DELIVERABLE 2.1

Report on the modelling and monitoring methodology and NBS performance indicators

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How to quote this document

Brogno, L. et al. (2025). Report on the modelling and monitoring methodology and NBS performance indicators *(LAND4CLIMATE Deliverable 2.1)*

Title of deliverable or scientific publication

Project description

PROJECT TITLE	Utilization of private land for mainstreaming nature-based solution in the systemic transformation towards a climate-resilient Europe
PROJECT ACRONYM	LAND4CLIMATE
GRANT AGREEMENT NO	101112781
INSTRUMENT	INNOVATION ACTION
CALL	HORIZON-MISS-2022-CLIMA-01
STARTING DATE OF PROJECT	SEPTEMBER, 1ST 2023
PROJECT DURATION	48 MONTHS
PROJECT COORDINATORS	PROF. STEFAN GREIVING AND PROF. THOMAS HARTMANN (TUDO)

Document Details

DELIVERABLE TYPE	R — Document, report	
DELIVERABLE NO	2.1	
DELIVERABLE TITLE	Report on the modelling and monitoring methodology and NBS performance indicators	
NAME OF LEAD PARTNER FOR THIS DELIVERABLE	UNIBO	
VERSION	V1.0	
CONTRACTUAL DELIVERY DATE	28-February-2025	
ACTUAL DELIVERY DATE		
Dissemination level		
PU	Public	X
SEN	Sensitive, only for members of the consortium (including the Commission)	

Revision History

Revision	Date	Description	Author (Organisation)
V0.1	10/02/2025	First Version	Luigi Brogno (UNIBO) et al.
V0.2	13/02/2025	Quality Control	Stefan Greiving (TUDO)
V1.0	21/02/2025	Final adjustments	Luigi Brogno (UNIBO)
V1.0	27/02/2025	General inspection	LAND4CLIMATE consortium
V1.0	27/02/2025	Submission	David Ellerbrake (TUDO)

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Abbreviations

LAND4CLIMATE	Utilization of private land for mainstreaming nature-based solution in the systemic transformation towards a climate-resilient Europe
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CER	Cost-Effectiveness Ratio
CO_2	Carbon Dioxide
CRA	Climate Risk Assessment
EU	European Union
FRR	Frontrunning Region
GA	Grant Agreement
GCEA	General Cost-Effectiveness Assessment
HMH	Hydro-Meteorological Hazard
HMR	Hydro-Meteorological Risk
IPCC	Intergovernmental Panel on Climate Change

LAD	Leaf-Area Density
NBS	Nature-based Solution
OAL	Open-Air Laboratory
OECD	Organization for Economic and Development
OPERANDUM	OPEn-air laboRAtories for Nature baseD solUtions to Manage environmental risks
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PHUSICOS	“According to Nature” in Greek
SES	Socio-Ecological System
WP	Work Package
2D	Two-Dimensional
3D	Three-Dimensional

Executive Summary

Deliverable 3.1 (DEL3.1) outlines the methodologies for modeling and monitoring the effectiveness and efficiency of Nature-Based Solutions (NBS) in mitigating Hydro-Meteorological Hazards (HMHs). It focuses on describing the approach that will be used for evaluating the performance indicators through integrated assessment frameworks applied in various frontrunning regions. The report emphasizes the importance of context-specific assessments and recommends adopting adaptable methodologies to optimize NBS implementation across different environments. Additionally, the deliverable lists and describes the main NBSs that are going to be implemented in each frontrunning region.

Keywords

Hydro-Meteorological Hazards and Risks, Modeling and Monitoring Methodology, Nature-Based Solution Effectiveness

1. Introduction and motivation

Hydro-Meteorological Hazards (HMHs) are atmospheric, hydrological, or oceanographic phenomena and processes (UNDRR2017) whose occurrence may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, environmental resources, and social and economic disruption (Masson-Delmotte et al., 2021). These hazards imply the degradation of ecosystems (e.g., eutrophication, soil and coastal erosion), transfer of water and energy between the land surface and the lower portion of the atmosphere (e.g., landslides, snow avalanches, and floods), or weather and climate processes (e.g., saltwater intrusion, storm surges, violent winds, extreme temperatures, and droughts; Debele et al., 2023).

Human's activities are impacting with high certainty the dynamics of the Earth's system through land-use transformations and ecosystem degradation as well as greenhouse gas emissions (Portner et al., 2022). These emissions have significant consequences on the climate. The 2011-2020 mean global temperature is 1.1 K higher than during the pre-industrial period 1850-1900 in which the human contribution to climate variability was not significant. Due to current warming, hot extremes (including heatwaves) with a 10-year return period are now 1.2 K hotter and 2.8 times more likely to occur than they would have been in the past. Projections show that the higher the emission scenario is, the more severe the worsening of hot extremes will be. A warming level of 4 K may result in increased magnitude and frequency by 5.1 K and 9.4 times, respectively.

This worsening of hazard characteristics may pose higher risks (i.e., the potential for adverse consequences) for both society and ecosystems. As theorized by the Crichton's Risk Triangle (Crichton et al., 1999), the cause-effect relationship between hazard and risk is affected by both exposure and vulnerability. Risks may result only if hazard, exposure, and vulnerability are simultaneously not null. Exposure refers to the presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, and economic, social, and cultural assets in places and settings that could be adversely affected by the occurrence of hazardous events. Vulnerability is the propensity or predisposition of these elements to be adversely affected by these events. Portner et al. (2022) estimated that approximately 3.5 billion people are currently highly vulnerable to climate change. Despite this number is projected to increase further, the future will be strongly affected by the current and next steps in human development. Steps include the adoption of adaptation and mitigation measures, which are, respectively, actions that enhance the adaptive capacities of the exposed elements (a sub-component of the vulnerability term) and mitigate climate change by preventing or removing greenhouse gas emissions in the atmosphere. Measures include Nature-Based Solutions (NBS), i.e., an umbrella concept that gathers measures learned from nature to provide benefits for both humans and ecosystems addressing societal challenges effectively and adaptively (Cohen et al., 2016). NBS consists of ecosystems that are preserved with no or minimal interventions (i.e., protection approach), managed in a sustainable way by balancing both human and ecosystem needs (i.e., sustainable-management approach), assisted with the ultimate goal of its recovery after degradation or destruction (i.e., restoration approach), and modified by introducing new natural elements or even creating a new ecosystem (i.e., implementation approach).

Despite NBS providing both human well-being and biodiversity benefits by definition, methods and long-term assessment of NBS are still limited. This research gap can be attributable to the relative novelty of the NBS concept, along with the difficulty in developing and applying a well-defined holistic assessment method for the NBS impact. The ability to interact as part of ecosystems makes NBSs capable of reducing Hydro-Meteorological Risks (HMRs). On the other hand, this feature complicates the theoretical description and modeling to properly include the interactions between NBS and the ecosystems in which these measures are implemented. Since the NBS spatial scale is usually lower than the ones associated with the occurrence of HMH events, the modelization of these interactions requires modeling chains and several data input as forcing and boundary conditions (Gallotti et al., 2021). In addition, NBS do not reduce HMRs by only affecting the hazard component. HMR assessment also requires a good representation of the positive and negative side effects provided by the NBS interventions (i.e., co-benefits and dis-benefits, Martin et al., 2020; Ommer et al., 2022). Since NBS consists of natural elements, these measures usually provide ecological side benefits, i.e., regulating ecosystem services such as the enhancement of air, water, and soil quality (Maes et al., 2013). These co-benefits may have socio-economic repercussions, i.e., side benefits related to the development of the society. For instance, the restoration of ecosystems can provide recreational and tourist areas supporting social cohesion and inclusion (Ferreira et al, 2020).

The provision of co-benefits is one of the potential positive characteristics of NBS that can foster their adoption and public acceptance in place of traditional engineering solutions (Pauleit et al., 2017). Anderson et al. (2022) report that the other positive characteristics of NBS interventions are lower costs and more cost-effectiveness (e.g., Kabisch et al., 2016), less long-term maintenance (e.g., Cheong et al., 2013), and larger climate adaptive capacity (e.g., Choi et al., 2021). On the other hand, negative characteristics include the longer time required to be effective in risk reduction (e.g., Kabisch et al., 2016) and the fact that ensuring stakeholder involvement throughout all project phases is time-consuming (e.g., Bark et al., 2021). Limited evidence concerning the NBS performance affects people acceptance that may perceive these measures as less reliable than traditional engineering grey solutions. However, people usually feel a sense of belonging to and pride of the community, improved sense of place, sense of responsibility for nature, and recognize NBS as a solution that promotes wildlife habitats, biodiversity as well as one that fits better aesthetically with nature (Anderson et al., 2021; Passani A., Janssen, A.L. and Hoelscher, K., 2020, and Dumitru A, and Wendling L 2021). As Kumar P, et al. outline to encourage the adoption of NBSs, which often require more time than grey solutions, more concrete proof of their economic and social advantages, as well as performance indicators, is needed to illustrate the various benefits that NBSs can deliver in both the short and long term (Kumar P, et al.2021).

LAND4CLIMATE aims to verify if the NBS carried out in the involved six frontrunning regions (FFRs) follows the definition of no-regret NBS introduced in Freyer et al. (2024) as NBS that will have more positive than negative effects on the livelihoods and ecosystems regardless of the changing climate and other developments in the region. In this regard, NBS should be cost-effective and socially accepted adaptation measures that reduce risks from HMHs and provide more co-benefits than unintended negative consequences. The following report introduces the methodology, indicators, and modeling chains that serve as the theoretical base for the complete assessment of the effects of NBS. After this introduction, this report is structured as follows. Chapter 2 explores the concept of NBS performance defined through the usage of three terms, namely, efficacy, effectiveness, and efficiency. Chapter 3 introduces the integrated assessment methodology, and the indicators needed for its application. Chapter 4 describes the modeling application of this methodology for each frontrunning region classified in the addressed HMHs. Chapter 5 reports the implications for future deliverables and project activities of WP2. Finally, Chapter 6 draws the conclusions.

2. The concepts of efficacy, effectiveness, and efficiency

The assessment of NBS presents a contemporary challenge in scientific literature because of the numerous environmental and socio-economic factors that must be considered when evaluating the effectiveness of these interventions. This challenge is complicated by the lack of a coherent definition, or standard, regarding what needs to be included in an NBS-performance assessment. NBS performance is often identified with several terms in the scientific literature without a distinction be-tween them. These terms include "efficacy", "effectiveness", and "efficiency". Table 1 illustrates how different authors and fields interpret these concepts. Despite commonly used as synonyms, their literal meaning differs depending on the depth of the assessment. The Merriam-Webster's Dictionary of Synonyms (1984) reports that the term “efficacy” refers to the potential provision of a promising effect. Conversely, effectiveness refers to the actual production of a given effect, while efficiency is a maximization of the effectiveness concept minimizing the loss of energy during the production of an effect. These concepts were assimilated into the medical literature (e.g., Marley et al., 2000; Patel et al., 2021). From the medical point of view, efficacy and effectiveness refer to assessing if a treatment works on an optimal set and a broad range of patients, respectively. Efficiency has been conjugated as a synonym of cost-effectiveness, i.e., a minimization of cost. Karpen et al. (2016) investigated these terms from a juridical point of view by referring to efficacy as the achievement of an intended purpose and effectiveness as the extent to which this purpose is achieved. Efficiency weighs up the final outcomes to the original legislator's intents. The economic point of view is similar to the juridical one (Segerson, 2013; Martin, 2014; Sellers et al., 2014). The economic efficacy of an action is the ability to move from imputs towards outcomes, while effectiveness is the validation of these actions and their generalization to be applied to other external studies. The economic efficiency consists of the maximization of the benefits and total welfare towards the costs required for the implementation of the analyzed action.

Table 1: Summary of definitions proposed in the literature for efficacy, effectiveness, and efficiency. These definitions are adapted to the assessment of NBS performance.

Author: **Merriam-Webster's Dictionary of Synonyms (1984); Zidane and Olsson (2017)**	Context: **Linguistics**
Efficacy	The possession of a quality or virtue that gives a thing potency or power that supports the production of an effect.
Effectiveness	The actual production of an effect or the power to produce a given effect.
Efficiency	The production of an effect in a manner that minimizes the loss or waste of energy in the production process.
Author: **Marley et al. (2000)**	Context: **Medical**
Efficacy	A treatment works during trials on the optimal set of patients (e.g., young, suffering from a single condition and using a single treatment).
Effectiveness	Treatment works in the real world over a broad range of patients.
Efficiency	Treatment is worth its cost to individuals or society.
Author: **Patel et al. (2021)**	Context: **Medical**
Efficacy	It means getting things done, i.e., is it working?
Effectiveness	It means doing the proper things, i.e., is it working well?
Efficiency	It means doing things right, i.e., is it working in the most economical way?
Author: **Karpen et al. (2016)**	Context: **Juridical**
Efficacy	It refers to the achievement of the intended purpose of a regulation.
Effectiveness	It refers to the extent to which the target is achieved.
Efficiency	It refers to the extent to which legislative actions achieve the legislator's intent.
Authors: **Segerson (2013), Martin (2014), Sellers et al. (2014)**	Context: **Economic**

Efficacy	The ability to produce a desired or intended result or carry out a course of action which shits the focus away from inputs and towards outcomes.
Effectiveness	The achievement of the objectives stated is additional to what would have been achieved in the absence of the intervention. Effectiveness is linked to whether findings could be validated and generalized externally.
Efficiency	Efficiency in decisions balances the associated societal benefits and costs. The decision to increase an activity is efficient from an economic perspective if the aggregate benefit to society from that increase exceeds the aggregate cost to society, maximizing total welfare and implying 'value for money' characteristics. Maximization of desired outputs given available inputs.
Author: **LAND4CLIMATE, current report**	Context: **Assessment of NBS Performance**
Efficacy	An NBS intervention works (= benefits for humans and ecosystems) in pilot-scale experiments carried out in laboratories or in simple virtual models in which all the variables are controlled.
Effectiveness	An NBS intervention works (= benefits for humans and ecosystems) in real-world experiments in which the variables are uncontrolled or in complex models in which several socio-economic and climate scenarios are tested.
Efficiency	The NBS provision of benefits is maximized for both humans and ecosystems by a co-development process with stakeholders that optimizes the NBS spatial extents and temporal conditions of functioning. This implies the minimization of the exploitation of both natural and economic resources and the maximization of risk reduction, co-benefits, and technological readiness levels.

This brief digression concerning the interpretation of the term's "efficacy", "effectiveness", and "efficiency" helps to formulate a LAND4CLIMATE definition of these concepts for NBS intervenetions. Following the previous definitions, efficacy refers to an NBS working in pilot-scale laboratory experiments and simple numerical or analytical modeling, while effectiveness refers to NBS assessment being carried out in real-world experiments or model chains that reproduce the complexity of the real world in the best way possible. Effective NBS provides multiple benefits for humans and ecosystems such as nature conservation, human health, and well-being. Since a no-regret NBS is a measure that produces more positive than negative effects regardless of climate and socio-economic pathways, the LAND4CLIMATE concept of no-regret NBS is consistent with an assessment of the NBS effectiveness by providing robust evidence from the modelization of target NBS in the six frontrunning regions. This evidence is provided by the comparison of scenarios with and without the NBS interventions. The comparison requires taking into account the background of previously set political and normative goals. These goals include expected degrees of protection for climate risks and development targets for quality of life, biodiversity, and social cohesion for co-benefits. This effort will also be beneficial to the assessment of NBS efficiency which refers to the maximization of both human well-being and biodiversity benefits. However, the achievement of an NBS-efficiency assessment requires a long-term monitoring process and the replication and upscaling of the NBS at optimal scales to affect the HMH characteristics (i.e., magnitude, duration, and frequency of occurrence) at a larger scale. The achievement of an efficient NBS requires optimal conditions of functioning along the NBS life cycle. These conditions can change over time due to several processes such as the required time to become fully operational at the beginning, the lack of NBS maintenance, changes in boundary conditions such as climate, and the NBS degradation due to HMH events. The difference between costs and benefits can be increased by optimizing the NBS spatial extent through replication and upscaling processes. These processes consist of changes in the institutional structures, laws, values, or mindsets, and the amount and coverage of successful NBS projects (Lam et al., 2020).

3. The Integrated Assessment Methodology and indicators for the NBS performance

The assessment of NBS effectiveness requires a multitude of expertise for a good representation of the complex processes that can affect the outcomes of an NBS intervention. Each NBS case study is a unique mosaic of climate, environmental, social, and economic conditions. Multiple types of indicators are essential to capture the interactions between NBS interventions and hazardous events in specific socio-economic and environmental contexts. A coherent methodology is essential to gather all these different types of indicators in a single assessment of the NBS outcomes and impacts.

In this regard, the following section proposes an integrated assessment methodology for NBS performance in the LAND4CLIMATE project. It was first developed within the OPERANDUM (OPEn-air laboRAtories for Nature baseD solutions to Manage Environmental risk, 2018-2022) project and will be adapted to the needs of the LAND4CLIMATE project. OPERANDUM was a Horizon-2020 project funded by the European Commission (under grant agreement GA 776848) for the provision of new evidence concerning the feasibility of addressing HMHs effectively through the implementation and analysis of NBS tested in 11 Open-Air Laboratories (OALs). The OALs are an expansion of Living Labs in which the NBS performance was assessed by taking into account cutting-edge numerical modeling approaches, innovative monitoring systems, climate projections, land use data, socio-economic conditions, and NBS acceptance.

Figure 1 shows the methodology that translates this OAL concept into an operative workflow. The key components of this workflow include: 1) the hazard-reduction assessment, 2) the assessment of indirect benefits (e.g., co-benefits), 3) the risk assessment, 4) the cost-benefit assessment, and 5) the evaluation of public acceptance. The application of this methodology requires each component to be descrived with suitable indicators (red rectangles, Fig. 1). These indicators encompass the assessment of four thematic areas: 1) the reduction of hazards by the NBS interventions (for component 1), 2) ecosystemic and socio-economic co-benefits (component 2 and 4), 3) the effect of the NBS on both vulnerability and exposure for the risk assessment (component 3 and 4), and 4) public acceptance (component 5) to evaluate the knowledge, acceptance, and mainstreaming of NBS interventions.

An example of selection of suitable indicators is provided by the library developed during OPERANDUM for the application of the methodology to the 11 OAL case studies (Table 2). The hazard-reduction indicators for the integrated environmental performance assessment are further subdivided into actionable and impact variables to represent the direct actions of NBS interventions on the hazard characteristics. The actionable variables are bio-geophysical quantities that are both directly affected by the NBS and affect in turn the targeted natural hazard processes. The ultimate goal of the NBS interventions is the modification of actionable variables to lead to a variation of the impact variables that quantify the local impact of an extreme event. In principle, these two variables can coincide. For instance, the actionable variables during the renaturalization of riversides by planting vegetation can be the vegetation cover and surface roughness, while the expected impact variable can be the decrease of the inundation depth in the surrounding areas.

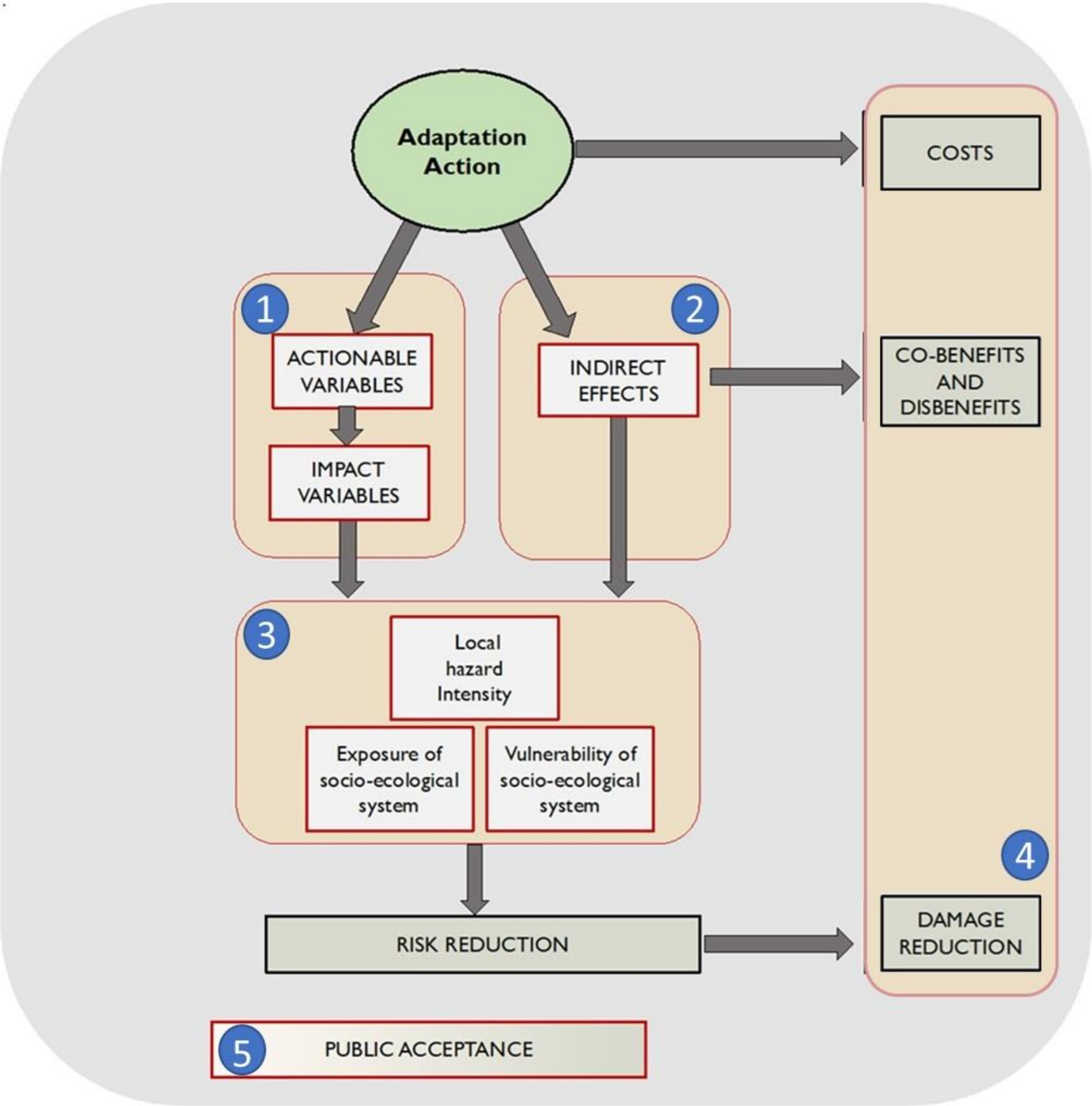


Figure 1: Schematic of the LAND4CLIMATE workflow for the assessment of NBS performance. Numbers from one to five label the colored shadings that identify the 5 steps of the methodology discussed in the body text. Red rectangles encompass thematic areas that are targeted by indicators. Green rectangles encompass categories of monetary costs and benefits (Adapted from Ruggieri et al., 2023).

Changes in impact variables imply the reduction of hazards (Component 1). In addition, an effective NBS case study can also provide co-benefits (Component 2). The co-benefits are socio-ecological non-market (indirect) benefits. For instance, the renaturalization of riversides can enhance biodiversity and human well-being by offering a place for leisure and sport activities. Both direct reduction of hazards and changes in exposure and vulnerability due to co-benefits can affect the risk assessment (Component 3). Furthermore, the estimate of both costs and benefits leads to cost-benefit analyses for the evaluation of the cost-effectiveness over the entire life cycle of an NBS intervention (Component 4). Lastly, the methodology includes the assessment of public acceptance

(Component 5) by the landowners. This assessment is achieved by the analyses of the direct engagement of stakeholders in the NBS interventions and the identification of drivers and barriers that affect the perception of the NBS performance.

Table 2: **Prospect of the indicator library selected during OPERANDUM for the assessment of the NBS performance. The columns show from the left to right: the thematic area of the indicators, categories, sub-categories, the number of indicators in each category, example indicators, and the main reference for each category. Source: adapted from Ruggieri et al. (2023).**

Area	Category	Sub-categories	# of indicators	Example	Main Reference
Hazard Reduction Co-benefits	Actionable variables	Drought, eutrophication, floods, heat waves, landslides, snow avalanche, salt-water intrusion, soil and coastal erosion, storm surges	29	Plant cover (m^2)	Alfieri et al. (2022), Ruggieri et al. (2023)
	Impact variables		55	Inundation depth (m)	
Co-benefits	Environmental Co-Benefits	Air quality, biodiversity, carbon storage, ecosystem disservices, habitat connectivity, soil health, vegetation cover, water quality	45	Threatened species (%)	Ommer et al. (2022) and Debele et al. (2022)
	Socio-economic and Well-being (Co-)benefits	Physical and mental health, well-being, public participation, finance and economy, noise attenuation	19	Noise Attenuation Potential (*dB*)	
Risk	Vulnerability	Ecosystem Susceptibility	33	Biodiversity Index	
		Social Susceptibility	32	Poverty (% of population)	
		Ecosystem Robustness	10	Restored wetlands (%)	
		Coping Capacity	27	Early warning system (% of	

Risk	Vulnerability			covered population)	Shah et al. (2020) and Dumitru and Wendling (2021)
		Adaptive Capacity	9	Existence of adaptation policies (yes/no)	
	Exposure	Ecosystem Exposure	9	Exposed area to landslide (%)	
		Social System Exposure	15	Residential area (ha)	
Public acceptance	Knowledge	-	6	Knowledge about adaptation measures	Ruggieri et al. (2023)
	Stakeholder Acceptance	-	6	Legitimacy/ trust in implementers	
	Mainstreaming	-	5	Willingness to increase funding/ investments	
Project Impacts	Key Performance Indicators	-	12	Number of products showing technological advancement (TRL)	OPERAN-DUM

Figure 2 reports an example of application of the selected indicators for an OPERANDUM case study (i.e., OAL-Greece) that serves as a guideline for future application. OAL-Greece is located in the Sterea Ellada region where two emergency flood water storage areas were constructed in the River Spercheios catchment. The intervention required the widening of riverbeds, the stabilization of embankments, the cleaning of the vegetation bedload, and the re-meandering of the river course. The outcome is the possibility of storing flood water to provide irrigation to crop fields during dry periods. Since the NBS collects floodwater, the actionable variable is the capacity of the reservoir, while the impact variables are the reduction of surface water levels, river discharge, and inundation depth. By addressing the hazard, the NBS reduces HMRs for the exposed elements located along the rivers such as people, properties, crop fields, roads, and other critical physical infrastructure. These elements are vulnerable to floods and drought for several reasons such as the lack of sustainable land-use planning into the floodplains that lead to the expansion of crop fields and the degradation of wetlands that can no longer act as natural retention areas. The renaturaliza-

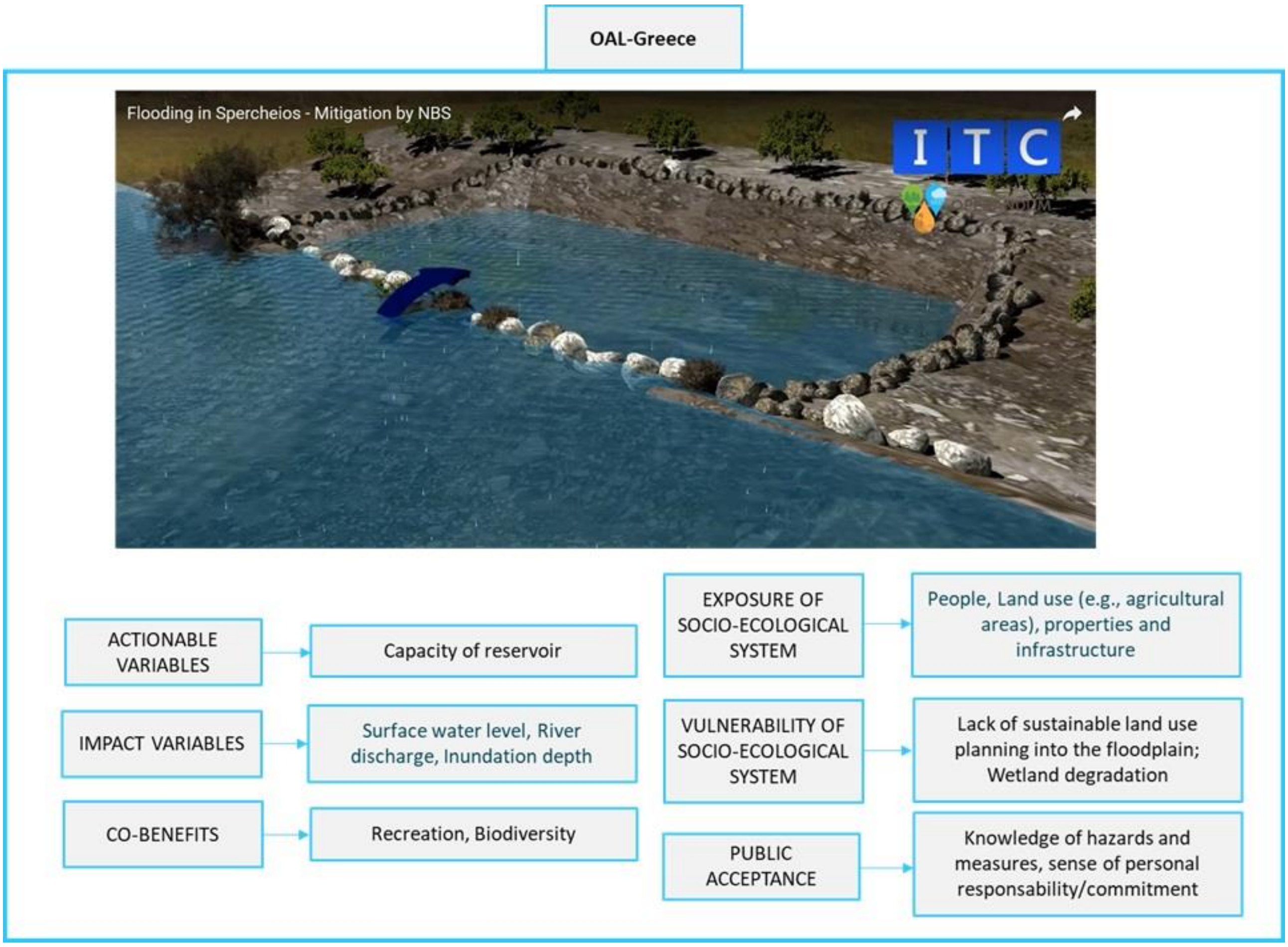


Figure 2: Indicator selection from the OAL-Greece (OPERANDUM) where two emergency flood water storage areas were introduced along Spercheios River. Source: adapted from https://www.youtube.com/watch?v=VaOJlPmvJwM&t=54s **, Innovative Technologies Centre (ITC), OPERANDUM Project**

tion of the river through re-meandering and other interventions can also increase biodiversity and provide more attractive areas for recreation. Finally, various meetings and consultations with the stakeholders led to an increase in both the knowledge concerning hazards and measures, and a sense of personal responsibility/ commitment. Future replications of the NBS along the river are already under discussion.

3.1 Hazard

The NBS assessment methodology outlined in this deliverable aims to evaluate the effectiveness and efficiency of NBS in mitigating HMRs identified in the Climate Risk Assessment (CRA) developed in WP1. Building on WP1, the methodology focuses primarily on four HMHs: heatwaves, drought, heavy rain, and river or coastal flooding. However, in specific cases, certain NBS may address additional hazards beyond those previously studied.

The aim of the CRA in WP1 was to identify, for each FRR and each hazard affecting it, hotspot areas where the risk for that specific hazard was particularly high compared to the rest of the FRR. In WP2, the focus shifts to evaluating the benefits of NBS implementation in mitigating the risks in the hotspot

Table 3: Scenarios and time periods considered in WP1.

	Baseline	Scenario A	Scenario B
Hazard Indicator	**1991-2020** **Current situation**	**2031-2060** **Moderate climate change:** RCP 4.5	**2031-2060** **Strong climate change:** RCP 8.5

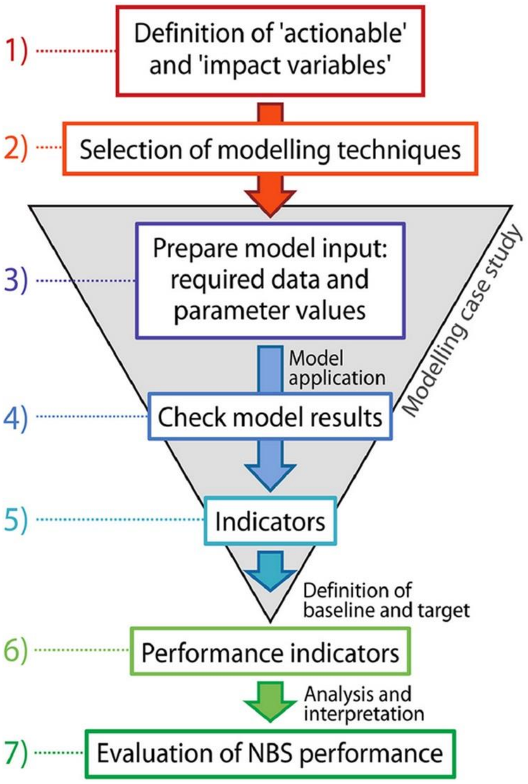


Figure 3: LAND4CLIMATE Methodology for the evaluation of the NBS performance with modeling techniques. Source: Bowyer et al. (2024), adapted from Zieher et al. (2021).

areas identified in WP1. In this process, we will adhere, where possible, to the main approach of WP1 regarding hazard indicators, time periods, and scenarios. The key indicators for each hazard included in the HMR assessment will be detailed in section 5 in a specific subsection dedicated to the single hazard.

For time periods and scenarios, we aim to maintain consistency with WP1 by analyzing a baseline scenario representing the current situation and two future scenarios covering the same period (2031–2060) with increasing climate change severity (see Table 3). Specifically, Scenario A will follow a moderate pathway (RCP 4.5), while Scenario B will represent a severe pathway (RCP 8.5).

The hazard-reduction assessment implies the evaluation of both actionable and impact variables through modeling experiments. LAND4CLIMATE adopts OPERANDUM methodology to evaluate the outcomes of these experiments (Figure 3). This methodology for modeling techniques is based on recommendations provided by the Organization for Economic Cooperation and Development (OECD) handbook for the construction of composite indicators (Nardo et al., 2005). This methodology encompasses seven steps:

1. the definition of actionable and impact variables based on the expected processes between NBS and hazard characteristics;
2. the selection of suitable modeling techniques;
3. the collection of input data and parameters needed for the application of the models;
4. the analyses of model results;
5. the definition of indicators;
6. the development of performance indicators by comparing the indicators with the baseline and target. The baseline can be defined as reference measurements collected before the NBS intervention or data concerning the hazard history in the investigated area;
7. the evaluation of the performance indicators to estimate the NBS performance over the actionable variables and in turn over the impact ones.

The selected performance indicators should comply with quality criteria such as credibility, salience, legitimacy, and feasibility (van Oudenhoven et al. 2018). The spatio-temporal coverage of the simulations needs to be aligned with the expected onset and evolution of the NBS effects. These effects may considerably change during the NBS lifecycle, and the maximum effectiveness could be reached after several years. However, continuous monitoring and evaluation of the NBS may not occur during or after the lifetime of the LAND4CLIMATE project, potentially limiting the ability to capture long-term outcomes and adapt strategies based on evolving performance.

3.2 Risk

Within LAND4CLIMATE, the approach to HMR analysis will leverage the methodology established in WP1, which provides a structured framework for evaluating vulnerability and exposure alongside hazard indicators. Wherever applicable, this deliverable aligns with the WP1 methodology to ensure consistency and maximize the comparability of results across different contexts.

The approach in WP1 for the exposure component relies on land-use data, including residential, industrial, agricultural, and forest areas. Practice partners provided these datasets, supplemented by CORINE land cover data, which offers pan-European land-use information with thematic classes based on Sentinel-2 and Landsat-8 satellite data. This openly accessible dataset (https://land.copernicus.eu/en/products/corine-land-cover/clc2018) was analyzed to establish the baseline scenario, with data considered static for future scenarios.

The vulnerability assessment in WP1 includes building and population density, considering vulnerable age groups, and soil water capacity. Building density is calculated by intersecting cadastral and land use data, while population data are disaggregated and weighted for vulnerable age groups, such as children and the elderly. Soil vulnerability is evaluated using water capacity data from the European Soil Data Centre. These indicators are normalized and integrated to identify areas with higher vulnerability. As in the case of exposure data, vulnerability data are considered static for future scenarios.

Finally, normalized indicators of hazard, exposure, and vulnerability are integrated to provide a common risk indicator. Hazard components are derived from specific scenarios (e.g., floods, heat, drought, see Section 4 and DEL1.3), while exposure and vulnerability indicators are integrated to reflect potential impacts. The final risk values are calculated by merging these components through multiplication and normalization, enabling the identification of climate risk hotspots across the regions. This approach allows for a comprehensive evaluation of risk tailored to local conditions. For further details on the estimation of exposure and vulnerability components, as well as the metrics used to generate a risk indicator, please refer to DEL1.3.

3.3 Co-benefits and trade-offs

The discussion on co-benefits and trade-offs of NBS is rather new with different conceptualisations emerging over the past decade. The number of scientific publications on the topic has significantly increased over the past years. Naturally, different aspects in diverse settings are researched and discussed with little common denominator so far. The focus of studies predominantly lies on assessing effectiveness, cost-benefit ratios as well as barriers and drivers in NBS implementation, with co-benefits merely mentioned but not systematically analyzed (e.g. Raška et al. 2022, Neumann et al. 2022, Vicarelli et al. 2024).

Overall, the evaluation of NBS effectiveness and efficiency is always directed towards certain main or core benefits. NBS are typically designed and implemented in locations to mitigate certain (climate) risks (Hartmann et al. 2019, Debele et al. 2023, Ferrario et al. 2024, Amirzada et al. 2023) or serve specific purposes (e.g. enhance biodiversity, establish habitat connection). Effectiveness and efficiency are – as presented in this report – a concern of comprehensive assessment approaches building on quantitative, qualitative, or mixed data and indicators.

Besides the main benefits, additional positive effects, often called co-benefits, are attributed to NBS favoring them over classic grey solutions. This multifunctionality should be an integral part of any comprehensive NBS valuation (Ommer et al. 2022, Raymond et al. 2017). Typically, co-benefits are classified by using the three core fields of sustainability:

- **Environmental co-benefits:** Here, biodiversity enhancement can improve natural habitats and support wildlife. At the same time, a contribution to climate change mitigation through carbon sequestration and storage can occur. Additionally, positive effects on water quality, groundwater recharge and regulating surface run-off are documented in recent studies (e.g. Chhetri et al. 2024, Epelde et al. 2024).
- **Economic co-benefits:** The economic dimension is an essential criterion in the evaluation of cost-effectiveness of NBS, but besides economic target values (e.g. reduce average annual loss and damage due to disaster events) additional economic co-benefits should be considered. For example, job creation due to maintenance work, the need for new fields of expertise that effect educational programs and diversify the job market in rural areas or also effects on real estate and land values (Stroud et al. 2022, Ruangpan et al. 2024, Aghaloo et al. 2024).
- **Social co-benefits:** NBS might also imply social co-benefits covering health and well-being (recreational spaces, improve mental and physical health), educational opportunities and social cohesion especially through participatory planning and implementation processes (Viti et al. 2023, Frumkin et al. 2022).

Thereby, the concept of co-benefits relates in the first place to additional Ecosystem Services (ESS) provided through NBS (EEA 2018).

Taking co-benefits deliberately into account, NBS implementation poses certain challenges and considerations:

- **Stakeholder engagement:** A clear identification and involvement of relevant stakeholders (power-interest relationship) to address co-benefits and trade-offs that are prone to cause conflicts.
- **Public perception and acceptance:** Communication about NBS projects to shape perception of affected/benefiting people and generating long-term acceptance (Giordano et al. 2020, Iungman et al. 2025).
- **Equity and inclusion:** Assessment of the beneficiaries of main as well as co-benefits and those who experience trade-offs with the overall goal, ensuring that inequalities are not exacerbated (Mendonça et al. 2024).

Another essential aspect in the discussion of main and co-benefits of NBS is the assessment of trade-offs. NBS typically need more land area for their implementation than grey solutions. The land required is often held by private landowners. Their perspective on benefits and trade-offs is therefore essential for any comprehensive valuation of NBS effects.

Overall, trade-offs can be qualified as negative co-benefits, meaning that certain ESS (e.g. agricultural production) are lost due to the implementation of NBS. This is sometimes also called disbenefits of NBS (Ommer et al. 2022). At the same time, the term trade-off is used by some scholars to describe the connection of benefits and co-benefits of NBS (Yang et al. 2023).

Within the LAND4CLIMATE project we go with the distinction (i) main benefits for the intended effects of a NBS, (ii) co-benefits for the additional ecosystem services delivered by a NBS, and (iii) trade-offs as the negative effects within the ESS classification.

The assessment of co-benefits and trade-offs can be conducted quantitatively by using pre-defined indicators or proxies (Ommer et al. 2022), solely quantitatively or with a mixed qual-quant approach. For LAND4CLIMATE a mixed approach will be applied. Co-benefits will be integrated into the numerical modeling conducted for different NBS in FRR. Due to data availability and qualitative criteria a comprehensive assessment of co-benefits and trade-offs will follow for all FRR under D2.4 applying a multi-criteria analysis (MCA).

3.4 Social acceptance as an aspect of social impacts

Social impact is described as “making a difference.” In its simplest form, it involves improving people’s wellbeing, both in breadth (more people) and depth (degree of improvement). Social impact refers to measurable changes brought about to individuals and society through interventions, in the case of LAND4CLIMATE – NBS measures. At the individual level, social impacts include acquiring knowledge, skills, and competencies, as well as influencing attitudes, values, behaviors, and ownership. At the societal level, social impacts cover aspects such as civic resilience, social cohesion, social capital, and empowerment (Passani A, Janssen AL, and Hoelscher K, 2020).

In the context of NBS, social impacts can stem from two sources. First, as a by-product of the implementation process adopted, and the type of stakeholder engagement undertaken, which views NBS as a social, environmental, and technical process. The derived social benefits are not necessarily linked to a specific NBS measure, but rather to the implementation process itself (e.g., co-creation, co-governance, Open Air-Laboratories, participatory approaches, Citizen Science, etc.) (European Commission 2023; Gallotti et al., 2021; Kumar P. et al., 2020). Second, as a secondary impact of natural risk and hazard reduction, sometimes an indirect or unintended consequence of building NBS infrastructure. Anderson CC, Renaud FG, Hanscomb S, and Gonzalez-Ollauri A (2022) state that the primary aim of all NBS remains risk reduction, with any co-benefits being secondary or indirect. However, they raise a valid point about the need for the public to value co-benefits, which could increase support for NBS and shift preferences away from grey infrastructure (Anderson et al., 2022).

In the brief scoping review conducted, these were the main social impacts deemed potentially relevant for the NBS measures in LAND4CLIMATE:

- **Public acceptance by landowners;**
- **Aesthetic values;**
- **Perceptions of risk;**
- **Empowerment, knowledge, and learning;**
- **Social capital and trust;**
- **Better access to nature and health benefits; and**
- **Policy governance and process transparency.**

Though not analyzed here, the negative consequences of NBS are rarely discussed; however, they should be considered in the selection and design phase of the NBS (e.g., job losses, land expropriation, social exclusion, etc.) (Dumitru A, and Wendling L, 2021; Alva A, 2022).

Perhaps unsurprisingly, the literature suggests that a key social impact resulting from implementing NBS is an increase in **public acceptance** of such measures. This is often linked to the participatory process and/or stakeholder engagement that typically accompanies NBS implementation. Anderson CC et al. (p. 2, 2021) state, "*A greater reliance on local stakeholders for cooperation with NBS during implementation, maintenance, management, and monitoring phases means public acceptance is crucial for their success*". Therefore, public acceptance becomes a cornerstone of the implementation of NBS, and its success generates more acceptance, a positive reinforcement loop.

NBS may induce a change in attitude and behavior through the activities linked to its design, planning, implementation, and maintenance. Public acceptance and, therefore, support for NBS measures is linked to an individual connection to place. Some studies have found that when discussing preferences between NBS, hybrid, and grey measures, focusing too much on co-benefits may, in the eyes of participants, reduce public acceptance and make the measures seem less effective at reducing risk. Therefore, it's important to find the right balance. (Anderson CC, et al. 2022, European Commission 2023).

When comparing NBS measures with hybrid or grey interventions, **aesthetic considerations** are often the main factor leading to support for NBS, as they are seen to blend more naturally into the environment (Anderson CC, et al. 2022). Landscape aesthetics and recreational values contribute to positive attitudes and greater public acceptance of NBS measures (Kumar, P et al. 2021).

Changes in **risk perception**s are a key social impact that NBS measures can affect. Monitoring and gauging any change in the perception of risk throughout the implementation of the NBS could illustrate how partaking in or witnessing an NBS can impact citizens' assessment of the very risks the measures are trying to mitigate. The perception of risk isn't necessarily aligned with effective risk reduction, as perceptions tend to be based on experience and impressions (IUCN 2020, European Commission 2023, Anderson CC et al. 2021). In another EU Horizon project on NBS in rural mountain areas, **PHUSICOS** explored the importance of landscape perception as NBS could be seen to improve and enhance nature and, therefore, contribute to the local identity of a place (e.g. nature trails, creation of landmark) (Auturi, S. et al. 2019). Changes in perception are often linked to changes in awareness and understanding of different elements like risks, climate change, resilience, and hazards.

Connecting to the above, another social impact, often a secondary effect of implementing an NBS, is **learning and empowerment.** NBSs, often due to their participatory processes, raise awareness and promote sustainability as well as community resilience (Strout et al., 2021; Palomo I, 2021). Public involvement and participation (Kumar P, 2021) can foster learning, leading to new skills, knowledge, education, and competencies (Passani A, Janssen AL, and Hoelscher K, 2020; European Commission, 2023; Palomo I, 2023). This attainment of skills and knowledge occurs through learning by doing, iterative learning, and social learning (at times, these are unintended outcomes) (European Commission, 2023; IUCN, 2020). This upskilling, in turn, generates capacity building, ensuring communities are more empowered and better equipped to cope and adapt (Shah et al., 2020). Community empowerment in NBS, with a strong component of collaboration (co-design and co-governance), is a key indicator to monitor (European Commission, 2023). The activities around an NBS process foster self-efficacy, agency, trust-building, transparency, and the sharing of practice and information. This results in an empowered community of practice (Passani A, Janssen AL, and Hoelscher K, 2020; European Commission, 2023; Palomo I, 2021). As Anderson CC et al. (2021) conclude, NBS measures, thanks to the element of community empowerment, can shift away from the “decide, announce, defend” dynamic between practitioners and the public, moving towards an “engage, deliberate, decide” approach, which enhances local culture, sense of belonging, pride, and connectedness to place (Passani A, Janssen AL, and Hoelscher K, 2020; European Commission, 2023; Palomo I, 2021). Therefore, monitoring any changes in learning and empowerment in the communities affected by the NBS is of great importance.

As Selman points out, social capital can be understood as the glue holding communities together through mutual interdependence (Selman, 2001). The four main components of social capital are: relations of trust; reciprocity and exchanges; common rules, norms, and sanctions; a connectedness, networks, and groups (Pretty and Ward 2001) – NBS measures influence these aspects and, therefore, can affect **social capital.**

Growth in social capital can be seen as a benefit of a co-design approach to NBS (European Commission 2023, Dumitru A and Wendling L 2021). In particular, the role of trust in the implementing authorities and organizations is paramount. Anderson CC et al. (2021) warn that there is a risk that acceptance of NBS will not increase without parallel gains in trust in those implementing and confidence in the effectiveness of NBS. Until NBS are widely adopted and scaled up, fostering trust in those who implement NBS is crucial. Gaining trust can be challenging; it can, equally, be easily lost in contexts of risk (Anderson CC et al., 2021). More specifically, assessing changes in the sense of belonging/place, connectedness to place and nature (Dumitru A and Wendling L, 2021; European Commission, 2023), social cohesion (Passani A, Janssen AL, and Hoelscher K, 2020; Autuori S et al., 2019), and social inclusion and inclusiveness, which can extend beyond the duration of the project intervention (Passani A, Janssen AL, and Hoelscher K, 2020; Autuori S et al., 2019; IUCN, 2020), is important to ensure that the intervention is not only effective but also just at the societal level. Social capital as a social impact of NBS illustrates the importance of aiming for more than an effective and efficient measure, but one that is robust, more equal, and fairer (Nurmi V. et al., 2017).

Another social impact that can often be measured with more empirical data is **better access to nature and health benefits**. Implementing NBS, such as tiny forests, wetlands, water retention pits/ponds, initiatives for unsealing surfaces, natural dunes, restoration of natural river courses, reconnection of floodplains, and reforestation, improves both access to and quality of nature. This means reaping the benefits of increasing green parks, natural surroundings, and green space management (Kumar P, 2021; European Commission, 2023; Dumitru A and Wendling L, 2021; Autuori S, 2019). This would also lead to an increase in biodiversity and wildlife and its enjoyment (Ruangpan L and Vojinovic Z, 2022; IUCN, 2020). These aspects link to changes in participation in recreational and outdoor activities (Autuori S, 2019; Anderson CC, 2022; Nurmi V et al., 2017; Dumitru A and Wendling L, 2021). The literature suggests indirect social impacts on mental and physical health (Kumar P et al., 2021; Dumitru A and Wendling L, 2021) and an overall improvement in quality of life and wellbeing (Strout et al., 2021; European Commission, 2023; Ruangpan L and Vojinovic Z, 2022).

Impact on policy and transparency of process is the last group of potential impacts stemming from implementing NBS measures. This bundle of potential benefits straddles both the social and the policy spheres. As mentioned previously, collaborative governance structures and participatory planning are an integral part of the NBS process (Palomo I, 2021; Dumitru A and Wendling L, 2021; Autuori S, 2019)—to such an extent that the EU Practitioner Handbook on Evaluating the Impact of Nature-based Solutions proposes an 'openness of participatory processes indicator' (Dumitru A and Wendling L, 2021).

The literature suggests that decision-making processes should be documented in a transparent and accessible way, drawing attention to which stakeholders were involved, how (e.g., which role they played), and why. This links to community empowerment and efficacy (IUCN, 2020). This focus on process transparency relates to the need to compensate for a decline in trust in policymakers, making the case that increased legitimacy and democratic, transparent decision-making can provide better outcomes in land-use planning (Anderson CC, 2021). Furthermore, such processes bring the public closer to science and increase trust in science, which can lead to a change in trust in policy if it is data-driven policy making with scientific impact (Nurmi V, 2017).

It is not suggested that all NBS measures will experience, bring about, or successfully measure these social impacts. In certain conditions, with certain NBS measures and monitoring tools (see Section 2.4 in DEL2.2: Report on Data Requirements for Biophysical and Socio-Economic Assessment of NBS Efficiency), these are some of the main social impacts to investigate. As outlined in this brief literature review, the need for good quality data is evident, but data completeness cannot be a reason for delaying action (Alva A, 2022).

4. The Methodology for each Frontrunning Region: target NBS, indicators and model chains

The current section aims to pave the way for the application of the methodology for the assessment of the NBS effectiveness in the deliverables of WP2. The first step has been the selection of the target no-regret NBS that will be included in the assessment process. Bilateral meetings have been organized with each front-running region to select the target NBS from the already-reported list in Freyer et al. (2024). This list includes all the no-regret NBS except for the novel Austrian implementation of the sponge city concept in the urban area of Rudersdorf located in the designated FRR.

The selection criteria for the target NBS taken into account during the bilateral meetings were:

- the judgment of implementers within the FRR concerning which proposed NBS is more likely to have the largest effect in risk reduction for each FRR;
- the probability of implementation based on the current engagement with local landowners;
- the availability of sufficient data for the assessment.

Target NBS have been selected for each front-running region except for 1) National Park Bohemian Switzerland and Krásná Lípa (FRR Czechia) due to the lack of available datasets for the assessment of the restoration of the small-scale NBS site in Pod Cimrakem (Krasna Lipa), and 2) Roňava River Catchment (FRR Slovakia) where a technical report is in preparation to analyze the suitability of an NBS portfolio to address floods and drought events in several private sites. The selected target NBS are:

- Tiny forest to address heat waves in the County of Euskirchen (FRR Germany)
- Sponge city to address heat waves and urban floods in the Lafnitz Catchment (FRR Austria)
- Reconnection of gravel pits with the river to address river floods in the Upper Timiş River Catchment (FRR Romania)
- Sand dune and Salicornia plantation to address coastal floods and salt-water intrusion in the Eastern Po Valley and Po Delta (FRR Italy), respectively.

The definition of experiments to monitor social impacts is on-going. Despite details are not currently available for each FRR, the following lines would provide a general idea concerning the tools that can be used to assess social impacts such as public acceptance; aesthetic values; perception of risk; empowerment and learning; social capital and trust; better access to nature and health; and transparency of process and impact on policy. These tools include:

- surveys with questionnaires administered to target participants or those affected by NBS intervention (carried out both at baseline/ pre-intervention and follow-up/post-intervention) or questionnaires done at the end of the project with retrospective anchoring questions;
- discussion or focus groups with a small number (usually 8 to 10) of participants or stakeholders (e.g. landowners);
- interviews ranging from informal conversations, collecting stories, short temperature checks, semi-structured interviews and in-depth structured interviews;
- ethnographic or participant observations - observing people in their natural surroundings;
- process feedback logs like a learning diary which logs things that worked and does that didn't;
- collection of local statistical data via dedicated surveys (e.g. wellbeing, quality of life, place, community);
- feedback forms post event (e.g. satisfaction survey);
- workshops can be used both as an opportunity to engage with participants as well as a research tool to inform delivery, and
- stakeholder mapping and analysis measuring their level of importance and their degree of influence with respect to the NBS and including assessment of how each stakeholder is/will be affected by NBS measure - both indirect and direct as well as positively or negatively measuring. This could be coupled with some more quantitative research activities like social network analysis or content analysis like sentiment analysis of digital text to determine the emotional tone or *zeitgeist* of the community.

These research activities would unpack values, understanding, knowledge, perceptions, attitudes, behaviors, participation and practices around the social impacts of relevance to the NBS in question. Most of the data collection could happen in person at events or on site, over the phone or online. A more participatory approach such as Citizen Science could be considered. If effectively implemented it can generate high-quality data, a greater sense of belonging, increased legitimacy and empowerment. These methods can generate both quantitative and qualitative data (for more detail see DEL2.2, Section 2.4 in particular Figure 3).

4.1 Heat waves

The heat assessment in WP1 focused mainly on heat wave days, defined as days when both the maximum apparent temperature and minimum temperature exceed the 90th percentile for at least two consecutive days during June-August. Baseline data were taken from high-resolution regional reanalysis, while future projections are based on global and regional climate models from the Copernicus Climate Change Service (C3S). For further details please refer to Holtkötter et al. (2024a, 2024b). In addition to heat wave days, the heat assessment also considered temperature statistics and the Universal Thermal Climate Index (UTCI). Temperature statistics were used to establish a relatively simple framework that serves two purposes: first, to validate the models (or model chains) against reanalysis data, and second, to assess the robustness of signals associated with global warming. UTCI was considered to evaluate the human physiological response to environmental conditions, including air temperature, mean radiant temperature, wind speed, and water vapor pressure. The UTCI is calculated using an analytical approximation of a dynamic physiological model, providing an equivalent temperature in °C, which is then categorized into different stress levels.

4.1.1 Germany: Tiny forests

This section details the methodology for evaluating Tiny Forests in Euskirchen, Germany, as a Nature-Based Solution (NBS) to mitigate urban heat waves. Tiny Forests are small, densely planted native forests designed to grow rapidly and deliver a range of environmental and social benefits.

The assessment focuses on three primary methodological objectives: analyzing air temperature reduction, assessing the potential decrease in heat-related excess mortality, and evaluating the cost-effectiveness of Tiny Forests. Given the challenges in monetizing health impacts (Boardman et al., 2011; Kumar et al., 2021), a Cost-Effectiveness Analysis (CEA) is preferred over a Cost-Benefit Analysis (CBA). According to Boardman et al. (2011, p. 464), “CEA compares (mutually exclusive) alternatives in terms of the ratio of their costs and a single quantified, but not monetized, effectiveness measure”. Although the CEA is not suitable for assessing whether it is worth implementing a Tiny Forest at all, as not all costs and benefits are quantified and monetized to calculate the necessary net benefits (Boardman et al., 2011; WHO, 2003), the calculated cost-effectiveness ratio (CER) can be used by decision-makers to decide whether a Tiny Forest or another NBS or intervention is more cost-effective in reducing temperature and heat-related excess mortality. This approach aligns with the World Health Organization's (WHO) guidelines for evaluating health-related interventions. Due to the thematic relevance to health, the methodology of this work (Fig. 4) is mainly based on the recommendations of the WHO Guide to Cost-Effectiveness Analysis (WHO, 2003).

In a first step, a context-specific effectiveness analysis is carried out in relation to temperature reduction through the implementation of a Tiny Forest, and a discussion of effectiveness in relation to the reduction of heat-related health impacts is carried out. With regard to the costs to be assessed,

both a context-specific and a general cost analysis are carried out in a second step. This approach provides an important basis for a future general CEA (GCEA) on temperature reduction, should further research be conducted on the overall impact of Tiny Forests implementation. In a third and final step, the results of the effectiveness analysis from step one and the various cost analyses from step two are combined to calculate context-specific cost-effectiveness ratios for temperature reduction and general cost-effectiveness ratios for heat-related excess mortality reduction.
In regard to FRR-Germany case study, the CEA workflow is organized into seven sequential steps: the selection of the study area, the definition of scenarios, data collection and preprocessing, model structure and setup, simulations using ENVI-met, and the subsequent analysis and interpretation of results (Fig. 5).

The selection of the study area is based on the Municipality of Euskirchen, from which key information was obtained regarding the location of Tiny Forest and the planting of trees (Fig. 6). The study focuses on two specific sites in Euskirchen, Germany, owned by the Eugebau housing association (Fig. 7). The primary site at Zülpicher Straße 5a-5d spans 1,383 m², with 370 m² dedicated to Tiny Forests. The secondary site at Jülicher Ring 55-61 covers 844 m² and serves as a comparative reference. Site selection was based on urban characteristics, limited green space availability, and potential microclimatic impact. To ensure accurate and comprehensive data collection, multiple sources were utilized for the model setup, including the use of satellite imagery, meteorological data from Meteoblue website, and data needed to calculate the PET were selected following a review of relevant literature. The simulation was conducted using ENVI-met and BIO-met software, employing a spatial resolution of 2 meters. ENVI-met is a widely recognized simulation tool for urban microclimate modeling that integrates various sub-systems, including atmospheric dynamics, surface energy balance, vegetation physiology, and soil hydrology (Yang et al., 2020).

The ENVI-met model was applied to three distinct scenarios to capture the evolving impacts of Tiny Forests over time:

1. **Baseline Scenario**: Represents the current environmental conditions without the implementtation of Tiny Forests. This scenario serves as the control, highlighting the existing urban heat retention and lack of vegetation cover.
2. **Mature Scenario**: Simulates conditions five years post-implementation, with trees reaching up to 10 meters. At this stage, significant canopy development enhances shading and evapotranspiration, contributing to localized cooling.
3. **Fully Grown Scenario**: Projects conditions twenty years post-implementation, where trees exceed 20 meters in height. This scenario captures the maximum potential of Tiny Forests to mitigate urban heat through dense canopy coverage and mature root systems that improve soil moisture retention.

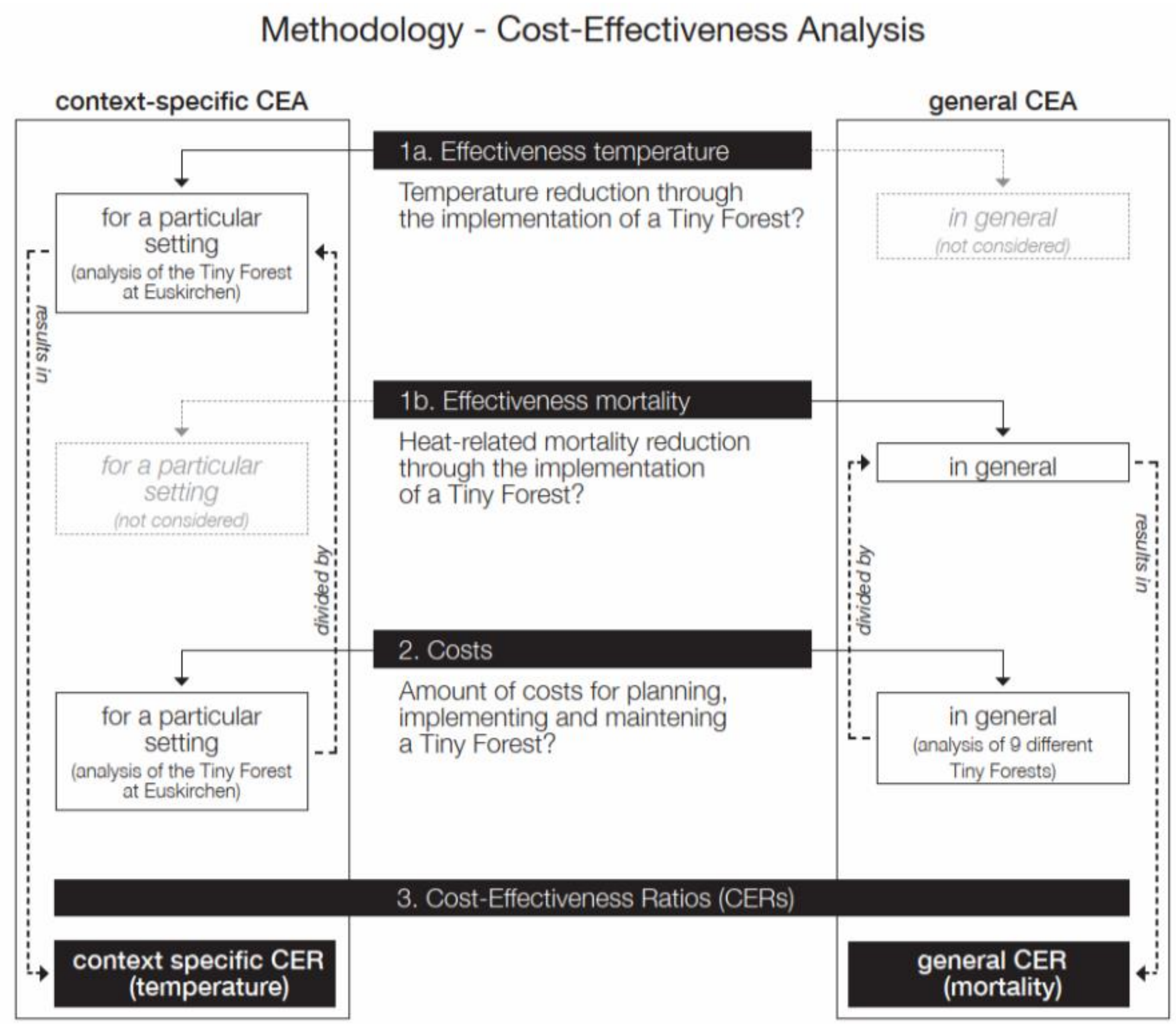


Figure 4: General methodology with ENVI-met (FRR Germany).

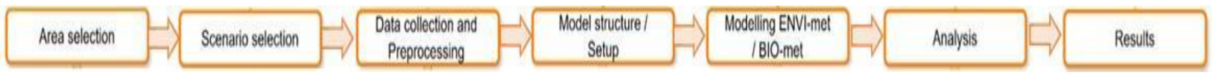


Figure 5: Methodological workflow (FRR Germany).

BIO-met is adopted for the analysis of the NBS effectiveness in excess-mortality reduction. The relationship between Tiny Forests and human health is primarily indirect, mediated through their influence on temperature and microclimate. While Tiny Forests directly affect microclimatic conditions, their potential impact on human health arises from secondary effects, such as reduced heat stress. Then, the efficiency assessment of Tiny Forests focuses on the costs associated with their planning, implementation, and maintenance. The first step involved describing the interventions, compiling data from semi-structured interviews and literature reviews to create detailed profiles of each implementation site. The cost survey identified all expenses necessary for the Tiny Forests to achieve temperature and heat-related mortality reductions.

Figure 6: Plan for the implementation of the tiny forest (FRR Germany).

Figure 7: Area selection (a) and territorial framework of the area (b)

Relevant costs included site preparation, planting, and maintenance, while additional costs unrelated to performance were noted but not fully analyzed. Where direct data were unavailable, informed estimates were made, with explanations provided for the assumptions. Costs were aggregated and adjusted for time differences using a 3% discount rate, aligning with WHO guidelines. This process standardized costs to a 2024 reference point, facilitating accurate comparisons across sites. The costs were then converted into per-square-meter values for each site, enabling the calculation of cost-effectiveness ratios (CERs) by dividing the costs of interventions by their effectiveness in reducing temperature and heat-related excess mortality. Context-specific CERs were determined for the Zülpicher Straße site by comparing specific costs with the observed temperature reductions.

4.1.2 Austria: Sponge city

Rudersdorf is a small municipality located in the Lafnitz Catchment (Styria, Austria) in which the people that live in the urban center are affected by heat stress due to the occurrence of heat-wave events. To address this HMH, the selected not-regret NBS is the construction of a sponge city in which trees are used to increase rainwater infiltration and improve thermal comfort. A modeling experiment will be set up to assess if NBS is locally effective in reducing air temperature. Data concerning the large-scale dynamics are obtained from ECMWF Copernicus Service, including general circulation models that provide several geophysical input variables such as relative humidity, temperature, wind, soil temperature and moisture, pressure, sea-ice cover, and snow depth. However, this data is not available at a resolution that is high enough for impact studies on a local scale. To address this limitation, local area models like the Weather Research and Forecasting Model (WRF) can be run. When initializing the model with the input data, if the required variables for the WRF initialization are not available they can be replaced with properly corrected data from climatology. The obtained input dataset is then fed to the model to perform a dynamical downscaling. Figure 8 shows an example with two nested domains over the Central European region. Tailored domains and grid spacing choices will be evaluated based on the test results. The model can also take advantage of specific modules for vegetation, designed to be directly integrated into the modeling experiment to allow a more realistic representation of the atmosphere-vegetation interaction.

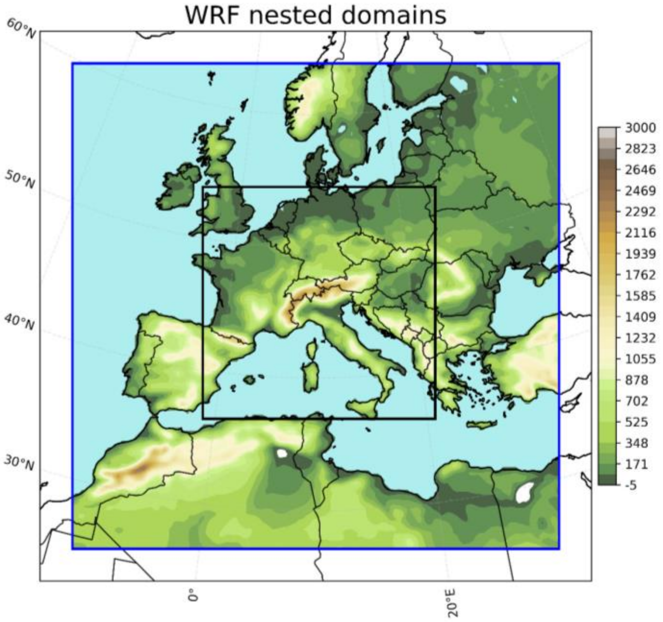


Figure 8: Selected nested domains for WRF modeling experiments.

4.2 Drought

The drought assessment in WP1 focused on two primary indicators: the Standardized Precipitation Index at a 6-month timescale (SPI6) and the mean number of dry spells exceeding five consecutive days. SPI6 measures the deviation of precipitation from the historical average over a specified period, providing a standardized score to identify drought conditions. Values below -1 typically indicate moderate drought, while lower values reflect more severe conditions. The dry spell indicator counts periods of uninterrupted days with less than 2 mm of precipitation, highlighting the frequency and duration of drought episodes. Data for these indicators were sourced from global and regional climate models provided by the Copernicus Climate Change Service (C3S). The spatial resolution of the model outputs was 0.1° x 0.1° for the European region, ensuring detailed regional assessments. For further details, refer to Holtkötter et al. (2024a, 2024b).

4.2.1 Slovakia: a system of NBS in agricultural and forest land

The most suitable modeling chain for FRR Slovakia will be selected after the definition of sites and implemented NBS. Possible no-regret NBS include water retention pits, contour trenches, and rain gardens in agricultural lands, and check dams, surface drains, and wetlands in both forests and crop fields. However, some assumptions can be made concerning which models are needed to assess the effects of these NBS on drought events. First, a general circulation model is essential for large-scale input data. This data can be downscaled for nesting a WRF experiment similar to the one shown in Fig. 8. This experiment needs to investigate how the NBS modifies both the local surface and groundwater hydrological circulation, and their contribution to latent and heat fluxes between surface and atmosphere.

4.3 Urban floods

4.3.1 Austria: Sponge city

Urban floods or heavy rain can have a variety of effects and consequences. Large surface run-off leads to high water levels in and outside of water bodies. Combined with high flow velocities, this impacts human well-being, properties, buildings, access to critical infrastructures, and transportation. Being able to store rainwater in the area of rainfall can help reduce surface run-off and consequently water levels. This can be achieved by increasing infiltration capacity of the surface e.g. by resealing them. Another approach is to create water retention volume to enable infiltration over a longer period even after the rain event.

The Sponge cities concept intervenes in precisely these processes. The actionable variables of soil infiltration capacity and retention volume in the area are addressed by various measures. Some examples are the use of porous road surfaces, underground retention basins or tanks, rain gardens, green roofs and bioswales. Impact variables that are affected by this are water levels, flow velocities, and river discharge.

Using suitable hydrodynamic models to calculate the effect of NBS in the context of sponge cities is difficult, since the spatial scales between NBS and their effect vary significantly. Hydraulic models such as Telemac 2D can be used to calculate the effect of altered infiltration rates or additional retention volumes. In that case, it is important to model a whole basin or sub-basin to ensure that all important physical processes are considered. Their output agrees with the impact variables needed in the evaluation of urban floods and heavy rain. However, whether the effect of small-scale NBS can show in the results of a hydrodynamic model in the scenarios chosen in this risk assessment still needs to be confirmed.

4.4 River floods

4.4.1 Romania: Reconnection of gravel pits with the river

River floods usually occur after prolonged rain events or snow melts. Increased inflow into the river leads to higher water levels and ultimately to overtopping of the riverbed. Areas adjacent to the river are flooded. In contrast to heavy rainfall events, the flooding during river floods lasts longer. This often leads to damage to buildings due to prolonged contact with water. Agricultural land can also be damaged by prolonged flooding, and this leads to crop failures.

Reconnecting areas with potential retention volumes can help reduce water levels in the vicinity of the measure. It can also help reduce the discharge and hence positively affect downstream areas. However, the latter strongly depends on the design of the measure. A reduction is only effective if the peak discharge is reduced. This only occurs if the retention volume is still available when peak discharge passes the retention measure. Regulated retention basins are designed to activate at specific discharges and water levels respectively. For NBS such as reconnecting gravel pits careful consideration to their design needs to be given if they are supposed to have a positive effect on river floods. The actionable variables here are retention volume and activation thresholds. Impact variables are water levels and discharge in the river.

The modeling chain will be defined after the definition of sites available for the NBS interventions. The chain will include hydrodynamic models such as Telemac 2D or HEC-RAS that are well established to calculate the effect of changes in the river course and the addition of retention measures. They can also account for predicting at what water levels the measures get flooded.

4.5 Coastal floods

4.5.1 Italy: Sand dune

An artificial sand dune is a barrier made up of biodegradable materials (e.g., rocks, sand, wood) that protects the coast from the action of sea waves. This structure offers protection from floods, storm surges, and sediment removal. LAND4CLIMATE will implement a dune on private lands in the municipality of Ravenna within the Po-Delta Regional Park. The dune will be built by following the patent developed during the OPERANDUM project in which tubular modules (i.e., sandbags) are arranged longitudinally to the coastline. These modules are provided with an innovative closing system (i.e., zips) to facilitate their refill in case of restoration. Coconut geotextiles and geomembranes will be added atop the dune to reduce erosion from wind, waves, and runoff water. These structures can also retain moisture helping the growing of vegetation that will be planted atop the dune for further reinforcement.

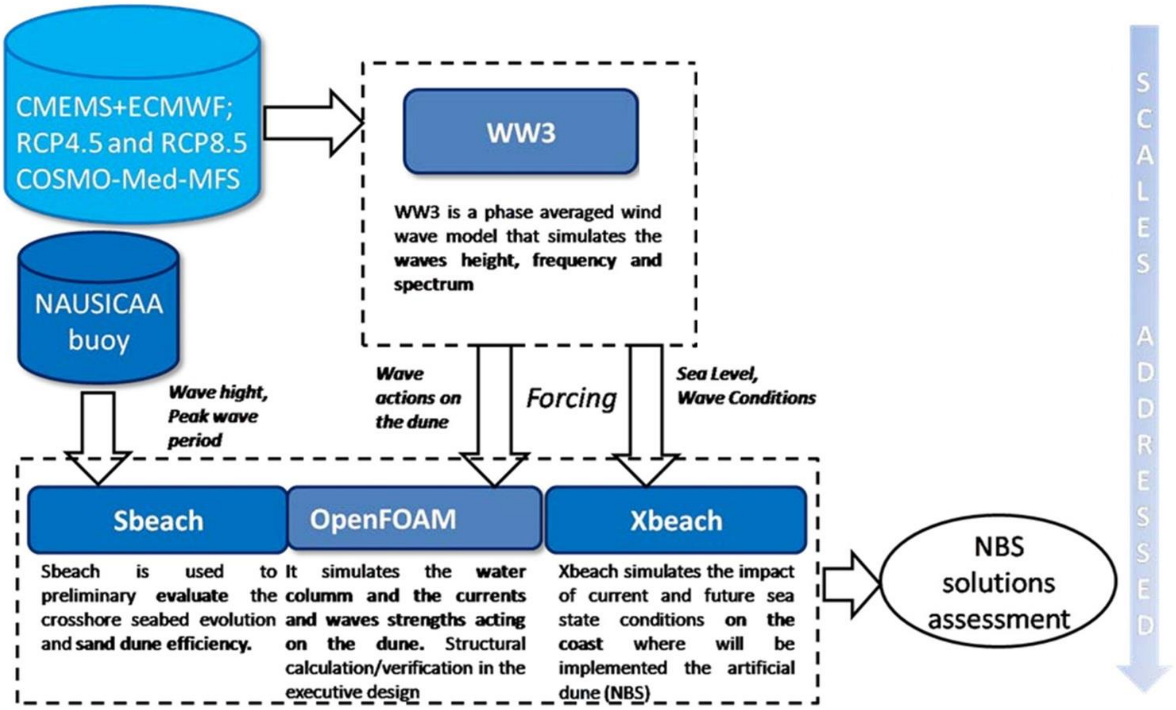


Figure 9: Modeling chain for the assessment of the sand-dune contribution in hazard reduction. Source: Gallotti et al. (2021), adapted from and Spyrou et al. (2022).

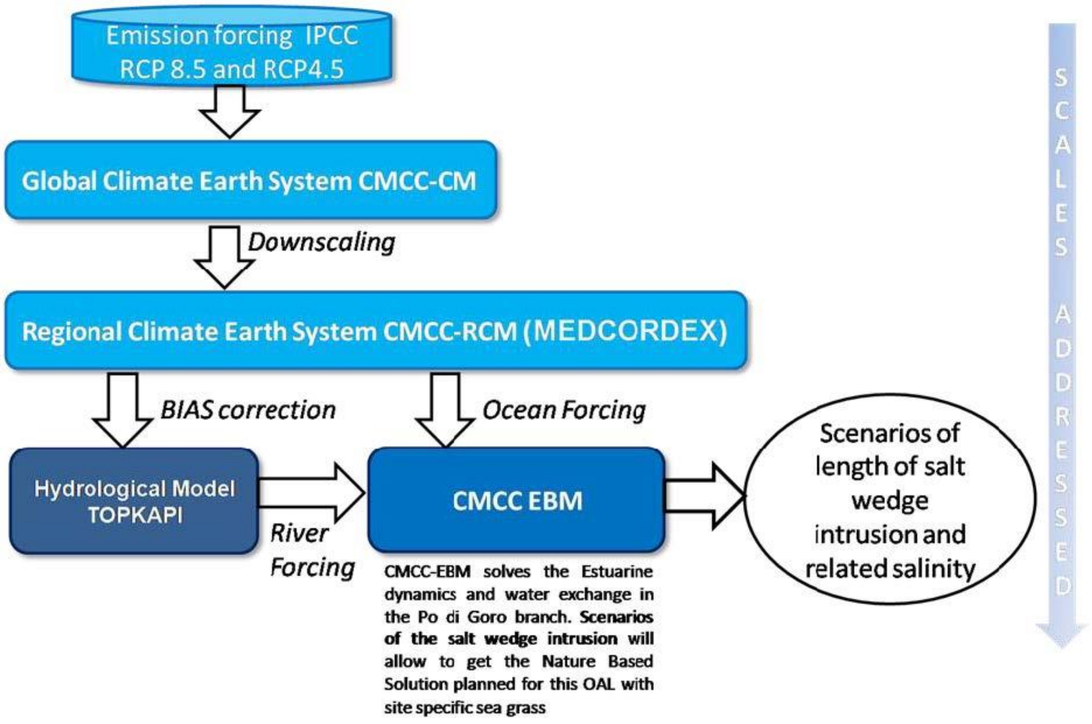
Since the dune is located on the coast where the sea interacts with the land, a multi-model strategy is needed to assess the impacts of the NBS implementation on the local hazard characteristics (e.g., duration, magnitude, and frequency of occurrence) in both present and future climate scenarios. Figure 9 shows the adopted modeling chain that starts from the ocean and atmospheric forcing that are extracted from ECMWF reanalyses and CMEMS data for the present climate and MedCORDEX (Ruti et al., 2016) for the future ones. These models provide input datasets for the unstructured WAVEWATCH III (WW3) model which allows the simulation of the wave motions by taking into account the ocean dynamics and the wind-wave interactions. WW3 model solves for several variables including the significant wave height, direction, mean and peak period, and the Stokes velocities induced by the wave motion. The sea level and waves are used in turn to force Xbeach which is a coastal-morphological and hydrodynamical model that includes depth-averaged advection-diffusion sediment transport equations based on equilibrium-sediment concentrations (Roelvink et al., 2009). These equations allow the analysis of the impacts of wave propagation, long waves, mean flow, and sediment transport due to near-shore processes that occur during storm-surge events. The final output are maps that show the inundation area and depth during hazardous events and morphological change of the coastline. Model results depend on the suitable representation of the bathymetric elevations along the coastline. Other models such as Sbeach and OpenFOAM can be adopted during the NBS design phase to verify the structural stability of the sand dune.

4.6 Salt-water intrusion

4.6.1 Italy: Salicornia plantation

The Delta-Po region is affected by the intrusion of saltwater along the stream. Especially in drought periods, the salt water can go up to the streams for several tens of kilometers in the worst cases (i.e., salt-wedge process). This phenomenon results in the contamination of woods and crops. To prevent this contamination, LAND4CLIMATE will plant Salicornia on uncultivated fields along a stream delta located within private lands in the locality “Vene di Bellocchio” (Delta-Po Regional Park, Ferrara). Salicornia is a genus of halophyte plants that are capable of absorbing salt from water and retaining it inside their cells. Some of these plants (e.g., Atriplex portulacoides) are autochtonous of the Po-Delta Region. Experiments during the OPERANDUM project have already confirmed the remarkable capacity of Salicornia to physiologically respond to short-term increases in water salinity.

The modeling assessment of hazard reduction requires the simulation of the interactions between the stream and the sea. In this context, Figure 10 shows the modeling chain that has been selected for the Emilia-Romagna coastline in both current and future climate scenarios. The input is the CMCC-CM, i.e., a coupled atmosphere-ocean general circulation model whose outcomes are down-scaled to the regional climate model CMCC-RCM (MedCORDEX). This model provides the ocean forcing to the estuary-box model CMMC EBM (Verri et al., 2020) which is the core of this model chain. CMCC EBM couples the ocean and the river forcing, which is provided in input by the hydrological model TOPKAPI. CMCC EBM estimates the length of the salt-wedge intrusion along the stream, and the net-river release at the estuary mouth in terms of volume flux and salt flux.



CMCC-EBM solves the Estuarine dynamics and water exchange in the Po di Goro branch. Scenarios of the salt wedge intrusion will allow to get the Nature Based Solution planned for this OAL with site specific sea grass

Figure 10: Modeling chain for the assessment of the Salicornia contribution to hazard reduction. Source: Gallotti et al. (2021), adapted from Spyrou et al. (2022).

Since salt-water intrusion is usually associated with a lack of water in streams during drought periods, WRF experiments (nested domain, Fig. 8) can be set up to further expand the analysis from a single HMH (i.e., salt-water intrusion) to concurrent ones (i.e., interactions between this hazard and drought).

5. Implications for subsequent deliverables in WP2

The current report defines the methodology and the suitable indicators for the assessment of the NBS effectiveness and efficiency in reducing risks resulting from the HMHs that affect each LAND4CLIMATE frontrunning region. The outcomes from this report serve as input for the subsequent deliverables in WP2, including DEL2.2 which will define the data requirements for the definition of the indicators most suited to the assessment of NBS effectiveness. Then, the collected information will be applied in DEL2.3 which will provide a modeling assessment for the evaluation of hazard reduction by target NBS following the modeling chains, baselines, and climate projections identified in the current report. The current report is also preparatory to DEL2.4 which will focus on the assessment of potential co-benefits and trade-offs resulting from the NBS implementation. All the mentioned deliverables will be merged into DEL2.5 which will provide both a risk assessment and an evaluation of the suitability of the proposed NBS. The risk assessment will follow the methodological framework developed in WP1. However, this framework may be combined with other ones proposed in the literature to extract the highest amount of information from the available data. The choice of the framework depends on the type of data and the analyzed temporal and spatial scales. Examples of already-existing frameworks for the assessment of NBS effectiveness include the VR-NBS developed during the OPERANDUM project (Shah et al., 2020) and the one proposed by Brogno et al. (2024).

6. Conclusions

This deliverable paves the way for a comprehensive and reliable methodological framework for assessing the efficacy and effectiveness of Nature-Based Solutions (NBS). The approach outlined in this document builds upon the Climate Risk Assessment methodology developed in WP1, ensuring a robust and adaptable framework to support assessments in the following deliverables of WP2 and inform decision-making processes regarding NBS implementation and replication.

The first step was a review of the effectiveness and efficiency concept from a linguistic, juridic, medical, and economic perspective. These several points of view allow for the application of these concepts to the assessment of NBS performance in LAND4CLIMATE. The NBS effectiveness is verified when the provision of benefits for humans and ecosystems is confirmed through real-world experiments with uncontrolled variables or complex models that test several socio-economic and climate scenarios. The NBS efficiency is a long-term process in which these benefits are maximized by an optimal selection of the NBS spatial extents and temporal conditions of functioning. Benefits optimization implies minimizing the exploitation of natural and economic resources while maximizing risk reduction, co-benefits, and technological readiness levels.

To assess these benefits, a LAND4CLIMATE methodology is proposed. This methodology includes hazard-reduction assessment, assessment of indirect benefits (e.g., co-benefits), risk assessment, cost-benefit assessment, and evaluation of public acceptance. Implementing this methodology requires selecting appropriate indicators and defining sub-methodologies for each assessment component. In this regard, the deliverable outlines various no-regret NBSs to be implemented in the FRRs involved in the LAND4CLIMATE project, offering tailored-modeling approaches for the assessment of each case study and the specific hazards impacting these regions.

References

1. Aghaloo, K., Sharifi, A., Habibzadeh, N., Ali, T., & Chiu, Y.-R. (2024). How nature-based solutions can enhance urban resilience to flooding and climate change and provide other co-benefits: A systematic review and taxonomy. Urban Forestry & Urban Greening, 95, 128320. DOI: 10.1016/j.ufug.2024.128320
2. Alfieri SM, Menenti M, et al. (2022) Data Record on the Evolution of OALs in Response to Interventions (OPERANDUM Deliverable 4.6)
3. Alva A, (2022) A critical perspective on the European Commission's publications 'Evaluating the impact of nature-based solutions', Nature-Based Solutions, Volume 2.
4. Amirzada, Z., Pavlova, I., de Chaisemartin, M., Denoon, R., Kalas, M., Vranić, S., Ommer, J., Sabbatini, T., Kumar, P., Debele, S., Leo, L. S., & Sabatino, S. D. (2023). Reducing hydro-meteorological risks through nature-based solutions: A comprehensive review of enabling policy frameworks in the European Union. Nature-Based Solutions, 4, 100097. DOI: 10.1016/j.NBSj.2023.100097
5. Anderson CC, Renaud FG, Hanscomb S, Gonzalez-Ollauri A (2022) Green, hybrid, or grey disaster risk reduction measures: what shapes public preferences for nature-based solutions? Journal of Environmental Management 310:114,727
6. Anderson CC, Renaud FG (2021) A review of public acceptance of nature-based solutions: The 'why','when', and 'how'of success for disaster risk reduction measures. Ambio 50(8):1552–1573
7. Anderson CC, Renaud FG, Hanscomb, S, Munro K, González-Ollauri A, Thomson C, Pouta E, Soini K, Loupis M, Panga D, and Stefanopoulou M. (2021). Public Acceptance of Nature-Based Solutions for Natural Hazard Risk Reduction: Survey Findings From Three Study Sites in Europe. Frontiers in Environmental Science. 9. DOI: 10.3389/fenvs.2021.678938
8. Autuori, S.; Caroppi, G.; De Paola, F.; Giugni, M.; Pugliese, F.; Stanganelli, M.; Urciuoli, G. Comprehensive Framework for NBS Assessment (Deliverable DEL4.1). Work Package 4—Technical Innovation to Design a Comprehensive Framework (UNINA WP Leader), H2020 Project PHUSICOS; Grant Agreement No. 776681; Norwegian Geotechnical Institute: Oslo, Norway, 2019. Retrieved from: https://www.phusicos.eu/publication--results/
9. Bark RH, Martin-Ortega J, Waylen KA (2021) Stakeholders' views on natural flood management: Implications for the nature-based solutions paradigm shift? Environmental Science & Policy 115:91–98
10. Berkes F, Folke C, Colding J (2000) Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge University Press
11. Boardman AE, Greenberg DH; Vining, Aidan R.; Weimer, David L. (2011). Cost-BenefitAnalysis. Concepts and Practice. Fourth Edition. Prentice Hall. Book chapter, retrieved from https://dlib.neu.edu.vn/bitstream/NEU/289/1/Cost-Benefit%20Analysis%2C%204_e%20%28The%20-%20Anthony%20Boardman.pdf [26.11.2024].
12. Bowyer P, Alfieri SM, Basu B, Cremin E, Debele S, Kumar P, Lechner V, Loupis M, Menenti M, Mickovski S, et al. (2024) Modelled effectiveness of NBS in reducing disaster risk: evidence from the OPERANDUM project. Nature-Based Solutions 5:100,127
13. Brogno L, Barbano F, Leo LS, Fernando HJ, Di Sabatino S (2021) Driving mechanisms of
14. double-nosed low-level jets during materhorn experiment. Journal of the Atmospheric Sciences 78(12):4037–4051
15. Cheong SM, Silliman B, Wong PP, Van Wesenbeeck B, Kim CK, Guannel G (2013) Coastal adaptation with ecological engineering. Nature climate change 3(9):787–791
16. Chhetri, S., Ruangpan, L., Abebe, Y. A., Torres, A. S., & Vojinovic, Z. (2024). Review of environmental benefits and development of methodology for EUNIS habitat changes from

nature-based solutions: Application to Denmark and the Netherlands. Ecological Indicators, 165, 112189. DOI: 10.1016/j.ecolind.2024.112189

17. Choi C, Berry P, Smith A (2021) The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. Journal of Environmental Management 291:112,583
18. Cohen-Shacham E, Walters G, Janzen C, Maginnis S (2016) Nature-based solutions to address global societal challenges. IUCN: Gland, Switzerland 97:2016–2036.
19. Common International Classification of Ecosystem Services (CICES) V5.1
20. Crichton D (1999) The risk triangle. Natural disaster management 102(3):102–103
21. Debele S, Leo LS, et al. (2022) Catalogue of NBS Including Location, Classification and Basic Information - First Updated (OPERANDUM Deliverable 7.2)
22. Debele SE, Leo LS, Kumar P, Sahani J, Ommer J, Bucchignani E, Vranić S, Kalas M, Amirzada Z, Pavlova I, et al. (2023) Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies. Science of the Total Environment 902:165,824
23. Dumitru A, and Wendling L (2021) Evaluating the impact of nature-based solutions: A handbook for practitioners
24. Epelde, L., Mendizabal, M., Gutiérrez, L., Artetxe, A., Garbisu, C., & Feliu, E. (2022). Quantification of the environmental effectiveness of nature-based solutions for increasing the resilience of cities under climate change. Urban Forestry & Urban Greening, 67, 127433. DOI: 10.1016/j.ufug.2021.127433
25. European Commission: Directorate-General for Research and Innovation, Andersson, I., Ferreira, I., Arlati, A., Bradley, S. et al., Guidelines for co-creation and co-governance of nature-based solutions – Insights form EU-funded projects, Ferreira, I.(editor), Lupp, G.(editor) and Mahmoud, I.(editor), Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/157060
26. Ferrario, F., Mourato, J. M., Rodrigues, M. S., & Dias, L. F. (2024). Evaluating Nature-based Solutions as urban resilience and climate adaptation tools: A meta-analysis of their benefits on heatwaves and floods. The Science of the Total Environment, 950, 175179. DOI: 10.1016/j.scitotenv.2024.175179
27. Ferreira V, Barreira AP, Loures L, Antunes D, Panagopoulos T (2020) Stakeholders' engagement on nature-based solutions: A systematic literature review. Sustainability 12(2):640
28. Frumkin, H., Shane, B., & Schottland, T. (2024). Promoting Health Through Nature-Based Climate Solutions. In Climate Change and Public Health. Oxford University Press. DOI: 10.1093/oso/9780197683293.003.0017
29. Gallotti G, Santo MA, Apostolidou I, Alessandri J, Armigliato A, Basu B, Debele S, Domeneghetti A, Gonzalez-Ollauri A, Kumar P, et al. (2021) On the management of nature-based solutions in open-air laboratories: New insights and future perspectives. Resources 10(4):36
30. Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., & Nanu, F. (2020). Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. The Science of the Total Environment, 713, 136552–136552. DOI: 10.1016/j.scitotenv.2020.136552
31. Hartmann, T., Slavíková, L., & McCarthy, S. (2019). Nature-Based Flood Risk Management on Private Land : Disciplinary Perspectives on a Multidisciplinary Challenge (1st ed. 2019). Springer International Publishing Imprint: Springer.
32. Holtkötter S, Tholen A, et al. (2024a) Future-oriented local climate adaptation scenarios – front-running regions (LAND4CLIMATE Deliverable 1.1)
33. Holtkötter S, Tholen A, et al. (2024b) Climate risk analysis - front-runner regions (LAND4CLIMATE Deliverable 1.3)

34. IUCN (2020). Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of NBS. First edition. Gland, Switzerland: IUCN.
35. Iungman, T., Caballé, S. V., Segura-Barrero, R., Cirach, M., Mueller, N., Daher, C., Villalba, G., Barboza, E. P., & Nieuwenhuijsen, M. (2025). Co-benefits of nature-based solutions: A health impact assessment of the Barcelona Green Corridor (Eixos Verds) plan. Environment International, 196, 109313. DOI: 10.1016/j.envint.2025.109313
36. Kabisch N, Frantzeskaki N, Pauleit S, Naumann S, Davis M, Artmann M, Haase D, Knapp S, Korn H, Stadler J, et al. (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and society 21(2)
37. Karpen U (2016) Efficacy, effectiveness, efficiency: from judicial to managerial rationality. Rational Lawmaking under Review: Legisprudence According to the German Federal Constitutional Court pp 295–313
38. Kumar P, Debele SE, Sahani J, Aragão L, Barisani F, Basu B, Bucchignani E, Charizopoulos N, Di Sabatino S, Domeneghetti A, Sorolla Edo A, Finér L, Gallotti G, Juch S,Leo LS, Loupis M, Mickovski SB, Panga D, Pavlova I, Pilla F, Löchner Prats A, Renaud FG, Rutzinger M, Sarkar Basu A, Aminur Rahman Shah M, Soini K, Stefanopoulou M, Toth E, Ukonmaanaho L, Vranic S, and Zieher T, (2020),Towards an operationalisation of nature-based solutions for natural hazards, Science of The Total Environment, Volume 731.
39. Kumar P, Debele SE, Sahani J, Rawat N, Marti-Cardona B, Alfieri SM, Basu B, Basu AS, Bowyer P, Charizopoulos N, Gallotti G, Jaakko J, Leo LS, Loupis M, Menenti M, Mickovski SB, Mun SG, Gonzalez-Ollauri A, Pfeiffer J, Pilla F, Pröll J, Rutzinger M, Santo MA, Sannigrahi S, Spyrou C, Tuomenvirta H, and Zieher T, (2021). Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations, Science of The Total Environment, Volume 784,147058, ISSN 0048-9697, DOI: 10.1016/j.scitotenv.2021.147058
40. Lam DP, Martín-López B, Wiek A, Bennett EM, Frantzeskaki N, Horcea-Milcu AI, Lang
41. DJ (2020) Scaling the impact of sustainability initiatives: a typology of amplification processes. Urban Transformations 2:1–24
42. Freyer J, Holtkötter S, et al. (2024) List of stakeholder preferred no-regret NBS measures – Front-Running Regions (LAND4CLIMATE Deliverable 1.9)
43. Maes J, Teller A, Erhard M, Liquete C, Braat L, Berry P, Egoh B, Puydarrieux P, Fiorina C, Santos F, et al. (2013) Mapping and assessment of ecosystems and their services. An analytical framework for ecosystem assessments under action 5:1–58
44. Marley JE (2000) Efficacy, effectiveness, efficiency. Australian Prescriber
45. Martin A, Gross-Camp N, Kebede B, and McGuire S, (2014) Measuring effectiveness, efficiency and equity in an experimental Payments for Ecosystem Services trial, *Global Environmental Change*, Volume 28, 2014.
46. Martin EG, Costa MM, Máñez KS (2020) An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice. Ecological Economics 167:106,460
47. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis M, et al. (2021) IPCC 2021: Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change
48. Mendonça, R., Roebeling, P., Fidélis, T., & Saraiva, M. (2024). Can policy instruments enhance the benefits of nature-based solutions and curb green gentrification? The case of Genova, Italy. Environmental Development, 50, 100995. DOI: 10.1016/j.envdev.2024.100995

49. Merriam-Webster I (1984) Merriam-Webster’s Dictionary of Synonyms: A Dictionary of Discriminated Synonyms with Antonyms and Analogous and Contrasted Words. Merriam-Webster
50. Nardo M, Saisana M, Saltelli A, Tarantola S, Hoffman A, Giovannini E (2005) Handbook on constructing composite indicators: methodology and user guide
51. Neumann, V. A., & Hack, J. (2022). Revealing and assessing the costs and benefits of nature-based solutions within a real-world laboratory in Costa Rica. Environmental Impact Assessment Review, 93, 106737. DOI: 10.1016/j.eiar.2022.106737
52. Nurmi V, Votsis A, Prampolini A, Passani A and Mägdefrau N (2017). DEL5.6 Report on iSCAPE socio-economic impact assessment methodology
53. Ommer J, Bucchignani E, Leo LS, Kalas M, Vranić S, Debele S, Kumar P, Cloke HL, Di Sabatino S (2022) Quantifying co-benefits and disbenefits of Nature-based Solutions targeting Disaster Risk Reduction. International Journal of Disaster Risk Reduction 75:102,966
54. Passani, A., Janssen, A.L., Hoelscher, K. (2020), Impact assessment methodological framework v1 ACTION (Participatory science toolkit against pollution) EU Horizon Project.
55. Palomo I, Locatelli B, Otero I, Colloff M, Crouzat E, Cuni-Sanchez A, Gómez-Baggethun E, González-García A, Grêt-Regamey A, Jiménez-Aceituno A, Martín-López B, Pascual U, Zafra-Calvo N, Bruley E, Fischborn M, Metz R, and Lavorel S (2021). Assessing nature-based solutions for transformative change, One Earth, Volume 4, Issue 5, Pages 730-741, ISSN 2590-3322, DOI: 10.1016/j.oneear.2021.04.013.
56. Patel P (2021) Efficacy, effectiveness, and efficiency. National Journal of Community Medicine 12(02):33–39
57. Pauleit S, Zölch T, Hansen R, Randrup TB, Konijnendijk van den Bosch C (2017) Nature based solutions and climate change–four shades of green. Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice pp 29–49
58. Pörtner HO, Roberts DC, Adams H, Adler C, Aldunce P, Ali E, Begum RA, Betts R, Kerr RB, Biesbroek R, et al. (2022) IPCC 2022: Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
59. Pretty P and Ward H, (2001)., *Social Capital and the Environment*, World Development, Volume 29, Issue 2, Pages 209-227. DOI: 10.1016/S0305-750X(00)00098-X
60. Raška, P., Bezak, N., Ferreira, C. S. S., Kalantari, Z., Banasik, K., Bertola, M., Bourke, M., Cerdà, A., Davids, P., Madruga de Brito, M., Evans, R., Finger, D. C., Halbac-Cotoara-Zamfir, R., Housh, M., Hysa, A., Jakubínský, J., Solomun, M. K., Kaufmann, M., Keesstra, S., … Hartmann, T. (2022). Identifying barriers for nature-based solutions in flood risk management: An interdisciplinary overview using expert community approach. Journal of Environmental Management, 310, 114725–114725. DOI: 10.1016/j.jenvman.2022.114725
61. Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environmental Science & Policy, 77, 15–24. DOI: 10.1016/j.envsci.2017.07.008
62. Ruangpan L and Vojinovic Z, (2022). A Framework for Evaluating Performance of Large-Scale Nature Based Solutions to Reduce Hydro-Meteorological Risks and Enhance Co-benefits. In P. Gourbesville, & G. Caignaert (Eds.), Editors Advances in Hydroinformatics: Models for Complex and Global Water Issues—Practices and Expectations (pp. 515-527). (Springer Water). Springer Nature. **https://doi.org/10.1007/978-981-19-1600-7_33**
63. Ruggieri P, Brogno L, Di Sabatino S, et al. (2023) Guidelines for replication and upscaling (OPERANDUM Deliverable 6.8)
64. Roelvink D, Reniers A, van Dongeren A, van Thiel de Vries J, McCall R, Lescinski J (2009) Modelling storm impacts on beaches dunes and barrier islands. Coast Eng 56, 1133–1152

65. Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., & Brdjanovic, D. (2024). Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. Journal of Environmental Management, 352, 119985–119985. DOI: 10.1016/j.jenvman.2023.119985
66. Ruti P, Somot S, Giorgi F, Dubois C, Flaounas E, Obermann A, Dell'Aquila A, Pisacane, G, Harzallah A, Lombardi E.; et al. (2016) Med.-CORDEX initiative for Mediterranean climate studies. Bull. Am. Meteorol. Soc. 97, 1187–1208.
67. Segerson K, (2013), Encyclopedia of Energy, Natural Resource, and Environmental Economics.
68. Sellers BC, Fiore SM, Szalma J (2014). Developing a scale of environmental efficacy. The International Journal of Sustainability Policy and Practice, 8(4), 169
69. Selman P, (2001). Social Capital, Sustainability and Environmental Planning. *Planning Theory & Practice*, *2*(1), 13–30. https://doi.org/10.1080/14649350122850
70. Shah MAR, Renaud FG, Anderson CC, Wild A, Domeneghetti A, Polderman A, Votsis A, Pulvirenti B, Basu B, Thomson C, et al. (2020) A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions. International journal of disaster risk reduction 50:101, 728
71. Shah M, Renaud F, et al. (2022) Refereed journal article on vulnerability and risk assessment in OALs (OPERANDUM Deliverable 6.3)
72. Shah MAR, Xu J, Carisi F, De Paola F, Di Sabatino S, Domeneghetti A, Gerundo C, Gonzalez-Ollauri A, Nadim F, Petruccelli N, et al. (2023) Quantifying the effects of nature-based solutions in reducing risks from hydrometeorological hazards: Examples from Europe. International journal of disaster risk reduction 93:103,771
73. Spyrou C, Apostolidou E, et al. (2022) Multi-impacts assessment for OAL and NBS (OPERANDUM Deliverable 5.2)
74. Stroud, H. M., Kirshen, P. H., & Timmons, D. (2023). Monetary evaluation of co-benefits of nature-based flood risk reduction infrastructure to promote climate justice. Mitigation and Adaptation Strategies for Global Change, 28(1), 5. DOI: 10.1007/s11027-022-10037-2
75. Strout JM, Oen AMP, Kalsnes BG, Solheim A, Lupp G, Pugliese F, and Bernardie S (2021). Innovation in NBS Co-Design and Implementation. Sustainability, 13, 986. DOI: 10.3390/su13020986
76. UNDRR (2017) The Disaster Risk Reduction (DRR) glossary. United Nations Office for Disaster Risk Reduction, https://www.undrr.org/drr-glossary/terminology. Accessed on 10/02/2023
77. van Oudenhoven APE, Schröter M, Drakou EG, Geijzendorffer IR, Jacobs S, van Bodegom PM, Chazee L, Czúcz B, Grunewald K, Lillebø AI. Mononen L, Nogueira AJA, et al. (2018) Key criteria for developing ecosystem service indicators to inform decision making, Ecological Indicators 95, 417 - 426.
78. Verri G, Pinardi N, Bryan F, Tseng YH, Coppini G, Clementi E (2020) A box model to represent estuarine dynamics in mesoscale resolution ocean models. Ocean Model 148, 101587.
79. Vicarelli, M., Sudmeier-Rieux, K., Alsadadi, A., Shrestha, A., Schütze, S., Kang, M. M., Leue, M., Wasielewski, D., & Mysiak, J. (2024). On the cost-effectiveness of Nature-based Solutions for reducing disaster risk. The Science of the Total Environment, 947, 174524. DOI: 10.1016/j.scitotenv.2024.174524
80. Viti, M., Löwe, R., Sørup, H. J. D., Ladenburg, J., Gebhardt, O., Iversen, S., McKnight, U. S., & Arnbjerg-Nielsen, K. (2023). Holistic valuation of Nature-Based Solutions accounting for human perceptions and nature benefits. Journal of Environmental Management, 334, 117498–117498. DOI: 10.1016/j.jenvman.2023.117498
81. WHO - World Health Organization (2003). Making Choices in Health: WHO Guide to Cost-Effectiveness Analysis. Retrieved from https://iris.who.int/handle/10665/42699 [11.12.2024]

82. Yang J, Hu X, Feng H, Marvin S (2021) Verifying an ENVI-met simulation of the thermal environment of Yanzhong Square Park in Shanghai. Urban Forestry Urban Greening, 66, 127384, 1-12. DOI: 10.1016/j.ufug.2021.127384
83. Yang, S., Ruangpan, L., Torres, A. S., & Vojinovic, Z. (2023). Multi-objective Optimisation Framework for Assessment of Trade-Offs between Benefits and Co-benefits of Nature-based Solutions. Water Resources Management, 37(6–7), 2325–2345. DOI: 10.1007/s11269-023-03470-8
84. Zidane YJT, Olsson NO (2017) Defining project efficiency, effectiveness and efficacy. International Journal of Managing Projects in Business 10(3):621–641
85. Zieher T, Pfeiffer J, Polderman A (2021) A report on protocols of experiments on NBS (OPERANDUM Deliverable 4.3)

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Funded by
the European Union