

Nature-Based Solutions for Demonstrating Climate-Resilient Critical Infrastructure



Deliverable 1.2: Methodology for NbS Integration Into Digital Tools



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Executive Summary

The increasing frequency and intensity of climate-related hazards pose growing risks to Europe's critical infrastructure systems. Nature-based Solutions (NbS) offer adaptive and multifunctional approaches that mitigate these risks while delivering ecological and societal benefits. When effectively designed and maintained, NbS enhance slope stability, regulate hydrological processes, and support biodiversity. The NATURE-DEMO project focuses on demonstrating how NbS can be integrated into infrastructure planning and management to strengthen resilience, sustainability, and adaptive capacity across diverse European contexts.

Deliverable 1.2 is the second deliverable of Work Package 1 – “Nature-Based Solutions for Infrastructure Resilience.” Building on Deliverable D1.1, which developed a catalogue of NbS and characterised their ecosystem and protective services, the present deliverable defines the selection and design requirements of NbS to support quantitative decision-support tools. A central contribution of this deliverable also is the development of a structured methodology for integrating NbS into digital tools designed to support a detailed risk assessment analysis of the climate-resilient critical infrastructures. The proposed framework aims to bridge the gap between the conceptual design of NbS and their practical implementation by aligning ecological, technical, and socio-institutional factors with the corresponding computational and data requirements.

The Site-specific selection methodology is based on a multi-stage framework for NbS design, employing a three-stage approach to support the identification, prioritization, and site-specific design of NbS for protecting the Critical Infrastructure (CI) from climate-related Natural Hazards. The first stage involves the assessment of NH, CI, and Geographical Management Zones (GMZ) to characterize climate-related hazards and define spatial units for tailored NbS planning. The second stage focuses on NbS Pre-Selection, utilizing a structured screening process that integrates Hazards–NbS matrices and detailed factsheets provided in Deliverable 1.1 to identify functionally relevant NbS for the identified hazards and GMZs. The third stage is dedicated to Feasibility and Design Optimization, where the selected NbS options are refined by integrating local knowledge, site-specific implementation constraints, and socio-institutional supportive factors through mapping exercises and project templates.

Monitoring Requirements for Digital Integration are emphasized too, highlighting the critical role of effective monitoring—both before and after implementation—to verify NbS performance, support adaptive management, and generate evidence for future replication and scaling. This includes guidance on selecting key monitoring parameters and reviewing available approaches such as on-site measurements and remote sensing.

Central to the project's digital integration efforts, Chapter 4 focuses on NbS Parametrisation for Integration into Digital Tools. This addresses the historical challenge of systematically integrating NbS into digital decision-support tools, often limited by natural systems' complexity and a lack of standardized parameters. To overcome this, the methodology introduces a parametrization framework based on the RAMSSHEEP approach (Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic, and Politics). This multi-criteria approach enables the assessment of overall infrastructure performance, ensuring a balanced perspective of reliability, safety, sustainability, and affordability. Within this framework, Performance Indicators (PIs) capture diverse factors influencing resilience, which are condensed into Key Performance

Indicators (KPIs): Safety, Reliability and Security (SRS); Availability and Maintainability (AM); Economy (€); Environment (E); and Health and Politics (H, P). These KPIs are qualitatively evaluated on an ordinal scale from one to five, with the results visualized in a multi-dimensional “spider net” diagram for comparing NbS options and their integration into digital tools.

To integrate NbS into climate adaptation, a five-sequential-step evaluation process has been defined. The steps include: Critical Infrastructure Baseline Assessment, Natural Hazards Analysis, Grey Protective Infrastructure (GPI) Measures, NbS Evaluation, and Integrated Risk Assessment and Scoring. This comprehensive framework enhances consistent performance assessment of NbS within digital planning, enabling direct comparison with conventional solutions and supporting climate adaptation and resilience.

The Algorithmic Integration of Risk-Reduction Effects further demonstrates how NbS influence the core components of climate risk, such as hazard, exposure, and vulnerability, within the IPCC AR6 risk concept. A multi-level algorithmic architecture is proposed, consisting of Level 1 for qualitative stakeholder risk perception, Level 2 for semi-quantitative pre-screening, and Level 3 for high-resolution quantitative risk assessment. Additionally, the architecture is combined with a strategic application of Geospatial Foundation Models (GFMs) to enable a scalable, high-resolution analysis for advanced decision support. A representative case study demonstrates the models’ robust ability to quantify the microclimatic cooling benefits and risk reduction effects of urban green and blue infrastructure across diverse contexts.

Ultimately, the framework enhances clarity, facilitates comparability across diverse contexts, and provides a structured decision-making pathway for end users. It highlights that NbS can deliver cost-efficient, multifunctional, and adaptive benefits for protecting critical infrastructure. While significant progress has been achieved, challenges persist in standardizing monitoring protocols, ensuring data accessibility, and integrating heterogeneous knowledge sources. The successful implementation and scalability of these solutions are heavily dependent on robust institutional support and active stakeholder engagement. D1.2 thus provides a transferable foundation for scaling up NbS integration across Europe and beyond, contributing to the EU’s overarching vision of adaptive, cost-effective, and multifunctional approaches to climate adaptation and infrastructure protection.

The deliverable D1.2 marks the transition toward Work Package 2 – “Develop the Digital Decision-Support Platform,” which aims to develop a quantitative framework for risk-reduction estimation and to build a digital platform integrating this framework to guide NbS implementation. The methodology for integrating NbS into digital tools, developed within the framework of the present deliverable and designed to support detailed risk assessment analyses, has been further incorporated into WP2 as a foundational element of Level 1 of the risk assessment framework, ensuring methodological continuity between the two Work Packages.

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List of Acronyms

Acronym	Definition
AF	Adaptation Factor
AM	Availability and Maintainability
CA	Consortium Agreement
COST Action 1406	A Standard, focused on bridge maintenance and life-cycle performance
CI	Critical Infrastructure(s)
CS	Condition State
DEM	Digital Elevation Model
DTM	Digital Terrain Elevation
EC	Economy/Costs
EU	European Union
EI	Exposure Index
EV	Environment
GC	Green Cover
GI	Green Infrastructure
GMZ	Geographical Management Zone(s)
GPI	Grey Protective Infrastructure
HP	Health and Politics
KPI	Key Performance Indicators
IPCC	United Nations Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MCA	Multi-Criteria Assessment
NATURE-DEMO	Nature-Based Solutions for Demonstrating Climate-Resilient Critical Infrastructure
NbS	Nature-based Solutions
NH	Natural Hazard(s)
PI	Performance Indicators
RAMS	Reliability, Availability, Maintainability, Safety
RAMSSHEEP	Acronym for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic and Politics, respectively

Acronym	Definition
QCP	Quality control plans
SRS	Safety, Reliability and Security
TRL	Technology-Readiness Level
WP	Work Package

Glossary of Terms

Term	Definition
Climate Hazard	The potential occurrence of a climate-related physical event, trend, or condition - either natural or anthropogenically influenced - that may cause adverse effects on critical infrastructure, or ecosystems. It includes acute (e.g., storms, floods, heatwaves) and chronic (e.g., gradual temperature increases, changing precipitation patterns, sea-level rise) phenomena.
Critical Infrastructure	Assets, networks, or systems essential for the functioning of society and economy, whose disruption or failure would significantly impact the public safety, health, social well-being, and economy of society. It includes e.g. critical transportation, energy, water, and communication infrastructures providing essential services to individuals, businesses, public institutions, and society at large.
Exposure	The spatial and temporal presence and distribution of people, critical infrastructures, ecosystems, or economic assets in areas that may be adversely impacted by climate hazards.
Green Cover (GC)	The proportion of land covered by vegetation such as trees, shrubs, grass, and groundcover, typically expressed as a percentage of total land area.
Green/Blue Infrastructure	Natural or semi-natural systems that incorporate vegetation, soils, and water to manage environmental processes – e.g. water runoff or heat regulation – and reduce climate-related risks while providing ecosystem services such as e.g. biodiversity support, improved air and water quality, and enhanced recreational and aesthetic value.
Grey Infrastructure	A suite of engineered, built assets designed to provide one or multiple (critical) services required by society, such as transportation (e.g., roads, bridges, railways), water supply and wastewater treatment (e.g., sewers, water treatment plants), and other built infrastructure systems (e.g., flood defences, hydro power plants). Grey infrastructure is typically characterized by the use of man-made materials, distinguishing it from green or nature-based infrastructure solutions that rely on natural processes.
Hazard	The potentially damaging physical event, phenomenon, or process (natural or human-induced) that can cause adverse impacts such as loss of life, injury, property damage, or disruption of essential services. In the IPCC risk framework, hazard interacts with exposure and vulnerability to create risk.
Hybrid Solutions	A deliberate combination of grey and green/blue infrastructure (or ecologically engineered infrastructure) designed to maximise system performance, resilience, and co-benefits.
Impacts	The direct and indirect consequences (positive or negative) of a hazard on human and natural systems, including physical, functional, economic, and ecological effects. In the document's context, it mainly refers to physical and functional damage to critical infrastructures.

Term	Definition
Impact Model	A computational or analytical model that estimates the effects of a hazard on a critical infrastructure performance, considering factors such as sensitivity, exposure, and adaptive or capacity.
Natural Hazards	A class of hazards originating from natural climatic events or processes (meteorological, hydrological, climatological, landslide and snow-related events or processes), which may cause damage to societies and infrastructure through their dominant physical and environmental drivers.
NbS (Nature-based Solutions)	Solutions inspired and supported by nature that contribute to climate risk reduction and deliver environmental, social, and economic benefits. Includes green infrastructures, ecosystem restoration, and hybrid solutions.
NbS Family	Categorisation of NbS based on functional similarities and context-specific applications.
NbS Type	An NbS Type is a specific intervention belonging to one of the seven NbS Families.
Performance Indicators (PI)	Quantitative or qualitative metrics used to assess an NbS' contribution to enhancing infrastructure resilience, in terms of reliability, availability, maintainability, safety, security, health, environment, economics and politics.
Resilience	The capacity or ability of a system or asset to cope with hazardous events by anticipating, withstanding, and recovering from climate-related impacts, while maintaining essential functions and adapting to long-term changes and uncertainties.
Risk	The potential for adverse consequences when a climate hazard affects a critical infrastructure, generating physical, economic, or social damages. In the IPCC framework, hazard interacts with exposure and vulnerability to create risk.
Risk Assessment	The systematic process of identifying climate hazards, evaluating exposure and vulnerability, and estimating potential consequences to infrastructure systems.
Risk Index	An integrated value that quantifies the potential magnitude of climate risk to a critical infrastructure by combining information on hazards, exposure, and vulnerability.
Sensitivity	The degree to which a system or infrastructure is affected (positively or negatively) by climate variability or change.
Urban Green Infrastructure (UGI)	NbS that integrate vegetation and natural elements into urban and peri-urban spaces to address climate and environmental changes.
Vulnerability	The propensity or predisposition of a system or asset (e.g. critical infrastructure system or asset) to be adversely affected and experience damage from a climate hazard. It depends on sensitivity, coping capacity, and adaptive capacity of a system or asset.

1

Introduction

The increasing frequency and intensity of climate-related hazards pose a growing challenge to the resilience of Europe's critical infrastructure systems. Effectively and properly implemented and maintained Nature-based Solutions have proven to be multifunctional measures that not only reduce climate risks but also deliver broader societal and environmental benefits. Unlike grey infrastructure, which typically provides single-purpose services and is less adaptive to changing conditions, NbS can respond to evolving hazard regimes, offer multiple functionalities, enhance both ecological and human well-being through essential ecosystem services, and exhibit more resilient failure behaviour [1, 2, 3]. In many cases, NbS can provide a standalone solution, while in other situations they are most effective when combined with grey infrastructure. Moreover, they are cost-efficient over the long term. Their integration is further supported by the EU's 2021 Adaptation Strategy, which recognizes NbS as adaptive, cost-effective, and multifunctional measures for building resilient infrastructure systems.

1.1. Background and Objectives

For NbS to be effectively adopted in infrastructure planning and risk governance, they must be translated into formats that align with established methods for analysing, evaluating, and managing infrastructure systems—particularly through digital tools. Within the NATURE-DEMO project, Deliverable D1.2 addresses this challenge by providing the methodological foundation for integrating NbS into digital environments that support climate-resilient infrastructure planning. Positioned at the interface between conceptual design and operationalisation, D1.2 builds on the results of Task 1.3 (evidence-based criteria for selecting and designing NbS) and Task 1.4 (parameterisation of NbS performance and contextual attributes for digital integration). It thus plays a central role in linking the ecological, technical, and spatial dimensions of NbS with the computational logic and data requirements of the digital tools developed in Work Package 2.

Objective: The specific objective of D1.2 is to define a structured and transferable methodology that enables NbS to be systematically assessed and integrated into decision-support environments. The methodology will:

- Define how NbS are selected in relation to climate hazards and infrastructure vulnerabilities.
- Establish approaches for monitoring and measuring NbS performance.
- Identify key parameters that can be linked to risk and resilience indicators in infrastructure planning.

Scope and Structure: The scope (Section 1.2) and structure (Section 1.3) outlined below specify the technical content and intended application of the proposed methodology across the NATURE-DEMO project. This ensures that Deliverable D1.2 acts as a bridge between conceptual NbS design and practical digital tools, enabling their effective use in resilient infrastructure planning.

1.2. Purpose and Scope of the Deliverable

The purpose of this deliverable is to present a structured methodology for integrating NbS into digital tools that support climate-resilient infrastructure planning and risk assessment. It contributes to the overarching objective of the NATURE-DEMO project by demonstrating how NbS can be tailored into critical infrastructure protection strategies, supported by accessible, evidence-based, and open digital tools. Deliverable D1.2 establishes the methodological foundation for translating NbS design principles, selection criteria, and performance indicators into formats suitable for digital application. Building on Tasks 1.3 and 1.4, it combines spatial, ecological, technical, and socio-institutional dimensions of NbS planning into a coherent framework. The deliverable introduces a three-stage framework for NbS selection and design, complemented by guidance on performance monitoring and parameterisation. This includes defining relevant indicators, identifying data sources, and applying modelling approaches to inform NbS planning across diverse infrastructure types and geographic contexts. A particular emphasis is placed on enabling the integration of NbS into the digital tools developed in Work Package 2, which will support site-specific decision-making in the project's demonstration cases. The scope of this deliverable is both methodological and operational: it provides the basis for integrating NbS into the digital tools of the NATURE-DEMO project while offering guidance that is scalable, transferable, and applicable to broader climate adaptation and risk management efforts in Europe and beyond.

1.3. Structure of the Deliverable

This Deliverable sets out a coherent methodology for integrating NbS into digital tools for climate-resilient critical infrastructure planning. The document is organised into six chapters, each addressing a core component of the proposed framework.

Chapter 2

Introduces the NbS Selection and Design Criteria through a three-stage framework. It first outlines the assessment of climate hazards and infrastructure vulnerability, providing guidance on their characterisation across different contexts. It then explains the rationale for pre-selecting NbS options based on hazard profiles and geographical conditions. Finally, it details how site-specific decision factors can be incorporated to refine choices under practical constraints, ensuring that NbS planning remains effective, feasible, and context-sensitive.

Chapter 3

Addresses Monitoring Requirements for NbS implementation and performance. It offers guidance on selecting key monitoring parameters, linking them to functional objectives and ecosystem services. The chapter reviews available monitoring approaches, including in-situ measurements and remote sensing, highlighting their ability to capture spatial and temporal dynamics. It further explains how monitoring results support adaptive management, long-term maintenance, and the evidence base required for replicating and scaling NbS across diverse contexts.

Chapter 4

Focuses on the Parameterisation of NbS for integration into digital decision-support tool. It introduces the RAMSSHEEP framework, which structures performance criteria across technical, environmental, economic, and societal dimensions. The chapter elaborates on how NbS parameters can be systematically linked to infrastructure performance indicators, enabling consistent assessment of their contributions to resilience. It also explains how parameterisation supports adaptation strategies by quantifying NbS impacts on reliability, safety, maintainability, and environmental performance, while allowing direct comparison with conventional infrastructure measures.

Chapter 5

Focuses on the algorithmic and computational requirements for assessing the effectiveness of NbS within existing climate risk analysis frameworks. It details how NbS interventions continuously influence the climate risk components as hazard, exposure, and vulnerability, within the established IPCC AR6 framework. Additionally, the chapter introduces a multi-level algorithmic architecture for NbS assessment, highlighting the use of advanced techniques, such as geospatial foundation models (GFMs), to enable scalable, high-resolution analysis needed for risk assessment, Level 2 and Level 3 decision support. A representative case study is provided to illustrate these capabilities, demonstrating the application of a fine-tuned geospatial foundation model to quantify the cooling benefits and microclimatic impacts of green infrastructure in urban environments.

Chapter 6

Provides Concluding Remarks by summarising key findings and reflecting on their application within the NATURE-DEMO demonstration cases. It discusses how the proposed framework advances the integration of NbS into digital planning and risk assessment tools and outlines next steps for the project. Remaining challenges, opportunities for refinement, and the broader policy and planning relevance of the methodology are also considered, with emphasis on its potential to support future scaling-up of NbS for resilient infrastructure.

Site-specific NbS Design Framework

2.1. The need for site-specific and diverse knowledge integration

In climate adaptation and infrastructure planning, NbS are increasingly recognised for their multifunctionality and long-term cost-effectiveness (e.g., [4]). However, despite this momentum, real-world implementation is often hindered by unforeseen obstacles that prevent projects from being executed as originally intended [5]. These include site-specific technical limitations, like unsuitable environmental conditions and limited land availability in densely built environments, as well as uncertainties regarding long-term functionality under changing climatic conditions [6]. This can result in implementation delays, incomplete works, or substantial deviations from the original design during the final stages of construction [7, 8].

On the other hand, **future infrastructure designs** should ensure that the full information of the surrounding environment where those infrastructures will lay is fully integrated into the design report and structural calculations. Moreover, the technical approach should include environmental assessment, climate projections and future scenarios analysis to inform the design.

A lack of stakeholder engagement and community involvement in the early planning phases can reduce social acceptance and lead to resistance during implementation, especially when NbS projects are perceived as externally imposed or compete with other land uses [9]. These barriers were further confirmed through stakeholder interviews and barrier analysis conducted under Task 1.2 of this project, which identified similar challenges in the implementation of NbS across demonstration sites [10]. Many of these obstacles are not immediately visible during early planning stages. This lack of visibility often stems from limited technical expertise and regulations in NbS implementation, insufficient experience with context-sensitive planning, and conventional financial mechanisms that fail to account for the full monetary value and long-term benefits of NbS. Factors such as operation, maintenance, and life cycle considerations are rarely included in feasibility studies, making it difficult to compare NbS with traditional infrastructure on equal terms. As noted above, among the over 20 stakeholders interviewed, many expressed the need for clearer evidence of long-term performance, standardised evaluation criteria, and guidance on implementation and maintenance practices to increase confidence in adopting NbS [10]. Making such barriers more visible and addressing them early in the planning process is essential for improving the feasibility and resilience of NbS implementation [7, 11].

To overcome these gaps, this chapter introduces the Site-specific NbS Design Framework, a structured, three-stage approach co-developed within Task 1.3 of the NATURE-DEMO project. This framework supports users in selecting and refining NbS options suited to site-specific climate risks and infrastructural needs. It anchors the preliminary planning phase of the overall NATURE-DEMO methodology and precedes and supports the next methodological frameworks being developed under Work Package 2.

The **Site-specific NbS Design Framework** supports the increasing demand for comprehensive NbS decision-making methodological approaches that integrate site-specific implementation constraints and opportunities for NbS mainstreaming in the face of climate risk responses and growing complexity in Critical Infrastructure (CI) systems [4, 12]. The Site-specific NbS Design Framework responds to this by providing a practical and operational pathway for aligning NbS pre-selection with real-world design constraints and legal and socio-economic factors. It introduces a logic that connects Natural Hazard (NH) mapping, CI identification and geographical management zoning (Stage 1), targeted screening of NbS Types (Stage 2), and site-tailored feasibility assessment and optimisation (Stage 3), in synergy with stakeholder engagement and multi-scale risk modelling.

The first stage of the above-mentioned three stages encompasses an analysis of the territory, main challenges and infrastructure components. The second stage is the pre-selection of suitable NbS Types to the identified risks. The final stage draws on the context-specific implementation considerations, whilst outlining how diverse sources of information (including implementation constraints, expert knowledge, and context-specific institutional factors) can be integrated to inform a more robust and context-sensitive NbS design. As part of the third stage of the framework, socio-economic and institutional dimensions are incorporated by stakeholders into the analysis as enabling factors, with the aim of providing comprehensive insight into the opportunities and drivers that support the mainstreaming of NbS, as referred to by the IUCN Global Standards [12]. The whole methodology aims to bridge the gap between scientific knowledge and accessible, user-friendly operational guidance to promote an optimised and effective planning and design of NbS systems [13].

By the application of the three stages, this framework provides the methodological foundation for identifying and refining NbS options suitable for integration into risk-based digital decision tools (see the last section of this chapter). It also complements the multi-level Risk Assessment Framework (D2.1) and will directly inform spatial tool development in subsequent project phases. The framework ensures that planning decisions are informed by spatial, socio-institutional, and site-implementation constraints or technical factors, and it establishes a structured, stepwise approach—from hazard-related impacts, identification of vulnerable infrastructure and definition of Geographical Management Zone (GMZ), to screening of suitable NbS Types and feasibility refinement. The framework serves as a bridge between qualitative stakeholder insights (captured in Level 1 risk assessments) and the more advanced, quantitative evaluations in Levels 2 and 3. In doing so, it supports the operationalisation of NbS design within the broader digital integration architecture being developed in Work Package 2 and lays the groundwork for monitoring, replication, and scalable deployment of effective NbS strategies.

2.2. How this framework was co-designed

The framework was developed within Task 1.3 of the NATURE-DEMO project, as a preliminary site-specific NbS planning approach. The approach aligns with overarching frameworks for NbS, such as the IUCN Global Standard for NbS, a user-friendly framework for the verification of NbS [12], as well as the European Commission's guidance on how to integrate Green Infrastructure

(GI) into various policies, including disaster risk reduction [14]. It builds on principles established in environmental management, spatial planning, and risk assessment literature [15, 16, 17], draws on scientific literature and expert input, and incorporates the Catalogue of NbS for CI protection from climate hazards presented in NATURE-DEMO Deliverable 1.1 [18].

It has been co-developed with practitioners, experts, and use case owners across Europe. Its practical application has been validated across five site-specific contexts (the project demonstration cases), providing insights into optimisation factors and contextual constraints, preceding the application of the Level 1, 2 and 3 of the Risk Assessment Framework. The validation was conducted through two in-person multi-actor workshops representing the five demonstration cases of the project and additional experts of the project. The first validation workshop was held in February 2025 in Vienna (Austria). The framework was further developed over the months of March, April and May 2025. The full framework was validated in a second workshop, held in May 2025 in Zvolen (Slovakia), during the NATURE-DEMO Consortium Meeting.

2.3. Structure of the Framework

The Site-specific NbS Design Framework is structured into three stages that systematically integrate relevant data to evaluate contextual constraints and critical decision-making factors, thereby assessing the site-specific suitability of NbS and enabling an effective and feasible nature-based or hybrid integrated infrastructure protection solution [19]. It follows a sequence that transitions from broad contextual understanding to implementable NbS designs, including the analysis of constraints and main drivers for their successful implementation and maintenance [19]. The three-stage sequence is introduced in the flowchart below, and elaborated in more detail in the subsequent sub-chapters. Figure 2.1 illustrates the flows of information and tools through the three stages.

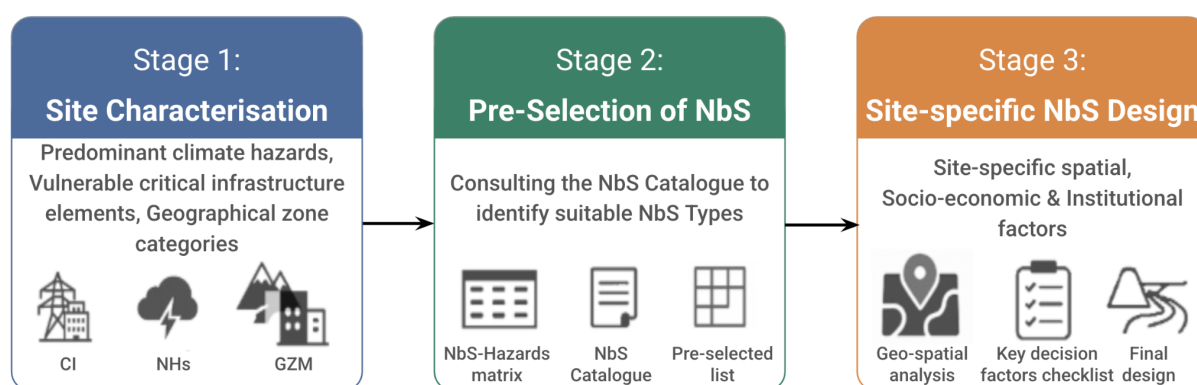


Figure 2.1: Flowchart for the whole Site-specific NbS Design Framework (Adapted from [19]).

Stage 1 – Natural Hazards (NH), Critical Infrastructure (CI) and Geographical Management Zone (GMZ) Assessment

This initial stage characterises climate-related hazards affecting CI and defines spatial units (GMZ) based on natural processes and territorial features. It identifies site-specific hazards and spatial boundaries of vulnerable assets to inform risk-prone areas and intervention priorities, which aligns with the UNISDR [20]. The zoning follows principles of landscape ecology and eco-regionalisation [21], serving as a spatial foundation for tailored NbS planning. This structured approach enables cross-sector integration and scalable application across diverse regions [19].

Stage 2 – NbS Pre-selection

Stage 2 links identified NH and GMZ to suitable NbS Types via a structured screening process. Using the Hazards–NbS matrix and factsheets from Deliverable 1.1 [18], users can filter NbS based on functional relevance, past performance, and compatibility with site characteristics. NbS are grouped into seven Families to support systematic comparison and option narrowing, supported by key design and implementation insights [18].

Stage 3 – Feasibility and Design Optimisation

This stage refines selected NbS options by incorporating local knowledge, constraints, and socio-institutional factors into a feasibility-focused design [19]. A digital Excel-based template guides users through key criteria (e.g. land use, governance, social acceptance), enabling context-sensitive, practical solutions. This aims to ensure the design of effective and multifunctional NbS by integrating multi-sector information and multiple key knowledge types on their location, scale, landscape integration and alignment with broader planning objectives [16]. It also supports early-stage identification of barriers and integration of Performance Indicators (PI) – such as reliability, availability, maintainability, safety, security, health, environment, economics, and politics – when applying the RAMSSHEEP framework for expert-based assessment by Fernandes et al. [22], which enables structured comparison across planning scales and sectors (see additional information about RAMSSHEEP under section 4.1 of this document).

The following sections 2.3.1 to 2.3.3 explore each of these three stages in greater depth, outlining their objectives, underlying logic, and practical implementation steps. By walking through the full sequence – from spatial hazard assessment to NbS pre-selection and feasibility refinement – this detailed guidance is intended to support practitioners, planners, and decision-makers in translating complex site conditions into robust, tailored, and actionable NbS interventions. Section 2.4 describes considerations for the scalability and transfer of this framework.

2.3.1. Stage 1 – Natural Hazards (NH) and Geographical Management Zones (GMZ) assessment for Critical Infrastructure (CI)

This section describes the processes and materials of the initial stage of the methodological framework. The purpose of Stage 1 is to establish the NH profile and GMZ relevant for NbS assessment for critical infrastructure elements under consideration. These elements form the essential input for the structured pre-selection of NbS in Stage 2. The framework requires user input to identify the CIs of interest, characterise CI exposure and vulnerability within defined zones, and to identify major climate risks and predominant NH Types, hotspots and site constraints. User-provided data primarily includes details on CI components, specific sub-hazard categories, and geographical characteristics of the site. In many cases, a single infrastructure element may be exposed to multiple sub-hazards – either simultaneously or as cascading effects – which further increases its climate vulnerability.

Data, tools and materials for Stage 1

A core step of this first stage is the identification and collection of key input data. To facilitate this, the project team has developed a structured Excel-based input tool, further referred to as the Site Context Characterisation Template, supporting practitioners and local experts in systematically compiling hazards and spatial data of geographical management zones and CIs required for NbS screening. Users select options from dropdown menus across three distinct domains – GMZ, CI, and NHs – and record key information on spatial features using maps (online or offline). The Site Context Characterisation Template is designed for consistency across demonstration sites and ensures that site information is gathered in a format that can be directly transferred to subsequent tools, including the Hazard–NbS Matrix and NbS Catalogue introduced

in Deliverable 1.1 [18]. Figure 2.2 illustrates this process with an example of how this tool was applied in the NATURE-DEMO project workshop in Zvolen (2025).

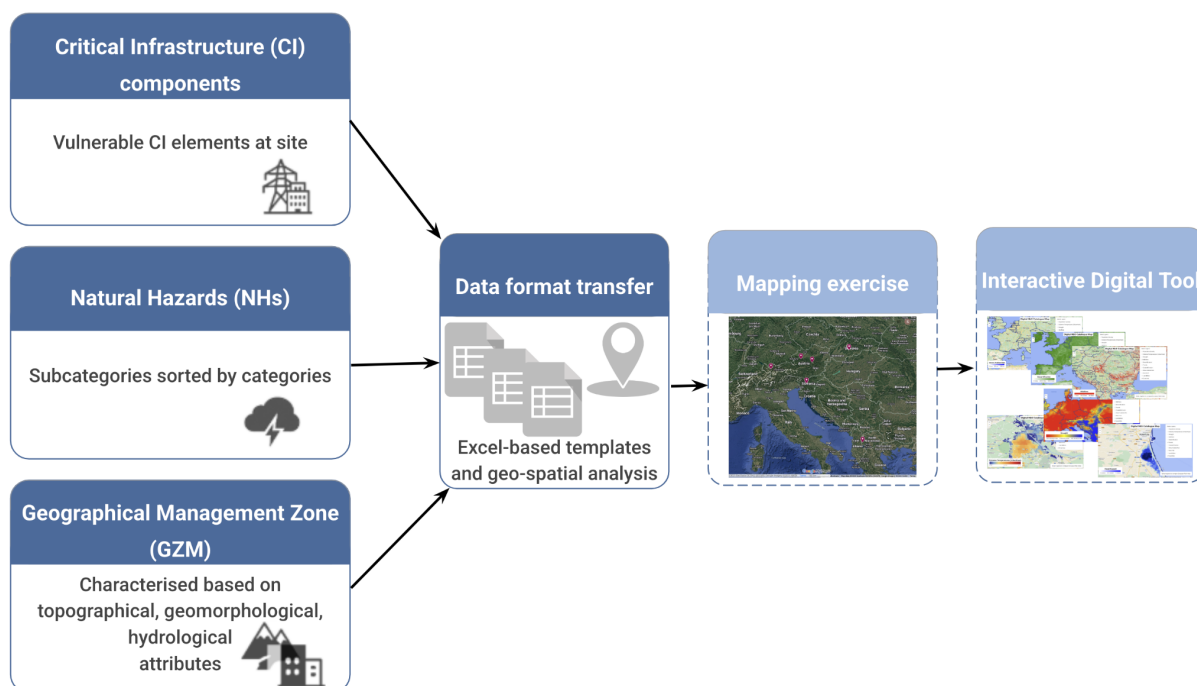


Figure 2.2: Instructions provided to NATURE-DEMO partners during the project workshop in Zvolen (2025) for fulfilling the Site Context Characterisation Template of the first stage of the framework (Adapted from [19]).

Definition of key categories in the Site Context Characterisation Template

(i) Geographical management zones: In the field of landscape and territorial planning, the delineation of ecoregions has served as an instrument to enhance ecological conservation, as it supports analysing the interrelationships between the natural processes in the environment and the planning components. In this approach, territorial units or ecoregions, are defined by natural boundaries rather than political borders [23].

Geographical management zones (GMZ) are defined by specific geomorphological, hydrological and climatological commonalities. The concept of delineating geographical zones for environmental management is grounded in spatial planning and environmental science, drawing on the principles of eco-regionalisation [21, 24]. These zones, often termed ecological regions, ecoregions, or bioregions, are defined by a recurring pattern of natural characteristics. Olson et al. [21] provide a global framework for ecoregions, highlighting how areas with similar biological communities, climate, and physiography can be delineated to inform conservation and management strategies. While broader in scale, the underlying principle of grouping areas by shared environmental features is directly applicable to local-scale GMZ for NbS. Bailey [24], through his work on ecoregions of the United States, demonstrates how integrated physical and biological factors can be used to classify land units, supporting a systematic approach to land management and planning.

This concept directly supports the idea that understanding geomorphological, hydrological, and climatological commonalities is critical for assessing the feasibility of the implementation of the pre-selected NbS and integration into current territorial strategic planning and land-use zones. In the framework developed herein, GMZ serve as functional spatial units for NbS planning,

enabling tailored intervention strategies that are ecologically coherent and locally adapted to existing planning frameworks and land-use zones. The Site Context Characterisation Template is based on available literature in eco-regions and biophysical ecosystem zones and is defined by NATURE-DEMO under the following categories:

- **Floodplains (including rivers, lakesides and wetlands):** characterised by distinct hydrological regimes, low-lying geomorphology, and alluvial soils, frequently influenced by fluvial or lacustrine processes. They exhibit unique moisture dynamics and support specific aquatic and riparian ecological communities.
- **Moderate-to-high urbanised environments:** defined primarily by significant anthropogenic modification, these zones feature extensive impervious surfaces, altered hydrological cycles, fragmented natural habitats, and unique microclimates. Their ecological and climatological characteristics are largely shaped by human activities and infrastructure development.
- **Coastal areas:** these zones represent the dynamic interface between terrestrial and marine environments, marked by distinct geomorphological features (e.g., beaches, dunes, estuaries, lagoons), specific hydrological processes (e.g., tidal influence, saltwater intrusion), and unique ecological communities adapted to saline conditions.
- **Alpine and mountainous regions:** are characterized by steep terrain and rapid elevation changes over short distances. These topographic features interact with climate (solar radiation, wind, snow distribution, and water availability) to create high habitat diversity, which drives elevated plant species richness in mountains [25]. The ruggedness of terrain (defined as elevation range within a specified area) [26], combined with the resulting steep climatic gradients, are key determinants of how mountain biota respond to environmental change [27, 28]. These conditions produce distinctive ecological patterns, including shorter growing seasons, snowmelt-fed hydrological systems, and species adaptations to extreme climatic conditions such as low temperatures, high precipitation, and strong winds. The term “alpine” refers to vegetation-covered land area above the climatic tree line (in elevations where trees cannot grow) [29].
- **Forests:** Forests are complex ecological systems and natural resources in which trees are the dominant life-form. Major forest types by latitude include: Tropical forests, located near the equator, having high temperatures and long growing seasons; temperate forests, found in mid-latitudes, which experience four distinct seasons and can be deciduous, coniferous, or mixed with varying levels of precipitation, including temperate rainforests; and boreal forests, situated in the subarctic, which have long cold winters and short growing seasons and are typically dominated by cold-adapted coniferous evergreen trees. Forest types are distinguished from each other according to species composition, the density of tree cover, type of soil found there, and the geologic history of the forest region. Altitude and unique meteorological conditions can also shape forest development. The concept of forest itself remains debated, as different definitions serve distinct assessment, management, and restoration objectives [30].
- **Pasture and agricultural land:** predominantly anthropogenically managed landscapes, defined by specific land-use practices for livestock grazing or crop cultivation. Their geomorphological and hydrological characteristics may vary, but their ecological composition and nutrient cycling are largely shaped by agricultural processes and human intervention. They often hold high cultural and biological value, as many species have adapted to traditional land-use regimes.

The delineation of GMZ in the first stage of this methodological framework is applied at the local scale to support territorial analysis and aims to link site conditions to the most suitable NbS Families and Types. For example, if we categorise an area as a floodplain characterised by essential natural processes for retention and infiltration, we become aware of the need to preserve and enhance those predominant hydrological functions. This understanding directly guides the prioritisation of retention or infiltration-based NbS from the corresponding family in the catalogue, Deliverable 1.1 [18]. NbS might work synergistically with the natural floodplain dynamics, e.g. constructed wetlands. Conversely, implementing NbS that contradict these natural processes would be counterproductive and potentially increase flood risk.

This zone-based approach ensures that NbS selection aligns with the inherent ecological characteristics and enhances rather than disrupts the natural functioning of the landscape. The geographical management and mapping of the local context helps planners to recognise dominant natural processes and prevailing climate signals, such as annual rainfall patterns, average temperatures or wind dynamics that shape feasible interventions. Drawing upon the principles of eco-regionalisation as described by Olson et al. [21], these geographical management zones represent areas defined by a coherence of specific biophysical and, in some cases, anthropogenic characteristics. Their delineation facilitates targeted NbS application. GMZ are further used to link local site characteristics to the NbS Families with associated NbS Types as outlined in Deliverable 1.1 [18].

For example, a site identified as a floodplain may be suitable for infiltration-oriented NbS. By contrast, applying drainage-oriented grey infrastructure in such areas may undermine natural hydrological function. This zone-based logic enables planners to match site-specific ecological processes (e.g., retention, infiltration, evapotranspiration) with appropriate NbS functions – ensuring that interventions enhance rather than disrupt landscape dynamics. It also supports spatial scaling and coherence across project sites. The delineation of geographical management zones helps recognise dominant physical and climatic signals – such as rainfall patterns, wind exposure, or seasonal temperature shifts – that shape feasible NbS configurations. This definition is thus foundational for selecting appropriate NbS Families, as it provides the biophysical filter through which effectiveness and ecological fit are assessed by the user.

(ii) Critical Infrastructures (CIs): The classification of CI developed within the NATURE-DEMO project [31] focuses on discrete, physical components such as transportation networks, energy systems, and water management facilities. This targeted approach deliberately excludes institutional and regulatory systems, concentrating instead on site-specific assets to enable precise planning of NbS. Such a scope reduction is essential to limit the complexity inherent in regional or national infrastructure networks, which are typically addressed in broader territorial planning frameworks [32].

Asset-level granularity facilitates detailed analyses of vulnerability, exposure, and interdependencies among critical nodes, aligning with established methodologies in infrastructure resilience research [33, 34]. This approach is particularly valuable for modelling cascading failures and site-specific mitigation strategies under climate-related hazards [35, 36]. Internationally recognised CI reference lists—such as the EU Directive on the Resilience of Critical Entities (CER Directive 2022/2557), the US Department of Homeland Security, and sectoral risk assessments in climate adaptation planning—serve as foundational tools for preliminary assessments [37, 38].

(iii) Hazard types: The specific classification system of hazard types and processes used herein was outlined in Deliverable 1.1 [18]. It groups extreme events and natural processes into a structured set of five main categories (climatological, meteorological, hydrological, landslide and

snow-related hazards), further subdivided into 25 hazard types that can be addressed with NbS under current and projected climate conditions. Each CI asset can be linked to multiple hazard types, either due to multi-hazard exposure at the site (e.g., overlapping wind and flood risks), or due to cascading effects (e.g., extreme rainfall triggering landslides that damage transport infrastructure). This logic is directly integrated into the Site Context Characterisation Template, enabling users to assign hazard pressures to infrastructure elements with appropriate specificity. This classification is essential not only for pre-selecting NbS (see Section 2.2), but also for later stages of digital modelling, where quantitative risk assessments will depend on accurate pairing of hazard types with infrastructure vulnerabilities and NbS mitigation functions.

2.3.2. Stage 2 – NbS Pre-Selection

This stage supports the identification of NbS that are functionally relevant to the hazards and GMZ in Stage 1. Based on the CI elements, hazard profiles, and spatial units previously characterised, users are guided to screen suitable NbS using a structured and transparent approach. A key instrument for this step is the Hazards–NbS Matrix, developed within the NATURE-DEMO project (Deliverable 1.1, [18]). Note that the use of matrices is a recognised method for systematically matching solutions to problems, facilitating a transparent and logical selection process [39].

The Hazards–NbS Matrix developed within the NATURE-DEMO project matches specific hazard types with NbS Types that have demonstrated effectiveness in either reducing hazard formation, mitigating impacts, supporting conventional grey infrastructure, or enabling post-disaster recovery and provides a preliminary basis for the pre-selection of NbS. It also organises the NbS Types into seven NbS Families that allows users to filter the solutions. Complementing the matrix, the NbS catalogue – also developed in Deliverable D1.1 – provides a set of detailed NbS factsheets, further detailing key information (ranging from key technical specifications to ecological requirements and performance metrics, core ecosystem services and indicative cost–benefit profiles) to support this pre-selection of NbS.

The factsheets serve as a bridge between screening and design by enabling users to evaluate the applicability and feasibility of each NbS in relation to local physical, regulatory, and socio-economic conditions. Importantly, the NATURE-DEMO factsheets are not prescriptive templates but flexible design references, offering a baseline for selecting and customising NbS according to specific functional targets and contextual needs. We stress that the NATURE-DEMO NbS factsheets are compiled as a catalogue to provide options for NbS types, ecosystem services they provide, which suitability can be assessed and adapted according to specific purposes, targets and functions and local site conditions.

Note that the NbS considered herein correspond to a minimum Technology-Readiness Level (TRL) of 6, i.e. they have been successfully demonstrated in their real operational environment. The factsheets follow the well-established ecosystem-service classification frameworks, based on descriptive profiles for biomes and ecosystem functional groups [40] in alignment with the IUCN Global Standards, ensuring clarity, comparability, and usability across disciplines and decision-making contexts.

By connecting hazard-specific needs with NbS functionality and local feasibility, this stage provides a crucial bridge between initial system assessment and site-specific design in Stage 3.

2.3.3. Stage 3 – Site-specific implementation constraints, socio-economic and institutional supportive factors and available tools and data for effective and feasible NbS design

The third stage of this methodological framework takes the pre-selection of NbS to the assessment of a site-specific design and spatial configuration in the planning unit. To this end, it provides a methodology that allows users to analyse site-specific contextual characteristics, socio-economic and institutional factors and the tools and data for assessing an optimised design and post-construction performance. This methodology combines a mapping exercise with the filling in of three Excel-based templates that are assessing the earlier mentioned aspects: *Site-specific implementation constraints*; *Socio-economic and institutional supportive factors* and *Available tools and data for effective and feasible NbS design*.

The *Site-specific implementation constraints* is the first aspect assessed through the Excel template; this questionnaire is filled in during a mapping exercise performed by users at their planning unit. The mapping exercise assesses some of the locations where the NbS could be placed while examining site-specific constraints for their successful implementation and long-term maintenance.

The Site-specific implementation constraints will vary according to the site's characteristics related to topography, geology, hydrology, built up surface distribution, green cover distribution, level of variety, vertical stratification and density of flora species of the identified green areas, and the meteorology (e.g. temperature and rainfall distribution, humidity, solar radiation, evapotranspiration rates or wind).

The *Socio-economic and institutional supportive factors* questionnaire is filled as a second step by users with the aim of identifying opportunities for an optimised design, implementation, operation and maintenance of the proposed NbS (Figure 2.3). Community-based support, as well as legal frameworks and financial mechanisms are among the main aspects considered in this questionnaire.

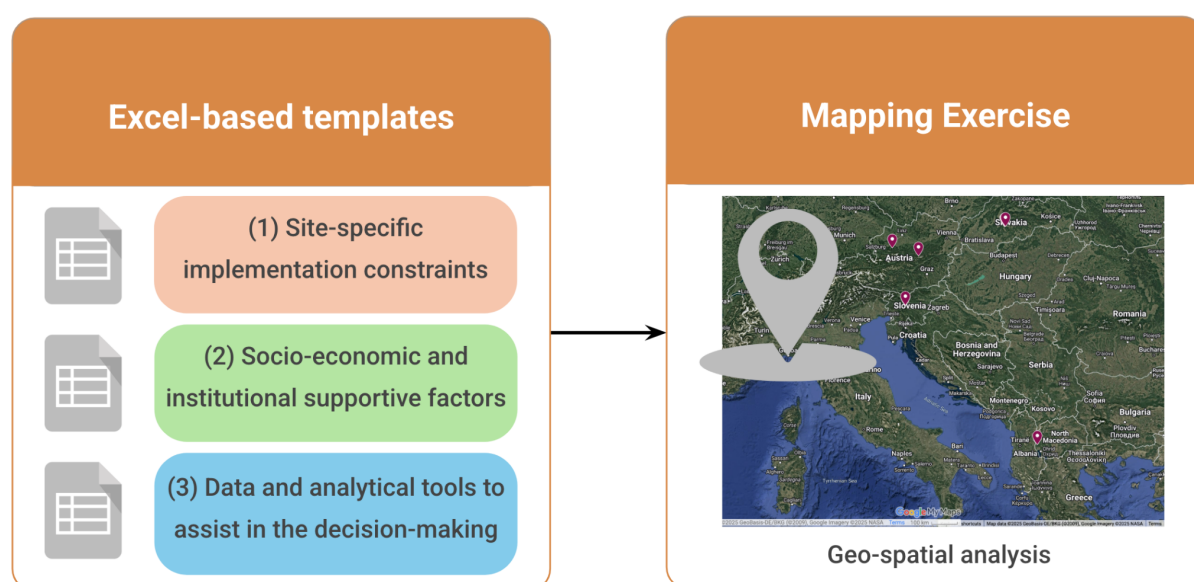


Figure 2.3: Instructions given to Nature Demo partners at the 2025 Zvolen workshop to inform feasible NbS design (Adapted from [19]).

The *Available tools and data for effective and feasible NbS design Excel-based questionnaire* collects information from users on existing tools and data for analysing the territory and support in the process of NbS modelling for an optimised design. Users can combine a second mapping exercise while testing the use of the tools and accessing the current geo-spatial data to support a more effective NbS configuration and planning.

While Deliverable 1.1 provides a catalogue of NbS, these additional site-specific implementation constraints, governance and socio-economic related considerations and collection of existing data and tools play a critical role in transitioning into the feasibility study for the NbS proposal. The third stage should assist in determining what specific NbS Types can be successfully implemented and maintained over the time, assessing different locations, sizes and specific designs.

Users assess biophysical characteristics, define what would be the main constraints to NbS site-specific implementation (e.g. soil instability, private properties, lack of space, vulnerability to flood exposure, etc.), reflect on socio-economic and institutional mechanisms for an optimised implementation and long-term maintenance (e.g. policy, funding availability, social acceptance), and the available tools and data for modelling the different proposals. The consideration of policy, funding and social enablers are often treated separately in the planning process. The reflection on all these aspects by users aims at improving current decision-making frameworks. Users identify the most important site-specific implementation limitations as well as enabling factors across multiple domains to enable a more effective planning (Figure 2.3). By doing this, the framework facilitates the implementation of NbS interventions, avoiding that they are not fully implemented, modified towards more conventional solutions, or even stalled, due to unprecedented obstacles.

This process guarantees identifying and reinforcing community-based support and financial viability for long-term operation and maintenance. It also highlights data and tools for post-construction monitoring towards optimised performance of the implemented systems (see Chapter 3). The below figure captures the instructions that were given to the stakeholders during the workshop for conducting the third stage of the framework. It depicts the three aforementioned site-specific templates, together with the online map that was prepared for them to perform the mapping exercise. Furthermore, it indicates to users that the data fill in the Excel-based format could be retrieved from the geo-spatial format where the NbS location was being assessed.

2.3.3.1. Site-specific implementation constraints

The third stage of the framework begins with the characterisation of **NbS implementation at site-specific locations** considering the territory (e.g. geodetic measurements, geology, geomorphology, hydrology, urban environment, built up areas, wind, temperature, rainfall distribution, etc). A mapping exercise is conducted concomitantly to the filling in of the Site-specific implementation constraints template, to allow users to identify implementation obstacles. The Excel-based template is used by users for rating the level of relevance for a set of implementation constraints related to NbS integration (Figure 2.3). Thus, the final stage provides a decision framework to assess the feasibility of the pre-selected NbS from Stage 2.

The site-specific planning of NbS requires assessing their spatial configurations at different scales, using a multi-scale approach [12]. For instance, users analysing an urban context may test NbS in a diverse range of space context, such as green areas within residential districts, green corridors between main traffic connections or large urban parks.

The analysis of the context and feasibility of the NbS implementation begins with identifying and mapping key biophysical constraints—such as slope, land cover, hydrological conditions, and

hazard exposure—that influence the feasibility of different NbS Types. In parallel, users are guided to assess non-physical implementation factors, including both limiting and enabling conditions, such as funding availability, legal frameworks, institutional capacity, and public acceptance. These socio-economic and institutional aspects are essential for optimising spatial layout and planning decisions.

The mapping of the NbS using a multi-scale approach acknowledges that the effectiveness and multifunctionality of the systems depends not just on their physical location, but also on their scale, landscape integration and connection with existing infrastructure and ecological networks [16]. For instance, Demo site 2 will test NbS in different urban environments, including inner green spaces within residential unit blocks and transitional green areas on the outskirts of residential zones. The green spaces created through the implementation of NbS will serve as effective stepping-stones both for regional biodiversity and for the provision of ecosystem services at local and regional levels, enhancing connectivity between urban elements and ecological habitats and new green corridors.

This spatial perspective helps consider trade-offs and synergies among benefits (e.g., hazard reduction, biodiversity enhancement, recreational value) and supports adaptation of the NbS to the site's unique biophysical and governance conditions.

The central challenge of the third stage lies in combining physical feasibility with socio-institutional readiness. Addressing both dimensions increases the likelihood that NbS principles are not only tailored to the local context, but also fully implemented and maintained over time. For instance, increasing awareness of NbS site-specific implementation constraints and the connection to supportive drivers may be a key enabler of the completion of the construction and continuous maintenance of the solution, which is critical to its long-term performance.

Ultimately, the third stage of the methodology enables users to evaluate the spatial configuration of different NbS through a structured workflow based on the conduction of a mapping exercise and the filling in of three Excel-based templates, supporting the feasibility study of possible scenarios for NbS allocation in space. This process facilitates the generation of possible implementation scenarios and the delineation of feasible NbS zones, based on spatial logic and contextual realities.

Delineating potential NbS sites offers an initial assessment of spatial feasibility and highlights possible land-use or topographical conflicts. Following this mapping exercise, users are asked to reflect on the key site-specific constraints and enabling conditions that may influence implementation. This includes both biophysical limitations and socio-institutional barriers or supports. To capture this, users complete two templates: one for site-specific physical constraints and one for socio-economic and institutional supportive factors.

Alongside the geospatial delineation and visualisation, the third stage of the framework incorporates an Excel-based questionnaire, which translates spatial design considerations and contextual enablers into tabular formats for comparison and planning (see Table 2.1 for classification of site-specific implementation constraints and Table 2.3 for classification of socio-economic and institutional supportive factors). Table 2.1 and Table 2.3 integrate the concepts from global frameworks for NbS, mainly the IUCN Global Standards for NbS (2020). The IUCN translates the NbS concept into targeted actions for implementation, reinforcing best practice, addressing and correcting shortfalls and enabling interventions to align with internationally accepted NbS principles. Also, the questionnaires are grounded on the main site-specific design factors considered in the NbS Catalogue from Deliverable 1.1, particularly addressed in the NbS Factsheets' sections named Site suitability, scale and coverage and Cost-benefit profile.

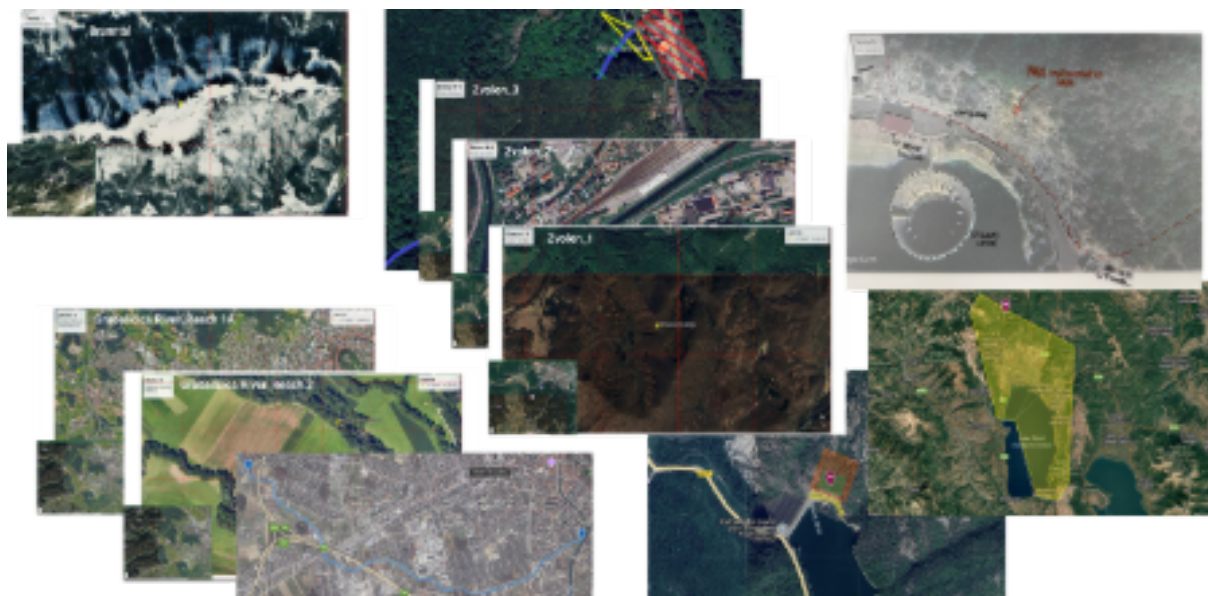


Figure 2.4: Examples of maps used during a NATURE-DEMO workshop in Zvolen (2025) for NbS implementation in the site-specific context (Adapted from [19]).

2.3.3.2. Socio-economic and institutional supportive factors

The third stage of the framework continues with the identification of **Socio-economic and institutional supportive factors**. An Excel-based template is used to make potential opportunities visible, identifying the main drivers that facilitate the design and implementation process from financial, institutional, and social perspectives. The main factors considered are derived from standardised guidelines, particularly the IUCN Global Standards, which provide a practical yet robust guidance for targeted NbS implementation and embed internationally accepted NbS principles [12].

criteria should be considered in terms of optimised and effective NbS planning, which can be further integrated to supportive digital platforms. The Excel-based RAMSSHEEP tool's [22] linked questionnaires enable the creation of an objective evaluation framework based on the RAMSSHEEP concept established in infrastructure engineering, see section 4.1 for further information. Within the project, this concept is contextually expanded to also capture soft factors—such as social acceptance, institutional frameworks, and socio-economic resilience—in a structured manner and to embed them effectively in decision-making processes.

2.3.3.3. Existing tools and data at a local, regional, national and trans-border scale

Finally, the Excel-based template Data and analytical tools to assist in the decision-making collects users' data on the tools and data available for assessing NbS implementation. These three Excel-based questionnaires set a basis for planning and design by moving beyond the 'what' NbS would be suitable, to address 'how' and 'where' they should be implemented for an optimised design in a given geographical, socio-economic and institutional context.

As part of the NbS pre-construction planning and post-construction evaluation process, users require access to data and tools that help for the definition of individual NbS specification. Further, these tools provide better understanding on evaluation of NbS in accordance with the country's organisational strategy, at local, regional, and national public administration scale and in alignment with the existing territorial planning and national strategies (e.g., National Biodiversity Strategy, National Strategy for Protected Areas). Therefore, as part of the last stage of the framework, relevant datasets and analytical tools are identified to support the preliminary

Table 2.1: Site-specific implementation constraints

Site constraints	Description	Level of constraint
Slope instability, risk of rock falls or avalanches	Soil structure, terrain slope, and the risk of rock falls or avalanches influence the implementation process. These could hinder adopting the solution or impede safe accessibility for site construction.	No / Minor / Moderate / High
Limited vegetation and low-quality soil	Limited growth due to altitude or cold temperatures, and poor-quality soil for plant growth.	No / Minor / Moderate / High
Limited access to implementation	Difficulty in accessing the site, transporting materials, or machinery due to steep slopes, among other factors.	No / Minor / Moderate / High
Lack or limited maintenance of infrastructure	Limited access to infrastructure required for long-term maintenance.	No / Minor / Moderate / High
Limited water availability	Seasonal variations in water flow or NbS requirements, or lack of water sources.	No / Minor / Moderate / High
Lack of connection to major services	Lack of proximity to roads or main connections to services (e.g., larger towns or cities with construction equipment, resources, and facilities to support implementation works).	No / Minor / Moderate / High
Space constraints	Limited land for planting vegetation or installing green infrastructure such as green roofs or rain gardens.	No / Minor / Moderate / High
Exposure to soil, water and/or air pollution	Soil, air, and water pollution that may hinder certain NbS implementation and/or maintenance.	No / Minor / Moderate / High
Limitations due to high population density	Increased human activity that could interfere with natural restoration processes.	No / Minor / Moderate / High

planning and design of NbS interventions. With regard to the post-construction phase, once the NbS is executed and operates on a permanent basis, continuous data collection, processing, modelling and interpretation will help in assessing the performance of the NbS, as further detailed in Chapter 3 of this document. Overall, identifying these tools and datasets ensures a robust basis for optimised planning, design, implementation and further monitoring of the NbS.

The information, classified under "Data" and "Analytical Tools," was structured as a database in an Excel table, and is summarised in Table 2.3.

The "Data" category compiles environmental and climatic information to assess NbS suitability within the scope of the methodological framework. The data domains include:

- **Geology:** as previously detailed, geological parameters such as soil type and composition (e.g., texture, organic matter, depth), subsurface geology (bedrock type, depth, karstic features), hydrogeology (groundwater table, aquifers), and geological hazards (landslide susceptibility, erosion potential) are fundamental for any type of intervention, including infiltration-based NbS, such as several types of Sustainable Urban Drainage Systems (SuDS) [41].
- **Geodetic measurements:** this domain includes high-resolution elevation models (e.g., Digital Elevation Models - DEMs), slope gradient, and micro-topographical features. Topographical data is crucial for delineating catchments, modelling surface water flow pathways, identifying accumulation zones, and assessing visual impacts of NbS [42]. It

Table 2.2: Socio-economic and institutional supportive factors

Supportive factor	Description	Level of support
Community engagement	Public perception and understanding of NbS and how this may affect the implementation of success	No/ Minor/ Moderate/ High
Cultural preferences	Local community's unattachment to traditional practices and non-resistance to unfamiliar NbS methods	No/ Minor/ Moderate/ High
Workforce availability	Local capacity to implement and maintain NbS, including training for workers and authorities in rural areas	No/ Minor/ Moderate/ High
Economic viability	Funding or financial resources for large-scale NbS	No/ Minor/ Moderate/ High
Long term operation and maintenance costs	NbS implementation and upkeep	No/ Minor/ Moderate/ High
Land ownership	Land excluded from tenure and private property rights, compatibility with zoning plans and protected areas, etc.	No/ Minor/ Moderate/ High
Regulatory conditions	Laws and regulations that are favourable for the implementation of solutions	No/ Minor/ Moderate/ High

informs the optimal placement and design of features like terraces and swales, to manage runoff and enhance landscape integration.

- **Hydrology:** data pertains to surface water bodies (rivers, lakes), drainage networks, stream flow rates, and the interaction between surface and groundwater. Comprehensive hydrological and sediment transport data is essential for understanding water and sediment budgets, designing effective flood attenuation measures, managing water quality, and assessing the performance of NbS on mitigating impacts.
- **Rainfall Datasets:** detailed time-series data on rainfall intensity, duration, and frequency (IDF curves), alongside historical trends and future climate change projections, are central to hydrological modelling, and particularly relevant for enabling the sizing and performance assessment of stormwater management NbS. Rainfall time-series data informs users on estimated water retention and/or detention capacity of such solutions, which becomes especially critical when modelled to manage projected rainfall extremes [43]. Additionally, data on historical flood extents, flood hazard maps for various return periods (e.g., 100 year flood), flood depth, velocity, and duration data support anticipating the identification of possible flood risk areas. The use of rainfall datasets in hydrological modelling tools can support the definition of critical locations for NbS water retention systems and is indispensable for quantifying flood risk to Critical Infrastructure (CI) and designing NbS [14].
- **Wind, Temperature, and Humidity:** climatic data, including prevailing wind speeds and directions, air temperature (mean, extreme highs/lows, urban heat island effects), and relative humidity, are critical for designing NbS that contribute to urban climate regulation and human comfort. NbS such as urban forests, green roofs, and vegetated facades can significantly alter local microclimates by providing shade, evapotranspirative cooling, and wind buffering [44].
- **Land-Use Map, Green Cover (GC) and Vegetation:** a detailed land-use map is fundamental for understanding the current spatial organisation of human activities and natural features. It identifies opportunities and constraints for NbS implementation, informs zoning regulations, and helps in strategic spatial planning to integrate NbS effectively within

Table 2.3: Data to assist in the decision-making

Topic / domain	Examples of data availability
Geology	Geological maps; Global Lithological Map v1.0; Raster/vector data at scale 1:50 000.
Geodesic measurements	Digital terrain elevation; Digital Terrain Model (DTM) produced by LIDAR technology; Aerial drone measurements: orthophotos, DOM, DTM; Roughness coefficients for different land uses; Bathymetric measurements; Topographic measurements
Hydrology	Flood maps for different return periods; Stream flow data; Directions of preferential stormwater flow paths; Suspended and bed load measurements.
Rainfall intensity	National/regional meteorological service data or local precipitation intensity and frequency data.
Wind	National/regional meteorological service data or local data on wind speed and direction.
Temperature	National/regional meteorological service data or local hourly/daily temperature data.
Humidity	National/regional meteorological service data or local high-frequency humidity measurements.
Land-use map, Green Cover, and Vegetation	Land-use map with green cover; Drone measurements; Vegetation classification and mapping of different vegetation species.

existing urban, peri-urban, or rural contexts [16]. Baseline data on existing vegetation cover, including its extent, density, and distribution (e.g., from remote sensing or land cover maps), provides a critical starting point. This information helps in identifying areas for enhancement, assessing the current provision of ecosystem services, and monitoring the impact of new greening interventions [45]. Green Cover (GC), referring to the proportion of land covered by vegetation such as trees, shrubs, grass, and groundcover, is a key indicator for assessing the ecological quality of an area. High levels of GC are associated with multiple ecosystem services, including urban cooling, air purification, water regulation, and improved human well-being. Mapping and quantifying GC—through aerial imagery, satellite data, or field surveys—helps to evaluate baseline environmental conditions and track changes over time, especially in response to NbS interventions. Additionally, and if available, more detailed information can be provided, such as dominant vegetation types, species composition, age structure, health, and the presence of invasive species. This more detailed information can help to refine selection of specific species for the interventions (e.g., native and climate-resilient plant species for NbS), which should enhance biodiversity, ecological functionality, and long-term ecosystem health [12].

Note that these different data domains are crucial inputs during the feasibility screening of the NbS. For instance, data on topography, hydrology, rainfall datasets, could inform on preferential flow paths, soil infiltration rates, ground stability, providing a foundational support for NbS planning and design at the preliminary phase. The previous data domains can, for example, be particularly relevant for the choice of water retention and/or infiltration-based NbS, sorted within the NATURE-DEMO NbS Catalogue (see [18]) under the River, Lakesides, Floodplains and Wetland Management NbS Family (e.g., RW8 Water Retention Basins and Ponds), the Urban Green Infrastructure NbS Family (e.g., UGI6 Raingardens, UGI7 Bioretention cells), or the Soil and Water Bioengineering NbS Family. Users can validate their choices by compiling and

analysing these data domains. Users should consult the NbS factsheets from Stage 2 and validate their preliminary choices by compiling and analysing the relevant datasets. Regardless of the NbS catalogues and hazard classifications developed within this project, it is of utmost importance that these tools serve only as idea generators. The process for data collection reflects the complexity of local and regional frame conditions, such as regional regulations and site-specific technical requirements. Indeed, the depth of data collection is determined by how extensively the user chooses to retrieve information. For actual implementation, it is essential to establish an expert team representing the various involved sectors: authorities, engineers, natural scientists, as well as other local stakeholders such as mayors and landowners. These individuals should have long-standing experience with the development of the area, be able to accurately assess prevailing conditions, and realistically evaluate the feasibility of proposed solutions while considering the complex interests involved—including budgetary and political frameworks.

The framework serves as a guide to help users consider these implementation constraints. As a background context, the “Alliance Contracting” serves as a reference of upfront coordination in a multi-level and transdisciplinary stakeholder environment. This model ensures efficient management of precise price formation and budget predictability among stakeholders and according to site specific requirements.

Table 2.3 summarises some available data to assist in the decision-making in diverse domains. In addition to the data used for Stage 3, post-construction monitoring data should be collected (see Chapter 3 of this document). The data needs to be analysed, compared, processed, modelled and interpreted using suitable analytical tools, which is fundamental for building robust scientific evidence in support of translating theoretical NbS concepts into effective, context-specific designs for CI protection [19].

Within this methodological framework, tools are categorised by their operational status, input/output capabilities, and software compatibility, and usability, ensuring comprehensive analytical support. Users are encouraged to list the software and other tools they intend to use to support NbS feasibility assessment. In this case, Geographic Information Systems (GIS) is considered as a very practical tool by NATURE-DEMO partners, due to their capability to manage spatial datasets and interfaces with other modelling platforms, digital-design and hydrological software, e.g., Storm-Water Management Models, CAD-Programmes, Hydrous, and HEC-RAS [46].

2.4. Scalability of the Site Selection Framework

2.4.1. Structured stepwise pathway replicable across regions and governance contexts

To ensure that NbS can be systematically deployed at scale, it is essential to bridge the gap between conceptual frameworks and scalable planning frameworks. The preceding sections have outlined a structured approach to NbS selection that accounts for site analysis, pre-screening of solutions, mapping of suitable interventions and identification of environmental, socio-economic, and institutional drivers to support long-term implementation and maintenance of NbS. The framework establishes a structured, stepwise pathway that connects hazard-related landscape impacts with spatial planning and ecosystem-based design that includes specific NbS Types analysed in Deliverable 1.1. However, to make the proposed framework replicable across diverse regions and governance contexts, it should be embedded into a systemic decision-support.

The framework is based on the analysis of the context, beginning with the delineation of Geographical Management Zones (GMZs), the process integrates the identification of vulnerable infrastructure and interplay with climate-driven hazards, followed by the systematic screening of suitable NbS Types provided in Deliverable 1.1 NbS Catalogue. After a screening of NbS Types (Deliverable 1.1), the framework proceeds with the feasibility for their implementation, and the filling of templates and conduction of the mapping exercises help users reflect which criteria should be considered in a future planning stage.

The templates and mapping exercises of this framework aimed to systematically integrate factors and projectual considerations into the planning and design of nature-based infrastructure measures. To test the development of such standardised formats, NATURE-DEMO carried out a second workshop, held in Zvolen during the Spring of 2025, together with partners and DS, where participants filled out tables on (1) Site-specific implementation constraints, (2) Socio-economic and institutional supportive factors; and (3) Data and analytical tools to assist in the decision making.

Project partners proceeded with a multi-actor workshop, where site experts were consulted to provide main resources and content on site factors. The stakeholders workshops supported the co-creation process. During these interactive sessions, various attendants discussed collectively and summarised key findings. The joint discussions facilitated a comprehensive understanding on the site characteristics, challenges, suitable actions and implementation constraints. The use of templates and maps supported the process of data collection and stakeholders' discussion.

These templates, together with the mapping exercises, structured types of information that are critical for decision-making. Those were reproduced as blank Excel templates in order to replicate the 3rd stage of the methodological framework in an effective and standardised manner. The templates and maps serve as an actionable guide, translating theoretical knowledge into the drafts of site-specific designs and feasibility assessment that incorporate NbS to mitigate risks posed by NH on diverse, discrete CI elements [19].

The use of different types of templates allows integrating heterogeneous data and local knowledge. Additionally, demo site partners contacted different experts, such as environmental scientists, local engineers, planning professionals and asset managers. Further, the framework enhances that the knowledge is aggregated in the form of expert and authority assessments in a dual format (where geo-spatial data is linked to Excel-based templates with stakeholder inputs). The Excel-based templates linked questionnaires enable the creation of an objective evaluation framework based on the concept of NbS planning for climate-driven hazards for CI. Within the project, this concept is contextually expanded to also capture soft factors such as social acceptance, institutional frameworks, and socio-economic resilience in a structured manner and to embed them effectively in decision-making processes.

The overall intensity of the project development process is variable and determined by the complexity of site-specific implementation constraints, country-specific regulatory differences, and the type and scale of the NbS selected. Navigating these constraints requires a high level of coordination and data integration across multiple sectors. To manage the associated resource requirements, users can adopt specialised responsibility models. One potential framework for addressing these complex coordination needs is 'Alliance Contracting'. Although this approach requires dedicated initial involvement from all involved entities to define specific responsibilities and navigate technical and legal constraints, it facilitates precise price formation and offers operational predictability through incentive structures for budget compliance.

2.4.2. Scalability of the conceptual framework by transitioning into a digital tool for decision-making

Digital tools for decision support have already been successfully applied in related domains and can provide the basis for robust, transparent, and replicable decision-making [47]. Clarifying the basis for site selection and expected outcomes can support institutional trust and policy coordination [48, 49]. When it comes to NbS, digital decision-support systems could help overcome some of the main barriers to their implementation, for example by enabling the tracking of measurable outputs over time, such as runoff reduction, vegetative growth, or biodiversity benefits. Standardised data and repeatable assessment protocols would also support cross-site comparison and replication, strengthening the evidence base for NbS effectiveness. To do so, targeted monitoring (described in more detail under Chapter 3 of this document) is a prerequisite, ensuring that the necessary input data and performance metrics are available for integration [50, 51].

Ultimately, advancing the step from conceptual frameworks towards operational tools for NbS site selection could enhance predictability, reduce perceived risks, and improve strategic alignment across stakeholders and governance levels, which was one of the main themes and wishes emerging from stakeholder interviews conducted within the scope of NATURE-DEMO task 1.2 [10]. This will be a critical step toward mainstreaming and scaling NbS under future climate scenarios.

For the case of NbS solutions planned in urban environments, as the Demo case 2, the solutions will be disseminated during implementation as well as afterwards to local, regional, and national public administrations, which may integrate NbS into territorial planning and national strategies (e.g., National Biodiversity Strategy, National Strategy for Protected Areas, etc.). The framework emphasises the need to embed the NbS principles into the existing governance frameworks and territorial planning strategies for real-world implementation. The Socio-economic and institutional supportive factors Excel-based template aims at covering these relevant questions. Likewise, NbS will also be promoted among relevant stakeholders who may, in the future, establish specific requirements for green space planning (e.g., protected area managers, environmental NGOs, etc.). Therefore, stakeholder engagement and participation is crucial and has been highlighted as one of the relevant factors to be assessed in this template.

As a scalable measure, the conceptual framework can be transitioned into a digital tool for decision-making. The scalability of the approach should then move towards operationalisation by generating a spatial decision-support instrument to guide users in NbS and ecosystem-based planning for CI protection against the impacts from climate-related hazards. In that context, the Excel-based data can be embedded into the geo-spatial tool and automatically guide a user to re-configure the NbS locations and types according to the site-specific constraints and socio-economic and governance-related conditions. This digital tool format can help for overcoming implementation and long-term sustainability constraints, to be applied consistently across sites, while ensuring comparable results.

However, this requires that the local knowledge, implementation constraints, and ecological conditions which were collected, are translated into shareable and standardised formats, which form the foundation for the subsequent planning and implementation stages, including studies on risk assessment (Deliverable 2.1) [31], feasibility and technical implementation. Developing a scalable systematised platform would support future multi-criteria analysis, scenario modelling, and trade-off assessments, allowing planners to adaptively manage NbS interventions under dynamic climate and land-use conditions [52, 53].

3

Monitoring Requirements of NbS for Digital Integration

When preparing NbS for implementation in the field, effective monitoring is crucial for ensuring effective delivery, performance evaluation, securing long-term success, and enhancing learning for scaling and replication. It provides essential evidence to understand whether (or not) the NbS achieves its intended social, environmental, and economic benefits and to guide adaptive management [54]. This is a core principle emphasised by the IUCN Global Standard for Nature-based Solutions, which provides a framework for the rigorous assessment of NbS projects [12]. The responsibility for monitoring can be shared among different actors (e.g., site or asset managers, municipalities, state environment agency in charge for environmental monitoring, selected subcontractors such as academia or NGOs), and there is no simple rule as it should take into account critical infrastructure and types of implemented NbS. NbS monitoring should be carefully defined during NbS planning.

Monitoring supports four core objectives (for more see [4]):

- **Measures the delivery of multiple benefits** – monitoring verifies to which extent NbS provide genuine benefits for biodiversity, soil health, ecosystem services, and human well-being, rather than assuming these benefits occur by default. We evaluate NbS performance, i.e., the effectiveness of NbS with respect to KPIs and then use this information to support adaptive management.
- **Supports adaptive management** – continuous monitoring allows relevant decision makers, in particular designers and asset managers, to adjust design and management practices of NbS based on observed outcomes, maximising positive impacts and mitigating trade-offs.
- **Generates evidence for replication and/or scaling** – documented monitoring data builds the science-based evidence database needed to justify investments, replicate successful NbS projects, and upscale up NbS interventions in different contexts.
- **Facilitates stakeholder engagement** – participatory monitoring (e.g., citizen science) involving local actors helps tailor NbS to local needs and increases community ownership and support.

Monitoring of NbS should be divided into two phases:

- **Premonitoring before NbS implementation** – This phase, which follows the preliminary assessment performed in stage 3 of the Site-specific NbS Design Framework (see section 2.3.3.3 Existing tools and data at a local, regional, national and trans-border scale), aims to establish baseline conditions and targets and therefore key elements to monitor including environmental baselines (e.g. risk status, biodiversity, soil health, meteorological, hydrological and geological conditions, level of safety and stability, existing ecosystem services and functions), socio-economic and cultural context (e.g. community needs and vulnerabilities related to risks, land use and infrastructure conditions), and Key Performance Indicators (KPIs) (e.g. measurable objectives aligned with local challenges, suitable metrics and monitoring protocols to track progress). Frequently, this phase is not adequately addressed or is left out, and monitoring starts after NbS implementation.
- **Actual monitoring after NbS implementation** – This phase guides adaptive management involving maintenance, management adjustments, or complementary interventions through data-informed reviews and therefore key elements to monitor shift to ecological changes (e.g. changes in biodiversity and habitat quality, soil health improvements, hydrological changes), social/economic impacts (e.g. reduction in flood risk and urban heat, reduction in risk of erosion, excessive sediment transport, mass mobilisation and landslide hazards related risks, improvements in human well-being and community resilience, cultural and recreational benefits), functional performance (e.g. effectiveness in managing water and sediment flows, stabilising soils and slopes, reducing runoff), longevity and maintenance needs of NbS features.

In summary, monitoring NbS is essential to evaluate NbS projects performance, to verify to which extent NbS projects effectively deliver intended environmental, social, and economic benefits, securing their long-term success, and enhancing learning for scaling and replication. Within the NATURE-DEMO project, monitoring at demo sites will be only partially effectively executed, as the project duration of 4 years does not support any long-term monitoring of NbS that are to be firstly carefully selected and then executed during the project.

3.1. Monitoring parameters and their significance

Monitoring plays a crucial role in understanding the performance and effectiveness of NbS. However, it often receives insufficient attention during NbS project planning and management. This oversight often results in the absence of meaningful monitoring, as no sufficient resources, tools, or protocols are made available to support data collection and performance evaluation. As a result, monitoring is often not conducted at all—due to a lack of early planning, allocated resources, or defined protocols. Moreover, monitoring efforts should account for both the spatial and temporal scales at which NbS processes unfold. Spatially, monitoring may need to range from localised site-level observations (e.g. infiltration rate, plant health) to broader catchment-scale assessments (e.g. hydrological or ecological impacts). Temporally, monitoring should reflect short-term changes (e.g. during establishment), medium-term responses (e.g. vegetation development), and long-term impacts (e.g. resilience and maintenance needs).

Monitoring requirements can evolve throughout the lifecycle of an NbS, as different stages involve distinct processes, risks, and indicators—necessitating adaptive monitoring strategies. Hence, the evolving conditions may trigger changes in what is monitored, how frequently, and using which tools. For example, early stages may prioritise plant survival and erosion control, while later stages may require monitoring of system resilience or habitat connectivity. Changes in monitoring requirements can be triggered by multiple factors, including e.g.:

- the transition between NbS lifecycle phases (e.g. from initial establishment to operational maturity),
- observed deviations from expected performance,
- the occurrence of extreme events (e.g. drought, storms, or flooding),
- the introduction of new policy, funding, or community engagement priorities.

In such cases, the scope, frequency, and tools for monitoring may need to be revised. Therefore, adaptive monitoring strategies must be developed from the outset and revised periodically to reflect these dynamic needs.

To ensure consistency and comparability of data, all measurements should use standardised units. While the International System of Units (SI units) is the preferred and most widely adopted standard, non-SI units may also be used if they are defined and recognised by international standards bodies, such as the Bureau International des Poids et Mesures [55]. This approach ensures clarity and allows for easy conversion and communication of data, regardless of the specific unit system employed.

Monitoring efforts should also account for the spatio-temporal dynamics of NbS, recognising that both spatial variations across the site and changes over time are critical to evaluate their effectiveness and adaptability. This often involves a combination of in-situ measurements, which provide detailed, direct data from specific locations, and remote sensing approaches, offering broader spatial coverage and insights into large-scale patterns. Interpreting this data in a spatially and temporally sensitive way is essential for assessing NbS performance over time.

The following tables present a selection of key parameters relevant for monitoring NbS, highlighting their inherent properties, core processes, and the ecosystem services they deliver. This list is indicative rather than exhaustive. Additional indicators are listed that can be employed to quantify specific parameters generally related to NbS-provided ecosystem services in support of climate resilience [4]. Final monitoring parameters should be defined by project teams, as their selection will critically shape NbS implementation, management, and evaluation. These parameters must also be adapted to the specific conditions and objectives of each individual demo-site, forming a tailored overview to match site-specific requirements and intervention goals.

Table 3.1 focuses on the physical and biological properties of NbS that enable them to deliver their functions.

Table 3.1: Essential inherent properties and core processes for NbS project monitoring (selection)

Parameter name	Description	Unit	Focus	Relevant NbS examples
Infiltration rate	Rate at which water enters the soil.	mm/hour	Hydrological process	Infiltration trenches, Bioswales, Green pavers
Water storage capacity	Volume of water the NbS can hold within its soil or substrate, or as surface water before becoming saturated.	Liters or m ³ per m ²	Hydrological property	Green Roofs, Wetlands, Bioswales, Infiltration trenches, Retention basins
Evapotranspiration rate	Rate water returns to the atmosphere from plants (transpiration) and soil (evaporation).	mm/day	Hydrological/ climate process	All vegetation-based solutions

Soil shear strength	Soil's intrinsic resistance to erosion and failure. The soil's resistance to forces that could cause slope failure or erosion.	Pascals (Pa)	Geotechnical property	Slope bioengineering, Reforestation
Root density / cohesion	Extent to which plant roots bind soil, enhancing its stability and resistance to forces that could cause slope failure or erosion.	kg/m ³ or kPa	Bio-geotechnical property	All vegetation-based solutions
Vegetation cover	Percentage of ground covered by vegetation. The percentage of ground covered by vegetation canopy, which intercepts rainfall and reduces splash erosion.	%	Biophysical/ecological property	All vegetation-based solutions
Shading capacity	Fraction of solar radiation blocked by a canopy. The fraction of incoming solar radiation blocked by a canopy.	% or ratio	Physical property	Open green spaces with tree planting, Vertical greenery

Assessing the ecosystem services provided by NbS is crucial for understanding their overall impact and value. They reflect the measurable environmental and social benefits that NbS deliver, supporting both the ecological integrity and human well-being. Table 3.2 highlights examples of the direct benefits and services that NbS provide for people and the environment, along with their associated measurement methods and data sources.

Table 3.2: Monitoring ecosystem service delivery and co-benefits (selection)

Ecosystem service	Indicator	Description	Unit	Measurement method/Data source
Flood regulation	Runoff volume reduction	The total volume of runoff prevented by the NbS.	m ³ per unit area, percentage reduction from baseline	Field/model/remote sensing/flow gauges (upstream/downstream)
Flood regulation	Peak flow reduction	The reduction in the maximum rate of runoff during a storm event.	% or m ³ /s	Models/flow gauges/historical weather data
Erosion control	Sediment yield	The amount of sediment lost from a unit area, indicating the effectiveness of erosion prevention.	kg/ha/year	Sediment traps/field/remote sensing/models
Erosion control	Soil loss reduction	The decrease in soil erosion compared to a baseline scenario (e.g., no NbS).	%	Field/erosion pins/soil surveys/remote sensing/models
Erosion control	Sediment transport rate	The total mass of sediments transported per time unit over unit width.	kg/m/s	Field/flumes/models

Microclimate regulation	Air temperature reduction	The localised cooling effect compared to the surrounding environment.	°C or K	Temperature sensors/weather stations/remote sensing (thermal)
Microclimate regulation	Surface temperature reduction	The reduction in the temperature of surfaces (e.g., pavement, roofs).	°C or K	Temperature sensors/weather stations/remote sensing (thermal)
Biodiversity & habitat	Species richness / diversity	The number and variety of species (flora and fauna) supported by the NbS.	Index (e.g., Shannon)	Field surveys/inventories/remote sensing (habitat mapping)/genetic analysis
Biodiversity & habitat	Habitat area	The area of suitable habitat created for target species.	m ² or ha	Remote sensing/GIS analysis/field mapping
Carbon sequestration	Carbon sequestration rate	The rate at which atmospheric carbon is captured and stored in biomass and soil.	tCO ₂ e/ha/year	Field (biomass/soil carbon)/remote sensing/models/eddy-covariance towers
Water purification	TSS reduction	The reduction in total suspended solids concentration in the water.	% or mg/L	Lab water analysis (before/after NbS)/field sensors/models
Water purification	Nutrient removal (N, P)	The reduction in nitrogen and phosphorus concentrations.	% or mg/L	Lab water analysis (before/after NbS)/field sensors/models
Water purification	Pollutant removal	The removal efficiency for specific contaminants (e.g., heavy metals, hydrocarbons).	%	Lab water analysis (before/after NbS)/field sensors/models

3.2. Remote sensing

Satellite mapping and derived products help to assess the before and after any type of intervention implementation. This assessment varies from extent and maturity of land use changes to the structural health of man-made structures.

The Nature-Demo project is implementing remote sensing technology from satellites and drones to make such assessments for critical infrastructures in the Demo sites. The technologies are explained in detail in Deliverable 2.2 of this project and includes InSAR interferometry to measure historical movements of infrastructures and surrounding areas prior and post NbS implementation for specific assets (eg: bridges and specific buildings) with high resolution radar imagery (CosmoSkyMed - 3m resolution) and regional scale linear infrastructures such as roads and railways (Sentinel-1, 10m resolution). This technology allows monitoring very large areas at day and night in any weather conditions; however, its latency is not high and as it takes days for the satellite to acquire new data and the algorithm to incorporate the new measurement. It is highly valuable to understand the historic infrastructure dynamic behaviour and make periodic updates after. These types of surveys can be done periodically for any location in Europe using Sentinel-1. High resolution radar satellites can be commissioned to focus on a specific asset upon request.

Another remote sensing dataset that is relevant in the project is data derived from NASA's Harmonized Landsat and Sentinel-2 (HLS) project, which provides high-quality, multi-source satellite imagery at a spatial resolution of 30 meters. The HLS dataset harmonizes data from the Landsat 8 Operational Land Imager (OLI) and the Sentinel-2 MultiSpectral Instrument (MSI), both of which operate in sun-synchronous orbits and offer complementary spatial, spectral, and temporal characteristics. Landsat 8 operates with a 16-day repeat cycle, capturing data with nine solar reflective bands resampled to 30 meters, while Sentinel-2 provides higher spatial resolution in visible and near-infrared bands (10 to 20 meters) with a 5-day revisit frequency, covering a swath of approximately 290 km. The HLS version 2.0 dataset, used to train IBM Prithvi models as detailed in Szwarcman et al. 2024, has been available since its completion in summer 2023, providing near-global at 30-meter resolution. The dataset spans from April 2013 onwards, offering a temporally dense time series of surface reflectance data acquired every 2 to 3 days on average, with a median of 66 cloud-free observations per pixel per year in 2022 when multiple satellites were operational. This comprehensive temporal and spatial coverage enables the Nature-Demo project to obtain initial estimates of the impacts of NBS and infrastructure interventions with relatively high spatial resolution and frequent revisit times.

In parallel, CATEC will implement the UAV-based remote sensing, to complement the satellite observations with high-resolution and on-demand data acquisition. Drone-based monitoring provides centimeter-level spatial resolution through optical, LiDAR, thermal sensors. Thanks to the integration of advanced sensor technologies as high-resolution RGB cameras, multispectral and thermal sensors, and LiDAR systems; it is possible to conduct comprehensive environmental monitoring to evaluate the performance of NbS over time.

Multispectral cameras facilitate the calculation of vegetation indices such as NDVI, GNDVI, and NDRE, enabling precise assessment of plant health, stress levels, and biomass dynamics. Thermal sensors detect temperature anomalies that may indicate water stress, leaks, or other ecological disturbances. LiDAR systems provide accurate three-dimensional data for generating digital elevation models and analyzing vegetation structure and canopy height. RGB cameras offer detailed visual imagery for mapping and change detection, complementing spectral and elevation datasets.

Collectively, these technologies support early issue detection and inform timely maintenance or corrective interventions, thereby enhancing the long-term effectiveness and resilience of NbS implementations. The combined use of satellite and UAV remote sensing enhances both scalability and data quality across different spatial and temporal scales.

4

NbS Parameterisation for Integration into Digital Tools

Climate change is altering the operating conditions of critical infrastructures and jeopardising the objectives for which they were originally designed. To safeguard their intended functionality, it is essential to adapt these systems and strengthen their resilience. One promising pathway is to complement conventional measures with NbS.

Yet, linking natural hazards with NbS for CI protection presents several challenges. NH are characterised by high complexity, including cascading effects and strong dependence on regional environmental and climatic conditions. Similarly, NbS exhibit ecological and temporal dependencies that influence their effectiveness.

Digital decision-support tools are increasingly employed to plan and manage CI under climate change. However, the systematic integration of NbS into these tools remains limited, largely due to the inherent complexity of natural systems and the absence of standardised parameters and data formats.

To address this gap, this section introduces an NbS parameterisation framework designed to facilitate comparability, traceability, and performance monitoring in digital planning environments. The approach unfolds in two parts: the definition of key parameters (Section 4.1) and their operationalisation in planning processes (Section 4.2).

4.1. Identification of Key Parameters Supporting Context-Tailored NbS

While infrastructures are exposed to a variety of risks and potential mitigation measures, their ultimate goal remains the protection and preservation of functionality. It is therefore essential to evaluate performance both before and after the implementation of NbS, using objective performance indicators.

The **RAMSSHEEP** framework—an acronym for **Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic, and Politics**—is a well-established multi-criteria approach for assessing overall infrastructure performance. Developed and formalised within the COST Action TU1406, it is widely applied in the management of roads, bridges, railways, and other critical assets, where it supports strategy development and decision-making processes

[56]. Originally introduced by Wagner 2012, the framework provides a balanced perspective by integrating considerations of reliability, safety, sustainability, and affordability [57].

RAMSSHEEP comprises a set of **Performance Indicators (PIs)** that capture the wide range of factors influencing infrastructure resilience (see Table 4.1). By explicitly integrating these components, the framework enables structured trade-off analyses and facilitates the optimisation of performance across technical, environmental, economic, and societal domains.

Table 4.1: Performance Indicators

Performance Criteria	Definition
Reliability	The probability that a system performs its intended function without failure under specified conditions for a given time interval.
Availability	The likelihood that the system is operational and ready for use when required.
Maintainability	The ease and speed with which maintenance can be performed within a specified time, while ensuring the system continues to fulfil its required function.
Safety	The protection of people and assets from unacceptable harm during operation.
Security	Safeguarding the system against malicious or unintended threats, such as vandalism or sabotage.
Health	The impacts on human well-being, including physical, mental, and social dimensions.
Environment	The degree to which the system aligns with environmental sustainability and supports ecosystem integrity.
Economics	The cost-effectiveness and fiscal value of interventions.
Politics	Alignment with governance structures, policy support, and administrative feasibility.

To effectively integrate NbS into climate adaptation strategies, this assessment must be embedded in a broader resilience planning process—one that also includes hazard assessments, risk modelling, and adaptive management frameworks.

COST Action 1406 aimed to develop a guideline for the establishment of quality control plans (QCP) for roadway bridges. In this standard, focused on bridge maintenance and life-cycle performance, a set of **Key Performance Indicators (KPIs)**, based on the RAMSSHEEP approach [58], was defined:

- Safety, Reliability and Security (S, R, S) – a combined KPI.
- Availability and Maintainability (A, M) – a combined KPI.
- Economy € (i.e., Costs).
- Environment (E).
- Health and Politics (H, P) – a combined KPI.

Note that combined KPIs are intended to serve as a practical aggregation of closely related performance dimensions—similar to how traditional RAMS frameworks combine reliability, availability, maintainability, and safety into coherent analytical categories. This helps simplify multi-criteria evaluation, particularly in digital decision platforms, while preserving operational relevance and interpretability. It is recommended to define explicit weighting schemes for combined KPIs that reflect context-specific prioritisation and provide transparency in how combined scores are calculated to ensure comparability and decision relevance.

These KPI should be evaluated qualitatively with an ordinal scale of one to five (Table 4.2). The aggregated overall CI performance across all criteria is visualised in a multi-dimensional “spider net” diagram (Figure 4.1), which supports comparison across NbS options and facilitates integration into digital decision-support tools. It is important to document how different KPI domains — particularly those combining technical, socio-political, and environmental factors — are weighted and aggregated, as this directly affects transparency, comparability, and practical use in computational environments.

Table 4.2: KPI Rating

Rating	Condition
1	Very good
2	Good
3	Fair
4	Poor
5	Very poor

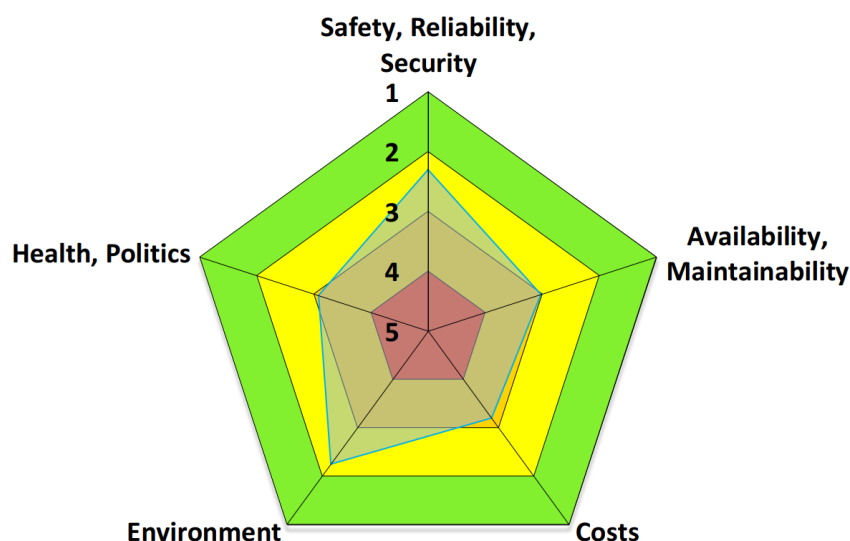


Figure 4.1: Spider net diagram [59]

This framework was adopted as the Level 1 risk assessment procedure for NATURE-DEMO.

4.2. Integration of NbS Parameters for Informed Climate Adaptation Strategies

To incorporate NH risks and NbS protection into the RAMSSHEEP matrix an extended methodological approach building upon the COST TU1406 procedure was developed. Considering that the goal is to protect existing CIs affected by extreme events for which mitigation measures are to be implemented, it is important to understand the various interactions involved in the process. The method consists of a multi-level assessment procedure, each level comprising the evaluation of the five KPI of the RAMSSHEEP approach. Five sequential steps form this evaluation process, supporting the alignment of NbS characteristics with CI performance requirements across multiple domains [22]:

1. **Critical Infrastructure (CI) Baseline Assessment** – identification of the existing infrastructure elements at risk, including their performance characteristics and vulnerabilities across RAMSSHEEP dimensions;
2. **Natural Hazards (NH) Analysis** – evaluation of the type, frequency, and severity of relevant natural hazards affecting the CI, considering regional and site-specific environmental factors;
3. **Grey Protective Infrastructure (GPI) Measures** – review of existing engineered (grey) mitigation structures and their effectiveness in risk reduction and system resilience;
4. **NbS Evaluation** – assessment of context-suitable NbS options from the NATURE-DEMO catalogue and their capacity to address site-specific hazard and CI performance challenges;
5. **Integrated Risk Assessment and Scoring** – synthesis of previous steps to evaluate residual risk and trade-offs using performance metrics mapped to RAMSSHEEP indicators, enabling prioritisation and design optimisation.

For each of these steps it is necessary to evaluate the condition state (CS) of the infrastructure, for each of the matrix's dimensions, before and after the occurrence of the NH, thus evaluating their impacts, and the implementation of the considered mitigation measures, to determine the benefits arising from them. This assessment procedure will require a comprehensive team of experts capable of assessing the multiple dimensions involved in the process [22].

4.2.1. Critical Infrastructure (CI) Baseline Assessment

In the first stage of the methodology the initial performance score (PS) of the infrastructure must be assessed, prior to the occurrence of NH and implementation of mitigation measures (Figure 4.2). This step begins by identifying the CI asset that is under evaluation and may be exposed to natural hazards. The assessment focuses on CI current performance state across the RAMSSHEEP dimensions: Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economy, and Politics. Each dimension is evaluated using a qualitative performance score (PS) on an ordinal scale from 1 (poor) to 5 (excellent). This initial assessment represents the baseline status of the infrastructure before any hazard event or mitigation intervention. The evaluation is based on available (monitoring) data, technical reports, expert judgment, and other relevant evidence. This creates a starting point to which post-intervention performance can be compared and the score determined for each KPI will be the basis for the following stages of the procedure [22].

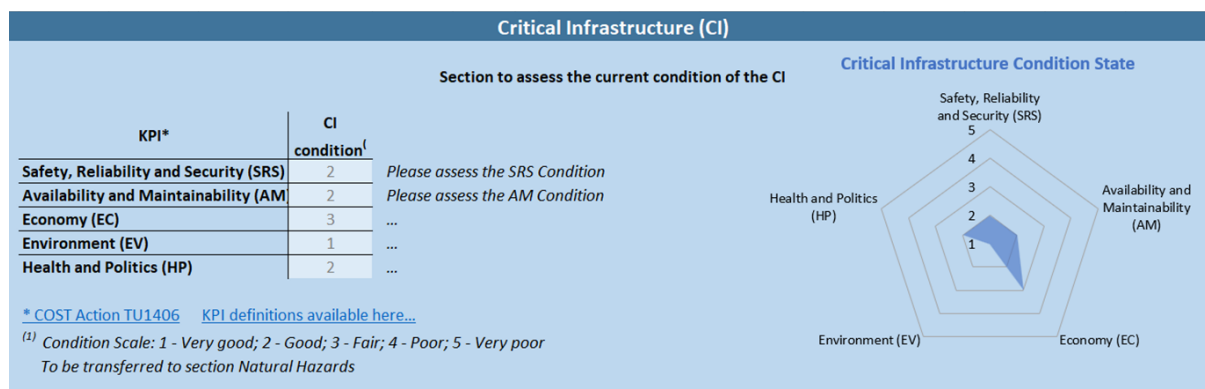


Figure 4.2: Section 1 of the decision-making tool [22]

4.2.2. Natural Hazards (NH) Analysis

In stage 2, the effects of NH on the infrastructure must be accounted for. For each identified KPI, the effect of a single NH, or the combination of two NH, on the condition of the CI must be assessed. Using flood hazard maps, climate projections, or historical event records, the intensity, return period, and geographic scope of the hazard are defined. The CI is then re-evaluated under the assumption that the hazard has occurred, to estimate the likely degradation in performance across the RAMSSHEEP criteria. This step reflects the potential vulnerability and fragility of the infrastructure under stress and highlights the need for protective intervention. The outcome of this step is the PS to which the CI will be reduced when affected by the NH (Figure 4.3) [22].

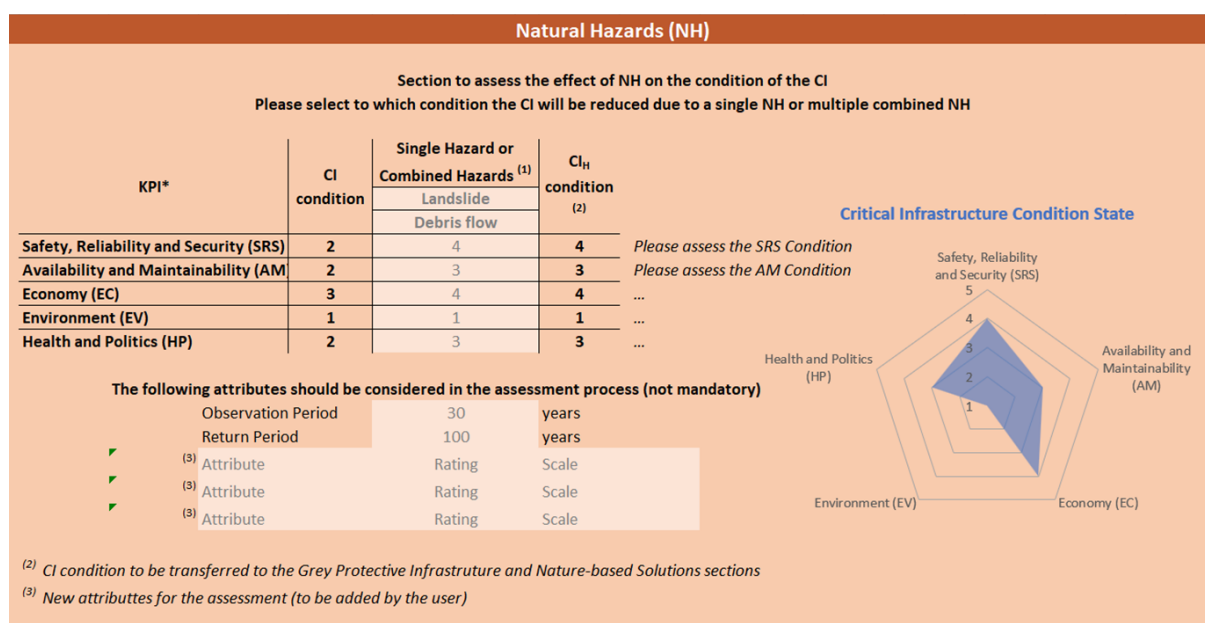


Figure 4.3: Natural Hazards effect of the decision-making tool [22].

4.2.3. Grey Protective Infrastructure (GPI) Measures

Although the aim of the NATURE-DEMO project is to evaluate the applicability of NbS, its combination with traditional engineering solutions (Gray Protective Infrastructure – GPI) should not be neglected. Therefore, and bearing in mind the use of the tool in a more broadly manner, namely in case studies for which GPI has already been implemented, the third step of the tool

aims precisely to evaluate the impact of GPI on their own, but also as a complementary measure to mitigate the effects of NH [22].

Therefore, the third phase of the methodology aims to determine the benefits of the applicability of one, or the combination of two, GPI directly on the behaviour of the CI. To this end, it is required to assess the effect of GPI on the condition of the CI not affected by any NH, for which is asked to select the PS the CI will be increased, and/or to assess the effect of GPI on the condition of the CI affected by the previously defined NH, for which is asked to select the PS the CI will be increased (Figure 4.4). Hence, in this setup the CI's performance score (PS) is again evaluated, this time assuming that a grey protection measure has been fully implemented. The assessment looks at how GPI improves (or fails to improve) scores across all RAMSSHEEP dimensions. This step serves as a benchmark for comparing traditional engineering interventions with nature-based alternatives, in terms of effectiveness, co-benefits, and trade-offs [22].

Grey Protective Infrastructure (GPI)

CI & GPI

Section to assess the effect of GPI on the condition of the CI not affected by any NH
Please select to which condition the CI will be increased due to a single GPI or multiple combined GPIs

KPI*	CI condition	Single GPI or Combined GPI ⁽¹⁾	CI _G condition ⁽⁶⁾	
Safety, Reliability and Security (SRS)	2	✓ ⁽⁴⁾ (5)	2	Please assess the SRS Condition
Availability and Maintainability (AM)	2		2	Please assess the AM Condition
Economy (EC)	3		3	...
Environment (EV)	1		1	...
Health and Politics (HP)	2		2	...

Critical Infrastructure Condition State



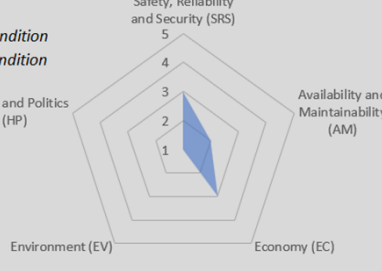
⁽⁴⁾ Name the GPI Family according to the definitions of project NATURE-DEMO
⁽⁵⁾ Name the GPI according to the definitions of project NATURE-DEMO
⁽⁶⁾ CI Condition including the effects of Natural Hazards and Grey Protective Infrastructure

NH & GPI

Section to assess the effect of GPI on the condition of the CI affected by the NH
Please select to which condition the CI will be increased due to a single GPI or multiple combined GPIs

KPI*	CI _H condition	Single GPI or Combined GPI ⁽¹⁾	CI _{HG} condition ⁽⁶⁾	
Safety, Reliability and Security (SRS)	4	Check Dams ✓ ⁽⁴⁾ Series (5)	3	Please assess the SRS Condition
Availability and Maintainability (AM)	3		2	Please assess the AM Condition
Economy (EC)	4		3	...
Environment (EV)	1		1	...
Health and Politics (HP)	3		1	...

Critical Infrastructure Condition State



⁽⁴⁾ Name the GPI Family according to the definitions of project NATURE-DEMO
⁽⁵⁾ Name the GPI according to the definitions of project NATURE-DEMO
⁽⁶⁾ CI Condition including the effects of Natural Hazards and Grey Protective Infrastructure

Figure 4.4: Section 3 of the decision-making tool [22]

4.2.4. NbS Evaluation

The fourth stage concerns the effects of NbS. In this section, the effect of a single NbS, or a combination of two NbS, on the condition of the CI affected by the NH and/or, in case a GPI exists, the effect of NbS on the condition of the CI affected by the NH and protected by the GPI. Hence, in this step, one or more NbS are selected and assessed in terms of their ability to mitigate the effects of the selected hazard on the CI. Appropriate NbS are identified using the NATURE-DEMO Catalogue (Deliverable 1.1), Wirth et al., 2025, considering the site's ecological, hydrological, and socio-political characteristics. Once the relevant NbS has been selected, the CI is re-evaluated a third time, assuming the NbS has been fully implemented. As with GPI, this yields a set of performance scores (PS) across the RAMSSHEEP framework. This scoring helps to reveal where NbS can offer integrated benefits beyond risk reduction and is required to identify which CS the CI will be increased due to the considered NbS (Figure 4.5) [22].

Nature-based Solution (NbS)

NH & NbS

Section to assess the effect of NbS on the condition of the CI affected by the NH
Please select to which condition the CI will be increased due to a single NbS or multiple combined NbS

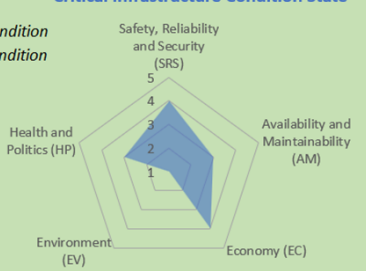
KPI*	CI _H condition	Single NbS or Combined NbS ⁽¹⁾		CI _{HN} condition (9)
		Forest	SWB	
		☒ ⁽⁷⁾	☒ ⁽⁸⁾	
Safety, Reliability and Security (SRS)	4	4		4
Availability and Maintainability (AM)	3	3		3
Economy (EC)	4	4		4
Environment (EV)	1	1		1
Health and Politics (HP)	3	3		3

Please assess the SRS Condition
Please assess the AM Condition

The following attributes should be considered in the assessment process

Minimum time for functionality	10	years
Maximum time for functionality	30	years

Critical Infrastructure Condition State



⁽⁷⁾ Name the NbS Family according to the definitions of project NATURE-DEMO
⁽⁸⁾ Name the NbS according to the definitions of project NATURE-DEMO
⁽⁹⁾ CI Condition including the effect of Natural Hazards and Nature-based Solution

NH & GPI & NbS

To be filled in case exists a Green Protective Infrastructure in the
Section to assess the effect of NbS on the condition of the CI affected by the NH and protected by the GPI
Please assess to which condition the CI will be increased due to a single NbS or multiple combined NbS

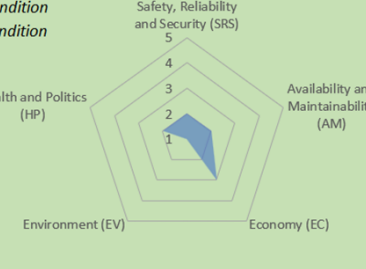
KPI*	CI _{HG} condition	Single NbS or Combined NbS ⁽¹⁾		CI _{HGN} condition (12)
		Forest	SWB	
		☒ ⁽¹⁰⁾	☒ ⁽¹¹⁾	
Safety, Reliability and Security (SRS)	3	2		2
Availability and Maintainability (AM)	2	2		2
Economy (EC)	3	3		3
Environment (EV)	1	1		1
Health and Politics (HP)	1	2		2

Please assess the SRS Condition
Please assess the AM Condition

The following attributes should be considered in the assessment process

Minimum time for functionality	10	years
Maximum time for functionality	30	years

Critical Infrastructure Condition State



⁽¹⁰⁾ Name the NbS Family according to the definitions of project NATURE-DEMO
⁽¹¹⁾ Name the NbS according to the definitions of project NATURE-DEMO
⁽¹²⁾ CI Condition including the effect of Natural Hazards, Grey Protective Infrastructure, and Nature-based Solutions

Figure 4.5: Section 4 of the decision-making tool [22].

4.2.5. Integrated Risk Assessment and Scoring

The fifth and final step of the assessment procedure, brings together the performance evaluations from all previous steps: baseline (Section 4.2.1), post-hazard (Section 4.2.2), with grey infrastructure (Section 4.2.3), and with NbS (Section 4.2.4). A comparative risk assessment is conducted using visualisation in four Risk matrices, representing each of the previous stages (Figure 4.6). In this section the consequence/impact of CI failure is represented, for each of the previous sections, using an **Extent of loss / CI Condition matrix**, considering the CS in which the CI is in the immediately previous stage. This allows decision-makers to identify trade-offs, co-benefits, and synergies between solutions. Weighting of performance dimensions may also be applied, based on project priorities (e.g., giving higher importance to safety or cost-effectiveness). However, when weighting dissimilar categories (e.g., economics vs. environment), transparency and stakeholder consensus are essential. Ultimately, this multi-criteria, multi-scenario approach supports informed and balanced decisions for CI adaptation planning in the face of natural hazards [22].

This extension of RAMSSHEEP, by including NH and NbS, results in a robust framework for infrastructure planning in vulnerable areas, aligned with climate adaptation, disaster risk reduction, and resilience-building that can be used by regional and supra-regional entities [22].

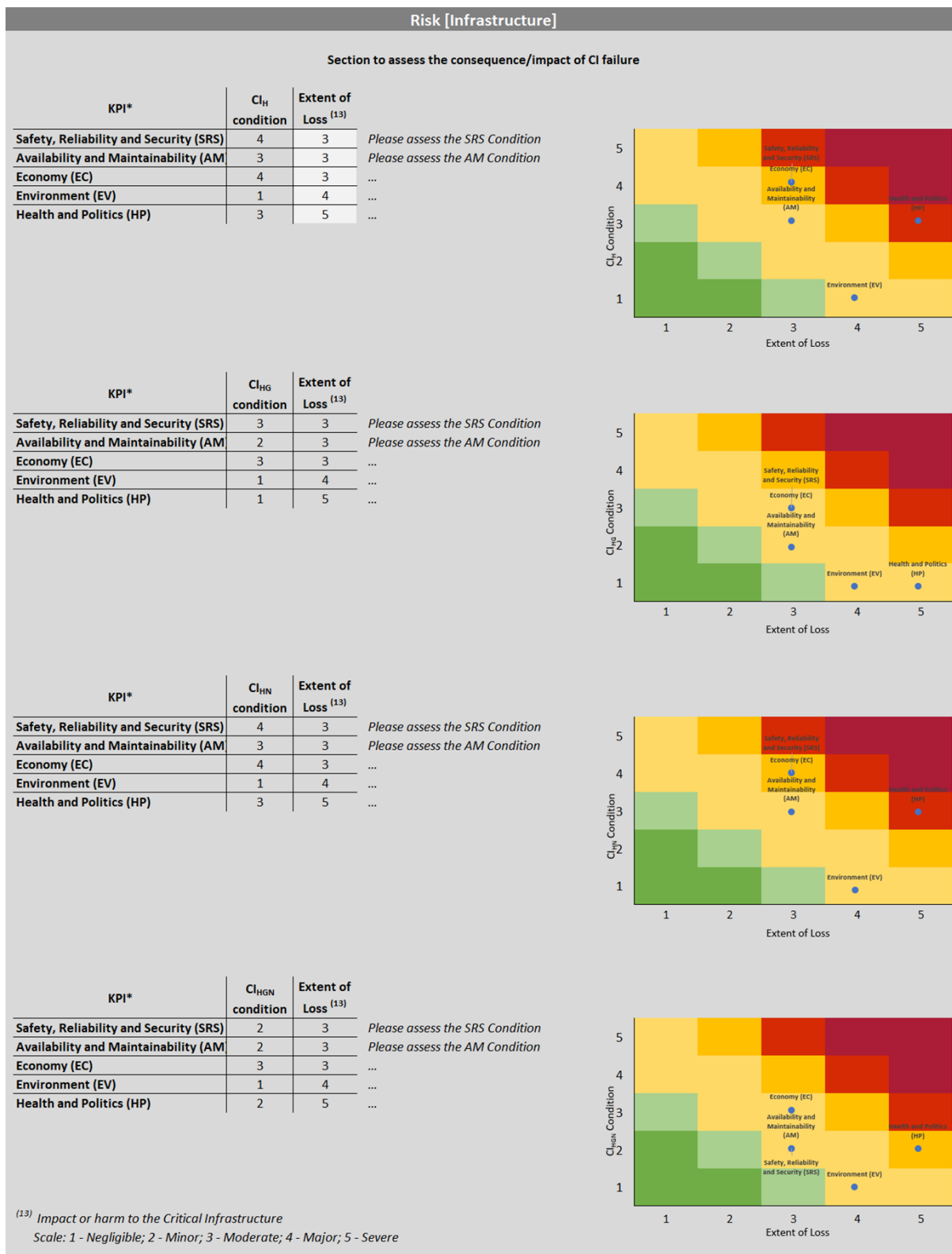


Figure 4.6: Section 5 of the decision-making tool [22].

4.3. Conclusions and Considerations

Within the current WPs, the RAMSHEEP framework has been employed as a methodological foundation and has been successfully adapted to meet the project's specific requirements. The NBS catalogue developed in D1.1 and the relevant natural hazard classifications have been systematically integrated into this framework. As a result, the developed approach enables a structured evaluation of infrastructure vulnerability and resilience, considering both environmental hazards and the mitigating potential of NbS. Based on this foundation, the risk assessment concepts have not only been adopted but also extended and tailored to the project context and objectives.

The quantitative outputs derived from the present work are consolidated through a risk matrix framework that maps risk levels for vulnerable infrastructure across multiple dimensions, including *reliability, availability, maintainability, environmental impacts, and costs*. The application of this extended RAMSSHEEP framework demonstrates the critical role of a risk matrix in synthesising complex, multi-dimensional data into a clear and actionable format.

The key outcome of this work is the development of the **Risk magnitude matrices**. They are bringing together both NBS and the technical-structural measures as hazard categories, together with complex performance evaluations of the various stakeholders across multiple conditions: baseline, post-hazards, with grey infrastructure and with NbS. The comparative risk assessment analysis enabled by these matrices is the core result of the proposed methodology, establishing a central link between the project's conceptual framework and its operational assessment tools.

The present methodology was recognised and integrated into Deliverable D2.1 as **Level 1 of the project's risk assessment framework**. Rather than serving merely as a pre-screening stage, it serves as the foundation layer for further levels of analysis, where the integration and comparative evaluation of the NbS are conducted at a coarse resolution. This Level 1 Methodology can be considered as an initial validation step, providing a stakeholder-informed "green-light" to progress to more detailed quantitative stages of risk assessment.

In the Level 1 stage of the risk assessment framework, the operability of climate change adaptation strategies is evaluated, enabling to ascertain the adequacy of mitigation measures in the context of infrastructure management. As such, the potential operational impact of each solution is evaluated, establishing a link with Level 2 of the framework in which the risk reduction for the adaptation measures is quantified.

Furthermore, the developed matrices provide a direct interface with the Level II and Level III assessment approaches established in WP2. They can be seamlessly integrated into these evaluation processes, enabling consistent and comparable analyses of the risks and impacts associated with different mitigation measures. In doing so, this approach provides a robust foundation for informed decision-making and supports the planning and implementation of future climate-resilient infrastructure strategies.

5

Algorithmic Aspects of Integrating NbS Risk-Reduction Effects in Climate Risk Analysis Frameworks

5.1. Introduction

The development of robust algorithmic frameworks for quantifying and ranking Nature-based Solutions in climate risk reduction constitutes an important methodological advancement in infrastructure adaptation planning. This chapter revisits the methodological foundation established in the NATURE-DEMO project deliverables D2.1 (“Methodological framework for risk reduction analysis of infrastructures based on NbS”) and focuses on the algorithmic and computational aspects required to operationalize the integration of NbS effectiveness assessment within climate risk analysis frameworks.

The risk-analysis framework developed in D2.1 adopts the IPCC AR6 risk conceptualization, where climate risk is formulated as the dynamic interaction between **hazard**, **exposure**, and **vulnerability**. Within this established framework, NbS are evaluated as integrated interventions that systematically modify each risk component through quantifiable adaptation factors. This chapter describes the main algorithms enacting this quantification in the course of the project.

To provide a progressive and scalable approach, the methodology distinguishes between multiple assessment levels. Level 1 is emphasized here, not as a pre-screening stage, but as the foundation for subsequent assessment where the integration and comparative evaluation of Nature-based Solutions take place at a coarse resolution. This stage links infrastructure adaptation to risk reduction using evidence-based metrics.

Advancing to higher assessment levels (Levels 2 and 3) requires models capable of operating at greater spatial and analytical resolutions. At these levels, algorithmic tools move beyond simple ranking or pre-screening to actively simulate and analyse the microclimatic impacts of NbS and other urban infrastructure. Within this landscape, foundation models, defined as large-scale multimodal deep learning architectures trained on diverse geospatial datasets, are emerging as valuable resources. These models learn from extensive geospatial datasets and integrate multiple data modalities to enable adaptable predictions and deep insights that traditional approaches often cannot provide.

In this chapter, after briefly summarizing the multi-level risk quantification framework established in Deliverable D2.1, the foundation models approach is introduced as a promising technological advance for conducting scalable, high-resolution urban analyses. Reference [60] will serve as source material for the sections on the use of foundation models for urban climate risk assessment, and can be referred to for a deeper dive into the topic.

These models, which learn from massive geospatial datasets and integrate multiple data modalities, enable the application of Level 2 and Level 3 risk assessment by supporting nuanced, context-aware analysis of NbS and urban infrastructure across diverse settings. By harnessing their generalization power, researchers and practitioners are equipped to robustly assess NbS effectiveness and infrastructure performance under varying conditions and at multiple scales. To concretely illustrate these capabilities, a representative case study is presented: the application of a fine-tuned geospatial foundation model to evaluate the cooling benefits of green infrastructure. This example illustrates the potential of foundation models to deliver high-resolution, data-driven insights, demonstrating how these advances can underpin more innovative and evidence-based strategies for enhancing urban climate resilience.

While this chapter focuses specifically on the use of foundation models for urban heat island mitigation, we think of this case study as a proof-of-concept meant to validate the technical approach more broadly and establish a replicable methodology that could be adapted to diverse climate risk scenarios. First of all, we're developing infrastructure, including pre-trained model access (via HuggingFace and IBM's TerraTorch platform), fine-tuning pipelines, and documentation that can be directly reused in new downstream applications that might be identified in the future (including by partners in NATURE-DEMO). Secondly, foundation models, by virtue of their pretraining, address key limitations of traditional site-specific models by demonstrating an approach that can transfer across different contexts, potentially enabling scalable, high-resolution analysis without requiring extensive model development from scratch for each new application.

5.2. Algorithmic Foundations for NbS in Risk Analysis

5.2.1. Core Mathematical Framework for Risk Quantification

The methodological foundation established in deliverable D2.1 ("Methodological framework for risk reduction analysis of infrastructures based on NbS") operationalizes the IPCC AR6 risk conceptualization adopted in D2.1, where climate risk emerges from the dynamic interaction between **hazard**, **exposure**, and **vulnerability** components.

The core algorithmic challenge in quantifying risk and its reduction due to Nature-based Solutions involves integrating their effect in the conceptual relationship

$$\text{Risk} = f(\text{Hazard}, \text{Exposure}, \text{Vulnerability})$$

formulated in D2.1 as an instantiation of the IPCC AR6 risk conceptualization. Importantly, NbS can achieve risk reduction by modifying each of the three components of the IPCC risk framework to reduce overall climate risk:

Hazard Modification

NbS can directly reduce or modify climate hazards through:

- **Impact Prevention Capacity:** Preventing or mitigating hazard formation processes (e.g., forests preventing landslides, wetlands reducing flood peaks)

- **Hazard Intensity Reduction:** Reducing the strength, spatial extent, or duration of hazards (e.g., vegetation reducing wind speeds, green corridors mitigating urban heat islands)

Exposure Modification

NbS can alter exposure by:

- **Spatial Protection:** Creating buffer zones that shield critical infrastructure from direct hazard impact
- **Land Use Management:** Influencing development patterns and asset placement relative to hazard zones
- **Infrastructure Integration:** Modifying the spatial relationship between assets and hazard sources

Vulnerability Modification

NbS primarily reduce vulnerability by enhancing:

- **Adaptive Capacity:** Improving the long-term ability of infrastructure systems to adjust to changing climate conditions
- **Coping Capacity:** Strengthening the ability to manage and overcome adverse conditions in the short to medium term
- **System Resilience:** Enhancing post-event recovery capabilities and reducing downtime

Mathematical modelling of these mechanisms is adapted to the selected analysis level, reflecting available spatial data and the required decision resolution.

5.3. Multi-Level Algorithmic Architecture for NbS Assessment

The analysis framework presented in Document D2.1 is a multi-level approach comprising a tiered computational structure where analytical complexity scales with data availability and decision-making requirements according to three levels:

- **Level 1 Algorithms:** Process qualitative stakeholder inputs using structured scoring matrices and statistical aggregation methods.
- **Level 2 Algorithms:** Implement semi-quantitative risk calculations using standardized indices and multi-criteria optimization.
- **Level 3 Algorithms:** Deploy high-resolution models with dynamic impact functions and uncertainty quantification.

This tiered architecture addresses the following key principles:

- **Proportionality Principle:** Following the inverse relationship between analytical complexity and uncertainty, the framework scales computational sophistication with decision importance and available resources. Level 1 provides rapid screening capabilities, Level 2 enables systematic comparison and prioritization, while Level 3 supports investment-grade decision-making.

- **Data Availability and Quality Heterogeneity:** Different contexts have varying data availability, from data-sparse regions requiring stakeholder-based assessments to data-rich environments enabling high-resolution modelling. The multi-level structure accommodates this heterogeneity while maintaining methodological consistency.

Having addressed Level 1 approaches in the previous section, including the RAMSSHEEP methodology for structured stakeholder input, rapid multi-criteria assessment, and qualitative scoring of Nature-based Solutions, this section now turns to advanced algorithms suited to higher-resolution analysis. The integration of foundation models at Levels 2 and 3 enables the transition from stakeholder-driven screening towards empirical, scenario-based decision support. These advanced models provide the ability to quantify climate risks and NbS impacts in a spatially explicit, data-driven manner, exemplifying the transformative capabilities of modern artificial intelligence (AI) for robust assessment and strategic planning in urban climate adaptation.

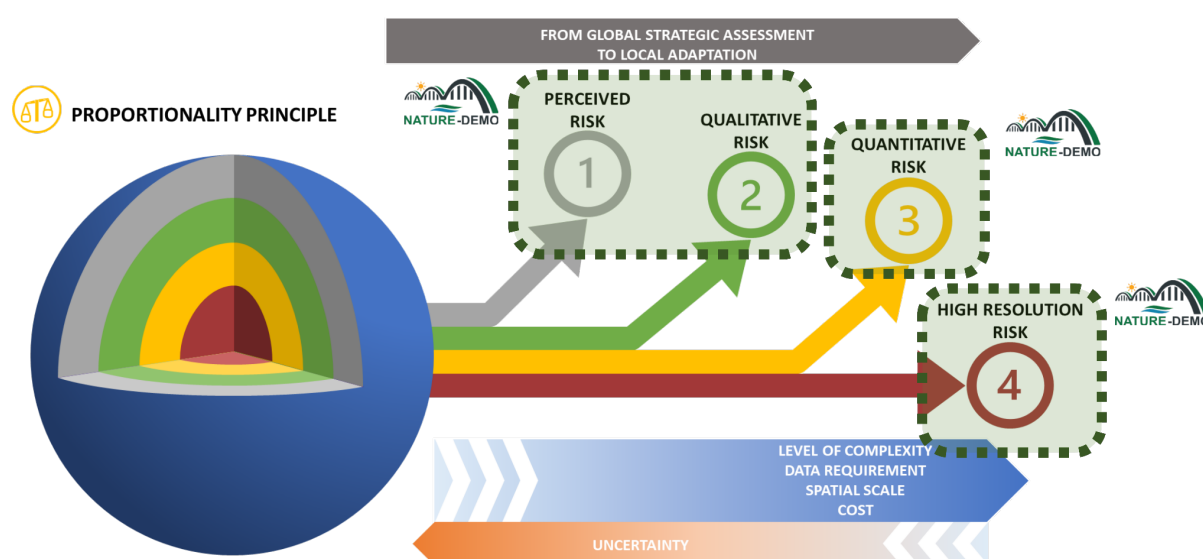


Figure 5.1: Proportionality principle in risk assessments (source: IHCantabria, adapted to NATURE-DEMO project)

5.4. Foundation Models for Urban Climate Risk Assessment

Geospatial foundation models (GFMs) represent a recent development in AI-enabled analysis of urban climate risk, offering improved generalizability, scalability, and context awareness compared to traditional models built on local datasets and hand-crafted features. A central model featured in this thesis is the IBM-NASA Prithvi model—a transformer-based geospatial foundation model pre-trained on NASA’s Harmonized Landsat-Sentinel (HLS) dataset, encompassing over 100 GB of multispectral satellite imagery at 30 m resolution. Prithvi is openly available to the research community via HuggingFace [61] and IBM’s TerraTorch platform.

5.4.1. Fundamental Principles of Foundation Models

Foundation models hinge on modern deep neural architectures, particularly transformer-based networks, which employ self-attention mechanisms to capture complex contextual relationships across long spatial and temporal ranges. This architecture enables the model to weigh the importance of every location relative to others dynamically, effectively encoding rich geospatial features and their interactions.

Training occurs in two stages. First, self-supervised pre-training on large unlabeled datasets, often comprising hundreds of gigabytes to terabytes of satellite, radar, and auxiliary geospatial inputs, allows the model to learn intrinsic data structure and latent correlations without explicit task supervision. Unlike prior machine learning that depended heavily on curated, labeled data, these models use objectives like Masked Image Modeling (MIM) or contrastive learning to predict missing or related inputs, fostering generalized spatial and temporal understanding.

After this costly pre-training phase, the model can be fine-tuned rapidly on smaller, labeled datasets for specific downstream tasks relevant to urban climate risk, such as land surface temperature (LST) prediction, land cover classification, or scenario-based impact estimation. For example, the Prithvi model was fine-tuned to predict land surface temperature (LST) for diverse city environments, resulting in the Granite Geospatial Foundation Model (Granite GFM). Granite GFM leverages not only surface reflectance data but also incorporates air temperature reanalysis, resulting in a robust model for spatially explicit urban microclimate mapping and Nature-based Solutions (NbS) impact assessment. The fine-tuned Granite LST model is publicly available on HuggingFace, allowing researchers and practitioners worldwide to simulate climate risk scenarios and evaluate cooling interventions at a fine spatial scale.

Recent GFMs extend the transformer architecture with domain-specific adaptations like 3D patch embeddings to integrate the temporal dimension, enabling simultaneous modelling of space and time dynamics. For example, the Prithvi model, leveraged in this thesis, was pre-trained on over 100 GB of data from NASA's Harmonized Landsat-Sentinel-2 dataset, achieving a rich, multimodal understanding of Earth's surface temperature and land cover variations.

5.4.2. Challenges and Opportunities

Implementing foundation models in the geospatial context introduces unique challenges. Geospatial data violate the standard i.i.d. assumption due to spatial autocorrelation—nearby locations tend to be more similar than distant ones—requiring architectural innovations that encode true geographic proximity rather than linear sequence order. Additionally, the integration of diverse data modalities necessitates sophisticated fusion methods to harness complementary information effectively.

Another important challenge concerns achieving geo-context awareness. For example, the meaning of vegetated land differs dramatically by urban context—a park in a dense city core serves different functions than agricultural fields in rural areas. Successful GFMs learn to incorporate these semantic nuances, moving beyond pixel-level pattern recognition to contextually grounded interpretation.

Although these challenges remain active areas of research, the potential benefits are significant: foundation models provide generalizable, scalable, and detailed environmental representations for climate risk analysis, scenario testing, and evidence-based urban planning (see discussion in [60]).

5.5. Case Study: Urban Heat Island Detection and Green Infrastructure Characterization

This case study summarizes a study on the application of the Granite Geospatial Foundation Model (Granite GFM) to detect urban heat islands (UHIs) and quantitatively assess the cooling effects of green infrastructure across twelve European cities. The study exemplifies the practical efficacy of foundation models in supporting NbS evaluation and urban climate risk analysis. For more details on the study, please refer to [60].

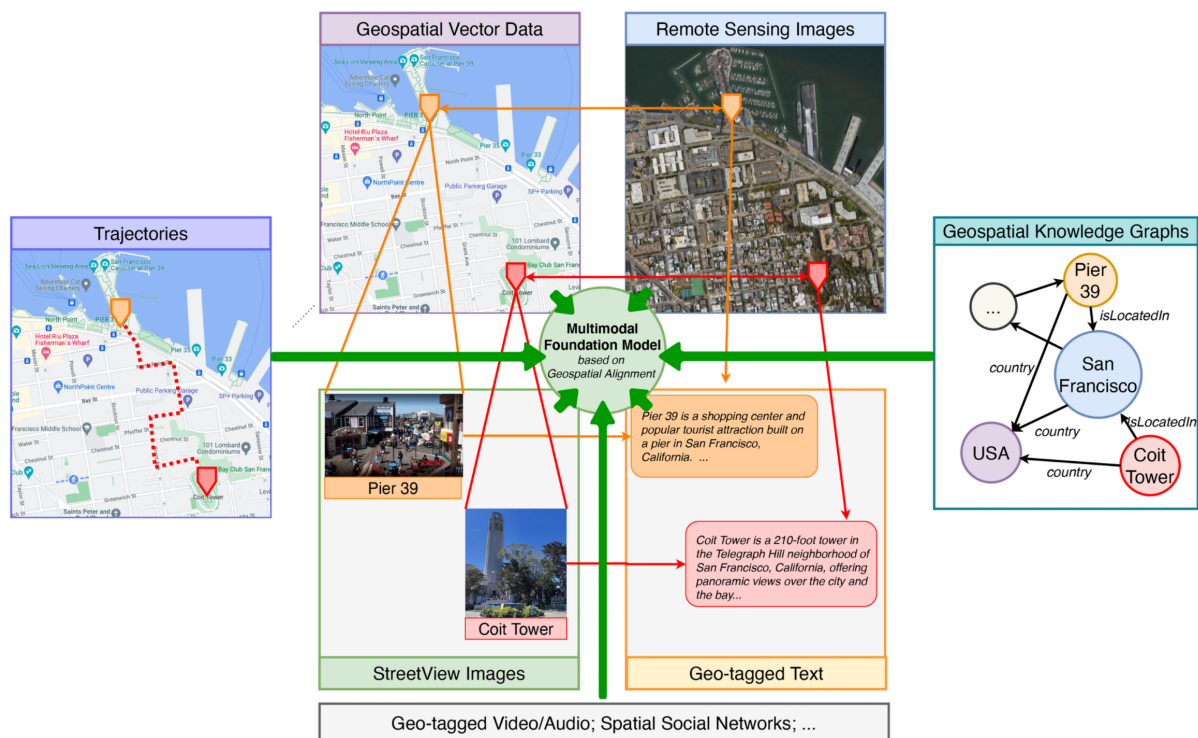


Figure 5.2: Conceptual model of a multimodal GFM that aligns various data sources, including remote sensing images, vector data, street-view images, and geo-tagged text, through their shared geospatial relationships. Source: Adapted from Mai et al. (2024) [62].

5.5.1. Study Design and Data Sources

The study area comprises twelve (see Figure 5.3) European cities selected to represent a range of climatic and urban morphologies. Input datasets include multi-temporal NASA Harmonized Landsat Sentinel-2 (HLS) multispectral and thermal imagery (30 m resolution) and vector-based land use/land cover data from the Impact Observatory (10 m resolution). Near-surface air temperature context is derived from ERA5-Land reanalysis data. Data preprocessing includes cloud filtering, spatial alignment, and bilinear interpolation of LST to the finer land use grid, ensuring congruent high-resolution analysis.

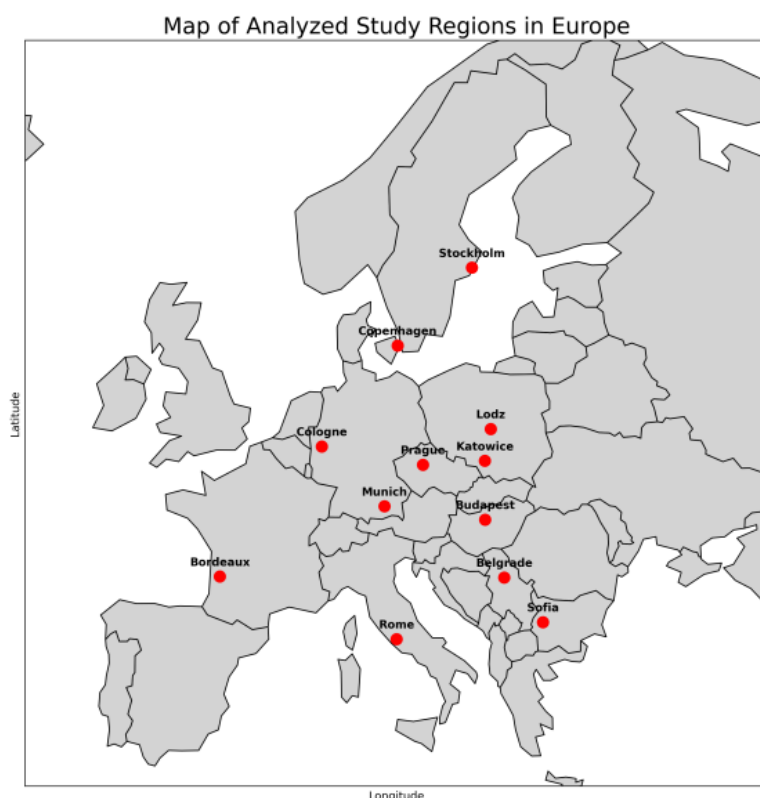


Figure 5.3: The twelve European cities selected as study regions, chosen for their diverse urban forms and suitability within the HLS satellite data tiling system [60]

5.5.2. Analytical Methodology and Empirical Results

The empirical analysis establishes a clear and consistent thermal signature of urban green spaces across all twelve European cities analyzed. Land surface temperature (LST) gradients exhibit robust spatial patterns characterized by internal and spillover cooling effects from parks and other blue-green infrastructure (BGI).

Three gradient analyses illustrated in Figure 5.4 quantitatively characterize urban microclimates and NbS cooling effects:

- **Urban Gradient Analysis:** LST variation with distance from urban centre
- **Spillover Cooling Gradient Analysis:** Cooling decay from green/blue infrastructure into built environment
- **Internal Cooling Gradient Analysis:** Temperature gradient from park edges moving inward

More in detail, the **Unified Spillover Gradient Analysis** is designed to systematically quantify and compare the “spillover” cooling effect of different types of urban infrastructure—specifically “Green-Only” (parks, vegetated areas), “Blue-Only” (water bodies), and combined “Blue-Green” spaces—on their surrounding built-up environment. The analysis operates by calculating the average land surface temperature (LST) anomaly in concentric distance buffers (e.g., every 10 meters) radiating outward from the edge of each infrastructure feature. The local baseline for comparison is typically the mean LST of all urban pixels. This approach enables direct comparison of the cooling decay from different infrastructure types, revealing both the magnitude (peak cooling in °C) and the spatial extent (distance of cooling effect) of spillover into adjacent neighbourhoods.

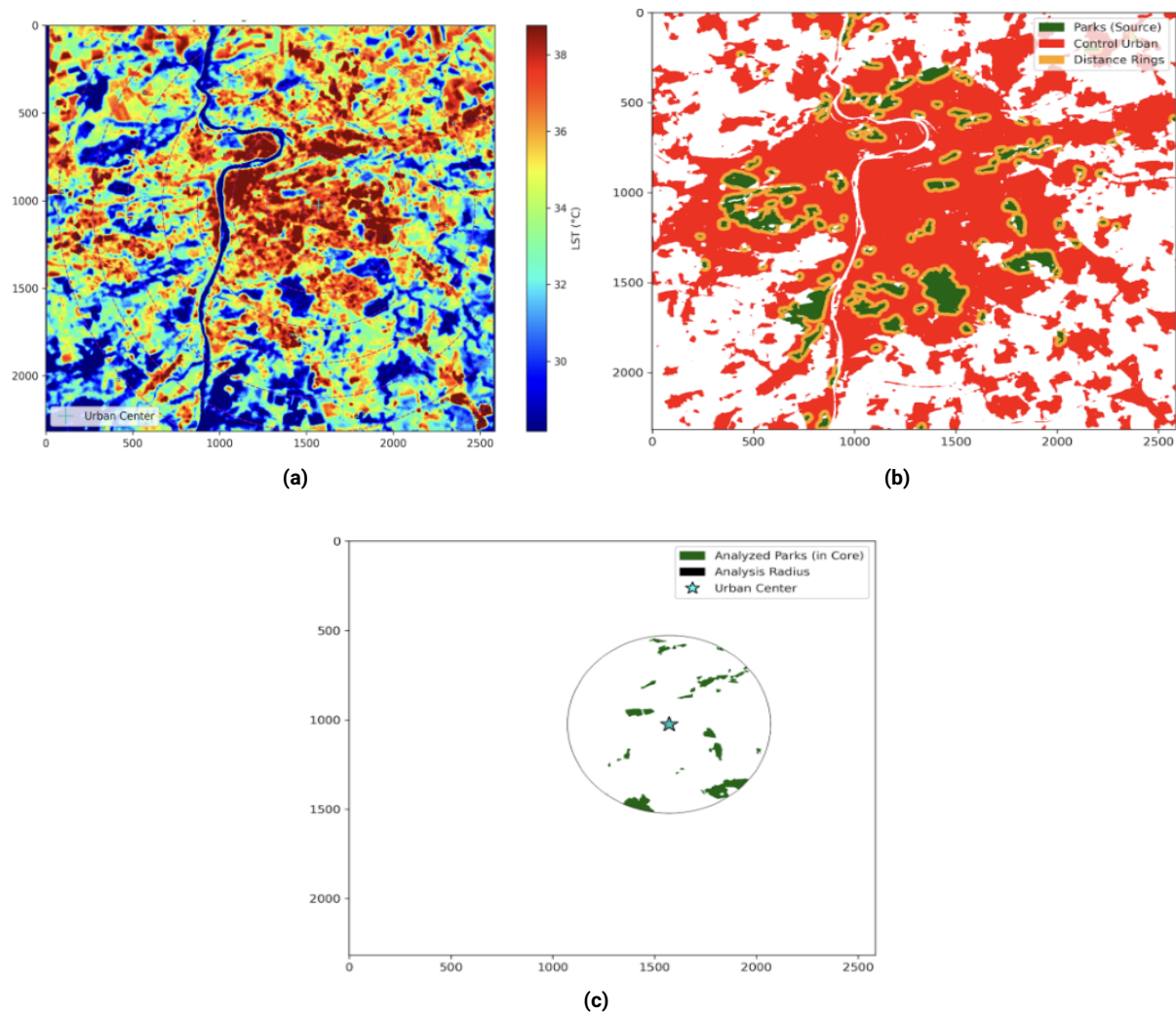


Figure 5.4: Conceptual visualization of the spatial analysis design for the three primary gradient-based experiments: (a) The Urban Gradient Analysis measures temperature in concentric rings from the city centre. (b) The Spillover Cooling Gradient Analysis measures temperature in buffers extending outward from an infrastructure feature. (c) The Focused Internal Cooling Gradient Analysis measures temperature moving inward from a park's edge in the dense city area [60]

The key finding of the Spillover Gradient Analysis aggregated across all analysed European cities shows a clear performance hierarchy:

- **Combined Blue-Green infrastructure** produces the most significant cooling effect, with a peak spillover ΔT of -4.1 °C at the immediate edge
- **Blue-Only infrastructure** follows closely with -4.0 °C
- **Green-Only infrastructure** has a peak cooling of -3.5 °C

For more details and results on the other two analyses quantifying the UHI effect (Urban Gradient Analysis and Internal Cooling Gradient Analysis) we refer the reader to [60].

5.5.3. Predictive Results: Spillover Cooling Gradient with Fine-Tuned Foundation Models

The aim of this study (detailed in [60]) is to evaluate whether state-of-the-art geospatial foundation models, when fine-tuned on diverse training cities, can accurately replicate the empirically observed spillover cooling effects of urban blue, green, and blue-green infrastructure. This step is essential for validating these models as planning tools capable of generalizing over complex microclimatic interactions across regions.

For this evaluation, two versions of the IBM-NASA Granite Geospatial Foundation Model (Granite GFM) were tested in [60]: Model v1, fine-tuned on 28 global cities, and Model v2, fine-tuned on an expanded dataset covering 52 cities across wider hydro-climatic zones. The models were tasked with predicting land surface temperature (LST) at 30 m resolution based on stacked multispectral satellite bands and atmospheric data, and their outputs were benchmarked against ground-truth cooling patterns using the standardized Spillover Gradient Analysis.

The results of the Spillover Cooling Gradient Analysis, illustrated in Figure 4.1 taken from [60], provide a direct visual comparison between the ground truth (empirically observed cooling profiles) and the profiles predicted by the fine-tuned foundation models for different types of urban infrastructure. In the plots, the measured land surface temperature (LST) anomaly is plotted as a function of distance from the edge of green, blue, or blue-green infrastructure into the adjacent urban area. The curves show the characteristic decay of cooling with increasing distance from each feature type.

The two models, Granite GFM Model v1 and Model v2, both demonstrate strong accuracy with respect to the ground truth spillover cooling gradients despite some differences. Model v2, fine-tuned on a larger and more diverse training dataset spanning 52 cities versus 28 for Model v1, exhibits improved consistency and lower error metrics, especially in dense urban core environments. In contrast, Model v1 shows slightly greater bias and larger errors in some conditions, including an underestimation of green-only cooling effects and overestimation of blue-green cooling near urban centres.

Despite these differences, the strong agreement between both models' predictions and empirical observations, as illustrated in the figures, strongly supports their use as reliable tools for urban microclimate prediction. This level of reliability is necessary for applying these foundation models in practical urban climate resilience planning, including simulating green and blue infrastructure interventions and evaluating their cooling impacts under future scenarios.

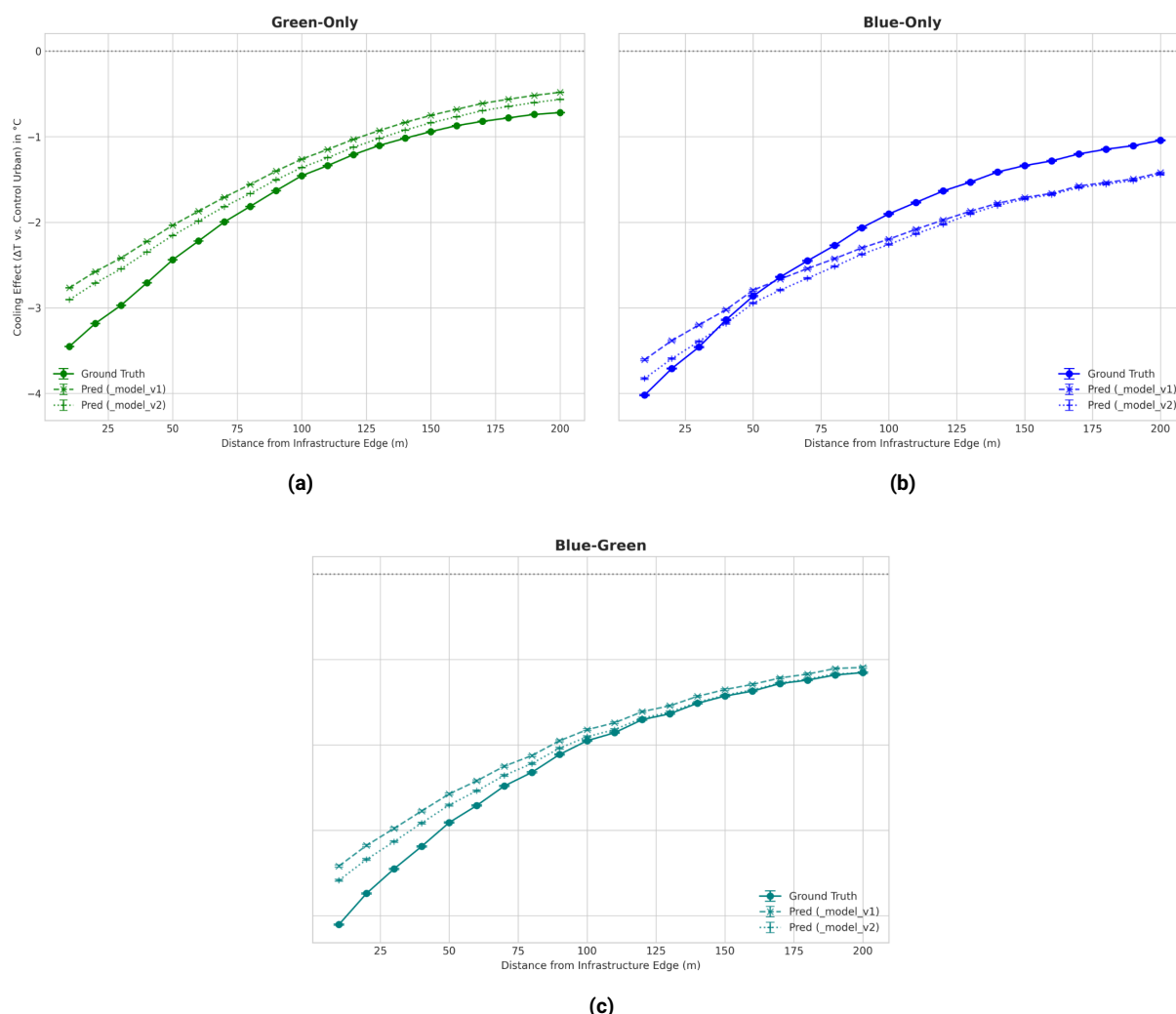


Figure 5.5: Comparison of predicted (v1 and v2) vs. ground truth spillover cooling for Green-Only areas, Blue-Only areas and Blue-Green areas as a function of distance from the edge of the infrastructure. Data points are averaged across infrastructures in the 12 analysed cities

5.6. Final Conclusions and Considerations

This chapter has demonstrated the significant potential of fine-tuned geospatial foundation models in advancing the understanding and predictive assessment of urban heat island (UHI) mitigation via NbS, particularly green and blue infrastructure. The strong agreement between empirical ground truth analyses of cooling gradients and model predictions confirms the models' ability to capture complex microclimatic interactions at high spatial resolution across diverse urban contexts.

The Granite Geospatial Foundation Model, leveraging satellite multispectral data and atmospheric reanalysis, has proven capable of replicating key cooling signatures, including the internal temperature reductions within green spaces and the spillover cooling effects that extend into surrounding urban fabric. These cooling gradients, quantified with rigorous spatial detail, provide actionable metrics for urban planners seeking to optimize green and blue infrastructure deployment.

Beyond retrospective analysis, an additional application concerns the simulation of future interventions. By modifying the geospatial input to represent hypothetical additions or modifications of green infrastructure (e.g., adding new parks, expanding existing waterways), the foundation models can predict the thermal impacts of such urban design decisions before implementation. This enables scenario testing, comparison of intervention alternatives, and evidence-based decision support that can accelerate climate-resilient urban development [60].

The multi-city validation and robustness of the models further advocate their use as scalable, generalizable tools that overcome the limitations of localized and data-scarce conventional modelling approaches. They contribute to bridging the knowledge-to-action gap by operationalizing high-resolution predictive insights into user-centric workflows and automated planning frameworks.

6

Conclusions and Considerations

This deliverable has presented a structured methodology for integrating Nature-based Solutions into digital tools that support climate-resilient infrastructure planning. By linking ecological, technical, and socio-institutional dimensions of NbS with the computational and data requirements of decision-support environments, the framework bridges the gap between conceptual design and operationalisation within the NATURE-DEMO project.

A key outcome of Deliverable D1.2 is the establishment of a **multi-stage framework** that systematically guides the identification, prioritisation, and site-specific design of NbS for protecting Critical Infrastructure against climate-related Natural Hazards. This structure enhances clarity, facilitates comparability across contexts, and provides a clear decision-making pathway for end users.

The site-selection methodology further highlights the importance of **cross-domain alignment**. Effective NbS integration requires tailoring solutions to the local hazard regime, infrastructure vulnerabilities, ecological opportunities, and institutional capacities. Embedding these diverse factors into a coherent design and decision-support process strengthens both the robustness and legitimacy of NbS in infrastructure planning.

A central contribution of this deliverable lies in the **parameterisation of NbS performance** for digital applications. By structuring NbS attributes through the RAMSSHEEP framework, the methodology enables transparent and replicable assessment of how NbS influences technical reliability, ecological functions, social acceptability, and economic efficiency. Such parameterisation not only allows consistent comparison with conventional grey infrastructure but also strengthens the integration of NbS into GIS-based planning, risk models, and multi-criteria decision-support systems.

The key outcome of this work is the development of the risk magnitude matrices. They are bringing together both NBS and the technical-structural measures as hazard categories, together with complex performance evaluations of the various stakeholders across multiple conditions: baseline, post-hazards, with grey infrastructure and with NbS. The comparative risk assessment analysis enabled by these matrices is the core result of the proposed methodology, establishing a central link between the project's conceptual framework and its operational assessment tools. In addition, the suitability of potential mitigation measures from an operational perspective is also assessed with a view to quantifying the risk reduction.

The framework also addresses the **critical role of monitoring**. Continuous assessment of ecological, technical, and social indicators—before, during, and after implementation—is essential to track NbS performance, support adaptive management, and ensure long-term credibility. Monitoring further contributes to the evidence base required for replicability and scaling of NbS across diverse infrastructure types and hazard conditions.

At the same time, important **challenges remain**. Standardisation of monitoring protocols, accessibility of long-term datasets, and integration of heterogeneous knowledge sources are prerequisites for advancing NbS assessment. Furthermore, the scalability and transferability of the proposed framework are strongly dependent on **institutional support** and **stakeholder engagement**. Without adequate capacity, resources, and governance mechanisms, mainstreaming NbS into infrastructure investment and planning cycles will remain limited.

Another key outcome of the present deliverable is demonstrating how the algorithmic integration of NbS into climate risk analysis enables quantification and comparison of their risk-reduction effects. Using fine-tuned geospatial foundation models, the approach captures complex interactions among hazards, exposure and vulnerability while supporting the simulation of NbS interventions across spatial and temporal scales. The approach provides a scalable means of translating complex environmental data into evidence-based decision support, enabling the optimisation of NbS implementation and performance.

Due to the fact that the task T1.4 remains ongoing until Month 24 (M24), the treated argument of “Algorithmic Aspects of Integrating NbS Risk-Reduction Effects in Climate Risk Analysis Frameworks” will be further elaborated and refined over the coming months.

As a whole, Deliverable D1.2 advances the methodological foundation for operationalising NbS in digital decision-support environments. It demonstrates how NbS can be systematically translated into computational formats that support risk governance and infrastructure resilience. Within the NATURE-DEMO demonstration cases, the framework will be further tested and refined, providing practical insights into its application. Beyond the project, the methodology offers a transferable basis for scaling up NbS integration across Europe and beyond, thereby contributing to the EU’s vision of adaptive, cost-effective, and multifunctional approaches to climate adaptation and infrastructure protection.

Deliverable D1.2 marks the transition to Work Package 2 “*Develop the Digital Decision-Support Platform*,” which is dedicated to developing a quantitative framework for risk-reduction estimation and establishing a digital platform that integrates this framework to guide the implementation of NbS. The structured methodology for integrating NbS into digital tools, developed within the framework of the present deliverable to support detailed risk assessment analyses, has been further incorporated into WP2 as a **foundational element of Level 1 of the risk assessment framework**, ensuring methodological continuity between the two Work Packages. This Level 1 Methodology can be considered as an initial validation step, providing a stakeholder-informed “green-light” to progress to more detailed quantitative stages of risk assessment.

Overall: Deliverable D1.2 provides a **structured, multi-stage methodology** for integrating NbS into digital tools that support climate-resilient infrastructure planning. By translating ecological, technical, and social dimensions of NbS into computational parameters, the framework enables their systematic assessment alongside conventional grey infrastructure. It strengthens decision-making by linking hazard and vulnerability analysis with site-specific NbS design, while offering clear guidance for monitoring performance and supporting adaptive management.

The framework demonstrates that NbS can deliver cost-efficient, multifunctional, and adaptive benefits for protecting critical infrastructure. However, successful implementation depends on

institutional capacity, stakeholder engagement, and the availability of robust data for monitoring and evaluation. By embedding NbS into digital decision-support environments, this deliverable provides both a practical tool for the NATURE-DEMO demonstrators cases and a transferable approach for scaling up NbS integration across Europe, in line with the EU Adaptation Strategy.

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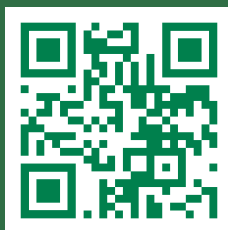
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History of Changes

Version	Date	Changes
v 1.0	31.10.2025	First version uploaded in the Horizon Europe portal
v 1.2	13.01.2026	Implementation of changes after Reviewer's comments [BOKU] – Removed unused acronyms and corrected RAMSSHEEP. – The term RAMSSHEEP was standardised and used consistently throughout. – Added a note on co-development and validation across five sites in section 2.2. – Added sentences on data collection complexity in section 2.3.3.3. – Added a paragraph describing the multi-actor workshop in section 2.4.1. – Added sentences in section 2.4.1 on expert consultations and coordination. – Added a sentence in section 4.3 explaining level 1 and 2 assessment links. – Defined the Chapter 5.1 case study as a scalable proof-of-concept. – Updated the Figure 5.3 caption to reflect selection criteria for cities. – Included an assessment of mitigation measures in Chapter 6.



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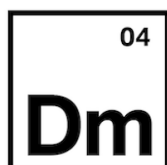
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