assessment. The validation after the decision has been made is through a detailed vulnerability assessment based on the fragility curve concept. However, this motivation has been hindered by the extensive need of data that was a scarce in this proposal and could not be achieved. Several databases existing covering climate data are significantly complex for non-experts to integrate and use. Hazard databases are usually not correlated with the event occurrence adding uncertainty to the confirmation of the reasons for impacts, the databases also tend to be missing information needed for performing needed calculations without using complex methodologies and finally construction details are another aspect of challenge especially with existing infrastructure.

This encouraged accepting the preliminary analysis and moving towards the next stage is the choice of adaptation measures which is a critical step for paving the way for Nature based solutions integration in the suggested solutions. A main challenge is present among the climate adaptation process is the involvement of different expertise with different priorities in the decision making. This creates a variation of choice selection randomized depending on subjective perspectives. The solution proposed is to create a standardized decision-making criterion for validation for climate change adaptation. This is based on addressing the underlying common language present among the different decision makers. Accordingly, the baseline decision can cover the resilience and sustainability aspects while also adapting to the choice of KPIs needed in the validation stage. This not only enhances the integration of NbS in the decision context but also allows considering the long-term solutions that not only serve the purpose of climate change adaptation but also contribute with Cobenefits in the context they're set in.

Incorporating NbS on the other hand can aid in improving the existing state of the conventional infrastructure projects, are targeted by this guidance which aims to create a quick analysis of the options available for adaptation and make a choice that can be later supported by a more detailed analysis. This should be showcased as a simplification of the current ways of doing this such that the implementation of the adaptation solutions can be made faster, more considerate, and prevalent to all the stakeholders simplifying the complexity of its reality. Future research trying to address the following issues is expected to showcase a clear improvement in the way climate consideration is put into practice.

According to the findings of this research, it was concluded that this methodology serves as a simplified track for decision-making and putting different expertise and insights into a common context to work on. However, it is recommended that the data is better organized, simplified and adjusted by the involvement of different stakeholders. Also, it is important that expertise is involved in the development of this project to cover the complex aspects of the identification. Future research covering the gaps followed can give a justification for the effectiveness of this approach. The full motivation of validating this methodology has been partially fulfilled due to the data constraints mainly. It is true that the ambition was to make use of the extensive databases and frameworks existing to create a unified methodology that can be adapted and used by different stakeholders however until the resolution of simplifying access to the data, it will remain a challenge to be carried on by future studies.

## FINDINGS AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT

**To resolve the data scarcity**, my recommendation for future works is to establish open source advanced, interconnected databases that integrate climate data with hazard occurrences. Implement Geographic Information Systems (GIS) and big data analytics to facilitate real-time correlation and spatial analysis of climate events and hazards. This approach will enhance predictive capabilities and decision-making processes. Also, develop and deploy automated reporting systems that utilize remote sensing and satellite imagery data to ensure comprehensive and up-to-date hazard records and improve the accuracy of hazard event documentation.

**To enhance the effectiveness of climate adaptation tools**, several improvements are necessary. There must be an increased focus on generating and disseminating high-quality, location-specific data. Investment in data collection and monitoring technologies can help bridge the data gap and provide the detailed information needed for tailored solutions. Second, fostering better coordination and communication among all stakeholders is crucial not only to resolve the need for innovative funding mechanisms to enable climate change adaptation. This stage should be explored to ensure the availability of resources for climate adaptation projects however it is only achieved through providing a clear understanding of the criticality of the situation and enable rapid understanding of the context thus rapid decision making.

**In terms of vulnerability assessment,** it is crucial to use this methodology as an integrated process to create an advanced multi-hazard impact assessment framework that integrate more than climate impact driver to understand the climate change effects, exposure conditions, and asset vulnerabilities. This can be done through machine learning algorithms to model and predict combined hazard impacts. Also, it is true that the risks are function of the hazard, vulnerability, exposure but still it is recommended to analyse the existing maps using GIS to understand on context specific and broader which element is the most contributing factor to the risks, thus create a set if weighing to improve the judgement.

**In the built environment and all its aspects having a common language among the different industry stakeholders is the main barrier to sustainability implementation.** For that, I urge that developing and implementing a standardized base set of KPIs using industry-wide benchmarks, consensus standards and international organizations can yield an even more detailed combinations of the commonalities present, the best practices for KPI selection and evaluation and as a result ensure consistency and reliability in performance metrics and decision making.

**Integrating sustainability metrics into decision-making frameworks** can highlight the co-benefits of various solutions thus promoting regenerative and nature-based approaches when dealing with uncertainties can address both immediate and long-term environmental impacts. The key gap is to analyse the effectiveness of utilizing nature-based solutions for chronic climate impact drivers such as permafrost. This can be done through assessing their effectiveness in pilot projects and case studies and integrate successful strategies into broader hazard management and resilience planning.

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