NATALIE

Accelerating and mainstreaming transformative NATure-bAsed solutions to enhance resiLIEence to climate change for diverse bio-geographical European regions

D3.1 – Regional climate and socio-economic scenarios

Jesús Soler (AQUA) & Beniamino Russo (UPC)

Co-author(s): Sandra Baki (NTUA), Stratis Boucoyannis (NTUA), Theano Iliopoulou (NTUA), Barry Evans (UNEXE), Peter van Thienen (KWR)

08/2024

Funded by the European Union

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

UK Research and Innovation

Disclaimer

This document arises from the European project "Accelerating and mainstreaming transformative NATure-bAsed solutions to enhance resilience to climate change for diverse bio-geographical European regions (NATALIE)", which has received funding from the European Union, under the Grant Agreement N° 101112859.

Intellectual Property Rights

Project Consortium

EXECUTIVE SUMMARY

This document presents the work developed by the **Work Package 3 (WP3) "Methodologies, models, resilience assessment tools"** in its first year (M12). **WP3** develops, adapts and deploys cutting edge and **tailored methodologies and tools including modelling frameworks**, cost benefit analysis and participatory multi-criteria decision approaches. Of particular importance is the development of co-created frameworks ensuring the engagement of local regional/communities in the development and testing of a broad spectrum of **Nature-Based Solutions (NBS) to better manage climate related hazards under a wide range of climatic and socio-economic scenarios.**

WP3 is structured in four Tasks. The first of them, **Task 3.1, "Leveraging climate and socio-economic scenarios"**, has produced a modelling framework to assess climate-related hazards from regional downscaled climate change projections determining future variations in the main climate hazard variables with special focus on extreme events frequency and intensity (e.g., temperature, precipitation, wind speed, sea level rise). Whitin a context of global change, in designing and developing an adaptation measure, as NBS, it is essential to consider a wide range of current and future climate and socio-economic scenarios to assess its effectiveness in the short, medium and long term. To achieve this, it is crucial to understand the effects of climate change on various climatic variables, identify the future socioeconomic scenarios to be tested and analyze the potential impacts in the study area, as such as the benefits produced by sustainable and cost-efficiency adaptation measures like NBS.

In this context, **Deliverable D3.1 aims to establish a modelling framework to evaluate the role of NBS in climate-related risk assessment process under tailored climate and socio-economic scenarios.**

This framework serves as a starting point for the ongoing work throughout the rest of the project. Presenting this framework in this document is crucial for providing context for the use of the regional climate and socio-economic scenarios that have been developed. In Task 3.1, specific climate and socioeconomic scenarios have been created that will be used as inputs for the models developed in Task 3.2. These scenarios will also be used for the NBS resilience assessment layer prepared in Task 3.3, which will serve as a foundation for the development of WP4. Additionally, Task 3.1 will establish a common framework for collaborating with local stakeholders in the case studies (CS) to develop mitigation and adaptation pathways in Task 3.4.

The work presented in this deliverable was developed using three main approaches:

a) Regular weekly meetings with the WP3 work team were held to establish the basic conceptual framework for the project.
b) Data collection from NATALIE Case studies, employing questionnaires and bilateral meetings.
c) Meetings with other European projects and working groups, such as ARSINOE and ICARIA, were conducted to create common frameworks and establish synergies.

The document is divided into two main parts:

The **first part** presents the **conceptual framework of risk assessment**, emphasizing the role of Nature-Based Solutions (NBS). It discusses modeling NBS in the context of hazards and multi-hazards assessment, as well as their potential contribution in terms of risk reduction and co-benefits. considering NBS as sustainable adaptation measure but also potential risk receptor. Additionally, the deliverable presents a list of possible indicators based on risk and impact variables to monitor and evaluate the impact of NBS.

The **second part of the document** focuses on **climate and socio-economic scenarios**. It outlines the impact of climate change and socio-economic scenarios for designing and implementing NBS. It also discusses the potential impact of tipping points and the approaches to be considered in the case studies of the NATALIE project.

As said, this document is the **first step in establishing the role of NBS in risk assessment in a context of** multiple hazards, multiple risk (including tangible, intangible, direct and indirect losses), co-benefits, and **how to model and quantify their potential impact and efficacy**.

This document generates European added value by **exploring the significant benefits and potential impact of integrating NBS into the risk assessment framework**. It emphasizes the crucial role of NBS in transforming traditional risk assessment methods, providing a sustainable approach to managing climate hazards. By utilizing the resilience and adaptability of natural systems, NBS offer innovative strategies that not only address risk adaptation but also provide additional co-benefits, with a comprehensive set of indicators and a tailored **future climate and socio-economic scenarios** designed to assess the **effectiveness of NBS**.

The results of this deliverable will be used:

d) by the rest of the tasks of WP3, laying its foundations,
e) by WP2, to develop the task 2.6, to mainstream NBS in the systemic transformation,
f) by WP4, to develop the NBS Knowledge Booster,
g) and WP5, responsible for coordinating, implementing, testing, monitoring, and validating activities for each CS; to be applied in the case studies when evaluating the performance of NBS under different future climate change scenarios.

This version submitted on 31 August 2024 (M12) shows the status of D3.1 on this specific date of submission. Please note that as of the delivery date of this document, the downscaling of climate data by World Climate Research Programme's Coordinated Regional Downscaling Experiment (EUROCORDEX), the main data source for its application in case studies, has not been published. This data and a related specific discussion on this point will be included in D3.2 (M24) once it becomes available.

RELATED DELIVERABLES AND WORK PACKAGES' CONNECTION

This section details if there are any related Deliverables (e.g. interim versions, prerequisites etc.) and highlights links with the other Work Packages:

- The work carried out was based on the **inputs from** WP3 (T3.1 and T3.2)
- The results presented in this deliverable **will feed** WP2 (T2.6), WP3 (T3.2, T3.3 and T3.4), WP4 and WP5.

DOCUMENT INFORMATION

Grant Agreement N°	101112859
Project Acronym	NATALIE
Project full name	Accelerating and mainstreaming transformative NATure-bAsed solutions to enhance resilience to climate change for diverse bio-geographical European regions
Start of the project	1 September 2023
Duration	60 months
Deliverable	**D3.1 : Regional climate and socio-economic scenarios**
Work Package	**WP3: Methodologies, models, resilience assessment tools**
Task	Task 3.1: Leveraging regional climate and socio-economic scenarios
Lead Beneficiary	AQUA
Author(s)	Jesús Soler (AQUA) & Beniamino Russo (UPC)
Co-author(s)	Sandra Baki (NTUA), Stratis Boucoyannis (NTUA), Theano Iliopoulou (NTUA), Barry Evans (UNEXE), Peter Van Thienen (KWR)
Quality check	External technical reviewers: Albert Chen (UNEXE) Dimitris Kofinas (UTH) Quality check: Sonia Siauve (OiEau)
Due Date	31/08/2024
Delivery Date	31/08/2024
Explanation of the delay (if any)	N/A
Citation	Soler J., Russo B., Baki S., Boucoyannis S., Iliopoulou T., Evans B., Thienen P. (2024): Regional climate and socio-economic scenarios, Deliverable D3.1, Public, Horizon Europe NATALIE Project, Grant agreement N° 101112859
Dissemination Level	Public

REVISION HISTORY

Version	Date	Who	What
V1	19/07/2024	Jesús Soler (AQUA)	First draft
V2	26/07/2024	Beniamino Russo (UPC)	Internal review
V3	16/08/2024	Dimitris Kofinas (UTH) Albert Chen (UNEXE)	External review
V4	29/08/2024	Jesús Soler (AQUA) Beniamino Russo (UPC)	Second draft
V4	29/08/2024	Sonia Siauve (Oieau)	Quality check
VF	31/08/2024	Jesús Soler (AQUA) Beniamino Russo (UPC)	Final edit

TABLE OF CONTENT

LIST OF ACRONYMS

AMOC	Atlantic Meridional Overturning Circulation
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BAU	Business As Usual
B-C	Bias Correction
CLU	Change of Land Use
CMIP	Coupled Model Intercomparison Project
CS	Case Study
D	Deliverable
DS	Demonstration Site
DSM	Digital Surface Models
DTM	Digital Terrain Models
EEA	European Environmental Agency
ESM	Earth System Models
EC	European Commission
EU-GL	European Guidelines
EO	Earth Observation
ESM	Earth System Models
EUROCORDEX	Coordinated Downscaling Experiment (European branch)
FL	Follower site
GCM	General Circulation Models
GDP	Gross Domestic Product
HILL	High impact and Low Likelihood
IPCC	Intergovernmental Panel on Climate Change
LABC	Labrador Sea Convection
MCA	Multi-Criteria Analysis
NBS	Nature-Based Solutions
NFF	Natura Future Frameworks
RCM	Regional Climate models

RCP	Representative Concentration Pathways
SDGs	Sustainable Development Goals
SSP	Shared Socio-economic Pathways
SPA	Shared Policy assumptions
UNFCCC	United Nations Framework Convention on Climate Change
UPC	Universitat Politècnica de Catalunya
WCRP	World Climate Research Programme
WGCM	Working Group of Coupled Modeling
WMO	World Meteorological Organization
WP	Work Package

LIST OF FIGURES

LIST OF TABLES

I Introduction

I.1 Objective, structure and context of the Deliverable 3.1

NATALIE addresses the risks posed by climate change and its impacts and proposes to advance the concepts of “Ecosystem-Based Adaptation” in Europe combined with climate resilient development pathways, as the means for impact driven Nature-Based Solutions (NBS), to accelerate and mainstreaming the adoption of NBS for resilience to climate change, which is also the cornerstone identified in the recent Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) [1]. NATALIE aims to provide innovative and practical sustainable solutions through co-creation processes, ensured by continuous engagement of local stakeholders during and beyond the project lifespan. Design, modelling, testing and monitoring activities will be supported by validation mechanisms that will help regions and municipalities to include NATALIE solutions in their climate adaptation policies bringing along valuable knowledge and experience as actionable knowledge for adaptation and benefits driven NBS.

In NATALIE, the work on development and implementation of the transformative NBS Booster Pack is organised around 25 solutions that will be developed through the concerted WP activities and demonstrated at the scale of the 8 Case Studies (CSs, Figure 1). **The main objective of WP3 is to develop streamlined assessment tools to evaluate the performance of NBS that support the planning and implementation of interventions for enhancing climate resilience of regions and communities through 8 CSs**. Each case study consists of a Demonstration Site (DS), sometimes twinned with a replication site which is called Follower Site (FL), which is the case for 4 of the 8 case studies. The total of 12 sites (8 DS and 4 FL) are in 5 different biogeographical regions and share common environmental challenges today or in the near future due to the impact of climate change (Figure 1).

WP3 is structured in four Tasks. Task 3.1 (T3.1), “Leveraging climate and socio-economic scenarios”, aims to produce a modelling framework to assess climate-related hazards from regional downscaled climate change projections determining future variations in the main climate hazard variables with special focus on extreme events frequency and intensity (e.g., temperature, precipitation, wind speed, sea level rise). Within NATALIE, local downscaled projections will be achieved combining dynamical and statistical approaches depending on data availability and the expertise of local partners. This means that regionalized/downscaled climate projections will hence be obtained from the outputs of the Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations and that downscaled approaches (statistical or dynamical) will be decided depending on data availability, the background and needs of local partners or due to synergies with other initiatives. The downscaled parameters will be applied to drive hazard and multi-hazard modelling in T3.2 (flooding, droughts, heatwaves, cold snaps, storm surge, gusts, erosions, salination, wildfires, etc.). Furthermore, socio-economic pathways (urbanization, population growth, economic trends) will be also considered.

The first deliverable of WP3, Deliverable 3.1 (D3.1) Regional climate and socio-economic scenarios aims to provide an overview of the entire WP and the work carried out during the first year. Specifically, this document includes the risk assessment framework developed so far and the role of NBS within it, with a particular focus on extreme events hazard modelling and their impacts, including compound events and cascading effects. This framework serves as a starting point for the ongoing work throughout the rest of the project. Presenting this framework in this document is crucial for providing the project context and establishing regional climate and socio-economic scenarios to be considered in each case study.

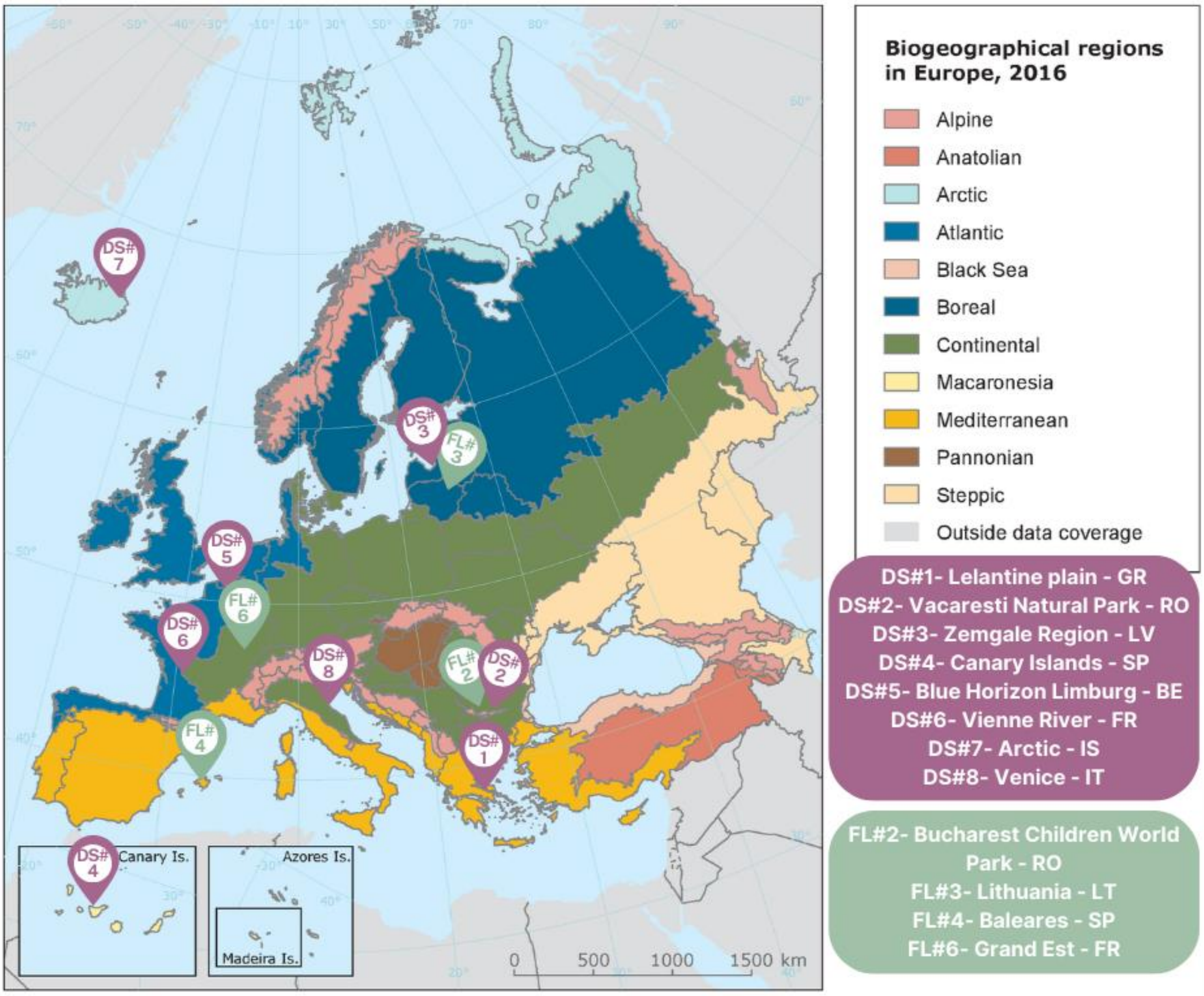

Figure 1. Location and related biogeographical regions of the NATALIE Case Studies (Demonstration Sites and Followers).

This version submitted on 31 August 2024 (M12) shows the status of D3.1 on this specific date of submission. Please note that as of the delivery date of this document, the downscaling of climate data by World Climate Research Programme's Coordinated Regional Downscaling Experiment (EUROCORDEX), the main data source for its application in case studies, has not been published. This data and a related specific discussion on this point will be included in D3.2 (M24) once it becomes available.

I.2 Structure of the document

The deliverable is organized as follows: Chapter II includes an overview of the risk assessment framework carried out by WP3. Chapter III details the rationale and the development of the regional climate and socio-economic scenarios, and Chapter IV presents the conclusions.

The deliverable is accompanied by an appendix containing a technical glossary of principal terms developed in WP3.

II NBS Modelling framework

II.1 Risk assessment framework

Since its creation in 1988, the Intergovernmental Panel on Climate Change (IPCC) actively works in shaping the methods for assessing climate-related risks and impacts. In its Fifth Assessment Report (AR5), the IPCC adopted a risk-based approach, which represents a significant shift from the vulnerability-oriented framework used in previous reports [3]. This risk-based approach draws on established principles and practices from risk sciences and emergency management, which have been widely applied in the context of geophysical hazards such as earthquakes, volcanic eruptions and tsunamis [4],[5]. By integrating these methodologies with advancements in earth and environmental sciences, the IPCC has brought together the Disaster Risk and Climate Change scientific communities, fostering a more holistic understanding of climate-related risks and their impacts [6].

The IPCC's risk assessment framework revolves around three fundamental components: hazard, exposure and vulnerability [3]. Hazard refers to potential climate-related physical events or trends, such as extreme weather events, sea-level rise or long-term changes in temperature and precipitation patterns. Exposure involves the presence of human, ecological or socioeconomic systems in areas that could be affected by these hazards. Vulnerability represents the likelihood of these exposed systems being impacted by hazards, considering their intrinsic characteristics (sensitivity and adaptive capacity). By evaluating these three components and their interactions, the IPCC's risk assessment framework provides a basis for understanding climate change impacts and informing effective adaptation and mitigation strategies [3].

In the AR6, the IPCC further refines its risk assessment framework, emphasizing the critical role of resilience in addressing climate-related risks and impacts (Figure 2, [7]). The AR6 highlights the interplay between resilience strategies and the core components of risk assessment (hazard, exposure and vulnerability) collectively referred to as "climate resilient development". This updated framing underscores the importance of an integrated approach to bolstering resilience against climate change impacts, recognizing the complex interplay between climate hazards, exposure and vulnerabilities [1].

The IPCC's risk assessment framework has been widely adopted and adapted by various research initiatives and projects aimed at evaluating climate-related risks and resilience. In the scope of NATALIE, this risk/impact assessment framework from IPCC AR6 [7] has been updated to describe the role of NBS and evaluate their performance as part of the overall modelling workflow. This framework aligns with the IPCC's AR6 conceptualization, emphasizing the interactions between resilience strategies (such as NBS) and the core risk components (hazard, exposure and vulnerability) (Figure 3). Leveraging the IPCC's risk assessment framework, NATALIE can contribute to the development of sustainable climate resilient pathways addressing the challenges posed by climate change and promoting the achievement of the Sustainable Development Goals (SDGs) through NBS.

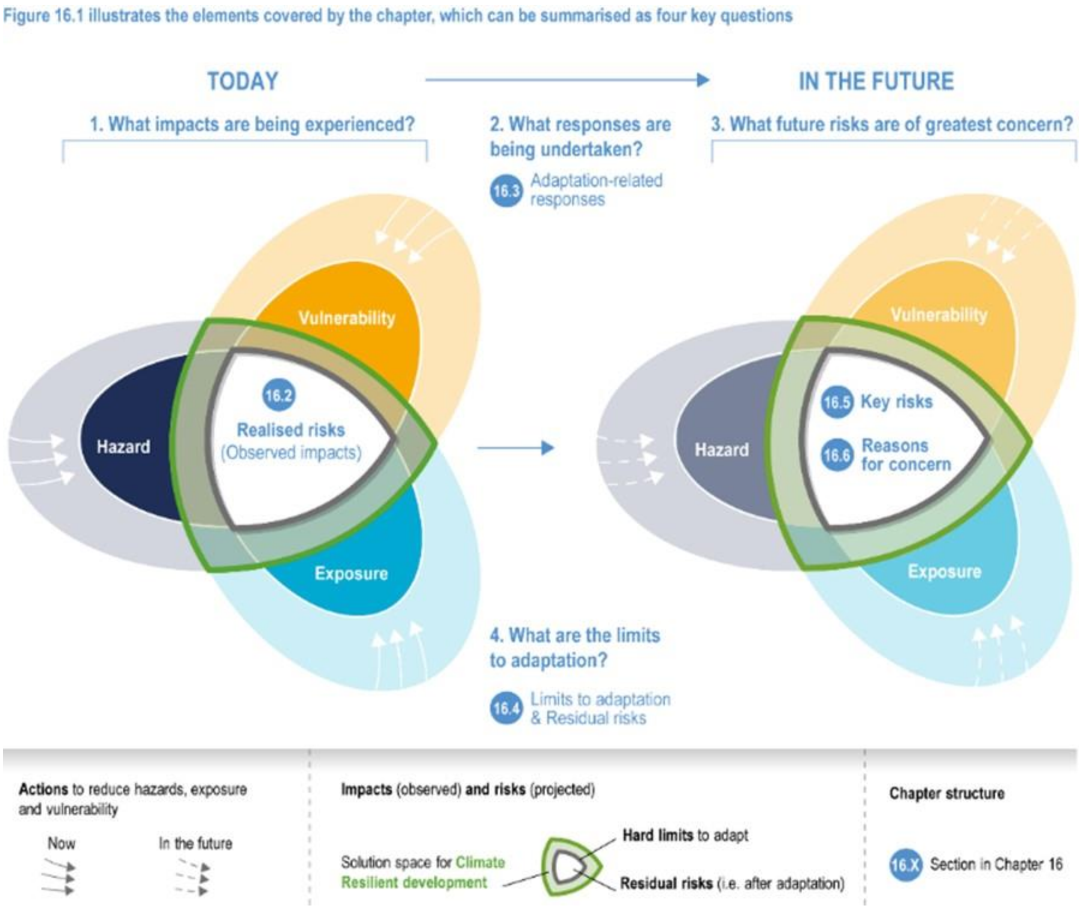

Figure 2. Conceptual framework for climate risk/impacts assessment and « climate resilient development » implementation in AR6 [3].

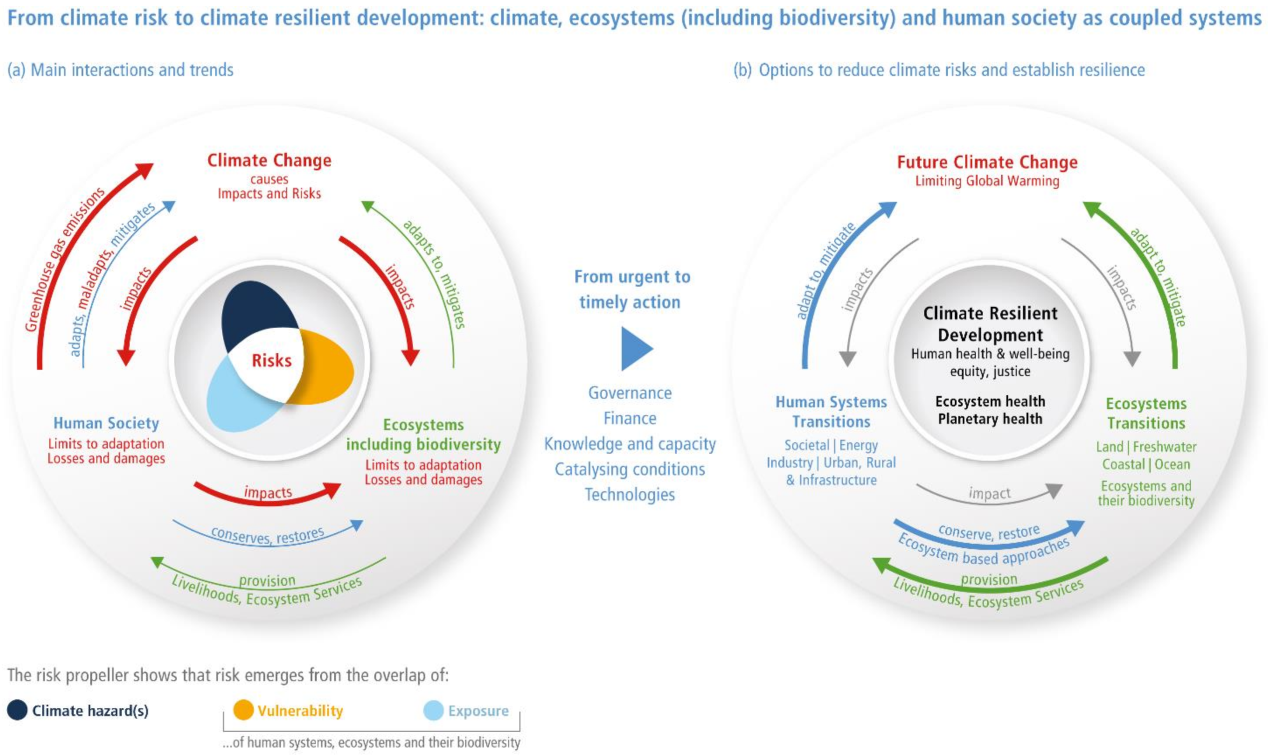

Figure 3. From Climate risk to climate resilient development. [7]

The NATALIE project starts from the climate-related risk assessment framework developed by ICARIA project (Figure 4, [8]). This framework guides NATALIE's approach to evaluating climate-related risks, their impacts across various sectors and systems, and the importance of resilience-building measures. Building on ICARIA's work, NATALIE's assessment framework provides a strong basis for understanding the interplay between climate hazards, human and natural system exposure, vulnerabilities and strategies to enhance resilience.

The approach to NBS can be addressed from two different perspectives: as an adaptation measure and as a risk receptor. When seen as an adaptation measure, NBS plays a role in enhancing the resilience of the system by reducing hazards and modifying exposure and vulnerability. When viewed as a risk receptor, the NBS itself is impacted by the Hazard, based on its location (exposure) and how fragile or damaged by hazards (vulnerability), which can change as its development over time. This vulnerability is dynamic given the intrinsic nature of the NBS being a natural element that evolves over time. Depending on its location and exposure, a NBS may be directly impacted by a hazard, with its ability to absorb and withstand those impacts determined by its vulnerability at that specific stage of development. The dynamic nature of NBS is a crucial aspect to consider, as these natural elements are inherently evolving systems. Unlike static infrastructure, the vulnerability of NBS to hazards can fluctuate over time as they mature and develop: a newly implemented NBS or with minimal vegetative development has a greater vulnerability compared to more mature natural systems.

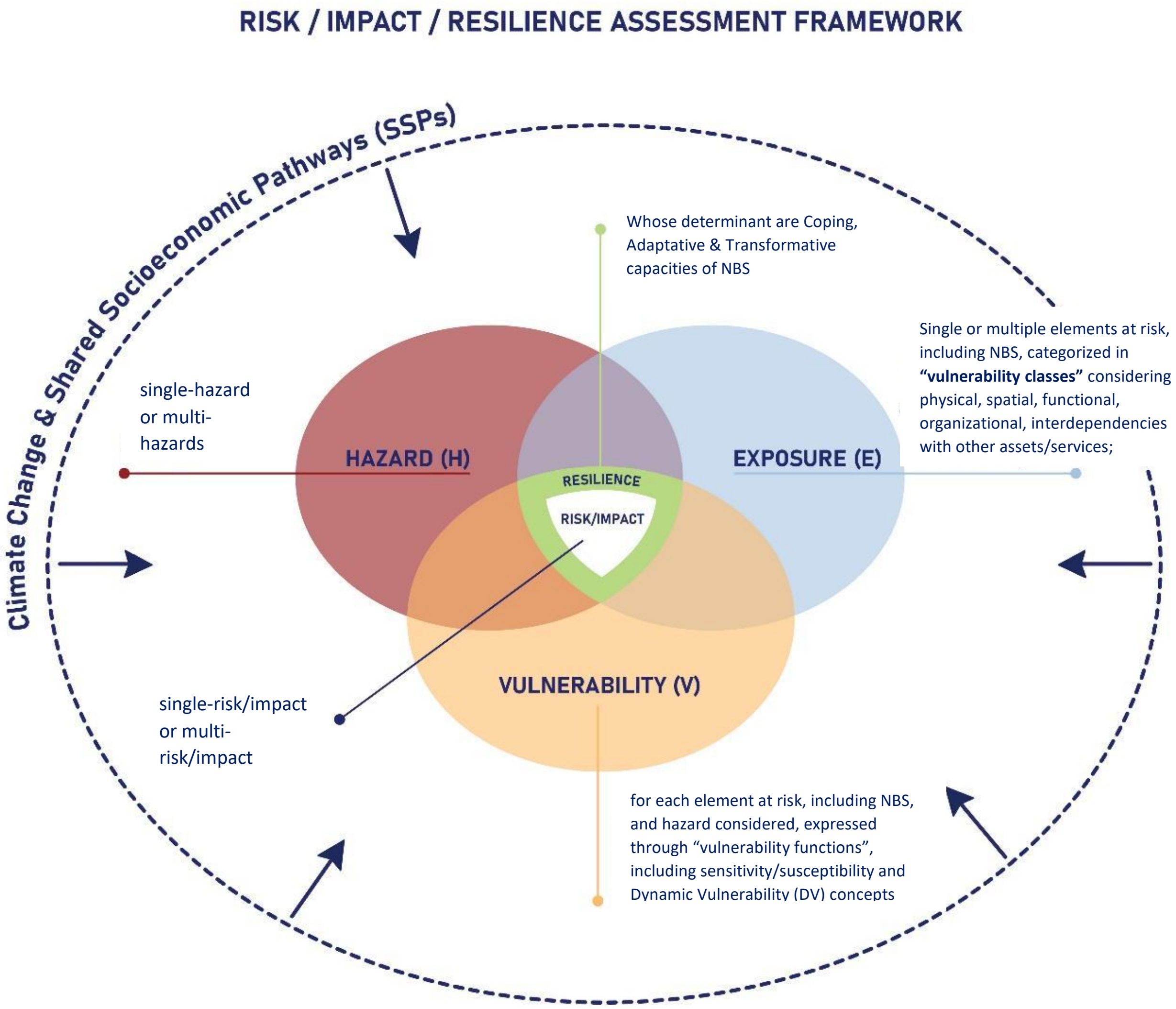

Figure 4. The risk/impact/resilience assessment framework modified from ICARIA [8], consolidated in the field of geophysical hazards ([4]; updated by the UNDRR, 2017 terminology) and harmonized in the context of climate change [1] introducing the resilience components.

Under the climate scenarios identified by Shared Socio-Economic Pathways (SSPs, see Chapter III), the risk/impact assessment depends on the following factors:

- **Hazard:** Potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In the IPCC context, the term hazard usually refers to "climate-related physical events or trends or their physical impacts¨ [3]. This is influenced by climate variables and local conditions that can amplify hazard intensity. For example, the effect of the Urban Heat Island on heatwave hazards or the effect of soil sealing or human-made changes to riverine and coastal environments on flooding hazards. This should be determined while considering the probability of occurrence of relevant compound events. As an adaptation measure, NBS can contribute reducing the intensity or likelihood of these hazards through various mechanisms.

- **Exposure:** Evaluation of the quantity, quality, and sensitivity of the elements at risk (e.g., people, buildings, infrastructure, services, activities, etc.) exposed to hazards, considering their spatial and temporal distribution. Exposure is usually combined with vulnerability and capacities of the elements, in order to quantify risks/impact associated with one or more hazards occurred [3]. This involves creating a comprehensive database of exposed assets and services, including all relevant information that supports vulnerability analysis related to the multiple hazards considered. It should be divided into vulnerability classes and should highlight organizational, physical, spatial and functional interdependencies with other assets and services. Viewed as an adaptation measure, NBS can act as a buffer or a barrier to reduce the exposure of human settlements, infrastructures and ecosystems. On the other hand, NBS themselves can be exposed to hazards. For example, a NBS designed to reduce flooding by acting as a buffer may be affected by floods, which can impact and damage it. Additionally, other hazards like droughts can reduce the development of vegetation, reducing its flooding reduction (less infiltration) and diminishing the associated co-benefits.

- **Vulnerability:** The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements such as sensitivity or susceptibility to harm and lack of capacity to cope and adapt [3]. This includes developing vulnerability functions that link the magnitude of hazard(s) to the expected damage threshold for each asset or element in the vulnerability model. It should also involve conducting sensitivity/susceptibility analysis and developing dynamic vulnerability functions where relevant. Viewed as an adaptation measure, NBS can offer potential co-benefits, by reducing the vulnerability and the resilience of the system. Viewed as a risk receptor, given the intrinsic nature of NBS being a natural element that evolves over time, a newly implemented NBS or one with minimal vegetative development has greater vulnerability compared to more mature natural systems.

- **Capacity**: The capacity is defined by the UNDRR [9] as "Ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management. Capacity may include infrastructure, institutions, human knowledge skills, and collective attributes such as social relationships, leadership and management."

- **Resilience:** The resilience is defined by the IPCC [10] as "the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation. This involves the NBS implemented, and other adaptative measures, that support coping and adaptive capacities for the identified assets and services".

The methods for determining Hazard, Exposure, Vulnerability, Capacity and Resilience may vary based on the specific hazards and assets being considered. To standardize a multi-hazard/impact assessment, the NATALIE framework outlines common requirements for each. This involves quantifying damage over time and space and accounting for various aspects of resilience including NBS.

The NATALIE modelling workflow includes several methodological steps, some of them based on ICARIA framework [8]:

- Co-identifying and defining current scenarios and future climate change narratives using SSP.
- Co-identifying the initial hazards (primary and secondary, if any) triggering events within the case study regions.
- Conducting a probabilistic assessment for each scenario of compound events, taking into account the occurrence of an initiating hazard of a specific magnitude.
- Assessing current and future Business As Usual (BAU) scenarios:
    - Evaluating the intensity of each of the hazards and compound events.
    - Evaluating exposure and vulnerability for each scenario, considering risk receptors to the hazards and integrating factors such as time, space, and human behavior.
    - Co-assessing the impacts in terms of risk reduction, economical, societal, and environmental impacts, considering the potential cascading effects.
- Co-definition of NBS components together with related metrics (indicators), and resilience assessment.
- Assessment of current and future NBS scenarios:
    - Evaluating the intensity of each of the hazards and compound events.
    - Evaluating exposure and vulnerability for each scenario, considering risk receptors to the hazards and integrating factors such as time, space, and human behavior.
    - Assessing the impacts in terms of risk reduction, economical, societal, and environmental impacts, considering the potential cascading effects.
- Comparing BAU and NBS scenarios through multi-criteria analysis.

II.2 Classification of NBS and their role in the risk assessment process

NBS are increasingly recognized as a crucial component of comprehensive risk assessment frameworks and resilience-building strategies in the face of climate change. NBS are defined as "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions" [11]. By taking advantage of the inherent capabilities of natural systems and processes, NBS offer multifunctional benefits that can contribute to mitigating climate-related risks, examined as a solution against compound and cascading effects, enhancing resilience and promoting sustainable development [12].

Within a common pathway of a risk assessment process (including risk reduction), NBS can play a pivotal role in addressing the three core components: hazard, exposure and vulnerability [1]. Regarding hazard reduction, NBS can help reduce the intensity and frequency of climate-related hazards such as floods, droughts, heat waves and coastal erosion. For instance, ecosystem-based approaches like wetland restoration, urban greening and sustainable forest management can regulate water flows, mitigate urban heat island effects, and stabilize soils, thereby reducing the likelihood and severity of these hazards [13], [14]. NBS can act as natural buffers or barriers to protect human settlements, infrastructure and economic assets from the adverse effects of climate hazards. Examples include the establishment of coastal dunes, mangrove forests, and riparian vegetation, which can act as natural barriers against storm surges, coastal erosion and riverine flooding [15].

Regarding vulnerability, NBS can enhance the resilience and adaptive capacity of socio-ecological systems by supporting ecosystem services and promoting biodiversity conservation [12], [16]. Healthy and diverse ecosystems are generally more resilient to disturbances and can better withstand and recover from the impacts of climate change. Additionally, NBS can contribute to improving human well-being, livelihoods, and social cohesion, thereby reducing the vulnerability of communities to climate-related risks [17], [18].

In the conceptual risk assessment process presented in Figure 5, NBSs play a pivotal role in addressing the various components and dynamics involved. The framework starts by defining a system, which encompasses a collection of assets, services and citizens that are affected by one or more combined hazards. The exposure and vulnerability of this system to the identified hazards ultimately determines the extent and severity of the resulting impacts.

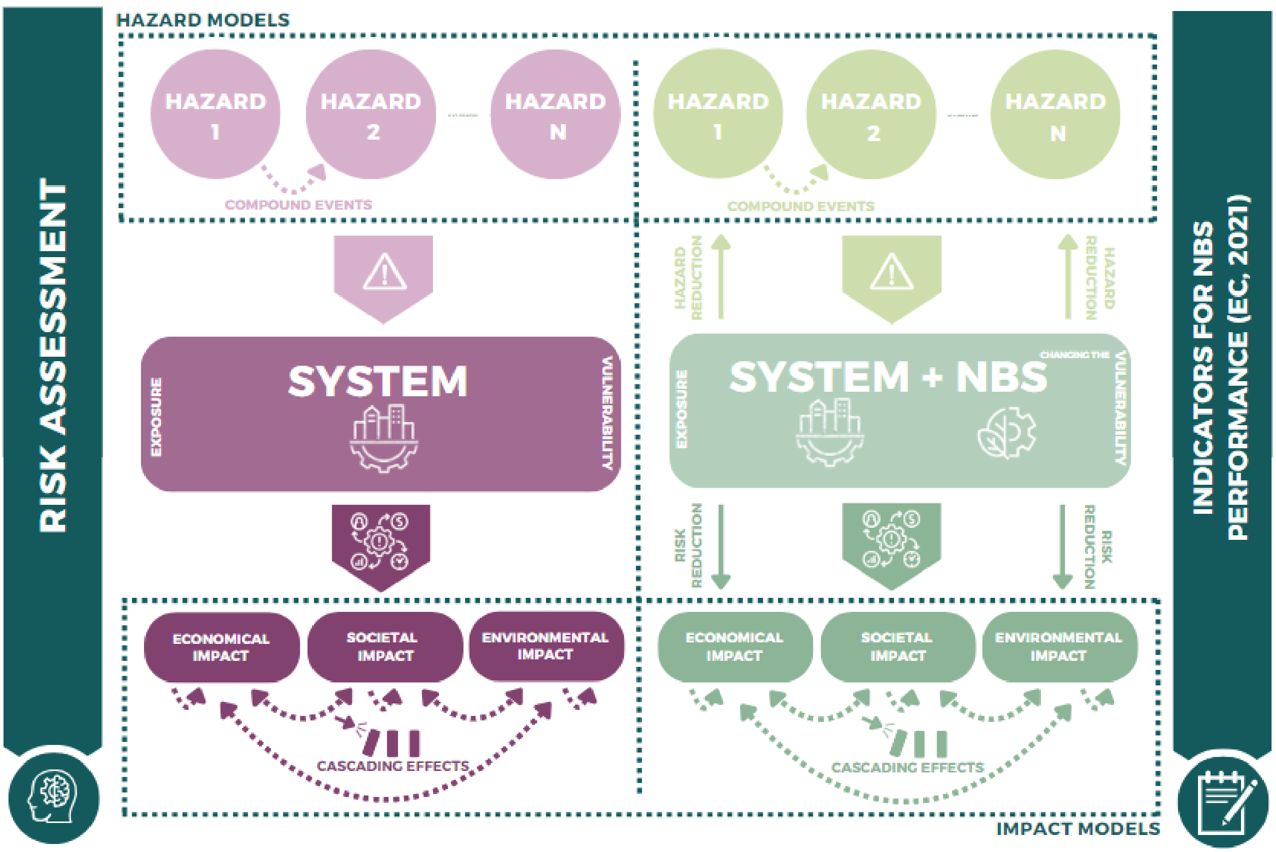

Figure 5. Role of NBS in a common process of risk assessment and risk assessment reduction within NATALIE project.

Climate-related impacts within NATALIE have been categorized into three main domains: economic, social and environmental. However, it is crucial to recognize that these impact domains are inherently interconnected and can propagate through cascading effects. For instance, an environmental impact, such as biodiversity loss, can have cascading consequences on economic activities like agriculture or tourism, which in turn can lead to social impacts on livelihoods and well-being (It should be noted that biodiversity loss can be considered an impact but also a hazard, depending on the approach and context of the study. This topic will be developed in subsequent deliverables within task 3.2).

The implementation of one or more NBSs within this system is strategically aimed at reducing vulnerability, and hazard and so the overall risk levels, while simultaneously providing additional co-benefits that can positively modify the nature and magnitude of the impacts across the economic, social and environmental domains.

The NATALIE project, particularly through its WP3, aims to identify and develop robust models for assessing climate-related hazards and their associated impacts, as well as for understanding and integrating the role of NBS within the proposed modeling framework and risk assessment process. This involves a comprehensive analysis of hazards and impacts, which is quantified using a range of carefully selected indicators tailored to the specific context and objectives of each case study.

Table 1 presents the initial list of NBS chosen by the different case studies within the NATALIE project for addressing specific hazards. It's important to keep in mind that the list of NBS and their classification may be updated during the project through the co-creation process in the transformation lab developed within WP2. The classification and the selection of NBS are complex processes. As the project progresses, the classifications may be refined or expanded to better reflect the specific contexts and objectives of each CS. A robust classification framework for NBS in the NATALIE project is currently under development as part of WP1 and WP3 activities. This framework is being developed through internal discussions among project partners and in coordination with other European projects and initiatives.

The ongoing discussions and development of the NBS classification framework in the NATALIE project will be documented and shared through future deliverables within WP3, such as D3.2. This deliverable will provide insights into the methodological approaches, criteria and considerations used in the classification process, as well as the resulting harmonized NBS taxonomy adopted by the project.

Table 1. Classification of NBS for each NATALIE CS.

Case Study		**NBS**	**Primary hazard**
CS#1	*Flood and wildfire risk mitigation in Greece*	River restoration Riparian Forest recreation Floodplain restoration Wetland restoration and management Restoration pond Forest management	Fluvial floods Wildfires
CS#2	*Fresh water habitat restoration in urban ecosystems in Romania*	Sustainable Drainage Systems (SuDS) Flood-prone Park	Droughts Heatwaves
CS#3	*Constructed wetlands in Latvia and Lithuania*	Constructed wetlands	Surface and Groundwater pollution
CS#4	*Alternative water management solutions in Spanish Archipelagos*	Sustainable Drainage Systems (SuDS) Flood prone park	Surface and Groundwater pollution (Gran Canaria site) Fluvial Floods (Tenerife site) Flash Floods Drain and sewer floods Groundwater floods

		Constructed Wetland Managed aquifer system	Surface and Groundwater pollution (Fuerteventura site)
CS#5	*Aquifer recharge for water reuse in Belgium*	Manage aquifer recharge	Droughts
CS#6	*Aquatic system restoration and water management in France*	Removal of ponds Wetland restoration	Droughts
CS#7	*Coastal management with NBS in Iceland*	TBD	Surface and Groundwater pollution Landslides
CS#8	*Sustainable river restoration, maintenance and management in Italy*	Floodplain restoration and management	Fluvial floods Riverbank erosion

II.3 NBS modelling within hazard and multi-hazard analysis

The number of climate-related disasters has increased over the past two decades, and this trend is expected to worsen due to global warming and associated climate change [19]. These disasters often involve compound events, such as floods and landslides triggered by heavy rainfall, as well as cascading effects like forest fires fueled by persistent drought conditions brought on by extreme heat waves. The cumulative impacts of these multi-hazard conditions may be greater than the sum of the effects of each individual hazard event [20], [21].

Traditionally, risk and impact assessments for meteorological extremes have been done by isolated analysis of each hazard [22]. However, this approach has limited the development of a comprehensive, integrated modelling framework for multi-hazard risk and impact assessment. An integrated framework would help in understanding the full impacts of climate change on complex socio-eco-technological systems and in defining climate-resilient pathways [23], [24]. Therefore, there is a need for a shift towards an effective multi-hazard and multi risk assessment approach that includes an overall resilience assessment [25].

This kind of assessment assumes that the combination of multiple climate events and/or drivers puts society, assets, services and the environment at compound risk in an interconnected manner. Depending on how these events unfold over time and space, they may cause more severe damage than isolated events. Additionally, the nature and characteristics of this damage will vary depending on the complexity of the hazards involved and the interdependencies between them [21], [26], [27], [28]. A comprehensive understanding of the implications of compound events on specific risk receptors and the cascading effects of impacts on interdependent assets and services is crucial for developing an effective asset-level modelling framework to improve overall resilience.

II.3.1 The role of NBS in compound event and multi-hazard mitigation

NBS are increasingly adopted across urban, peri-urban and rural areas, to address environmental challenges and natural hazards while promoting social well-being. They are often viewed as multi-purpose urban planning projects characterized by 'co-benefits' [29]. While much attention has been given to their societal benefits, the potential of NBS in mitigating multiple hazards and contributing to multi-hazard resilience has been less explored. Concurrently, multi-hazard resilience is increasingly being considered in holistic risk management frameworks, assessing various hazard scenarios and societal vulnerabilities [30].

This section explores and highlights the role of NBS in addressing multiple climatic and other natural hazards or their combinations. Hazardous events arising from combinations of climatic and climate-driven hazards and drivers, are commonly referred to in climate science as 'compound events' and are considered a category of 'complex risk' [31]. In this respect, the IPCC SREX [32] defines compound events as:

- two or more extreme events occurring simultaneously or successively,
- combinations of extreme events with underlying conditions that amplify the impact of the events, or
- combinations of events that are not themselves extremes (could be characterized as 'average' events) but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different type(s).

The term 'compound events' emphasizes systemic approaches in risk analysis, augmenting scenarios traditionally based on simplified single-process analyzes of drivers or hazards. For example, assessing flooding solely due to extreme rainfall, without considering other contributing factors (e.g., increased runoff contribution from burned areas), or studying floods based solely on river overflow while neglecting other potential concurrent hazards, e.g. storm surges in coastal areas. Such compound events are highly pertinent in holistic risk assessment frameworks because they can intensify the impacts of natural hazards, leading to more severe and complex challenges compared to when these hazards or drivers occur in isolation.

A useful typology of compound events has been provided by Zscheischler *et al.* [33], who classified compound events into the following categories:

- **Preconditioned** referring to events where a weather-driven or climate-driven precondition aggravates the impacts of a hazard (e.g., heavy rain on saturated soils). This sequential interaction often leads to more severe impacts than if the events occurred independently, since the initial event creates conditions of increased vulnerability.
- **Multivariate** referring to events where multiple drivers and/or hazards occurs concurrently in the same region, with each one contributing to the overall impact (e.g. drought and heatwave). Their drivers are usually causally related through associated weather patterns, although causality is not an explicit criterion in this typology (such a classification is given in Section II.4, p.35). Furthermore, this type considers multivariate climatic dynamics that have significant impacts even if their contributing variables are not as extreme.
- **Temporally compounding**, where a succession of hazards (usually of the same type but could be of different types as well) leads to an aggravated impact (e.g. temporal clustering of heavy precipitation events). These events typically unfold consecutively, with the impacts of one event influencing or exacerbating the impacts of subsequent events.
- **Spatially compounding**, where hazards in multiple connected locations cause an aggregated impact (e.g. floods at regional scale). This phenomenon is facilitated by a system that integrates these hazards across different areas, thereby amplifying the effects in distant locations. The occurrence of these hazards and their drivers is often due to a modulator, which establishes a physical connection between the affected locations (e.g. large-scale storm event).

NBS can serve as tools to mitigate compound events, either in conjunction with traditional technical infrastructure or as primary approaches. They offer advantages such as cost-effectiveness and community-oriented benefits [29], [34], as well as climate adaptability and multi-hazard resilience. In particular, NBS, by leveraging various natural processes and ecosystems, may adapt more effectively to diverse climatic conditions compared to traditional technical infrastructure (which tends to be monofunctional), thereby addressing multiple hazards. For instance, green roofs and urban green spaces mitigate the urban heat island effect by cooling through evapotranspiration and providing shade.

Table 2. Examples of NBS for different categories of compound events and related hazards.

Event	Compound Event	Related hazard(s)	Example NBS
Preconditioned	Heavy rainfall on burned areas after a wildfire	Flash floods, mudslides, erosion, debris flows	Reforestation and riparian buffers to stabilize soil and reduce erosion
	Soil saturation from multi-day rainfall event followed by a storm	Flooding, landslides, soil erosion	Wetland restoration to increase water absorption and permeable pavements to reduce runoff
	Heatwave followed by a wildfire	Heatwave, wildfire, air quality degradation, biodiversity loss	Establishing fire-resistant vegetation zones and using prescribed burning to reduce fuel load
Multi-variate	Heatwave combined with air pollution	Heatwave, air quality degradation	Urban green spaces to improve air quality and provide cooling through shade and evapotranspiration
	Heatwaves and droughts	Heatwave, droughts	Collecting and storing rainwater from green roofs and other surfaces can provide a supplemental water source during droughts, while green roofs provide natural cooling.
	Flooding combined with sewage overflow	Water pollution, flooding	Constructed wetlands to treat wastewater and manage excess stormwater
Temporally-compounding	Sequential hurricanes hitting the same coastal region	Storm surges, coastal erosion, flooding	Coastal dune restoration and wetland creation to absorb storm impacts and provide storm-surge protection
	Severe thunderstorms in an urban area	Flash floods	Implementing urban green infrastructure to manage stormwater, including rain gardens and retention ponds
	Sequence of heatwaves	Heatwaves	Urban green spaces and blue-green corridors to mitigate the urban heat island effect by providing shade and cooling through evapotranspiration
Spatially-compounding	Floods in various river basins within a large watershed	Flash floods, riverbank erosion	Riparian buffers and floodplain restoration to manage water flow within the catchment and reduce downstream flooding
	Wildfires occurring over large regions	Wildfires, air pollution, ecosystem degradation	Creating firebreaks with natural vegetation and managing forest undergrowth
	Simultaneous heatwaves over urban areas	Heatwaves	Urban forestry and green roofs to reduce heat island effects across cities

Concurrently, they also contribute to rainwater management by absorbing and filtering it, thereby reducing runoff and alleviating the pressure on stormwater drainage systems. This may ensure long-term effectiveness in flood mitigation, complementing traditional stormwater infrastructure, which otherwise may necessitate costly upgrades to handle increased stormwater runoff. Examples of NBS able to respond to different scenarios of compound events and related hazards are shown in Table 2.

II.3.2 Mapping of NBS to hazard and multi-hazard scenarios

Having introduced the concept of multi-hazard mitigation potential in NBS, the focus of this section shifts towards introducing a conceptual framework for its identification. This framework aims to methodically pinpoint and assess the multi-hazard resilience component, inherent in NBS, providing a structured approach to explore their effectiveness in mitigating diverse environmental threats. To this aim, it introduces a systematic mapping of NBS to multiple hazards based on the natural processes they leverage. A process-based mapping of NBS to natural hazards involves categorizing NBS according to the natural processes they enhance or utilize, and then linking these processes to the specific hazards they mitigate. This approach allows for a comprehensive understanding of how different NBS can be applied across various environmental challenges. The key questions of interest are:

- **Which types of NBS are effective for each natural hazard?**
- **Which NBS may address a combination of hazards?**
- **How can a process-based mapping of NBS to natural hazards inform the selection of appropriate NBS under multi-hazard scenarios?**

This framework may help inform both the selection of appropriate NBS for areas under multi-hazard risk, as well as the understanding of the existing NBS potential in addressing other environmental challenges. This task is particularly relevant in the frame of the NATALIE project, the goal of which is to highlight and mainstream NBS to enhance resilience against natural hazards. The framework also intends to provide a roadmap for the implementation of NBS modelling, which is expected at the next steps of the project (Task 3.2).

The underlying basis behind identifying the key processes is that each NBS is characterized by a unique mitigation mechanism by which it responds to a specific hazard. As mitigation mechanism, it is possible to define the whole functioning (dynamics) of a NBS to reduce a certain hazard and/or its impacts. For instance, retention ponds help reduce flood hazard by absorbing and storing floodwaters and attenuating flood flows. NBS may have mitigation mechanisms for more than one hazard. While mitigation mechanisms are specific and may differ among the different NBS, they may be decomposed to more general natural processes, the combination of which creates the hazard mitigation mechanism. For example, retention ponds reduce floodwater volumes and peaks, because they enable infiltration and exhibit storage potential, i.e., water retention. The latter are natural processes that can be found in more than one NBS, e.g., green roofs also share the same processes. The more general characterization of 'NBS processes' allows a systematic classification of the different NBS, their mapping to various hazards and may also inform a physically-based modelling roadmap. This conceptual basis is depicted in Figure 6.

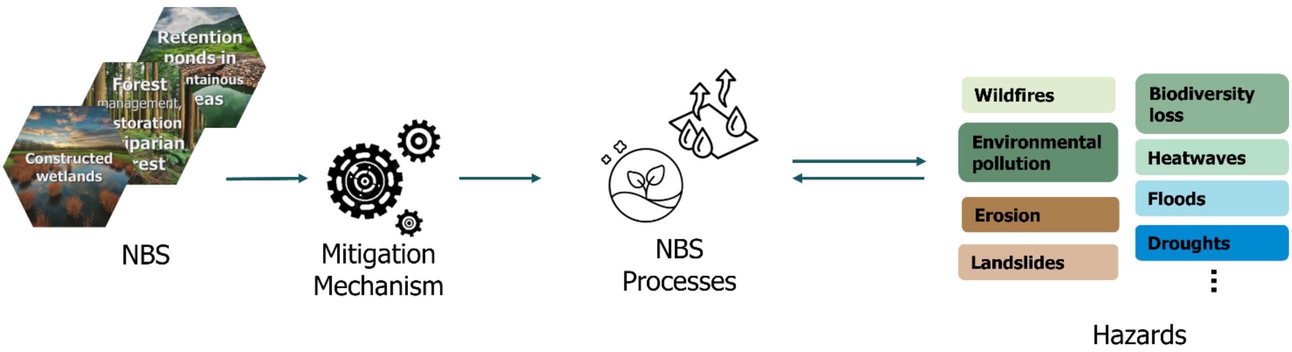

Figure 6. NBS mapping to hazards through their hazard mitigation mechanisms and related natural processes.

Therefore, to establish a process-based mapping of NBS to natural hazards, the following steps are necessary:

- **Identification of key processes**: This initial step involves compiling a comprehensive list of primary natural processes (e.g., infiltration, water retention, soil stabilization) utilized by NBS.
- **Matching processes to specific NBS**: Subsequently, it entails identifying particular NBS that either enhance or leverage these identified processes.
- **Linking processes to hazards**: This step focuses on mapping the natural processes (and thus, the corresponding NBS) to the natural hazards they effectively mitigate.
- **Evaluation of multi-hazard mitigation potential**: Ultimately, these preceding steps enable the assessment of each NBS capacity to address multiple hazards through the identified associated natural processes.

To derive the NBS processes that are the most relevant within the NATALIE framework, a detailed characterization of the different hazard mitigation mechanisms of the NATALIE NBS needs to be carried out before the identification of the corresponding **key natural processes**. Having identified the key processes and their mapping to natural hazards, it is then possible to derive the multi-hazard mitigation potential of a specific NBS. An example of the case of wetlands is shown in Figure 7.

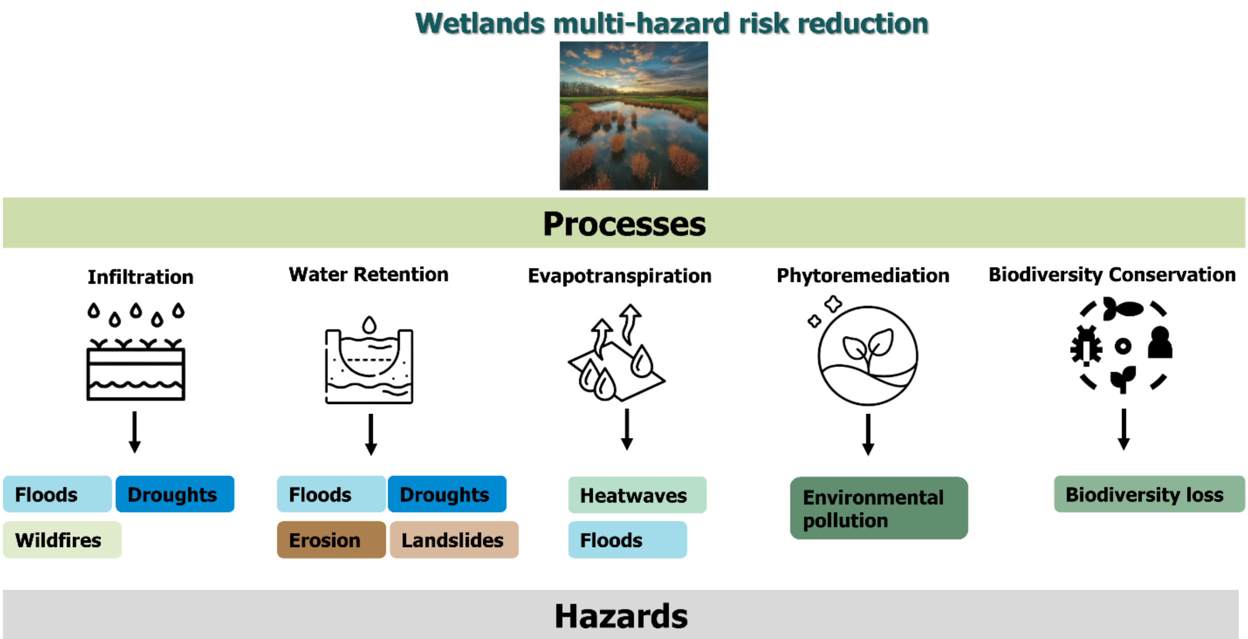

Figure 7. Example of process-based mapping of wetlands to various natural hazards.

The potential of a NBS to mitigate hazard and multi-hazard scenarios, can be further classified according to the contributing processes to mitigate each hazard (e.g., forests mitigate various flood drivers) and/or to the number of different hazards that can be addressed (e.g., wetlands may treat more hazards than prescribed burning). Another example of the mitigation potential of NBS is shown in Figure 8 for the case of forest management.

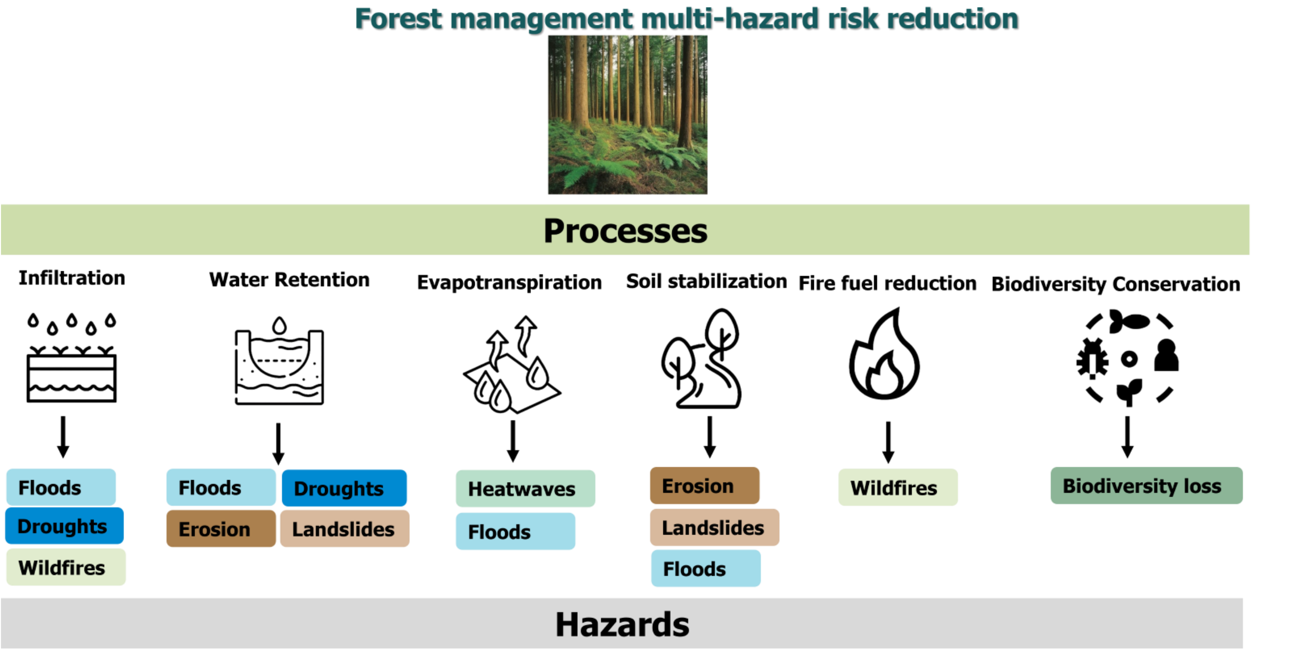

Figure 8. Forest management multi-hazard mitigation potential.

Therefore, a process-based mapping approach provides a structured method to understand and apply NBS for mitigating natural hazards. By focusing on key natural processes, this approach systematically identifies NBS that can address multiple hazards. Evaluating the overlap of these processes and the hazards they mitigate helps develop a strategic plan for implementing NBS in multi-hazard scenarios, in view of multi-hazard resilience. It should be noted though, that this framework may provide a systematic approach to assess the **potential** of each NBS to provide multi-hazard resilience. The actual suitability of NBS to address specific multiple hazards should also consider, from a technical perspective, the regional context of application (urban, peri-urban, rural), any pre-existing technical infrastructure, as well as the locals' experience.

II.3.3 Identification of NBS for specific multi-hazard scenarios

Introducing a process-based mapping of NBS to natural hazards is instrumental in identifying their potential for multi-hazard resilience. However, for practical design purposes, it is essential to consider the regional context. Not all NBS are universally applicable; their effectiveness can vary significantly based on local environmental and climatic conditions, as well as specific hazard profiles, including the scale of application. For instance, while green roofs and permeable pavements are highly relevant for managing urban flood hazards, they might not be as effective in rural areas or regions with different climatic conditions. Therefore, it is crucial to tailor the selection and implementation of NBS to the unique characteristics of each region to maximize their impact and sustainability.

As an example, the following scenario is considered, and the suggested steps are outlined.

Scenario: An urban area facing issues with urban flooding, heatwaves and water scarcity.

1. **Identify the hazards:**
    - Urban flooding
    - Heatwaves
    - Water scarcity (drought)
2. **Determine the key natural processes** (based on the context of application)**:**
    - Urban flooding: Infiltration, water retention
    - Heatwaves: Evapotranspiration, shading
    - Water scarcity: Infiltration, aquifer recharge, water collection/reuse
3. **Match processes to NBS** (based on the context of application)**:**
    - Infiltration: Rain gardens, permeable pavements, bioswales, urban parks/forests
    - Water Retention: Wetlands, retention ponds, urban parks/forests
    - Evapotranspiration: Green roofs, urban forests
    - Shading: Urban forests, green roofs
    - Aquifer Recharge: Managed aquifer recharge, constructed wetlands, bioswales
    - Water Collection/Reuse: Rainwater harvesting systems, green roofs
4. **Evaluate NBS multi-hazard mitigation potential:**
    - **Green Roofs:**
        - **Processes:** Infiltration, evapotranspiration, shading, water collection/reuse
        - **Hazards Mitigated:** Urban flooding, heatwaves, water scarcity
    - **Urban Forests:**
        - **Processes:** Evapotranspiration, shading, infiltration, water retention
        - **Hazards Mitigated:** Urban flooding, heatwaves, water scarcity
    - **Constructed Wetlands:**
        - **Processes:** Infiltration, aquifer recharge, water retention, phytoremediation
        - **Hazards Mitigated:** Urban flooding and water pollution, water scarcity
5. **Assess NBS integration and adaptation:**
    - Ensure that the selected NBS consider local environmental and socio-economic contexts, allowing for adaptive management and integration with existing infrastructure.

While steps 1-4 may follow a theoretical approach, as the one previously outlined, the final step is necessarily based on the local context. Therefore, to optimize the effectiveness of NBS in mitigating multiple hazards, it is crucial to engage local communities and stakeholders in the planning and implementation process to ensure that the selected NBS align with local needs and values. Additionally, integrating NBS with traditional engineering solutions can provide a hybrid approach that maximizes local resilience [35]. For instance, combining green roofs with existing urban drainage systems can enhance urban water management and reduce vulnerability to urban flooding.

II.4 Multi-risk assessment and cascading effects

Regions within the European Union are exposed to a variety of climate driven hazards including but not limited to heat extremes [36], droughts [37], flooding (coastal and inland) [38], windstorms [39] and wildfires [40]. Based on climate prediction models, it is expected that there will be an increase in the frequency and magnitude of various hazard types across some regions in Europe shown in Figure 9 [41].

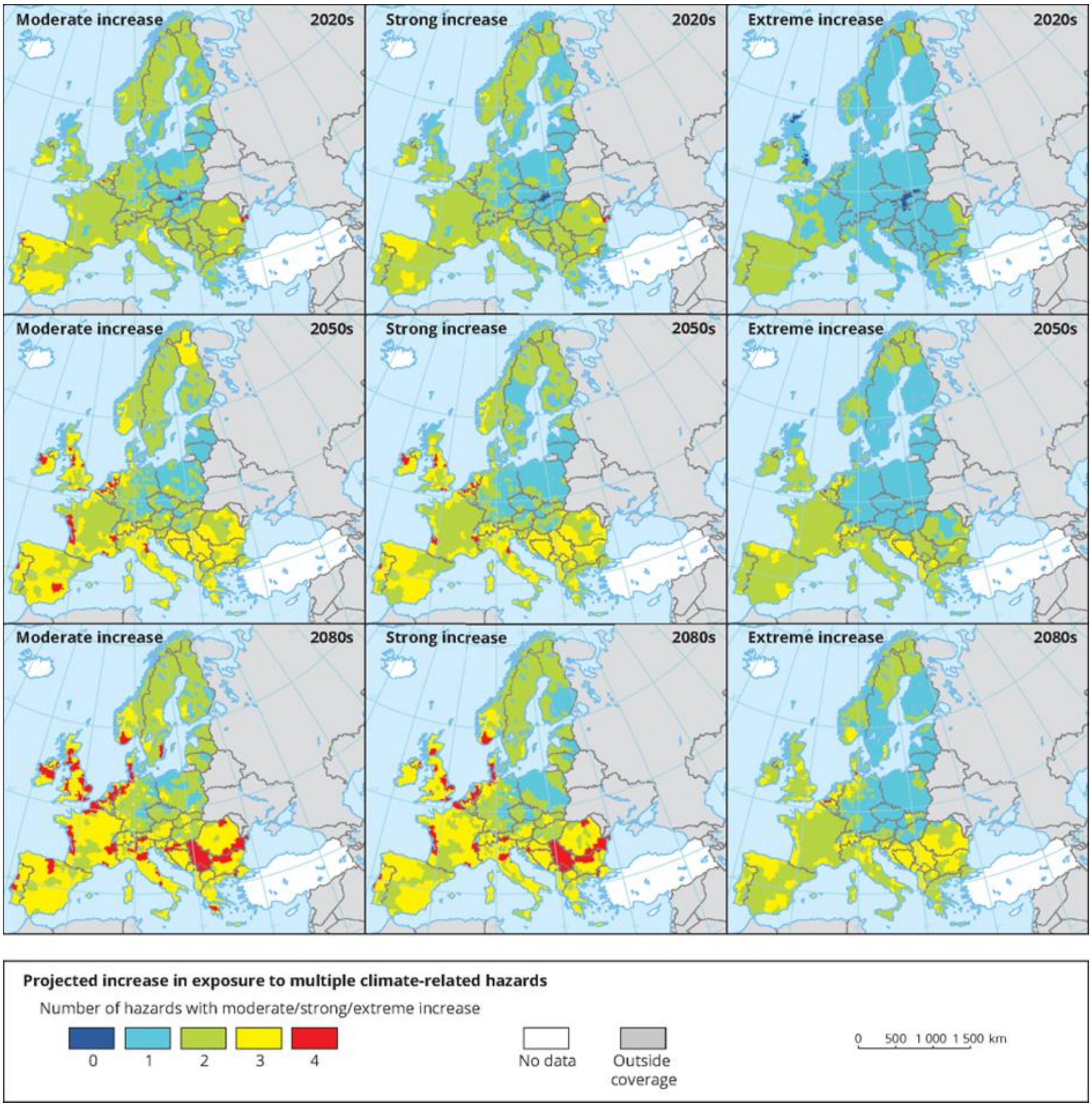

Figure 9. A multi-hazard assessment, considering the following seven hazards: heat waves, cold waves, droughts, wildfires, river floods, coastal floods and windstorms [41].

The derivation of what risks/impacts are the assets exposed (infrastructure, services people, etc.) is commonly derived as the product of Hazard, Exposure and Vulnerability, where:

- Hazard defines the magnitude and severity of an event over time and space.
- Exposure relates to the distribution of risk receptors in the affected region e.g. buildings, people, services, etc.
- Vulnerability refers to the susceptibility of the exposed risk receptors to damage or disruption from respective hazards.

When analyzing the risks posed by climate driven hazards, it is important to consider that these hazards (and their associated risks) may not necessarily occur in silo, with regions being potentially affected by multiple hazards and risks simultaneously or consecutively [7]. Thus, in the context of a multi-risk assessment, a complex variety of risks derived from various combinations of hazards and respective vulnerabilities to said hazards needs to be assessed [42], [43].

Through the mapping of interdependencies between assets and services and simulating "What-If" scenarios for different hazards, multi-risk assessments and cascading failures within modelled regions can be undertaken [44]. Figure 10 depicts a conceptual example of multi-risk assessment as a result of a compound coincident hazard event (two hazards affecting same region at the same time). Here assets can be regarded as being in four possible states:

- **Directly affected**: The asset is directly exposed to the hazard and as such is impacted resulting either in damage or disruption to a service it provides.
- **Indirectly affected**: The asset is not directly impacted by a hazard but is affected due to disruption caused to an asset or service whose is dependent upon.
- **In recovery**: The asset or service was previously affected either directly or indirectly by a hazard and is currently in "recovery phase" whereby its characteristics such as vulnerability may be different and change over time when compared to its pre-affected state.
- **Unaffected**: The asset or service is neither directly nor indirectly affected by any of the hazards

In the example shown in Figure 10, asset A_3 is being directly impacted by both hazards 1 and 2 and as such the magnitude of disruption could potentially be less or greater than the sum of the impacts if the hazards were to occur separately [45]. In addition, here asset A_4 is being indirectly affected by hazard 1 and directly affected by hazard 2. As such the level of risk A_4 is subjected to could potentially be higher than if it was not indirectly affected by hazard 1.

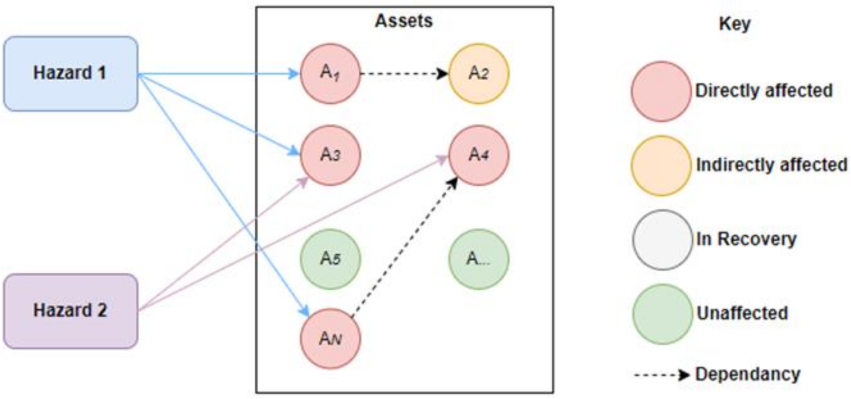

Figure 10. Schematic representation of compound coincident hazard interactions on assets.

Modifying the example shown in Figure 10 such that hazards 1 and 2 are now separated by time *Δt*, it is possible to highlight how the preceding influence of hazard 1 on the set of assets may affected the response of the assets to hazard 2. In this example, assets A_3 and A_4 may both still be in the recovery phase following hazard 1, affecting their respective vulnerabilities and degree of risk/impact they're subjected to from hazard 2 (Figure 11)

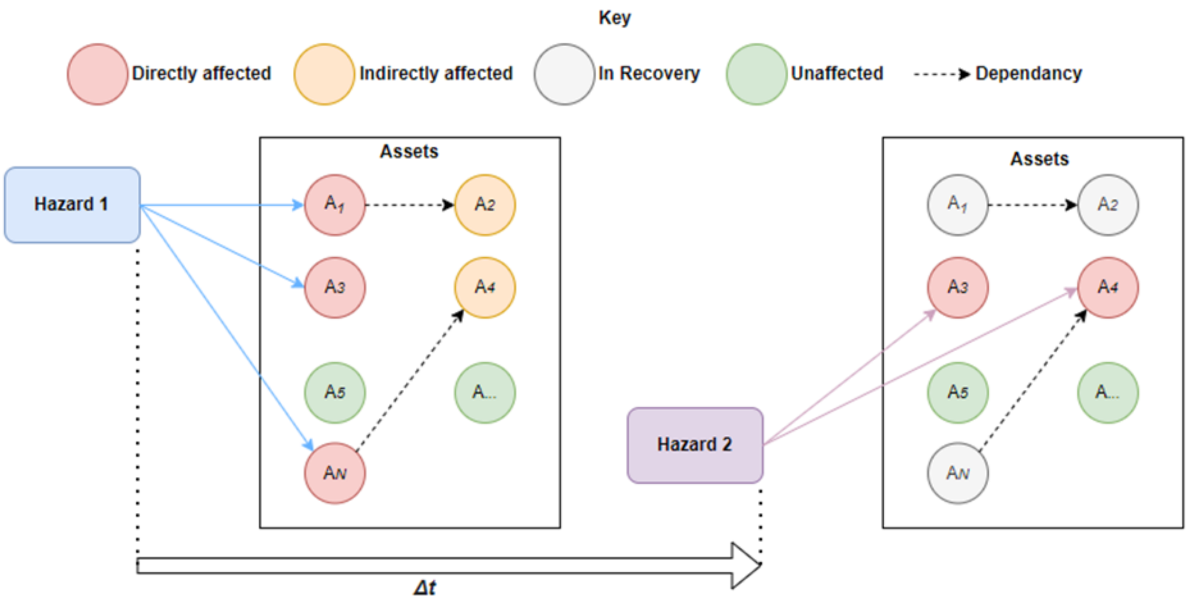

Figure 11. Schematic representation of compound consecutive hazard interactions on assets.

With Figure 10 and Figure 11 illustrating examples of potential cascading effects at the asset level for multi-hazard events, the interactions between hazards become more complex when the causal relationship between hazards, their environment and respective drivers are also considered. In Heilkema *et al.* [46], five potential interrelationships between compound hazards are defined:

1. **Independent**: Two or more hazards affecting the same region with no triggering relationship or dependence between them.
2. **Triggering or Cascading**: The influence of one hazard in a region leads to the causation of a subsequent hazard (e.g. flood triggering landslide).
3. **Change conditions**: Environmental conditions within a region are altered by one hazard that subsequent influences the likelihood and/or magnitude of a subsequent hazard (e.g. region affected by drought alters the likelihood of wildfire within said region).
4. **Association**: Two or more hazards are the result of the same triggering event (e.g. storm surge and extreme winds both driven by a cyclonic event).
5. **Mutual exclusion**: Negative dependence between hazards (e.g. Flooding from severe rainfall event reducing likelihood of wildfire).

These interrelationships between hazards can thus potentially alter both the magnitude and likelihood of compound hazards affecting a region. Also, preceding hazard events can result in changes in both vulnerability and exposure to subsequent hazards within an affected region. For a more comprehensive depiction of multi-risk over time the standard risk derivation formula becomes more complex. Figure 12 highlights this whereby the magnitudes and likelihoods of hazards can change over time and/or are influenced by prior hazards, with both exposure and vulnerability also being time and previous event dependent [47] (Figure 12).

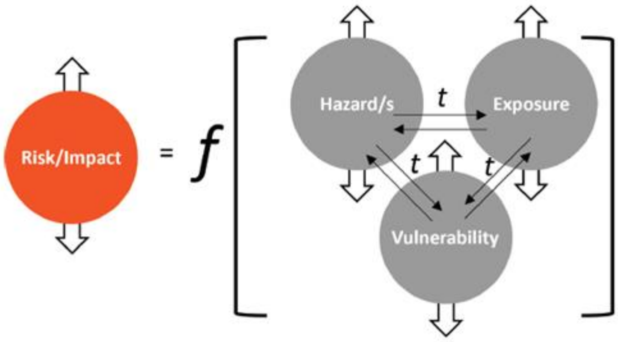

Figure 12. Dynamic risk equation based on interactions between hazard, exposure, and vulnerability over time [47].

Within the ICARIA project [25] these complex interactions between hazards are considered in the adopted holistic modelling approach whereby the interdependencies between hazards and how each hazard can affect the exposure and vulnerability off assets within a region are captured within a modelling timeline/chain (Figure 13). Within this approach, the effects of climate change and human behavior are considered along with potential application and influence of adaptation measures. Through a combination of coupling of hazard models and statistical and mathematical analyzes, the magnitude and likelihood of these compound events within the modelling chain is assessed with and without adaptation measures. Within the scope of NATALIE, a similar modelling chain approach is to be adopted with the focus on how the implementation of NBS solutions within the timeline of the modelling chain will change the risks posed to selected assets within the modelled regions.

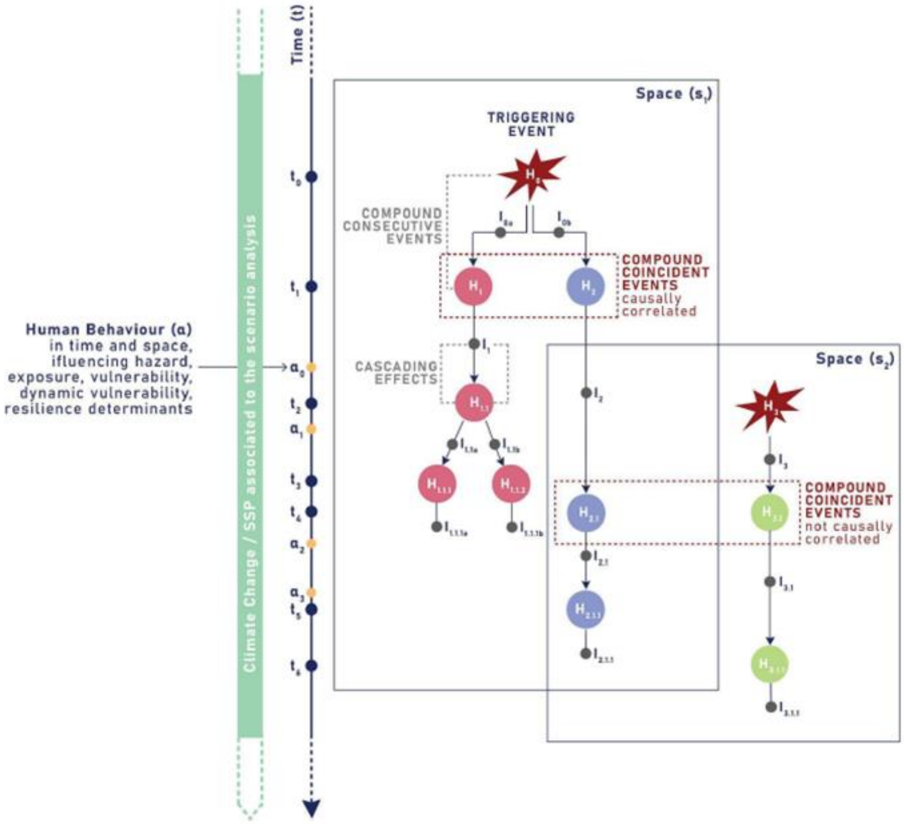

Figure 13. Timeline of events showing compound (coincident, causally or not causally correlated, and consecutive) events and cascading effects where "H" is Hazard, and "I" is Impact. The influence of key-variables (i.e., time, space, and human behavior) in the risk/impact/resilience assessment process has been considered (modified after Zuccaro et al. [27], outlined in ICARIA D1.1 [8]).

II.5 NBS as an adaptation measure providing co-benefits

NBS are assets that protect, sustainably manage, and restore natural or modified ecosystems. They effectively address societal challenges and adapt to provide benefits to human well-being and biodiversity [16]. NBS are adaptation measures that yield co-benefits for communities and ecosystems. For instance, agroforestry practices, such as integrating trees into agricultural systems, can enhance food security and increase resilience to drought and extreme weather events [48], while restoring and protecting wetlands can improve water quality, support biodiversity and provide recreational opportunities [49]. Co-benefits of NBS include:

- **Enhanced biodiversity and ecosystem services:** NBS can create, restore or protect habitats for various plant and animal species, supporting biodiversity conservation [14]. Restoring wetlands can provide breeding grounds for migratory birds and other wildlife [50]. NBS can enhance ecosystem services like pollination by supporting pollinator populations, water purification through natural filtration processes and carbon sequestration by preserving and restoring carbon sinks like forests and peatlands [13] [50].

- **Climate change mitigation:** Forests, wetlands and other natural ecosystems act as carbon sinks, absorbing and storing atmospheric carbon dioxide [51] [52]. Sustainable forest management, reforestation and the restoration of degraded lands can increase carbon sequestration potential, while also providing other co-benefits like biodiversity conservation and soil protection [53].

- **Economic opportunities:** Well-managed protected areas and natural landscapes can attract eco-tourists, providing income for local communities [54] and increase property value [55]. NBS can support sustainable agriculture, forestry and fisheries, contributing to local livelihoods and food security [56]. NBS can also create green jobs in sectors such as ecosystem restoration, urban greening and sustainable resource management [57] [57].

- **Improved human health and well-being:** Urban green spaces provide opportunities for physical activity, which can reduce the risk of obesity, cardiovascular diseases and other chronic conditions [59]. Exposure to natural environments has been shown to lower stress levels, improve mental well-being, and enhance cognitive function [59] [60]. Green spaces can also improve air quality by filtering particulate matter and absorbing gaseous pollutants, leading to better respiratory health [62], [63].

- **Social and cultural benefits:** NBS can help preserve cultural landscapes, traditional practices and indigenous knowledge related to natural resource management [64]. NBS can provide opportunities for environmental education, community engagement, and citizen science initiatives, fostering a connection with nature and promoting sustainable behaviors [18].

Figure 5 illustrates the conceptual framework that encompasses three major groups of impacts in the form of co-benefits: environmental, social and economic, which emphasizes the modelling and quantification of these potential co-benefits, as well as the cascading effects and interaction between them.

The environmental co-benefits of NBS include the enhancement of biodiversity, the improvement of air and water quality, the regulation of local climate conditions, and the provision of ecosystem services such as carbon sequestration, soil erosion control and flood regulation. These environmental benefits not only contribute to the overall health of ecosystems, but also have direct and indirect impacts on human well-being.

Social co-benefits encompass the positive effects of NBS on human health, both physical and mental, as well as the promotion of social cohesion, cultural heritage preservation, and environmental education opportunities. Green spaces in urban areas, for instance, can provide recreational opportunities, reduce stress levels, and foster community engagement, thereby improving the overall quality of life for residents.

Economic co-benefits arise from the potential of NBS to generate sustainable income streams through activities such as eco-tourism, sustainable resource management and the creation of green jobs. Additionally, NBS can contribute to increase property value [55] and cost savings by providing natural solutions to challenges such as flood mitigation, coastal protection and urban heat island mitigation, potentially reducing the need for costly traditional infrastructure.

Furthermore, the cascading effects of these co-benefits should be considered. For example, improved air quality and access to green spaces can lead to better public health outcomes, which in turn can reduce healthcare costs and increase productivity. Similarly, enhanced biodiversity and ecosystem services can support sustainable agriculture and tourism, contributing to local economic development.

Traditionally, assessment of NBS have focused primarily on the direct costs and benefits related to the specific objective, such as flood risk reduction or coastal protection. However, this narrow approach fails to capture the full range of benefits that NBS can provide to communities and ecosystems. By quantifying and including these co-benefits in the assessment, the overall cost-benefit ratio of NBS can be significantly improved, making them more viable compared to traditional gray infrastructure solutions [34], [65].

The integration of co-benefits, such as improved human health, enhanced biodiversity and social and cultural benefits, into economic evaluations has the potential to significantly enhance the overall economic efficiency and viability of NBS [34]. By considering these additional benefits alongside the primary objectives of NBS, decision-makers can make more informed choices that maximize economic efficiency while simultaneously addressing the multifaceted challenges posed by climate risks (Figure 14, [34]).

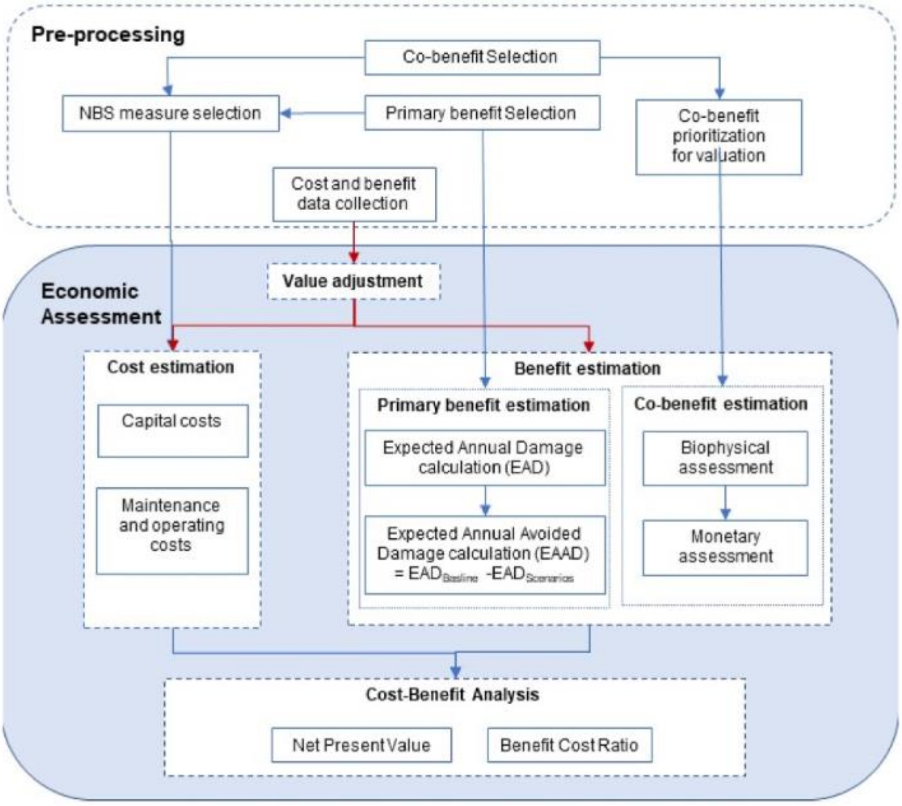

Figure 14. Overall methodology for economic assessment of NBS for flood risk reduction and co-benefits. [34]

However, reducing the value of co-benefits to a cost-benefit analysis is a controversial issue. There is also the opposite opinion considering monetization of ecosystem services would reinforce the commodification of nature which leads to opposite outcomes than the desired ones [66]. For this reason, in the NATALIE project, in addition to cost-benefit analysis, a multi-criteria analysis (MCA) is included [67]. Multi-criteria analysis, commonly referred to as MCA, involves assigning weights to various normalized indicators, a task typically undertaken by subject matter experts and local stakeholders in a co-creation process. One of MCA's primary strengths lies in its ability to evaluate a diverse array of variables within a unified framework. This includes the capacity to analyze monetary (including cost-benefit analysis), quantitative and qualitative data simultaneously. At the same time this capacity can be considered as its major disadvantage, as trying to simplify and normalize different units and criteria can lead to a loss of accuracy [67], [68] . In this context, NATALIE project aims to reach a comprehensive assessment of NBS impact reduction and co-benefits applying both CBA and MCA analysis.

II.6 Indicators to assess the impact of Nature-Based Solutions

Indicators play a pivotal role in evaluating the performance and impact of NBS for climate change adaptation. They serve as simplified, quantifiable measures that provide valuable insights into complex phenomena. Indicators can be single or aggregated parameters that describe in synthetic form the impact on the elements exposed in a study [8]. The role of indicators in environmental projects is multifaceted, encompassing design analysis, optimization, hazard and risk reduction estimation, as well as co-benefits estimation.

To clarify the distinction between key terms, variables are the data values measured directly or modelled, such as temperature, rainfall, or flood depth. Indicators, on the other hand, can then be derived from these variables and represent broader concepts or trends, such as heat island intensity or flood risk [69]. Monitoring is the ongoing process of collecting and analyzing data over time that can facilitate the evaluation of indicators, among other issues.

Indicators contextualize variables by interpreting them within specific reference points/thresholds established for each case study and the related scope. For instance, if a flow threshold is set, below which a riverine ecosystem is threatened, then the measured/modelled flow time series can be expressed in relation to the aforementioned threshold in the frame of assessing the river ecological status. This means that while variables provide raw data, indicators translate this data into meaningful insights relevant to the particular conditions at a site of interest and goals of a project. For instance, water quality measurements can be used to evaluate different indicators depending on the context; in one case study, it might be an indicator related to ecosystem health, while in another, it could indicate the effectiveness of a water purification NBS. By contextualizing variables in this way, indicators help stakeholders understand and evaluate the specific impacts and performance of NBS interventions in a targeted and relevant manner [70].

Within the scope of assessing NBS, indicators are crucial for several reasons [71]:

- **Design/feasibility analysis and optimization:** During the planning phase, indicators can help assess the feasibility and effectiveness of various NBS designs and types, identify, and therefore allow for NBS optimization. For instance, in the case of urban greening projects, indicators related to soil stability, water retention capacity and native species viability can guide the selection and design of appropriate NBS [17].
- **Hazard and Risk reduction estimation:** A primary goal of NBS is to mitigate risks associated with climatic and environmental hazards, such as flooding, erosion and extreme weather events. Indicators like flood frequency, sedimentation rates and vegetative cover provide estimates of how effectively a NBS reduces hazards and the associated risks [12].

- **Co-benefits estimation:** Beyond direct climate adaptation benefits, NBS often provide additional co-benefits such as enhanced biodiversity, improved air and water quality, and recreational opportunities. Indicators related to ecosystem health, environmental pollution levels, the local economy and community well-being in general, can help quantify various co-benefits stemming from NBS implementation, demonstrating the broader value of NBS interventions [51].

In the NATALIE project, a targeted set of indicators will be used to assess the effectiveness of NBS. A compilation of multiple indicators from various sources will be used to ensure an interdisciplinary evaluation of the proposed measures in each CS (Figure 15). Such sources can include the EU Handbook for the evaluation of NBS measures [72] or other sources such as connecting projects (ICARIA, RECONNECT, ARSINOE, euPolis…). Part of this work is going to be elaborated within Task 3.2 by identifying relevant indicators under each hazard examined within NATALIE. This work is also going to inform WP4 and specifically Task 4.5 that will operationalize the developed indicators through the NATALIE NBS Knowledge Booster. By effectively utilizing indicators, stakeholders in projects like NATALIE can gain valuable insights into the efficacy of NBS in promoting climate change adaptation across Europe.

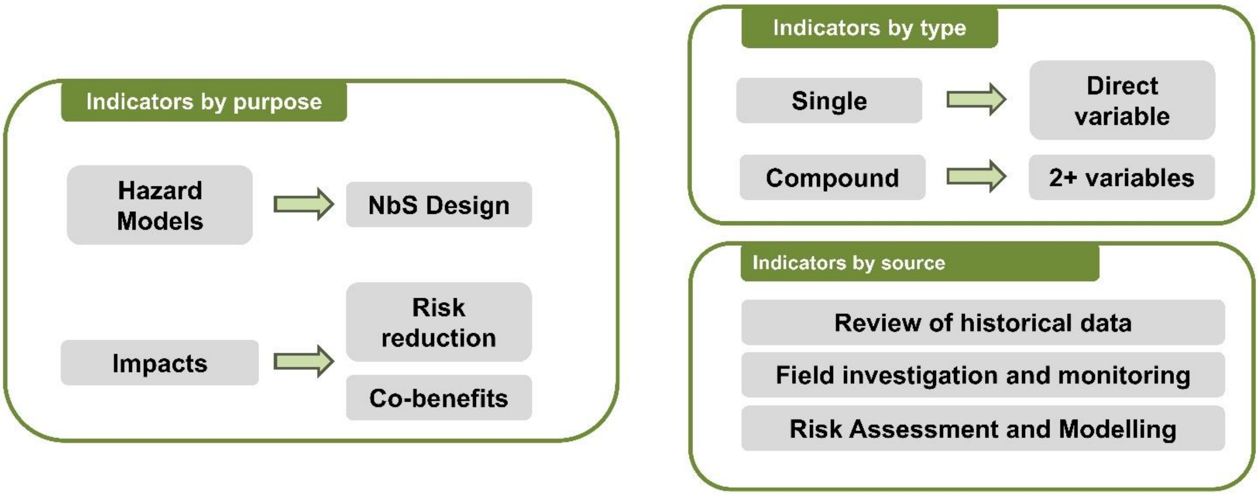

Figure 15. Classification of indicators by purpose, type, and source.

II.7 Monitoring and evaluation of NBS

NBS are increasingly recognized as sustainable and cost-effective approaches to address various environmental, social, and economic challenges. NBS involve the use of natural processes and ecosystems to provide benefits such as climate change adaptation, disaster risk reduction, water and air purification, and biodiversity conservation [51]. However, the successful implementation and long-term effectiveness of NBS rely heavily on robust monitoring and evaluation frameworks.

Monitoring NBS is crucial for several reasons. First, it allows for the assessment of the performance and impacts of NBS interventions, ensuring that they are achieving their intended objectives and providing the expected benefits [17]. Second, monitoring data can inform adaptive management strategies, enabling adjustments and improvements to NBS design and implementation based on real-world observations [73]. Third, monitoring contributes to the knowledge base and evidence-based decision-making, supporting the mainstreaming and upscaling of NBS as viable solutions [64].

Monitoring is a continuous and transversal process that needs to be carried out across all stages of NBS operationalization. It involves measuring, recording, and comparing achievements against predefined targets, thereby informing project outcomes to managers and policymakers to assist them in decision-making. Monitoring can be conducted by internal (individuals or project participants) or external organizations/institutes (e.g., European Commission), or collaboratively, to assess the performance and effectiveness of NBS, revealing their wider benefits and impacts [74].

This 'across all stages' approach helps devise long-term plans and goals [17] for effective NBS implementation, utilizing the acquired knowledge about NBS functioning [75]. Monitoring should be carried out both before and after the implementation of NBS. Prior the implementation, various data sources are utilized to establish a baseline or reference point for monitoring purposes. These sources include municipal records, previous monitoring studies, statistical databases and platforms, peer-reviewed literature as well as grey literature (research and materials produced outside of traditional academic or commercial publishing channels), interviews, workshops, and questionnaires. Once NBS are implemented, monitoring efforts shift to assessing both on-site and off-site indicators. Physical indicators, such as land use patterns and the growth rates of green NBS elements, are evaluated. Additionally, socio-economic indicators are tracked, including cost-benefit analyzes, social changes like migration rates, and other relevant data points. This comprehensive monitoring approach aims to capture the multifaceted impacts of NBS initiatives during the post-implementation phase. [74].

Monitoring is usually carried out throughout the lifespan of NBS projects (ex-ante and ex-post project execution stages; Figure 16), either by internal or external organizations/institutes, or collaboratively. It is a process of measuring, recording, and comparing achievements against predefined targets, thereby informing project outcomes to managers and policymakers to assist them in decision-making.

The importance of NBS monitoring extends beyond project-level evaluations. It plays a vital role in risk assessment processes, particularly in the context of climate change adaptation and disaster risk reduction [76]. By monitoring the effectiveness of NBS in mitigating risks, enhancing resilience and co-benefits, decision-makers can better understand the potential benefits and limitations of these solutions, informing risk management strategies and resource allocation [77].

Furthermore, NBS monitoring contributes to the development of standardized methodologies and indicators, facilitating comparisons across different contexts and enabling the integration of NBS into broader environmental and urban planning frameworks [29], [72].

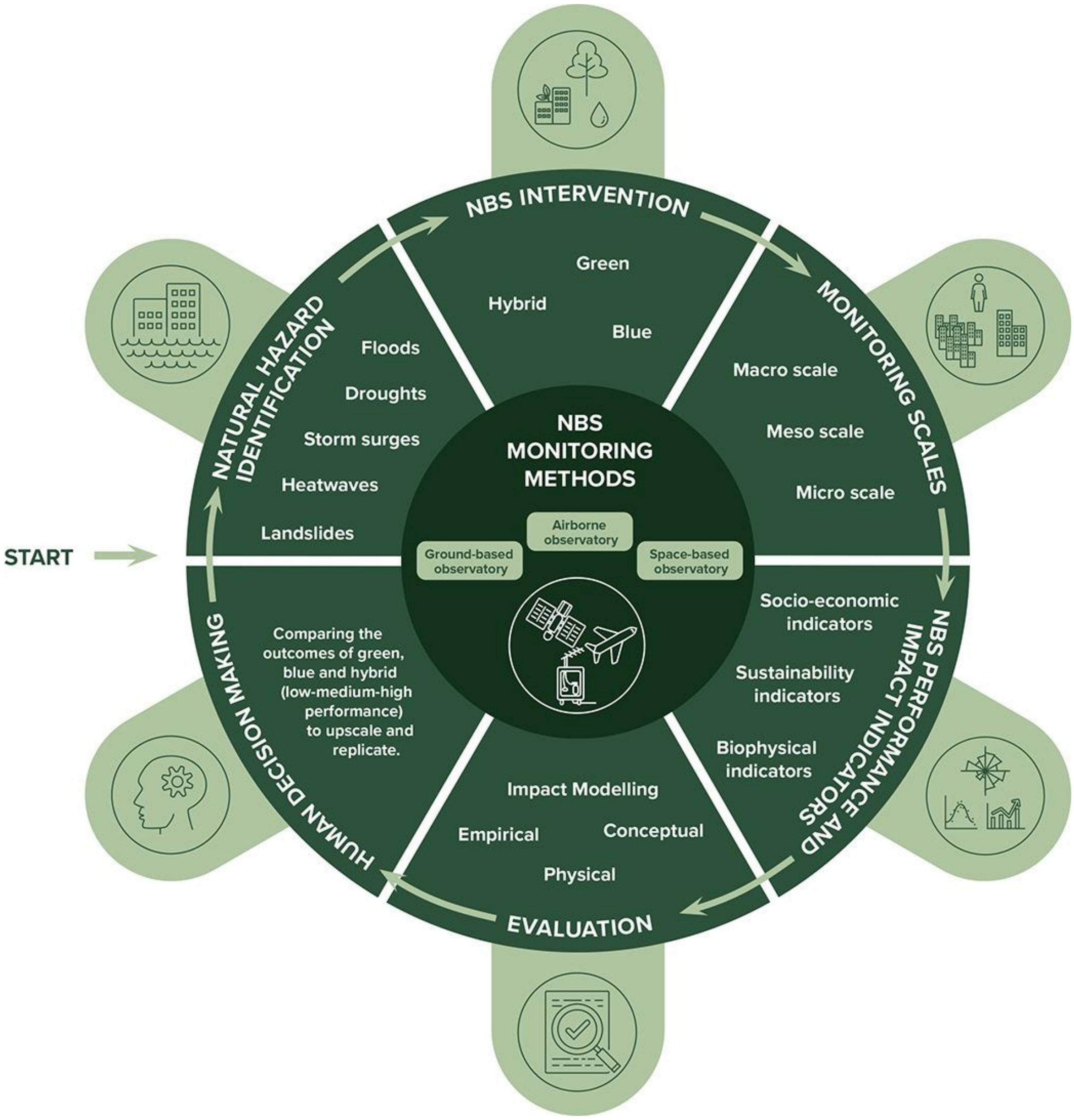

Figure 16. A schematic diagram showing the NBS monitoring cycle along with the potential methods, technologies and the scale of monitoring [74].

II.7.1 Case Study monitoring

To comprehensively assess the performance of the NBS measures implemented, it is crucial to design and follow-up robust monitoring campaigns. These campaigns aim to measure various variables (biological, physico-chemical, hydrological, etc.) that could differ from one CS to another, depending on the local climatic challenges, the specific NBS measure(s) implemented and the objectives to achieve.

The monitoring process involves collecting field data, either manually or through automatic systems. This data can then be used for direct statistical CS response before and after the implementation of the NBS measures. By analyzing the changes in the measured variables, it becomes possible to build evidence on the efficiency and effectiveness of the implemented measures.

Additionally, the collected data can be combined with existing databases (meteorological, water-related, etc.) to calculate indicators that further demonstrate the robustness and efficiency of the NBS measures.

These indicators can provide valuable insights into the performance of the measures and their ability to address the specific challenges faced at each site.

In some cases, modeling techniques may be employed to enhance the analysis and interpretation of the collected data. WP3 can provide support and guidance in this regard, offering expertise in data analysis, modeling and indicator development. To facilitate this process, WP3 partners need to be informed about the specific variables that each NATALIE CS plans to measure in the field and/or collect from existing databases. This information is crucial for developing tailored approaches and methodologies for data analysis and performance assessment. A questionnaire (Table 3) has been conducted among the case studies to collect, in an initial phase, the variables that will be measured, along with the equipment to be used, their location, scale and measurement plan. The responses to this questionnaire for each case study can be found in D5.2.

Table 3. CS's monitoring questionnaire.

Demonstration Site #Y	**Leading partner: YYYY** **Leading person: JJJJJ**
Site #X	**Name of the site (only if there are several sites in the DS)**
Measure #X.Z	**Name of the measure implemented**
Monitoring #Y Please create multiple sections for each variable or group of variables being monitored	
Related hazard or impact	*Could you please provide a description of the primary hazard or impact associated with the indicator?*
Variable	*Can you please provide detailed information on which monitored variables you are planning to monitor?*
Description and justification	*What is the purpose for monitoring these variables? (model calibration, Hazard / Impact assessment, NBS performance assessment)*
Equipment	*Could you please provide a detailed description of the equipment necessary for monitoring purposes?*
Location and scale of measurement	*Please describe the location and scale of the monitoring equipment, such as NBS inlet and outlet, spillways, etc.*
Data collection frequency	*Could you please provide more information about the frequency (how often) of the monitoring?*
Campaign dates	*Indicate the period of monitoring and the number of campaigns*
Other sources	*Could you indicate the other sources of data you plan to use?*

II.7.2 Earth observation (EO) and environmental sensing datasets

Earth Observation (EO) and environmental sensing datasets can help to address various challenges relevant to the **identification, modelling and monitoring** of compound and multi-hazard events and related cascading effects.

In terms of **identification**, EO data can help to identify patterns and relationships between different hazards and environmental variables. This can help in detecting potential compound events, including multi-variate events and understanding their underlying drivers, as well as the precise combination of climatic variables (and their associated temporal and spatial scales) that could trigger system failure (cascading effects), particularly for more complex systems. For instance, EO data, such as those from Synthetic Aperture Radar (SAR), can identify areas of heavy rainfall and resultant flooding. By overlaying this information with topographical data, it's possible to identify regions at high risk of landslides due to saturated soils.

In terms of **modelling**, EO data can provide key inputs for **model setup and calibration,** for instance by providing estimates of soil parameters required in rainfall-runoff models. EO data may also help when **modelling pre-conditions** aggravating a hazard (preconditioned compound events), e.g., high soil moisture (saturated soils), or land cover changes (burnt areas). For example, remote sensing data on soil moisture and terrain characteristics can be incorporated into landslide susceptibility models to predict the likelihood of landslides triggered by heavy rainfall.

In terms of **monitoring**, EO data can be utilized to monitor both the spatiotemporal occurrence of hazards (spatially and temporally compounding events and multi-hazard events) and implement real-time monitoring systems that utilize open datasets to detect the onset of multiple hazards or compound events. Likewise, EO can be used to monitor hazard impacts (related to cascading effects), e.g., air quality degradation after a fire event, and are increasingly employed in this respect. For instance, California's 2020 wildfires, triggered by a heatwave and lightning strikes, were monitored using NASA's MODIS for damage assessment and air quality monitoring [78]. Similarly, Hurricane Maria's 2017 impact in the Dominican Republic was analyzed using Sentinel-1 and RADARSAT-2, mapping ground saturation to identify flood and landslide-affected areas [79], while Sentinel-1 and Sentinel-3 data were used to map flooded areas resulting from Cyclone Idai [80].

EO data may also be used for monitoring specific NBS and assessing their performance, particularly when large spatial scales are of interest, where some trade-offs in accuracy may be accepted [74]. For example, the GlobWetland project demonstrated how EO technology can support large-scale wetland conservation and management by inventorying, monitoring, and assessing wetland ecosystems [81].

III Climate and socio-economic scenarios

When developing an adaptation measure, as NBS, it is important to consider a range of scenarios to assess its effectiveness in the short, medium and long term. These scenarios should not only be based on historical climate data, as historically done in infrastructure design, but should also incorporate future scenarios based on different socioeconomic narratives [1].

To achieve this, it is essential to evaluate the potential effects of climate change on various climatic variables, identify the future socioeconomic scenarios to be tested, and analyze their possible impacts in a study area. This section treats the scenarios building philosophy in NATALIE and their application to the case studies.

First, an introduction is provided about the impact of climate change on climate variables, explaining the importance of considering these scenarios for designing and implementing NBS. Additionally, the socio-economic scenarios outlined in the 6th IPCC report are defined [1]. The discussion then focuses on the potential impact of climate tipping points (critical thresholds that, when exceeded, will lead to significant and often irreversible changes in the state of the climate system), which may extend beyond the scope of the IPCC reports and should be taken into consideration as applicable. Lastly, the text delves into the climate scenarios and the approaches to be considered in the case studies of the NATALIE project.

Please note that on the delivery date of this document, the downscaling of climate data by EUROCORDEX, the main data source for its application in case studies, has not been published. This data and further discussion will be included in D3.2 (M24) once it becomes available.

III.1 Effects of climate change on weather variables

The IPCC's AR6 report [1] develops a thorough analysis of the current scientific understanding of climate change, including its impacts and potential future risks. The report focuses on how climate change affects different weather patterns and its significant implications for natural and human systems around the globe.

One of the most well-documented effects of climate change is the increase in global mean surface temperature. The report states that the global surface temperature has increased by approximately 1.1°C since the pre-industrial era (1850-1900), with the last decade (2011-2020) being the warmest on record. This warming trend is expected to continue, with projected increases ranging from 1.0°C to 5.7°C by the end of the 21st century, depending on future greenhouse gas emission scenarios.

Climate change is also altering precipitation patterns globally. The report indicates that precipitation has increased in many mid-latitude and high-latitude regions, while it has decreased in several subtropical and tropical regions. These changes are projected to become more pronounced in the future, with an overall increase in the frequency and intensity of heavy precipitation events in many regions. However, some areas, particularly in the subtropics, are expected to experience more frequent and severe droughts [1].

The IPCC's AR6 report [1] highlights the increasing frequency and intensity of extreme weather events as a direct consequence of climate change. These include heat waves, heavy precipitation events, pluvial and fluvial flooding, droughts, and tropical cyclones. Figure 17 illustrates the anticipated occurrence of extreme precipitation events as the maximum annual daily precipitation, in a 10-year return period (depicted in blue) and 50-year return period (shown in orange) with respect to the reference period of 1850-1900. The data presented pertains to land areas worldwide. Each graphical element consists of a central line indicating the median, while the surrounding box represents the 66% confidence interval for intensity variations across multiple models. The extended lines, or 'whiskers', denote the 90% confidence range. These projections are derived from an ensemble of global climate simulations, specifically those contributing to the AR6 of the

Coupled Model Intercomparison Project (CMIP6). The models incorporate various Shared Socio-economic Pathway (SSP) scenarios to forecast future climate scenarios.

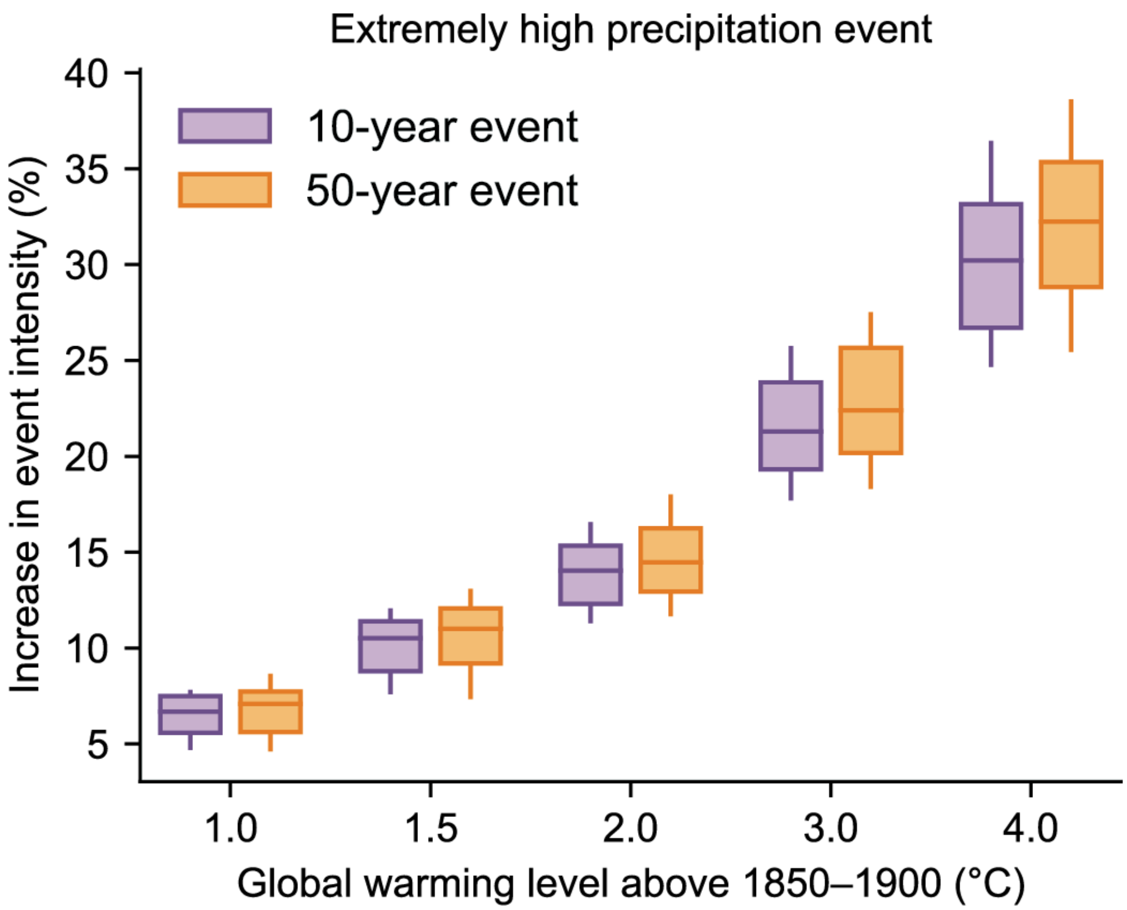

Figure 17. Projected changes in the intensity of extreme precipitation events under 1°C, 1.5°C, 2°C, 3°C, and 4°C global warming levels relative to the 1850–1900 baseline. [1]

Rising sea levels are another significant impact of climate change, primarily driven by the melting of glaciers and ice sheets and the thermal expansion of ocean water (Figure 18). The report projects that global mean sea level will continue to rise throughout the 21st century, with estimates ranging from 0.28 to 1.01 meters by 2100, depending on future greenhouse gas emissions and the response of the Antarctic ice sheet.

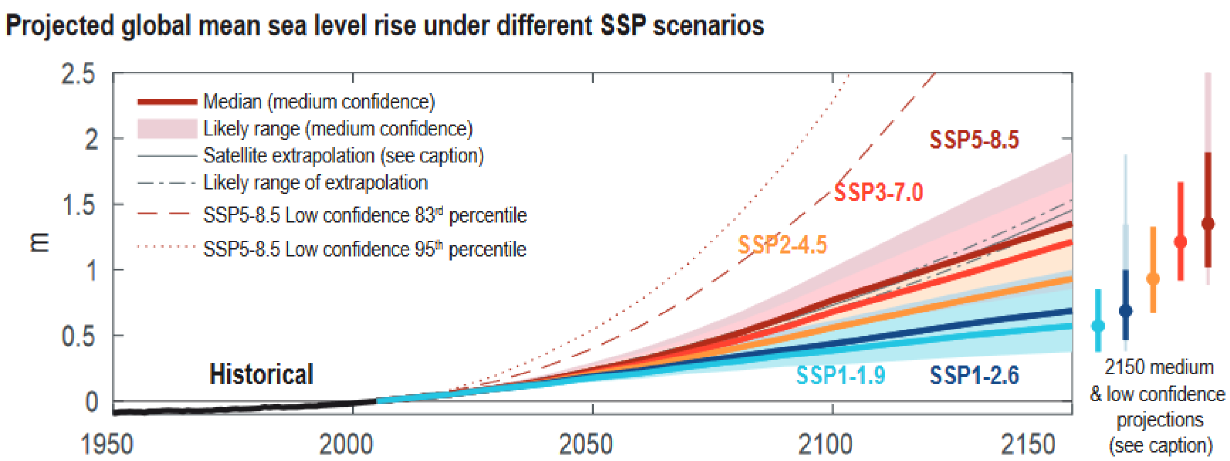

Figure 18. Projected global mean sea level rise under different SSP scenarios.[1]

III.2 Future socio-economic scenarios from the IPCC 6th report

III.2.1 Natures Futures Framework

NBS are integrated within the Nature Futures Framework (NFF) as part of the broader approach to envisioning and planning for desirable futures for both people and nature. The NFF, developed by IPBES, is designed to support the creation of scenarios and models that reflect different value perspectives on the relationship between humans and nature [82], [83].

The Nature Futures Framework (NFF) employs a triangular model to illustrate three distinct yet interconnected perspectives on the value of nature [82]. These perspectives are represented by the triangle's vertices: the intrinsic value (nature for its own sake), the relational value (nature as a cultural element), and the instrumental value (nature's benefits to society). Overlapping colored circles at each vertex symbolize the interplay between these perspectives, emphasizing that they are not mutually exclusive. The area within the triangle represents positive future scenarios for nature, while the space outside denotes unfavorable outcomes for both nature and humanity. This framework acknowledges that certain futures may seem advantageous for specific aspects of nature or its contributions to people but could potentially lead to detrimental effects on numerous other fronts. The triangle's edges signify that the distinction between desirable and undesirable futures often depends on context and location. Importantly, the NFF does not prioritize any single value perspective over the others. Users have the flexibility to position any of the three values at the triangle's apex, depending on their specific needs or focus.

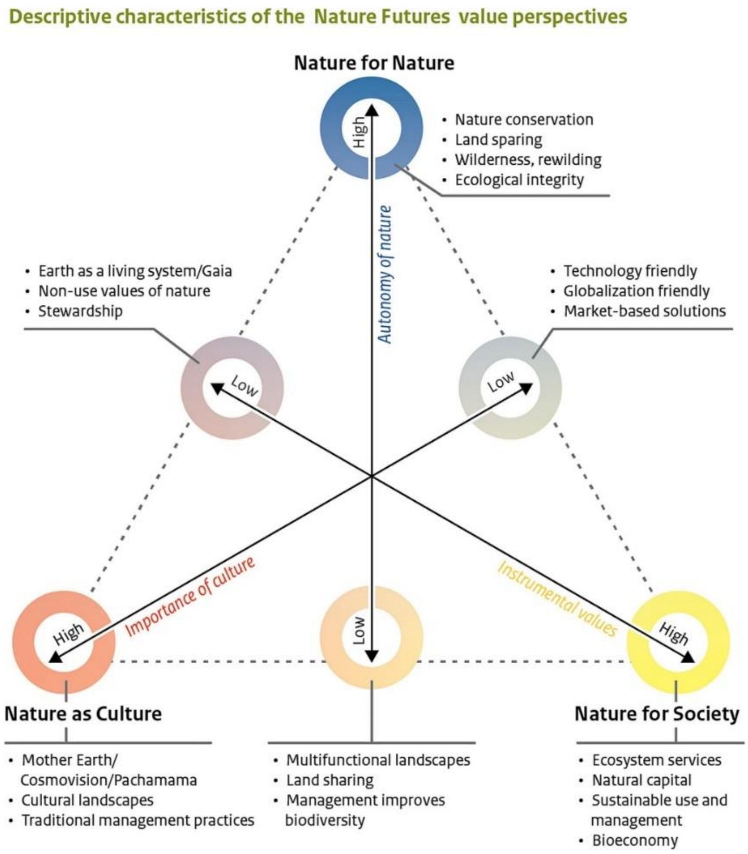

Figure 19. Descriptive characteristics of the Nature Future value perspectives and the space between these perspectives where the values converge.

Within this framework, NBSs are typically aligned with the "Nature for Society" perspective, which emphasizes the benefits that nature provides to human well-being and societal development [84]. This perspective focuses on leveraging natural processes and ecosystems to address societal challenges, such as climate change, food security, and urban resilience. NATALIE project adopts this perspective to develop future socio-economic scenarios according to it.

III.2.2 The IPCC AR6

The IPCC serves as a pivotal organization in the global response to climate change. This body is tasked with compiling and synthesizing scientific, technical, and socioeconomic data related to anthropogenic climate change, its potential consequences, and strategies for adaptation and mitigation. The IPCC's comprehensive assessments are instrumental in guiding the United Nations Framework Convention on Climate Change (UNFCCC), the primary international agreement addressing climate-related issues. The UNFCCC's core objective is to stabilize greenhouse gas levels in the atmosphere, thereby averting dangerous human interference with Earth's climate system [1].

Regarded as the preeminent authority on climate science, the IPCC has recently released its AR6. This latest report, which has garnered support from both the scientific community and governmental bodies worldwide, encapsulates the most current research and findings in the field of climate science. By consolidating and presenting this information, the IPCC plays a crucial role in shaping global understanding and policy responses to the ongoing challenge of climate change.

The CMIP, a collaborative initiative established in 1995 by the Working Group on Coupled Modeling (WGCM) under the World Climate Research Programme (WCRP), forms the foundation for the state-of-the-art climate change science presented in the IPCC's AR6. CMIP has evolved through successive phases, with its latest (sixth) iteration incorporating advanced Earth System Models (ESMs) and introducing new emission scenarios tailored to current adaptation and mitigation needs.

ESMs, which are at the core of CMIP6 [85], are sophisticated coupled atmosphere-land-ocean general circulation models (Figure 21). These models represent all components of the climate system, including the carbon cycle, allowing for interactive calculation of atmospheric CO2 or compatible emissions. Some ESMs may also incorporate additional elements such as atmospheric chemistry or dynamic vegetation, though these are often addressed through static input data like monthly leaf area index [86].

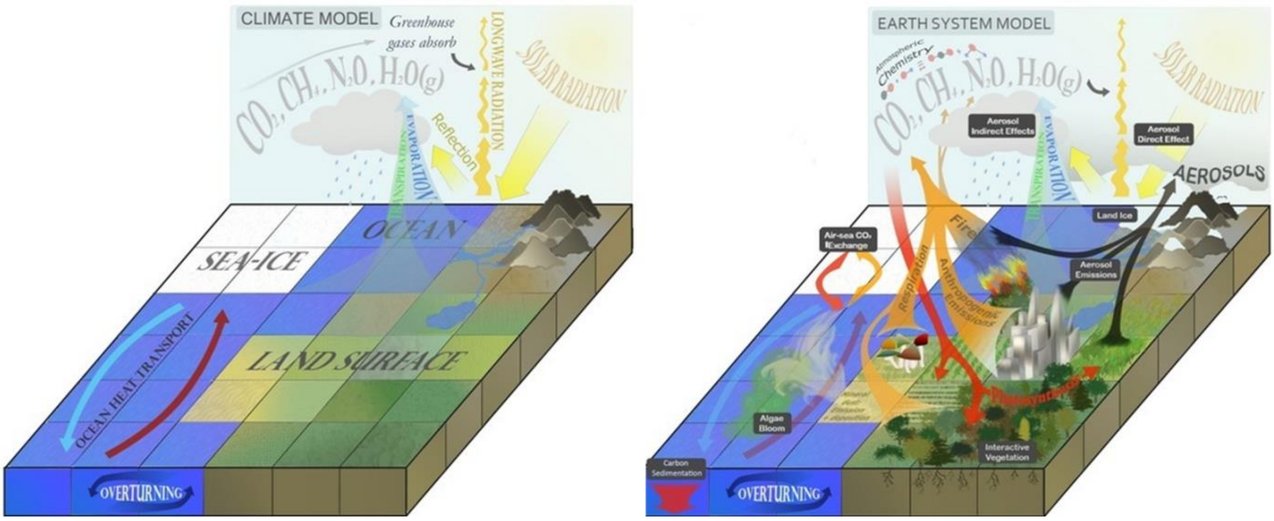

Figure 20. Key features of climate models and earth system models: Earth system models gain complexity by considering the biological and chemical processes that feedback into the physics of climate [87].

CMIP's standardized experiment protocols, forcings, and outputs have significantly enhanced our understanding of historical, present, and future climate changes within a multi-model framework. This initiative not only drives improvements in climate models but also supports global and national climate change assessments. By providing a comprehensive, multi-model approach, CMIP has become an invaluable tool in comprehending and addressing the complexities of climate change, underpinning the critical work of the IPCC in informing global climate policy.

The latest iteration of the CMIP6 has introduced significant advancements in climate modeling, particularly in the consideration of future greenhouse gas (GHG) concentration scenarios. This new approach replaces the Representative Concentration Pathways (RCPs) used in CMIP5 with the SSPs. The SSPs represent a notable improvement as they provide a narrative on potential societal evolution alongside emission scenarios.

Climate models employ these concentration scenarios, derived from emissions scenarios to project future climate outcomes. Emission scenarios depict plausible future substance releases, including greenhouse gases and aerosols, based on various factors such as demographic trends, socio-economic development, land-use changes, and technological evolution. The resulting climate scenarios offer simplified yet plausible representations of future climate conditions, driven by internally coherent physical relationships [88].

As reported in the IPCC's AR6 [1], CMIP6 models demonstrate higher spatial resolution and an increased ability to represent atmospheric circulation patterns compared to previous CMIP generations. Moreover, these new models display higher sensitivity and project more severe climate change impacts than anticipated by CMIP5. This enhanced capability provides additional valuable information for further studies and risk assessments. The scenarios generated by these models are specifically designed to explore the potential consequences of human-induced climate change, serving as crucial inputs for impact models. Given the advancements in CMIP6, there is a consensus among experts that its data should be utilized for future studies and risk assessments, as it offers a more comprehensive and nuanced understanding of potential climate futures [88].

Scenarios offer a logical, coherent and plausible portrayal of potential pathways of changing conditions, supporting decision-making for adaptation under uncertainty [89]. They are employed to explore how the future might unfold under various alternative circumstances and better anticipate related outcomes. Below, a set of recommendations for climate impact assessments is provided, along with a brief review of resources and climate projections, as well as an explanation of the SSP/RCP framework and its implications.

III.2.3 The SSP-RCP framework

The SSPs are scenarios that describe alternative scenarios as possible future socioeconomic conditions, such as population growth, economic development, and technological progress. They are used in combination with the RCPs, developed by CMIP5 models, to assess the potential impacts of climate change and the effectiveness of adaptation and mitigation strategies.

III.2.3.1 Representation Concentration Pathways (RCP)

The RCPs are a set of greenhouse gas concentration trajectories adopted by the IPCCs AR5 report. These pathways serve as crucial tools for climate scientists and policymakers, providing a framework to model and predict potential future climate scenarios based on different levels of emissions and mitigation efforts. The RCPs were instrumental in the climate model simulations conducted for CMIP5. The RCP scenarios are named according to their projected radiative forcing values in the year 2100 (Figure 21). Radiative forcing, measured in watts per square meter (W/m²), represents the difference between incoming solar radiation absorbed by the Earth and energy radiated back to space. A higher value indicates a greater warming effect.

- **RCP 2.6** is the most optimistic scenario, envisioning a future where global efforts to reduce greenhouse gas emissions are highly successful. In this pathway, radiative forcing peaks at approximately 3 W/m^2 around 2050 before declining. This scenario assumes rapid and significant reductions in greenhouse gas emissions, widespread adoption of renewable energy sources, and potentially the implementation of carbon capture technologies. It aligns with the Paris Agreement's goal of limiting global temperature increase to well below 2°C above pre-industrial levels.

- **RCP 4.5** is considered a moderate mitigation scenario. It projects radiative forcing to stabilize at about 4.5 W/m^2 by 2100. This scenario assumes some level of climate action, but not as aggressive as in RCP 2.6. It envisions a future where emissions peak around 2040 and then decline, with moderate shifts towards cleaner energy sources and improved energy efficiency. While more optimistic than higher emission scenarios, RCP 4.5 still presents significant challenges and potential climate impacts.

- **RCP 6.0** represents a future with higher emissions, where radiative forcing reaches roughly 6 W/m^2 by the end of the 21st century. It assumes only limited success in reducing greenhouse gas emissions. In this scenario, emissions continue to rise until mid-century before starting to decline. It implies slower adoption of clean energy technologies and less emphasis on improving energy efficiency compared to lower emission scenarios. RCP 6.0 suggests a world where climate change mitigation efforts are present but insufficient to prevent substantial warming.

- **RCP 8.5** is often referred to as the "business as usual" scenario and is the most pessimistic of the four. It projects radiative forcing to increase to 8.5 W/m^2 by 2100. This pathway assumes continued high greenhouse gas emissions with minimal efforts to mitigate climate change. It envisions a future characterized by high population growth, relatively slow income growth, and modest rates of technological change. Under RCP 8.5, fossil fuels would remain the dominant energy source, leading to significant increases in greenhouse gas concentrations and, consequently, more severe climate change impacts.

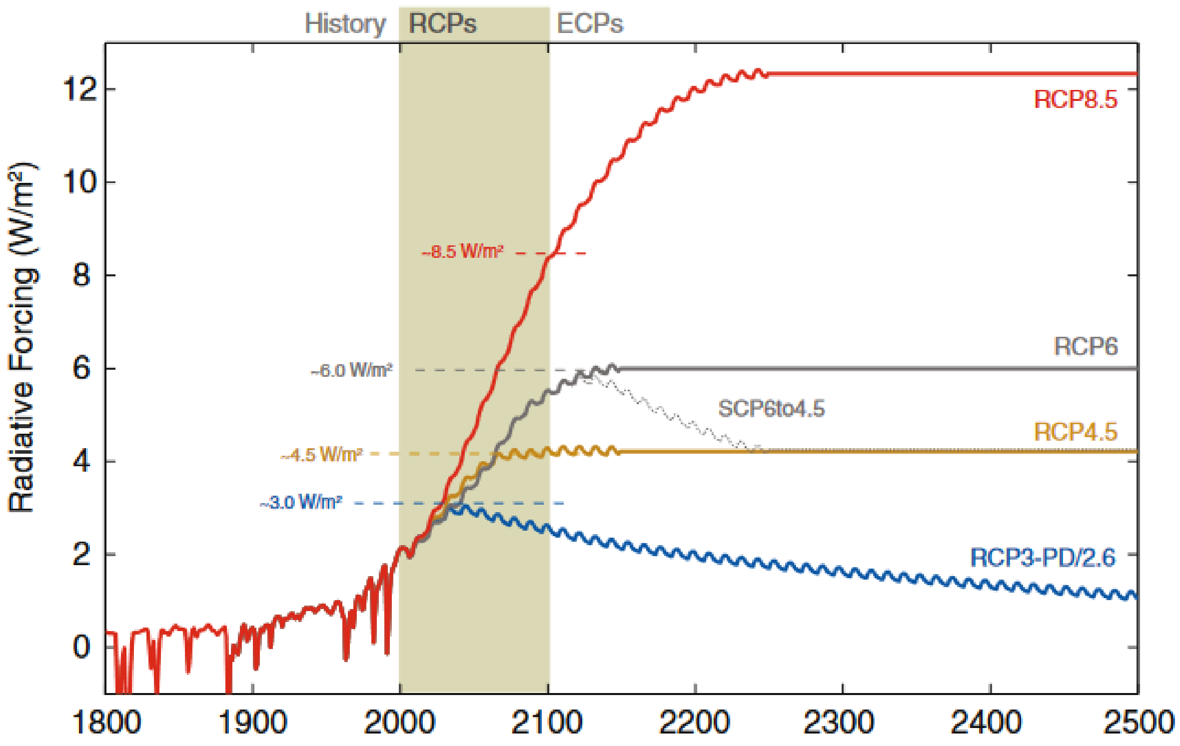

Figure 21. Representation Concentration Pathways (RCP) [90]. Total radiative forcing (anthropogenic plus natural) for RCPs, - supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP2.6 (called as well RCP3-PD), RCP4.5 & RCP6, as well as RCP8.5, respectively. Note that the stated radiative forcing levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future radiative forcing levels. Short-term variations in radiative forcing are due to both volcanic forcings in the past (1800-2000) and cyclical solar forcing-assuming constant 11-year solar cycle (following the CMIP5 recommendation), except at times of stabilization.

III.2.3.2 Shared Socioeconomic Pathways (SSP)

The CMIP6 introduced a new set of scenarios, building upon and refining the approach used in CMIP5. These new scenarios, known as SSPs, provide a more comprehensive framework for understanding potential future emission trajectories, based on the challenges each path presents in adapting to climate change, and the challenges in mitigating climate change [91]. The SSPs are scenarios that describe alternative scenarios as possible future socioeconomic conditions, such as population growth, economic development, and technological progress (Figure 22). They are used in combination with the RCPs to assess the potential impacts of climate change and the effectiveness of adaptation and mitigation strategies.

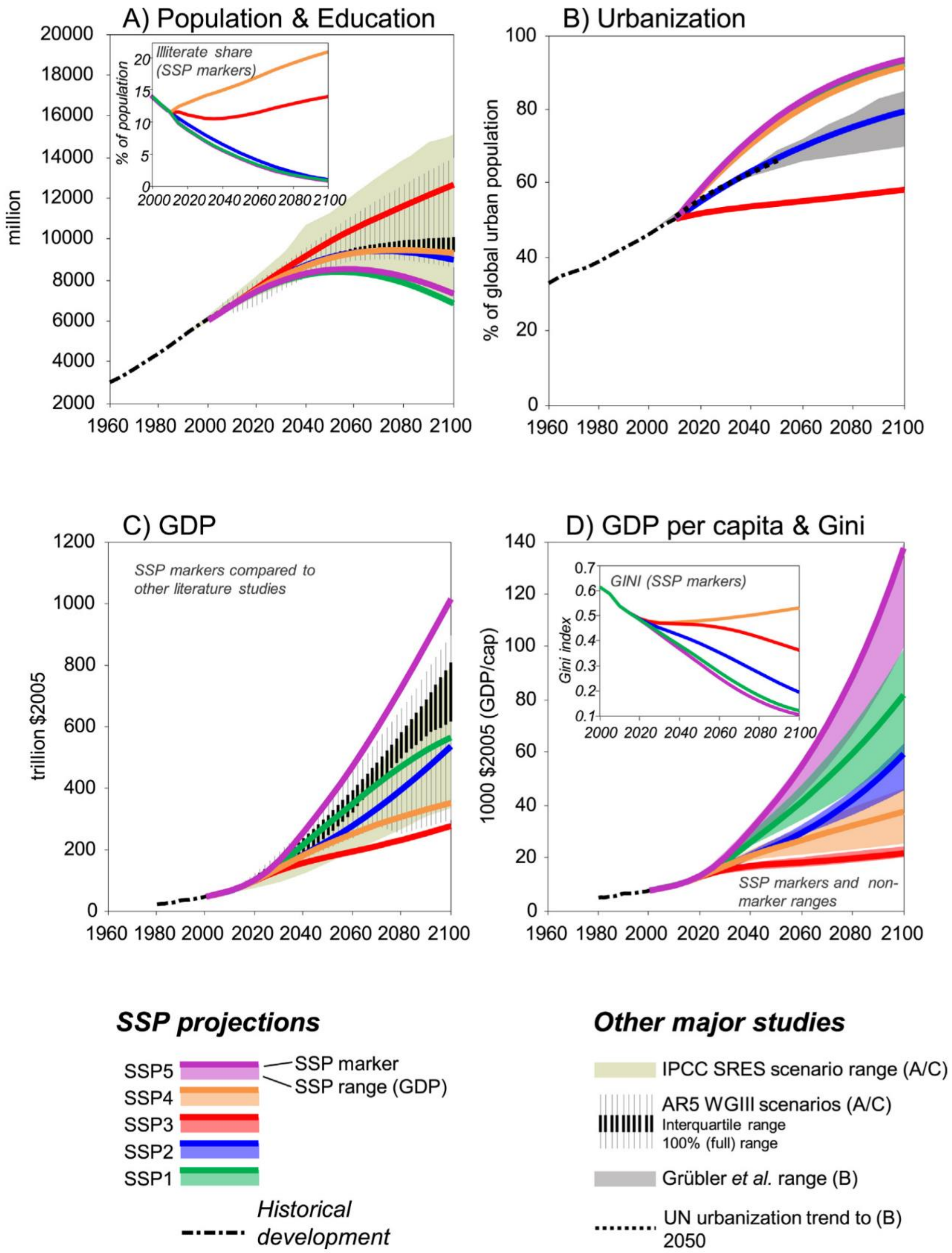

Figure 22. Development of global population and education (A), urbanization (B), GDP (C), and GDP per capita and the Gini index (D) [1]. The inset in panel A gives the share of people without education at age of 15 years, and the inset in panel D denotes the development of the global (cross-national) Gini index. The SSPs are compared to ranges from other major studies in the literature, such as the IPCC AR5. [1]

Five SSPs have been developed based on two features of society: the challenges each path presents in adapting to climate change, and the challenges in mitigating climate change. In CMIP6, four main scenarios have been designated as Tier 1: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

One of the key advancements in CMIP6 is the improved representation of the global climate system. This enhanced understanding has led to a wider spread in projected global mean temperatures across the Tier 1

SSPs compared to their RCP counterparts. In fact, the temperature projections associated with these SSPs extend beyond the range covered by the RCP ensemble [90].

Figure 23 shows temperature changes relative to pre-industrial levels across various timeframes and scenarios. It includes historical temperature data (represented by the front band), current temperatures as of 2020 (shown as a small central block), and projections for different socio-economic pathways throughout the 21st century. Each scenario's temperature trajectory is illustrated, with small black bars on the 2100 pillars indicating potential temperature levels. These levels were calculated using the MAGICC 7.0 default settings to generate greenhouse gas concentrations for the range of SSP scenarios available from the Integrated Assessment Model (IAM) community when the benchmark SSP scenarios were created. The more prominent, opaque bands, represent the five tier 1 SSP scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) prioritized by the IPCC. Less prominent, transparent bands show the remaining "Tier 2" SSP scenarios, including SSP3-7.0-LowNTCF (used in AerChemMIP), SSP4-3.4, SSP4-6.0, and SSP5-3.4-OS. Additionally, a blue bar on the right side of the figure demonstrates the potential impact of mitigation efforts. This bar illustrates how various levels of mitigation can reduce temperatures throughout the 21st century and by 2100, depending on the reference scenario and the extent of mitigation actions taken [90].

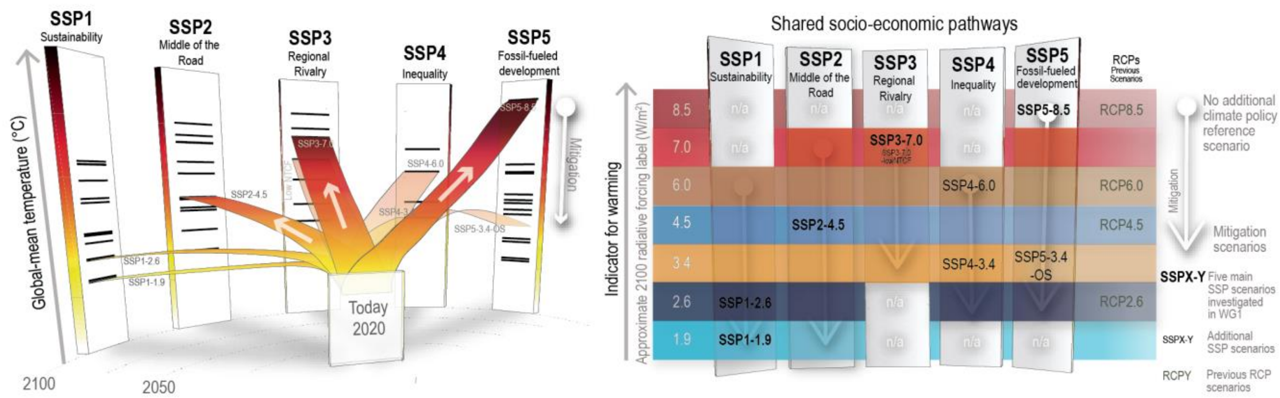

Figure 23. The SSP scenarios used in this Report, their indicative temperature evolution and radiative forcing categorization, and the five socio-economic storylines upon which they are built [1] .

The tier 1 scenarios developed by IPCC AR6 are delineated as follows, and summarized in Figure 24:

- **SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation):** The world is slowly but surely moving in the direction of sustainability, prioritizing more equitable development that respects arbitrary natural constraints. The demographic transition is accelerated by investments in health and education, the management of the global commons gradually improves, and the focus on economic growth is replaced with a broader emphasis on human well-being. As a result of a growing dedication to accomplishing development goals, inequality is declining both internationally and domestically. Low material growth and decreased resource and energy intensity are the goals of consumption.

- **SSP2 Middle of the Road (Medium challenges to mitigation and adaptation):** Global trends in social, economic and technological domains do not deviate significantly from past patterns. Growth in income and development occurs unevenly around the world, with some nations meeting expectations while others are not achieving them. Institutions at the national and international levels strive to achieve sustainable development goals, but their progress is sluggish. While there are occasional advances and a general decrease in the intensity of resource and energy usage, environmental systems nevertheless undergo degradation. The second part of the century saw a moderate slowdown in the world's population growth. There are still difficulties in lowering susceptibility to societal and environmental changes, and income disparity either stays the same or only gets better very slowly.

- **SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation):** Countries are focusing more on internal or, at most, regional issues because of rising nationalism, worries about security and competition, and regional wars. Over time, policies change to become more focused on concerns related to regional and national security. At the expense of more broadly based growth, nations prioritize meeting their local targets for food and energy security. Education and technology development investments are falling. Slow economic growth, material-intensive consumption, and enduring or escalating inequality are the hallmarks of this era. In developed nations, population growth is slow, while in developing nations, it is rapid. Certain regions experience severe environmental degradation due to environmental issues receiving little worldwide attention.

- **SSP4 Inequality – A Road divided (Low challenges to mitigation, high challenges to adaptation):** Increasingly uneven political and economic power differentials, along with highly unequal investments in human capital, cause inequality and stratification both within nations. A dispersed group of lower-class, illiterate cultures operating in a labour-intensive, low-tech economy gradually separates from an internationally integrated society that supports the knowledge- and capital-intensive sectors of the global economy. Conflict and discontent are more frequent, and social cohesiveness declines. The high-tech industries and economy have rapid technological advancements. With investments in low-carbon energy sources as well as carbon-intensive fuels like unconventional oil and coal, the globally interconnected energy sector diversifies. Environmental policy focuses on neighbourhood problems in middle-class and upper-class regions.

- **SSP5 Fossil-fueled Development (High challenges to mitigation, low challenges to adaptation):** To achieve sustainable development, our globe is putting more and more faith in innovative, competitive marketplaces, and participatory societies that foster rapid technical advancement and the development of human capital. The integration of global markets is growing. To improve human and social capital, significant investments are also made in health, education, and institutions. Simultaneously, the global embrace of resource- and energy-intensive lifestyles and the exploitation of copious fossil fuel resources are linked to the drive for economic and social progress. The world economy is growing quickly as a result of all these reasons, while the world population is peaking and declining in the twenty-first century. Air pollution and other local environmental issues are effectively addressed. People believe they can manage social and ecological systems well.

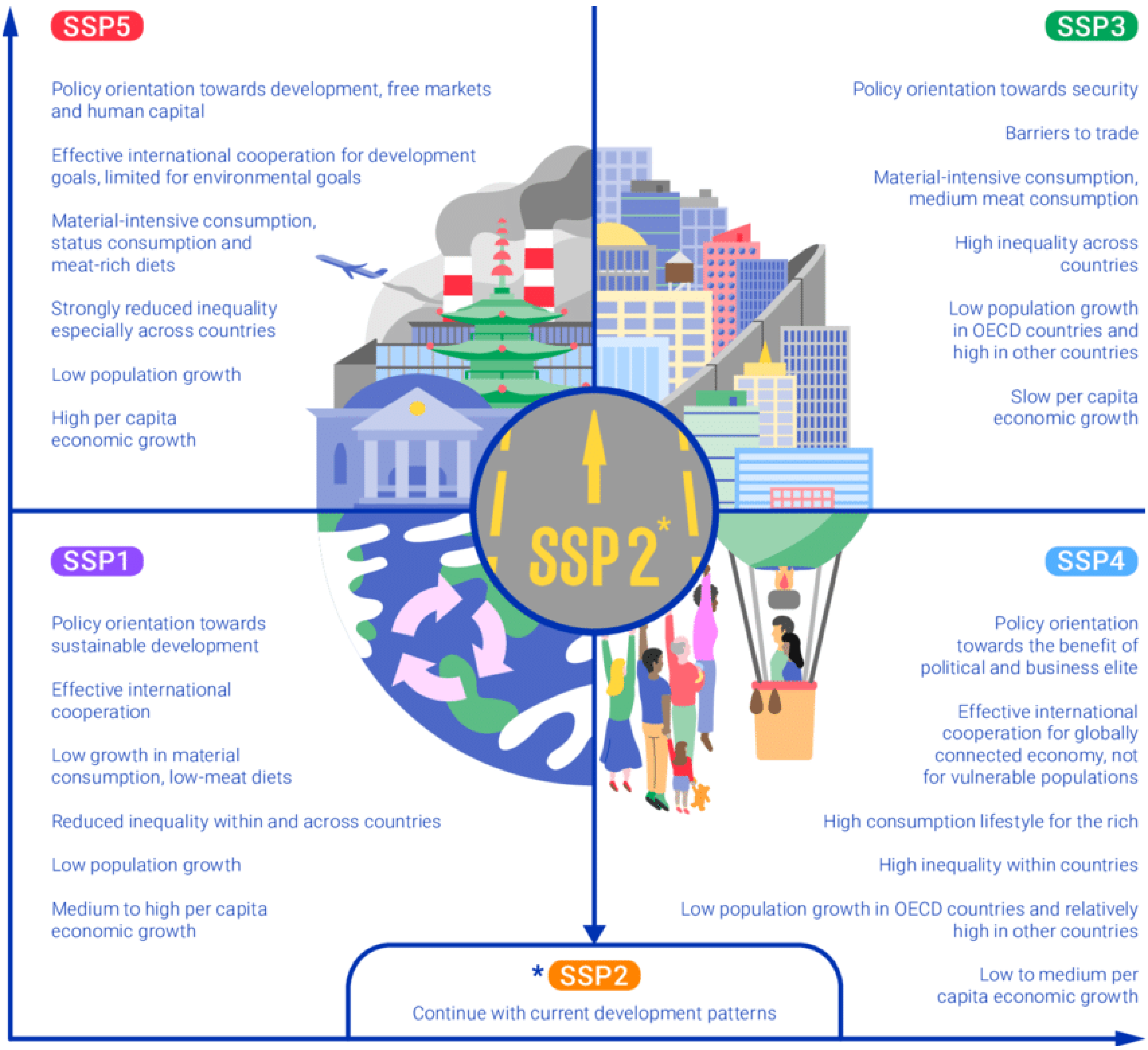

Figure 24. Shared socioeconomic pathways (in the figure, OECD stands for Organization for Economic Co-operation and Development). Adapted from [89]

III.2.3.3 SSP-RCP Framework

A matrix of scenarios that can be used to investigate the possible effects of climate change under various socioeconomic and emission situations is created by combining the RCPs and SSPs. For instance, a scenario with high greenhouse gas emissions and little international collaboration would result in more severe climate change impacts. This scenario would be represented by the combination of RCP 8.5 (high emissions) and SSP3 (regional rivalry). On the other hand, a scenario with aggressive mitigation efforts and sustainable development, represented by RCP 2.6 (low emissions) and SSP1 (sustainability), would result in less severe climate change impacts.

Figure 25 shows the multiple combinations of SSP-RCP scenarios [89]. It presents a matrix of SSPs and RCPs, illustrating the frequency of their combined use in various applications. The color intensity in each cell corresponds to the number of times a particular SSP-RCP combination has been employed, with blank cells indicating no usage. On the right side of the figure, green rectangles display the aggregate usage for each RCP (row totals), while similar rectangles at the bottom show the total applications for each SSP (column totals). It's worth noting that certain SSP-RCP combinations are marked as unlikely, signifying that integrated assessment models found these scenarios implausible given the assumptions inherent in the SSPs and Shared Policy Assumptions (SPAs).

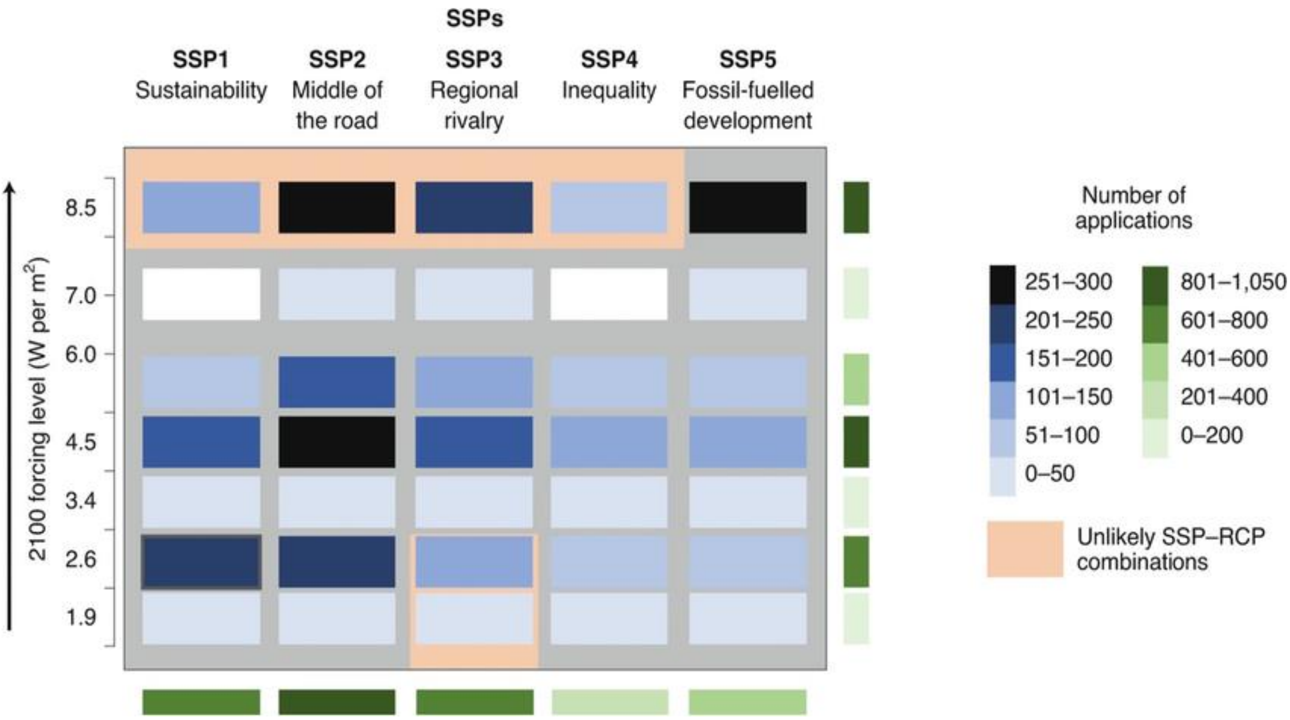

Figure 25. Numbers of applications of SSP–RCP combinations in 715 total studies applying integrated scenarios, published over the period 2014–2019 [89].

III.2.4 CMIP6 Global Climate models and climate downscaling

NATALIE's climate information is built upon the latest CMIP6 models and incorporates current SSPs, aligning with recent scientific recommendations. This approach has resulted in a unique set of high-resolution future climate projections provided by EUROCORDEX [2]. These models will serve as the foundation for the project's Risk Assessment and inform the design and implementation of adaptation measures emerging from NATALIE's research.

The project adopts a robust scientific methodology by employing two distinct downscaling techniques: statistical and dynamical: The dynamical downscaling based on the EUROCORDEX data and the statistical approach in certain CSs were EUROCORDEX data won't be available or when the uncertainty of the dynamic model is too high due the physical dynamics of the region, as in the case study of Canary Islands (CS#4).

When comparing the two main downscaling techniques, we find distinct characteristics. Dynamical downscaling employs Regional Climate Models (RCM) to enhance the resolution of Global Climate Models (GCMs) in specific areas of interest. This method takes into consideration local features and modifies physical processes, resulting in a more accurate representation of atmospheric dynamics. One of its key advantages is the ability to generate results for regions lacking observational data, such as entire watersheds. On the other hand, statistical downscaling focuses on establishing empirical connections between large-scale GCM variables and high-resolution surface variables (For example, utilizing the precipitation data from GCM and establishing empirical correlations with historical precipitation patterns.). This approach excels in producing highly localized results, even at the village level, with a lower margin of error compared to its dynamical counterpart. By leveraging these relationships, statistical downscaling offers a more precise method for obtaining site-specific climate projections [88].

This dual approach ensures the provision of reliable climate information, enabling a comprehensive understanding and representation of uncertainties inherent in climate projections. Both methods draw from the same primary data source: GCMs from the most recent CMIP6.

III.2.5 Future socio-economic scenarios and their impacts

The purpose of the SSP scenarios is to facilitate climate change research and policy analysis. They were created to offer five distinct paths regarding potential socioeconomic progressions when no further policies or measures are taken to limit climate forcing or improve adaptive capacity. Its aim is to encompass a wide range of challenges related to both mitigation and adaptation to climate change [91]. Within NALAIE, these scenarios provide a series of climate variables that serve as input for the modelling of NBS, as explained in the previous chapters. However, these narratives have an impact on other drivers or inputs, like population growth, Gross Domestic Product (GDP) or the evolution in land use [92]. The inclusion of these inputs is often omitted in modelling and risk assessment analysis, even though they have a significant influence on the results. Their inclusion in pessimistic SSPs can lead to an increase in the negatives impact of hazards, and the opposite for optimistic SSPs. In the same way, that downscaling of climate data results from the SSPs of the IPCC AR6 is carried out, downscaling of these variables must be considered.

For example, SSPs are drivers for the Change of Land Use evolution. Land use maps are one of the crucial drivers or inputs in hazard modelling and exposure, with a crucial role in the performance of NBS. The main hazards of the Natalie project related to precipitation, such as flooding or drought, are dependent on land use and have a direct impact on hazard outcomes, and therefore, on risk. The evolution of land use marks the evolution of a territory's permeability. The more permeability, the less runoff produced, and therefore, the less flood risk. On the contrary, an evolution of the urbanized area increases the percentage of impermeability leading to greater runoff. Also, more population and urbanization increase the exposure to the hazards, affecting the risk. Similar to the case of temperatures and heatwaves. Land use directly affects the heat island effect, vegetated areas have less impact than hard or impermeable areas. When designing an NBS, it is key to consider these future narratives for proper sizing. In NATALIE project a methodology has been developed to downscale the land use change in socio-economic scenarios, following the approach of the ARSINOE project [93].

III.2.5.1 Methodology

The present study adhered to the approach employed by Huber *et al.* [94]. The land use change detection is frequently used to examine historical events; this process involves comparing land use maps from two distinct timeframes (Figure 26). Through this comparison, it's possible to recognize shifts in land use from one category to another during the period under observation and serve as a calibration and develop the model of the future change of land use within each SSP narrative. For this study, the land use maps for the years 1990, 2000, 2006, 2012 and 2018 were sourced from the CORINE Land Cover data, accessible via the European Environmental Agency (EEA). However, it's essential to keep in mind that the data isn't available for all years in every research area, and differences in classification and errors between years might complicate comparisons from year to year in certain cases. To calibrate the land use model, a change use detection is carried out to determine the change relationship in land uses between different types of uses.

For the sake of simplification, given that the purpose of land use maps analysis in hydrological models is to determine infiltration, four characteristic types of land use have been determined from the Land Corina maps: Urbanized/impermeable, green area, crops and forest area, based on ICARIA’s approach [88]. The evolution of these four major types of land use will be studied based on different future socio-economic scenarios.

1990 classes ⇩ / 2006 classes ⇨	Sealed area	Sparsely vegetated areas	Bare rocks	Glaciers and perpetual snow	Natural grasslands, moors, heathland	Transitional woodland/shrubs	Pastures	Non-irrigated arable land	Fruit, vine, complex patterns	Agriculture with nat. vegetation	Broad-leaved forest	Coniferous forest	Mixed forest	Water
Sealed area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Sparsely vegetated areas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bare rocks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Glaciers and perpetual snow	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nat. grasslands, moors, heathland	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transitional woodland/shrubs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Pastures	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Non-irrigated arable land	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fruit, vine, complex patterns	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Agriculture with nat. vegetation	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Broad-leaved forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coniferous forest	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Mixed forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 26. Example of matrix of historical land uses changes [94].

III.2.5.1.1.1 The CHANGE OF LAND USE models

The Change-of-Land-Use models (CLU models, like CLUEMONDO or iCLUE) are models used in numerous studies for land use planning, environmental impact, and for territorial planning (Figure 27). Using a combination of I) empirically measured relationships between a land use class and its drivers and II) dynamic modelling of the competition between various land use classes (urban, forest, crops, wetland...), CLU models are spatially explicit models that simulate land use change. Through the application of a statistical relationship that indicates location's suitability for a certain land use, the model links the driving forces to each land use. CLU models facilitate the description of a link between a land use class and predictive factors using a variety of statistical techniques. Stepwise regression is the statistical technique we employed in this investigation [94].

CLU models necessitate several inputs for their operation. Firstly, an assessment of the factors or descriptors selected as drivers influencing the variation in land use is required. Secondly, the results of the evaluation of land use variation, typically obtained through change detection techniques applied to historical land use maps, such as those provided by the CORINE European project, are essential. Additionally, an estimation of the ease-of-change value for each land use type within each case study area is crucial. This value will be utilized to fine-tune the model outcomes and calculate the probability of an area undergoing a land use change. Furthermore, information regarding land use demands is indispensable. Finally, a base map representing the initial point of the time series under consideration is a prerequisite.

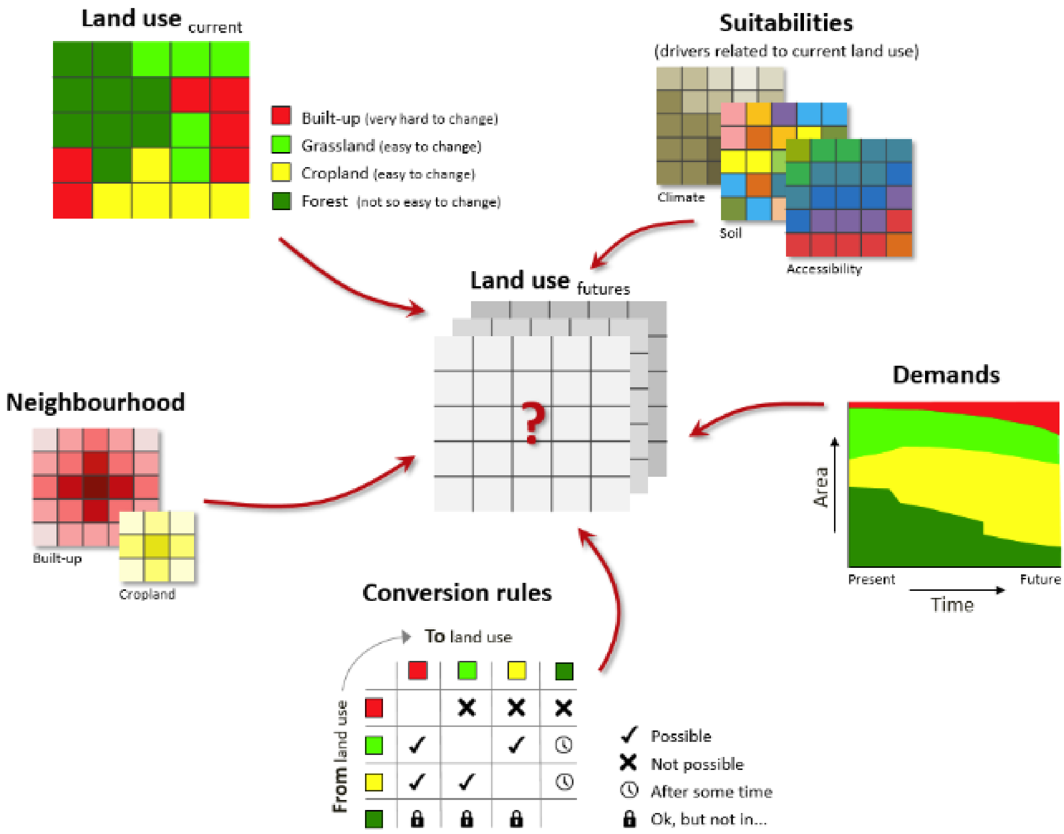

Figure 27. CLUEMONDO model scheme [95].

It is therefore necessary to establish which drivers are causing changes in land use. Numerous studies have been conducted to downscale the main factors for each SSP [92]. One of the primary values is population growth, which can be linked to an increase in impervious area [96]. Another key factor is the rise in GDP. These variables have been scaled down to the state level, serving as a starting point for each region.

This model will calculate the probability of a land use change occurring in a location by employing three main variables: ease-of-change, suitability's for each type of land use determined by selecting the most significant drivers using a stepwise regression model to estimate the overall suitability for each land sector, and overall land use demands. The model will utilize these probabilities to generate land use map projections. Given that this method will be applied for the chosen SSPs, there will ultimately be one map for each scenario. Upon completion of these simulations, the next step involves evaluating the quality of the simulations. When examining the results of CLUEMONDO model, the following aspects must be considered: the correct simulation of persistence (correct rejections), the simulation of persistence as change (false alarms), the simulation of change as the wrong category (wrong hits), the correct simulation of change (hits), and the simulation of change as persistence (misses).

III.2.5.1.1.2 The CHANGE OF LAND USE drivers

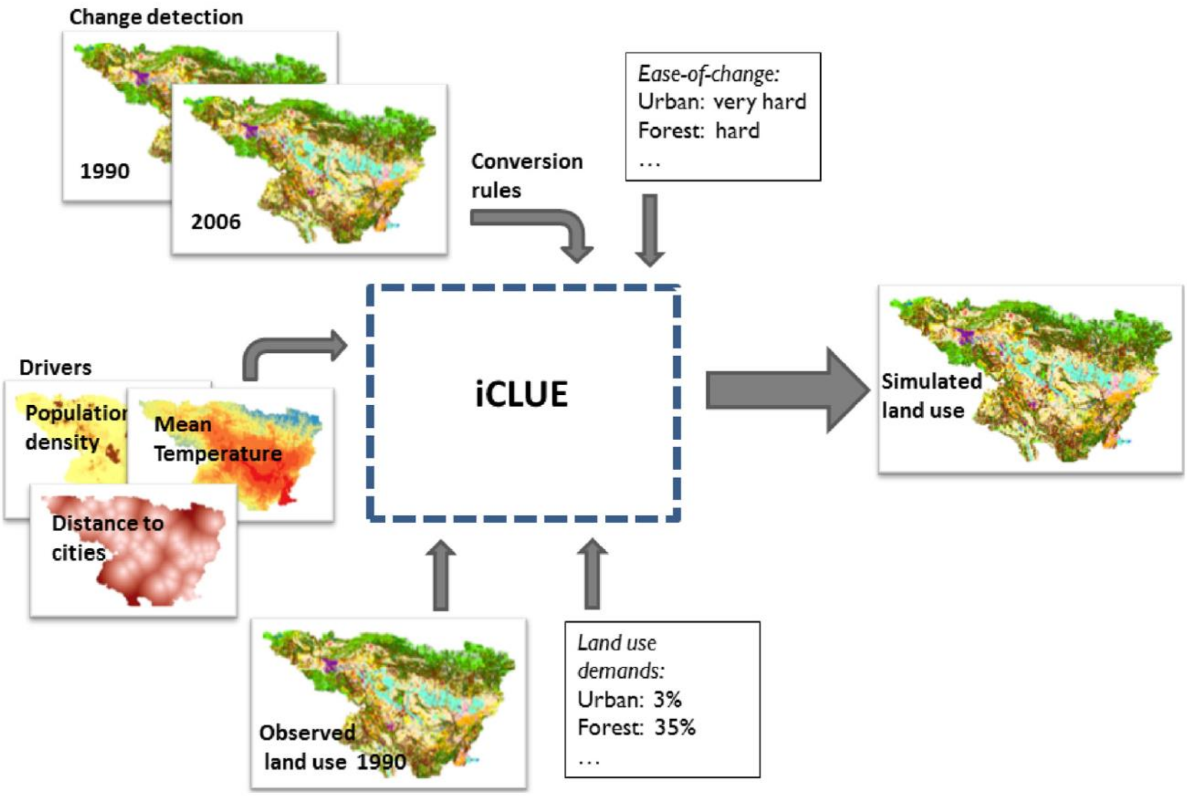

Figure 28. Flowchart describing the procedure of the land use change modelling and the needed inputs [94].

To create the future land of use scenarios corresponding to climatic and socio-economic scenarios, the model requires a series of input data:

- Land use
- Topography
- Meteorology
- Soil
- Position
- Socio-economy

These are some of the factors that can be utilized to develop the land use change projection model. It is important to note that the more information collected and used, the higher the confidence level of the projection. Additionally, this input data should be developed through a co-creation process with local stakeholders to verify the viability of the different future scenarios. Once the aforementioned information is collected, the parameters that the model will use to project the proportion of land use change in the simulation years must be established. To do this, the following matrices need to be defined:

- Conversion order matrix

  Land use changes in response to variations in demand (Figure 27). However, because each type of land use can supply one or more ecosystem goods or services, and because the demand for these goods and services can be met by various land uses, it is not immediately clear how land uses will adapt to demand changes. This parameter matrix specifies the types of land use changes that will be prioritized to meet the demand.

- Conversion resistance

  This parameter is related to the reversibility of land use change. Indicate the resistance of each land use for conversion.

- Conversion matrix

  The matrix indicates what types of land-use conversion are allowed by the model.

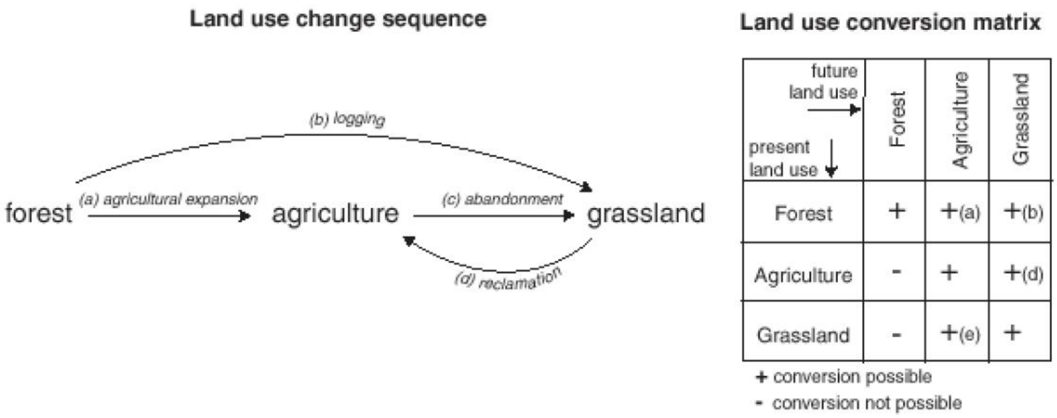

Figure 29. Example of translating a hypothetical sequence of land use changes into a land use conversion matrix [95].

- Logistic regression analysis

  A statistical examination is employed to uncover and measure the connections between the placements of particular land-use categories and a group of explanatory variables, also referred to as covariates. These covariates are determined by the user's understanding of the factors influencing land use change in the area under study.

Utilizing these biophysical and socio-economic conditions of a given area, the relative likelihood of encountering a specific land use type at that spot can be calculated using a binomial logit model. This model expresses the probability of encountering a land use type in a particular location compared to the probability of not encountering that specific land use type in the same location.

III.2.5.2 Conclusion and discussion

This section outlines a methodology for creating land use maps corresponding to different climate scenarios. These maps are intended to be used as inputs for various models, such as hydrological, ecological, or environmental impact models, to assess the potential effects of climate change on land use patterns.

Figure 30 shows the downscaling process from the SSPs. On one hand, climate downscaling is performed to obtain regional climate data that will be the input for hazard and impact models. On the other hand, a series of regional socio-economic data is obtained from the SSPs, which are derived from local and global trends in a co-creation process with local stakeholders. This data is used to design future land uses, another input for the hazard and impact models, as well as to modify the exposure and vulnerability that will result in risk.

The accuracy of the regional socio-economic data and land use projections heavily relies on the quality and availability of data for each specific case study area, as well as the level of engagement and collaboration with relevant stakeholders. Regions with comprehensive and high-quality data, as well as active participation from local experts and decision-makers, can yield more reliable land use projections.

It's important to note that these land use maps involve a high degree of uncertainty due to the complex nature of climate change and its interactions with various environmental, social, and economic factors. Modelers need to carefully interpret and incorporate these maps into different models, considering the uncertainties and limitations of the land use projections.

Modelers play a crucial role in integrating the land use maps into their respective models, accounting for assumptions, limitations, and potential sources of error. They may need to perform sensitivity analyzes, calibrate model parameters, or use other techniques to address the uncertainties associated with the land use projections.

Additionally, it's important to recognize that these land use maps are dynamic projections that may need updating as new data, improved methodologies, or changing circumstances become available. Continuous monitoring, evaluation, and refinement of the land use models, working with stakeholders, and their underlying assumptions are necessary to ensure their relevance and accuracy in the face of evolving climate conditions and socio-economic dynamics.

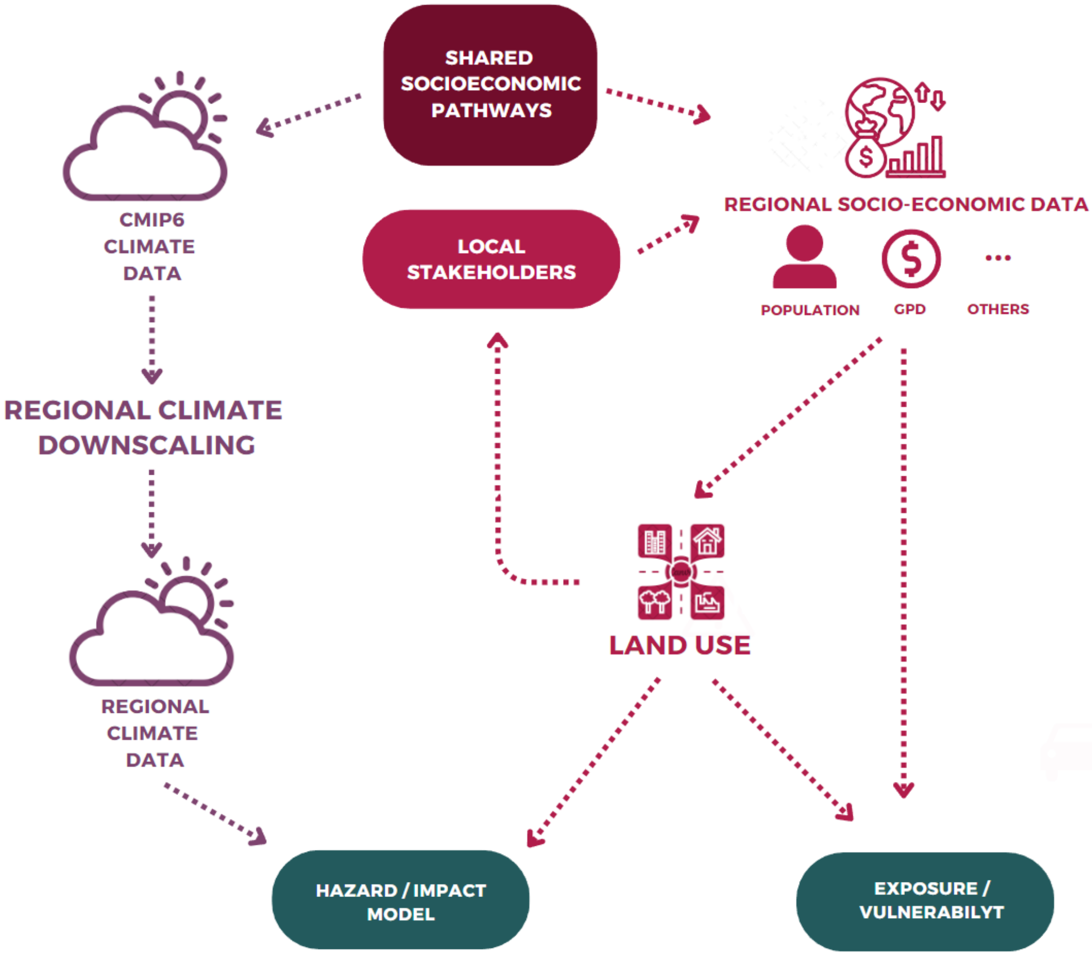

Figure 30. Process of downscaling of climate and socio-economic scenarios pathways.

III.3 Effects of plausible High Impact and Low Likelihood scenarios through tipping elements activations

III.3.1 Climate projections and uncertainties

Scenarios for changing climate, built on Representative Concentration Pathways and Shared Socioeconomic pathways, as described in the previous section, are a crucial resource for preparing for and adapting to changing conditions of operation and risks. However, significant and rapid deviations from these climate scenarios—already imbued with a degree of uncertainty—are possible, particularly when climate tipping elements are triggered that are not included in or emerging from coupled Global Circulation/Ocean and Earth System Models. While there is broad scientific consensus on the causes, processes and general consequences of anthropogenic climate change, there is much less agreement on the significance and potential impact of tipping elements on Earth's climate. The current generation of state-of-the-art models has been reported as inadequate for studying the interactions of tipping elements and their impact on the overall stability of the climate [97], [98], [99], even though their activation does sometimes emerge or can be induced [93], [94] [95], [96]. However, paleoclimate proxies provide substantial evidence for the repeated occurrence of rapid climate change in Earth's past [104], which may be linked to the activation of tipping points [98], [99], [100]. The IPCC [108] noted that "it is difficult to assess the probability of occurrence of abrupt climate events [but] they are physically plausible events that could cause large impacts on ecosystems and societies and may be irreversible." As the consequences of deviations from canonical climate scenarios resulting from tipping element activations may be severe (see below), and the likelihood uncertain (which is not the same as low), these additional scenarios merit particular attention.

III.3.2 Climate tipping elements and tipping points in Earth system

A tipping point can be defined as "a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system"; tipping elements refer to the associated large-scale components of the Earth system [109]. The scientific community's understanding of tipping points and elements has significantly grown over the past one-and-a-half decade (Lenton *et al.* [110] provided the most up-to-date overview)**,** though it is still incomplete and many uncertainties remain. Armstrong McKay *et al.* [111] provided a recent overview of tipping elements, threshold values, timescales and impacts, which is summarized in **Erreur ! Source du renvoi introuvable.** and Figure 31. In this figure, each rectangle represents a tipping element. Its range along the horizontal axis represents the uncertainty on the globally average temperature increase at which the tipping element could be activated. The vertical line inside the rectangle indicates which value is considered the best estimate. The range of a rectangle along the vertical axis and the horizontal line within the rectangle similarly indicate the uncertainty and best estimate of the time scale of activation. The colors of the rectangle indicate the average temperature effect the tipping point can give at global (left half) and regional (right half) scales. Hard edges indicate known boundaries, soft edges indicate unknown or unspecified boundaries.

The tipping elements most relevant to Europe are located in the lower left corner (low threshold, short time scale) of Figure 31 and have a high impact (more intense color): for Europe, these are particularly the Atlantic Meridional Overturning Circulation (AMOC) and Labrador Sea Convection (LABC). The AMOC is part of a global network of superficial and deep ocean currents that provide long-term exchange of heat, CO_2 and nutrients between the surface and the deep ocean. In the North Atlantic, this flow overturns in the sense that northward-flowing surface seawater sinks downward due to cooling and evaporation (which increases salt concentration and thus density) and flows back southward at depth. The LABC is a linked part of the ocean circulation west of Greenland. As the LABC system is smaller and more remote from Europe, a possible AMOC collapse can be the primary tipping element to be evaluated. For the other known tipping elements, beyond LABC and AMOC, the reported timescales and magnitudes (Figure 31) are not expected to result in appreciable deviations from the SSP-based climate projects in the coming decades.

Table 4. Overview of climate tipping elements. Explanation of symbols used: ⤵ collapse; ✕ die-off, (abrupt) loss; ≈ abrupt thaw; ◣ gradual thaw; ⬀ northern expansion, greening; ⬂ southern die-off; ↘ weakening; ø dissociation. Based on [111].

Global core tipping elements		tipping elements with regional impact		THRESHOLD-free nonlinear impacts	
GrIS	Greenland Ice Sheet ⤵	REEF	Low-Latitude Coral Reefs ✕	PFGT	Boreal Permafrost ◣
WAIS	West-Antarctic Ice Sheet ⤵	PFAT	Boreal Permafrost ≈	ASSI	Arctic Summer Sea Ice ✕
LABC	Labrador Sea / SPG Convection ⤵	BARI	Barents Sea Ice ✕	LAND	Global Land Carbon Sink ↘
EASB	East-Antarctic Subglacial basins ⤵	GLCR	Mountain glaciers ✕	PUMP	Ocean Biological Pump ↘
AMAZ	Amazon Rainforest ✕	SAHL	Sahel & West-African Monsoon ⬀	MMHD	Marine Methane Hydrates ø
PFTP	Boreal Permafrost ⤵	BORF	Boreal Forest ⬂		
AMOC	Atlantic Meridional Overturning Circulation ⤵	TUND	Boreal Forest ⬀		
AWSI	Arctic Winter Sea Ice ⤵				
EAIS	East-Antarctic Ice Sheet ⤵				

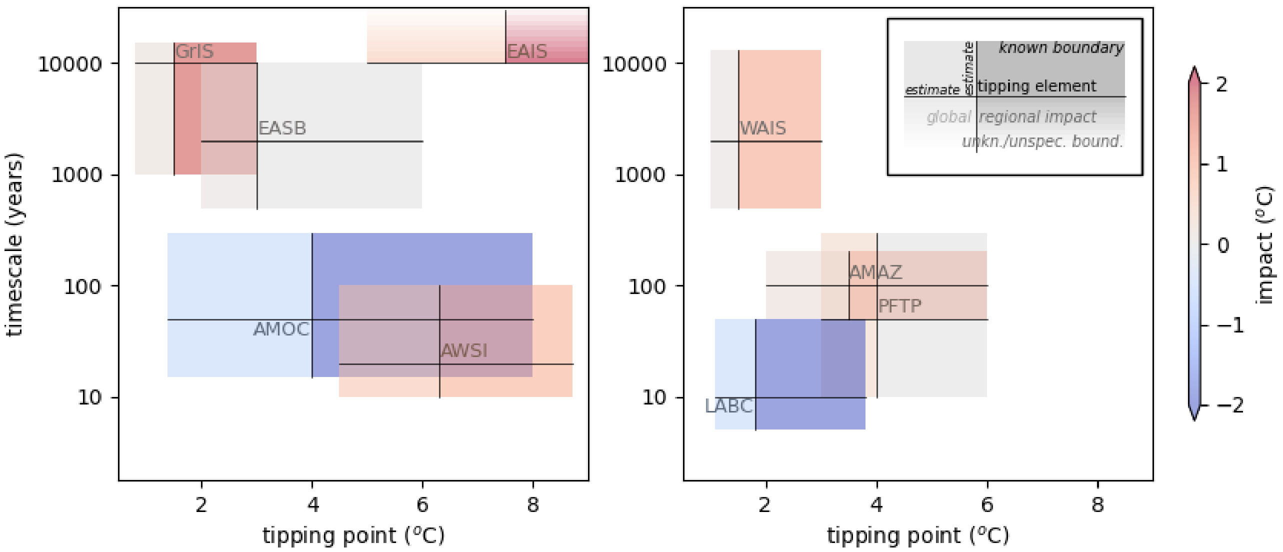

Figure 31. Overview of tipping points, time scales and maximum impact on mean temperature (left: global and right: regional) for the global core tipping elements from Table 5. Based on [111].

It is known from analysis of recent observations that the AMOC has been weakening since the 1950s (or perhaps longer). Numerical models also show weakening with a warming atmosphere [112]. Last summer, a publication even came out predicting, based on statistical analysis, that the AMOC will collapse between 2025 and 2095 [113]. Other researchers also warn that the AMOC may be on the verge of overturning [107] [108], [109]. Yet predicting its occurrence remains extremely difficult. Changes in the AMOC and the interaction between ice sheets and the ocean have had a major impact on ecosystems and human civilizations over the past 30,000 years [105]. Earth System Model simulations by [103] and [102] show that for a reduction in the AMOC strength of about 50%, the mean annual temperature may drop 1-3 °C in the Mediterranean region, 2-4 °C in central and western Europe, and 2-6 °C or more in northern Europe, and 4-9 °C or more in Iceland. Also, reductions in annual precipitation of up to 200 mm/year are projected for most of southern and central Europe, with stronger reductions in western Norway, Scotland, and over the northern Atlantic Ocean [92]. These numbers are all expressed in comparison to unperturbed control simulations. Simulations by [114] that eventually show a more or less complete shutdown of the AMOC, project correspondingly stronger effects in European climate: mean annual temperatures drop by approximately 3-4°C for Vienna, 7°C for London, and more than 10°C for Reykjavik, with mean summer temperature drops being mild in comparison to much stronger wintertime temperature drops. These authors also find a dynamic sea level effect due to AMOC collapse of +70-100 cm over large parts of the northern Atlantic Ocean, approximately +50 cm in the North Sea, and approximately +30 cm in the Mediterranean Sea. Note that the predicted temperature changes will more than offset anthropogenic temperature increases, in particular in winter times, along with bringing more droughts and extreme weather conditions – as such, this is not to be considered a local "dampening" of anthropogenic climate change. Note also that, as the reported effects are in comparison to a pre-industrial reference state, these numbers need to be considered as effects in addition to and on top of the direct effects of increasing atmospheric CO_2 concentrations. However, it needs to be kept in mind that dynamical effects are likely to make a simple arithmetic addition inadequate. Below, we propose how to apply the simulation output of "moderate" AMOC collapse simulations of [103] and [102] in Natalie's case studies.

III.3.3 Relevance for case studies

Several effects can be anticipated as a result of changing temperatures, precipitation and sea level. Ditlevsen [113] provides potential and/or anticipated additional stresses on the case study systems. It is intended to motivate the consideration of the AMOC collapse scenario in addition to the RCP-SSP-based climate scenarios for NBS evaluation, depending on their sensitivity to sea level rise and/or changes in temperature and precipitation. Note that this is merely a preliminary evaluation – a more detailed analysis is required for a more definitive assessment.

Table 5. Overview of potential and/or anticipated effects of AMOC collapse on the case study areas and objectives, based on a preliminary evaluation. ↓ reduced system stress, → unchanged system stress, ↑ increased system stress

Case Study		***Potential or anticipated effects***					
		Additional sea level rise		*Temperature decrease/severely cold winters*		*(Additional) decrease in precipitation*	
CS#1	*Flood and wildfire risk mitigation in Greece*	→		↓	reduced wildfire risk	↑	increase wildfire risk
CS#2	*Fresh water habitat restoration in urban ecosystems, Romania*	→		→		↑	reduced availability of freshwater
CS#3	*Constructed wetlands in Latvia and Lithuania*	↑/→	close to/well above sea level	→		↑	reduced availability of freshwater
CS#4	*Alternative water management solutions in Spanish Archipelagos*	→		↓	reduced water demand	↑	reduced availability of freshwater
CS#5	*Aquifer recharge for water reuse in Belgium*	→		↓	reduced water demand	↑	reduced availability of freshwater
CS#6	*Aquatic system restoration and water management in France*	→		→		↑	reduced availability of freshwater
CS#7	*Coastal management with NBS in Iceland*	↑	at sea level	↓/↑	increase stability of soil (permafrost), sea-ice pack expansion, coastal ecosystem	→	
CS#8	*Sustainable river restoration,*	→/↑	close to sea level	→		↑	reduced availability of freshwater

	maintenance and management in Italy

III.3.4 Approach for studying effects

III.3.4.1 AMOC collapse: hosing experiments

The consequences described in section **Erreur ! Source du renvoi introuvable.** provide sufficient ingredients to generate additional conceptual climate scenarios. However, to allow a quantitative evaluation of NBS in the context of the Natalie project in the same way as is done for the Arsinoe-derived climate scenarios based on CMIP6 simulations (see section III.4.2), more detailed and geographically specific information is needed.

Numerical models provide a tool to study the effects of an AMOC collapse on the European climate in the required level of detail. In particular, hosing experiments are commonly used for this purpose. In these numerical experiments, a steady influx of freshwater into the northern Atlantic Ocean is imposed in the model in order to drive the model towards AMOC shutdown. This approach was also used in the papers cited above in section **Erreur ! Source du renvoi introuvable.** [102], [103], [114].

From these and other, similar simulations, time series for temperature, precipitation and evaporation can be extracted for particular sites or areas relevant for the case studies, in a similar way and format to CMIP/SSP derived time series. Note that some preprocessing, including bias correction, is required (see below). This is currently being done for the hosing experiments by [95] and [96]. The resulting simulation datasets are offered to case studies to optionally be applied as drivers for the local or regional models that are used to study the resilience of NBSs in the case studies, as an additional climate scenario next to selected CMIP/SSP-based scenarios.

III.3.4.2 Data preparation and bias correction for application of hosing experiment results in case studies

Climate models generally exhibit a bias in comparison to observations. This has been known for a long time and many so-called Bias Correction (B-C) methods have been developed to correct simulation results for these biases. Dinh and Aires [117] provide a recent review of methodologies with a focus on their application in impact studies.

Raw simulation results for hosing experiments by [103] and [102] have been kindly supplied by these researchers. Simulation results include control runs (for pre-industrial conditions: forcing representative of 1850) and perturbed experiments with different amounts of hosing (0.1, 0.3, and 0.5 Sverdrup = 10^6 m^3s^{-1}). In order to apply B-C to the hosing experiment results, the applied methods are described in 7, copying the approach applied by [118]. The methods in this approach are commonly used, relatively straightforward, and their application contributes to the reusability of the bias-corrected simulation results in other projects that apply the same approach. Note that for all fields, bias corrections are computed on a monthly basis with linear interpolation between month midpoints to prevent discontinuities at month boundaries. Bias correction factors are obtained by a comparison.

- between the control runs (1850 forcings) and the earliest available historical dataset with adequate geographical coverage, which is ERA5 [119] for the period of 1940-1950, or
- between a present-day simulation of the respective models with otherwise unchanged parameter setting and ERA5 [119] data for the corresponding period

individually for each node of the simulation grid of the hosing experiment results.

Table 6. Bias correction methods to be applied in the Natalie context to hosing experiment output.

Field	*method*
Temperature	linear offset
Precipitation	dry days correction, followed by linear scaling, such that bias corrected signal has the number of monthly wet days as the observations and the total monthly precipitation is preserved
Evaporation	linear scaling

III.3.5 Discussion: added insights and limitations

The AMOC collapse scenario is generally treated as one of high impact and low likelihood. However, the scientific community lacks the means to estimate the true likelihood of the materialization of this scenario. It is known that it has happened before in the geological past, and that signs of a slowdown are observed over the past decades. This appears to be sufficient ground to designate the scenario both plausible and relevant.

The inclusion of the AMOC collapse scenario in the evaluation of NBS therefore helps to understand whether and how these solutions may perform under a wider range of plausible and relevant climate conditions, as such increasing our understanding of the resilience of these systems.

For sure, the dynamics of the coupled climate-ocean system are so complex, that a single set of hosing experiment results cannot be considered representative. Indeed, the differences between the results by [95], [96], [107], discussed above, illustrate this point very clearly. However, these are differences of magnitude in a scenario that is qualitatively quite different from the CMIP/SSP projections. The inclusion of a hosing experiment-based adds a class of potential climate evolutions that helps underline the deep uncertainty that we are dealing with and the need to introduce as much flexibility in our solutions as possible.

III.4 Climate and socio-economic scenarios within NATALIE

The eight case studies of the NATALIE project cover a wide variety of climatic, socioeconomic, and environmental zones. They represent a faithful reflection of the different European regions and the threats of climate change in the context of sustainable development with green and blue infrastructures. It is necessary to establish baseline scenarios across all the different case studies to allow for proper systematic evaluation and to enable the replicability of results beyond the NATALIE project. To this end, collaboration is also taking place with other European projects related to climate change adaptation, as ARSINOE [93], where several partners are shared, determining common baseline scenarios: SSP1-2.6 and SSP3-7.0.

The primary source of climate downscaling data will be obtained from EUROCORDEX [2] . In certain case studies, data from other European projects, like ARSINOE [2] in the Canary Islands, or from local institutions, will be used. Please note that as of the delivery date of this document, the downscaling of climate data by EUROCORDEX [2], the main data source for its application in case studies, has not been published. This data will be included in D3.2 (M24) once it becomes available.

III.4.1 Definition of climate variables of interest

In each case study, specific NBS solutions are used as adaptation measures to address various climate-related risks in different regions (refer to Chapter II.2 for details). These solutions cover a wide range of types and methods and are aimed at dealing with different climate hazards. Each hazard is linked to certain climate variables, which will be used as inputs for the models that measure the effectiveness of the solutions. It is important to accurately identify these variables, not just in terms of their definition, but also in terms of their spatial and temporal characteristics.

In each case study, a set of primary and secondary hazards have been identified based on the framework presented in Chapter II.3. The primary hazards guide the design and implementation of the NBS solution through modeling, determining the size of the infrastructure. The secondary hazards are assessed as additional benefits, with biodiversity loss being considered as an impact after the sizing has been completed.

The two main climatic variables collected are precipitation and temperature. Precipitation is associated with hazards involving hydrological processes, such as various types of floods (flash, fluvial, drain and sewer, and groundwater) and pollution transported by rain events. For droughts, the spatial resolution of this variable depends on each case study and the ability to perform climate downscaling. A minimum spatial resolution of 0.11°, approximately 11 km, is recommended, corresponding to the resolution provided by EUROCORDEX [2]. In cases where a higher resolution will be available, especially for floods, its use will be prioritized. For extreme flood events, a temporal resolution of 10 minutes is optimal, even if the ultimately hazards are related to pollution. For this last cases, although EUROCORDEX [2] only provides daily resolutions, it is recommended to perform a new downscaling to obtain sub daily extreme data up to the resolution of 10 minutes [120], [121], [122]. For droughts, a minimum daily temporal resolution is recommended.

Regarding temperature, associated with heatwaves and wildfires, a minimum spatial resolution of 0.11°, approximately 11 km, is recommended. The recommended temporal resolution is hourly. Although EUROCORDEX only provides daily resolutions, it’s recommended to develop statistical analysis to downscale projected data up to hourly resolution.

Table 7 shows the climate variables needed at each Case Study and the recommended resolution.

Table 7. Overview of primary hazards for each region and the climate variables associated with the resolution needed for conducting the modelling.

Case Study		**Climate variables of interest**		
		Primary hazards	Climate variables	Recommended resolution
CS#1	*Flood and wildfire risk mitigation in Greece*	Fluvial floods Wildfires	Rainfall intensity (mm/h) Air Temperature (T) Cº	Spatial min: 0.11 degree (11km) Temporal optimal: 10 min Spatial min: 0.11 degree (11km) Temporal optimal: Hourly
CS#2	*Fresh water habitat restoration in urban ecosystems, Romania*	Droughts Heatwaves	Rainfall intensity (mm/h) Air Temperature (T) Cº	Spatial min: 0.11 degree (11km) Temporal min: daily Spatial min: 0.11 degree (11km) Temporal optimal: Hourly
CS#3	*Constructed wetlands in Latvia and Lithuania*	Surface and Groundwater pollution	Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal min: Daily
CS#4	*Alternative water management solutions in Spanish Archipelagos*	Surface and Groundwater pollution (Gran Canaria) Fluvial Floods (Tenerife) Flash Floods Drain and sewer floods Groundwater floods	Rainfall intensity (mm/h) Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal optimal: 10 min Spatial min: 0.11 degree (11km) Temporal optimal: 10 min Spatial min: 0.11 degree (11km) Temporal min: Daily

		Surface and Groundwater pollution (Fuerteventura)	Rainfall intensity (mm/h)	
CS#5	*Aquifer recharge for water reuse in Belgium*	Droughts	Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal min: Daily
CS#6	*Aquatic system restoration and water management in France*	Droughts	Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal min: Daily
CS#7	*Coastal management with NBS in Iceland*	Surface and Groundwater pollution Landslides	Rainfall intensity (mm/h) Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal optimal: 10 min Spatial min: 0.11 degree (11km) Temporal optimal: 10 min
CS#8	*Sustainable river restoration, maintenance and management in Italy*	Fluvial floods Riverbank erosion	Rainfall intensity (mm/h) Rainfall intensity (mm/h)	Spatial min: 0.11 degree (11km) Temporal optimal: 10 min Spatial min: 0.11 degree (11km) Temporal optimal: 10 min

III.4.2 NATALIE climate scenarios

To simultaneously account for uncertainties in future socio-economic pathways, greenhouse gas concentration trajectories and climate projections, it is ideal to simulate numerous combinations of SSPs and RCP using an ensemble of climate models and the corresponding regionalized projections. Incorporating regional downscaling and impact models will further compound the complexities involved.

For practical applications, considering and simulating many combinations of SSPs and RCPs using a large ensemble of climate models, along with regional downscaling and impact models, is extremely computationally expensive and therefore not feasible to implement across the full modelling chain from global to local scales. The alternative and more common approach, including in cases of lower data availability, is to analyze only a few representative examples that are relevant and fit-for-purpose [123]. This can be done in various ways:

- For studies focusing on the differences between climate scenarios and their underlying narratives, simulations representing the ensemble mean of available global or regional climate projections driven by a specific scenario are commonly used. This approach assumes that the projected ensemble mean represents the most robust result, given the uncertainties associated with climate models.
- Alternatively, the number of climate scenarios considered can be reduced by analyzing only a few scenarios, such as a high and a low mitigation scenario. This approach can simplify the analysis while still capturing the range of potential outcomes.
- For studies examining extreme events like floods and droughts, climate model uncertainty is generally more important than scenario uncertainty. In such cases, it may be useful to base the analysis on a selection of climate scenarios or projections that represent the spread of the combined ensemble, thereby sampling the full range of uncertainty. This can be achieved by selecting

representative simulations from a set of climate projections forced by an "extreme" (non-mitigated) scenarios.

- For very short time horizons, such as the coming few decades, natural climate variability and climate model uncertainty dominate, and the choice of climate scenario can be neglected. In these cases, the focus may be on capturing the range of potential outcomes due to natural variability and model uncertainties, rather than on the specific scenario.

All case studies will take this within a common "workspace" using two reference scenarios: SSP1-2.6 and SSP3-7.0 (Figure 32). These scenarios have been chosen following the approach of the ARSINOE Project [93]. These scenarios represent different ends of the scale in terms of global emissions and mitigation efforts.

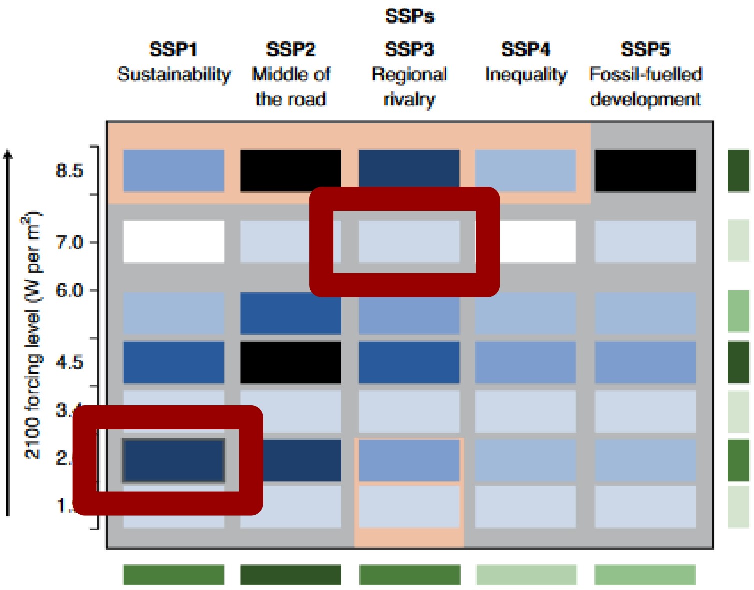

Figure 32. Selected base scenarios for NATALIE Case Studies. (based on [89]).

Anthropogenic climate change is not just happening at a defined pace and magnitude; its severity depends on the underlying society, behavior, and development. There are various pathways of future climate and societal development that may be equally likely, making it more complicated than simply picking what we believe is realistic.

SSP1-2.6 is a high mitigation scenario aligned with the goals of the Paris Agreement and a "green" socio-economic pathway that aligns with the targets of the European Green Deal and the Sustainable Development Goals. In contrast, SSP3-7.0 is a "new" low mitigation scenario that resembles a business-as-usual scenario with high mitigation and adaptation challenges. According to the IPCC AR6, the projected warming in 2100 under SSP3-7.0 scenario from CMIP6 is comparable to the estimated levels of warming under RCP8.5 scenario from CMIP5, ranging from 3-6.5°C above pre-industrial levels.

Downscaling the GCM SSPs scenarios to regional levels may be challenging, since there is currently no standardized methodology. This will be done within each CS on a case-by-case basis, bearing in mind that regional and local policies and developments may not follow global or even national trends.

Table 8. Briefly summary of the SSP1-2.6 and SSP3-7.0 narratives chosen for the NATALIE project [125].

SSP1-2.6	SSP3-7.0
The world shifts gradually, but pervasively, toward a **more sustainable path**, emphasizing more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being, even at the expense of somewhat slower economic growth over the longer term. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives and changing perceptions make renewable energy more attractive. Consumption is oriented toward low material growth and lower resource and energy intensity. The combination of directed development of environmentally friendly technologies, a favorable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand results in relatively low challenges to mitigation. At the same time, the improvements in human well-being, along with strong and flexible global, regional, and national institutions imply low challenges to adaptation.	A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. This trend is reinforced by the limited number of comparatively weak global institutions, with uneven coordination and cooperation for addressing environmental and other global concerns. Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. There are pockets of extreme poverty alongside pockets of moderate wealth, with many countries struggling to maintain living standards and provide access to safe water, improved sanitation, and health care for disadvantaged populations. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. The combination of impeded development and limited environmental concern results in poor progress toward sustainability. Population growth is low in industrialized and high in developing countries. Growing resource intensity and fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply high challenges to mitigation. The limited progress on human development, slow income growth, and lack of effective institutions, especially those that can act across regions, implies **high challenges to adaptation** for many groups in all regions.

It is recommended to conduct simulations for each of the two baseline scenarios using at least three different Regional Climate Models (RCM), which are based on different combinations of GCM-RCM models (or statistically) from CORDEX and CMIP6 [124], [93]. This is important to account for the uncertainty in climate projections. Although an exact timeline is not available, it is expected that the EUROCORDEX repository will house an increasing number of CMIP6 downscaling simulations by at least Month 18 of NATALIE. As outlined in Section 3 of the deliverable and through interactions with individual CS, the relevant forcing data for SSP1-2.6 and SSP3-7.0 will be provided to CS modelling teams around Month 24.

NATALIE defines the "near future" as the time from 2040 to 2060 (present day + 30 years) and the end of the century as 2080 to 2100. These time frames align with the conventions used by the IPCC and other studies.

III.4.3 Data sources and downscaling pathways for CS

III.4.3.1 Available data sources

The primary source of climate downscaling data will be obtained from EUROCORDEX [2]. In certain case studies, data from other European projects, like ARSINOE [93] in the Canary Islands, or from local institutions, will be used. Please note that up to the delivery date of this document, the downscaled climatic data from EUROCORDEX [2], the main climatic data source in the project, has not been published. These data will be included in D3.2 (M24) once it becomes available.

IPCC relies heavily on the collaborative efforts of the CMIP to conduct its assessments. These projects establish standardized scenarios and methodologies for climate modeling groups globally, ensuring consistency and validation of the results used in IPCC reports and by the broader scientific community. The CMIP climate model ensembles produce extensive simulations that are openly accessible through the Earth System Grid Federation network of data servers.

While the AR5 utilized GCMs and ESMs from the CMIP5 cycle, the AR6 incorporates outputs from over 100 GCM included in CMIP6. Global models typically provide information at coarse spatial scales of approximately 100 square kilometers, so it's necessary to use Regional Climate models (RCMs) or statistical downscaling techniques to obtain finer details crucial for climate risk and adaptation assessments.

EURO-CORDEX provides downscaled climate projections from state-of-the-art RCMs across 14 strategically located global regions, generally at a 50-kilometer horizontal resolution. However, for certain regions like Europe, projections are available at even finer resolutions of 11 square kilometers or less. EUROCORDEX RCMs use reanalysis data or GCMs as boundary conditions, covering historical periods and future projections primarily until 2100, with some simulations extending to 2300. Efforts are currently underway to downscale the new global CMIP6 runs, with the expectation that a substantial number of simulations forced by CMIP6 models will populate the EUROCORDEX database by the end of 2024.

III.4.3.2 Modelling pathways for NATALIE CS

Figure 33 showcases the main modeling framework used in the NATALIE project's case studies. This framework details the primary data sources and the general workflow for creating and implementing the models.

The modeling process starts with a pre-processing stage where crucial information about the study area is gathered. This includes data such as digital terrain models (DTMs), digital surface models (DSMs), soil maps, and other relevant infrastructure data affected by the hazard under consideration. The specific data requirements may differ depending on the hazard and the study area's characteristics.

The modeling framework is divided into two main phases: calibration and diagnosis, followed by prognosis.

1. Calibration and Diagnosis Phase:
    - This phase uses historical climate data to calibrate and validate the models.

- The models are fine-tuned and adjusted to accurately represent the current or past conditions within the study area.
- This phase acts as a diagnostic tool, identifying potential issues, uncertainties, or limitations in the models.

2. Prognosis Phase:
   - After calibrating and validating the models, the prognosis phase incorporates projected scenarios related to NBS and climate change.
   - These scenarios could include different climate projections, such as changes in temperature, precipitation patterns, or other relevant climatic variables and socio-economic projections such as population growth, GDP or land use changes.
   - The NBS scenarios might involve implementing various nature-based interventions or strategies aiming at mitigating or adapting to the impacts of climate change.

By incorporating these projected scenarios, NATALIE models could simulate and assess the potential impacts and risks associated with different hazards under varying climate and NBS conditions. The modeling framework then uses the outputs from the hazard simulations, along with exposure and vulnerability data, to determine the potential for risk reduction and evaluate the environmental, social, and economic impacts of the projected scenarios.

It's important to note that the specific models, data sources, and methodologies used within this framework may vary across different case studies, depending on the unique characteristics, data availability, and requirements of each study area. Additionally, the framework allows for iterative refinement and adaptation as new information, or improved techniques become available.

The modeling framework provides a structured approach to integrate diverse data sources, climate projections and NBS scenarios, enabling a comprehensive assessment of hazard risks, strategies to reduce potential risk, and their associated impacts within the context of climate change adaptation and mitigation efforts.

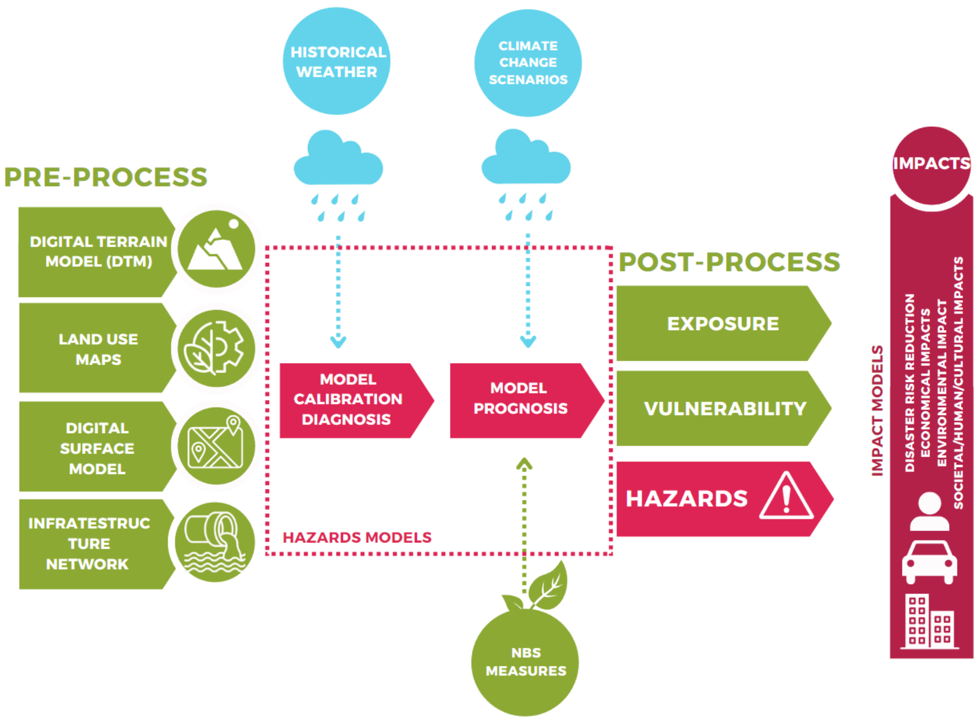

Figure 33. General modeling process for NATALIE project.

Figure 33 illustrates the process of climate risk assessment for NATALIE's CS. The process begins with a preliminary phase where physical information about the study area's system is gathered, including DTM, DSM, Land Use maps, and infrastructure network data, among others. Based on this information and an analysis of the current situation using historical data, hazard modeling is conducted. This modeling yields a diagnosis of the system's state, which, when combined with exposure and vulnerability data, allows for the determination of risk levels and associated economic, social, and environmental impacts. Following the diagnosis, NBS are designed and scaled to reduce the impact of selected hazards, considering future climate scenarios. This step leads to a prognosis, enabling the prediction of new economic, social, and environmental impacts under the implemented NBS. This data collection process, result of Hazard models and impact calculations will be outputs that should be integrated into WP4.

Table 9 provides an overview of the proposed scenarios in NATALIE for each CS as a minimum baseline. It outlines the hazard model that will be developed and the scenarios to be considered. It's important to note that this scheme may change over time based on specific CS requirements and the data availability during the project.

Table 9. Overview of NATALIE's scenarios for each CS. The first column shows the case study, followed by the model's name and a short description, scenarios currently used and planned to be implemented within the project, associated time horizon, input and output data. For the input data several links are attached to the available source.

Case Study		*Expected goal*	*Hazard model*	*Description*	*Scenarios*
CS#1	*Flood and wildfire risk mitigation in Greece*	Flood reduction Wildfire reduction	UTHBAL HEC-HMS HEC-RAS	Hydrological modeling tool used for estimating water balance components Hydrological modeling to simulate the complete hydrologic processes of dendritic watershed systems. Hydraulic modeling to design hydraulic structures and floodplain analysis	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS
CS#2	*Fresh water habitat restoration in urban ecosystems, Romania*	Water quality and quantity improvement	TBD		Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS
CS#3	*Constructed wetlands in Latvia and Lithuania*	Water quality improvement	CONSTRUCTED WETLANDS EXCEL SHEET	Design and model of constructed wetland based on balance of mass of ideal piston flow reactors	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS
CS#4	*Alternative water management solutions in Spanish Archipelagos*	Water quality and quantity improvement Flood reduction	ICM INFOWORKS PHAST FEFLOW GEOMODELLER	Hydrological and hydrodynamic 1D/2D modeling to simulate pluvial and fluvial floods, including stormwater and wastewater networks. Computer program for simulating groundwater flow, solute transport, and multicomponent geochemical reactions Model to simulate groundwater flow, mass transfer and heat transfer in porous media and fractured media. Model to define the 3D geological architecture (lithologies and faults) of an area	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS AMOC BAU AMOC NBS

			CONSTRUCTED WETLANDS EXCEL SHEET	Design and model of constructed wetland based on balance of mass of ideal piston flow reactors	
CS#5	*Aquifer recharge for water reuse in Belgium*	Water quality and quantity improvement	MOFLOW MT3DMS	Modular finite-difference flow model, which is a computer code that solves the groundwater flow equation. The program is used by hydrogeologists to simulate the flow of groundwater through aquifers A 3D multi-species solute transport model for solving advection, dispersion, and chemical reactions of contaminants in saturated groundwater flow systems.	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS HILL BAU HILL NBS
CS#6	*Aquatic system restoration and water management in France*	Water quantity improvement	SIM 2 and EROS	A semi-distributed modelling software e dedicated to modelling large catchment areas	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS
CS#7	*Coastal management with NBS in Iceland*	Water quality improvement Lansdlide reduction	TBD		Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS HILL BAU HILL NBS
CS#8	*Sustainable river restoration, maintenance and management in Italy*	Flood reduction	HEC-HMS HEC-RAS	Hydrological modeling tool used for estimating water balance components Hydraulic modeling to design hydraulic structures and floodplain analysis	Current SSP1 2.6 BAU SSP3 7.0 BAU SSP1 2.6 NBS SSP3 7.0 NBS

IV Conclusion

This document presents an overview of the entire WP3 and the work completed during the first year of the project with special focus on the role of NBS for the risk assessment framework regarding climate change and socio-economic scenarios. It creates a common baseline for all the CS to model future climate and socio-economic scenarios based on two different narratives developed in IPCC 6th report, SSP1 2.6 and SSP3 7.0. As a result, the following achievement can be highlighted:

- **Definition of the role of NBS in the risk assessment framework**: Clarifying and establishing the specific functions and contributions of NBS within the overall risk assessment process. It aims to determine how NBS can be effectively integrated and utilized to assess and mitigate various hazards through modelling.

- **Development of the framework for multi-hazard analysis, based on compound events, and the impact of the co-benefits of NBS and its cascading effects:** Creating a comprehensive framework to analyze and assess the risks associated with multiple hazards occurring simultaneously or in succession (compound events). It also considers the potential co-benefits and cascading effects of implementing NBS, like their ability to provide multiple ecosystem services and their potential.

- **Development of the framework for indicators of performance and monitoring in each CS:** Establishing a set of measurable indicators and a monitoring framework to evaluate the performance and effectiveness of NBS implementations in each specific CS. These indicators and monitoring protocols will help to track the progress, impacts and outcomes of NBS interventions, enabling data-driven decision-making and adaptive management.

- **To describe the effects of climate change by using weather and socio-economic scenarios from the IPCC AR6 report and beyond, including tipping points and their possible effects in Europe:** Analyzing and describing the potential impacts of climate change from various climatic and socio-economic scenarios outlined in the IPCC AR6 and beyond. It also includes identifying potential tipping points or thresholds that could trigger significant and potentially irreversible changes and assessing their possible effects on the European region.

- **To set a common baseline of climate and socio-economic scenarios, variables and data sources for all the case studies to model the effectiveness and impact of NBS**: This involves establishing a consistent and standardized set of climates and socio-economic scenarios, variables, and data sources that will be used across all case studies. This common baseline will ensure consistency and comparability in modelling and assessing the effectiveness and impacts of NBS implementations, enabling cross-case study analysis and synthesis of findings.

This document is the first step in **establishing the role of NBS in risk assessment** in a context of multiple hazards, multiple risk (including tangible, intangible, direct and indirect losses), co-benefits, and how to model and quantify their potential impact and efficacy. The result of this deliverable will be used by the rest of the task of WP3, by WP2, to develop task 2.6, to mainstream NBS in the systematic transformation, by WP4, to develop the NBS Knowledge booster, and WP5, to be applied in the case studies when evaluating the performance of NBS under different future climate change scenarios. Please note that up to the delivery date of this document, the downscaled climatic data from EUROCORDEX [2], the main climatic data source in the project, has not been published. These data will be included in D3.2 (M24) once it becomes available.

REFERENCES

[1] Intergovernmental Panel On Climate Change (Ipcc), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1.ª ed. Cambridge University Press, 2023. doi: 10.1017/9781009157896.

[2] «CORDEX». [On line]. Available in: https://cordex.org/

[3] Intergovernmental Panel On Climate Change (Ipcc), *Climate change 2014: impacts, adaptation, and vulnerability Working Group II contribution to the fifth assessment report of the Intergovernmental panel on climate change*. New York: Cambridge university press, 2014.

[4] UNDRO, «Natural disasters and Vulnerability Analysis. Report of Experts Group Meeting of 9-12 July 1979.», United Nations Disaster Relief Organization, Geneva, Switzerland, 1980.

[5] UN-DHA, «Internationally agreed glossary of basic terms related to disaster management», United Nations Department of Humanitarian Affairs, Geneva, Switzerland, 1993.

[6] A. Connelly, J. Carter, J. Handley, y S. Hincks, «Enhancing the Practical Utility of Risk Assessments in Climate Change Adaptation», *Sustainability*, vol. 10, n.º 5, p. 1399, may 2018, doi: 10.3390/su10051399.

[7] Intergovernmental Panel On Climate Change (Ipcc), *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1.ª ed. Cambridge University Press, 2023. doi: 10.1017/9781009325844.

[8] ICARIA, «D1.1 Holistic modelling framework», 2023.

[9] UNDRR, «Capacity». [On line]. Available in: https://www.undrr.org/terminology/capacity

[10] UNISDR, «Handbook for local government leaders», 2017.

[11] European Comission, «Nature-Based Solutions». 2022.

[12] N. Seddon, A. Chausson, P. Berry, C. A. J. Girardin, A. Smith, y B. Turner, «Understanding the value and limits of nature-based solutions to climate change and other global challenges», *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 375, n.º 1794, p. 20190120, mar. 2020, doi: 10.1098/rstb.2019.0120.

[13] L. Ruangpan *et al.*, «Nature-Based Solutions for hydro-meteorological risk reduction: Astate-of-the-art review of the research area», 30 de abril de 2019. doi: 10.5194/nhess-2019-128.

[14] S. Keesstra *et al.*, «The superior effect of nature based solutions in land management for enhancing ecosystem services», *Sci. Total Environ.*, vol. 610-611, pp. 997-1009, ene. 2018, doi: 10.1016/j.scitotenv.2017.08.077.

[15] M. D. Spalding *et al.*, «The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards», *Ocean Coast. Manag.*, vol. 90, pp. 50-57, mar. 2014, doi: 10.1016/j.ocecoaman.2013.09.007.

[16] IUCN, «IUCN Global Standard for Nature-based Solutions», 2020.

[17] N. Kabisch *et al.*, «Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action», *Ecol. Soc.*, vol. 21, n.º 2, p. art39, 2016, doi: 10.5751/ES-08373-210239.

[18] N. Frantzeskaki *et al.*, «Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making», *BioScience*, vol. 69, n.º 6, pp. 455-466, jun. 2019, doi: 10.1093/biosci/biz042.

[19] M. Velasco, B. Russo, y E. Martínez-Gomariz, «Integrated Assessment of Climate Change Impacts and Urban Resilience: From Climate and Hydrological Hazards to Risk Analysis and Measures», *Sustainability*, vol. 12, n.º 16, p. 6430, ago. 2020, doi: 10.3390/su12166430.

[20] S. Hochrainer-Stigler *et al.*, «Toward a framework for systemic multi-hazard and multi-risk assessment and management», *iScience*, vol. 26, n.º 5, p. 106736, may 2023, doi: 10.1016/j.isci.2023.106736.

[21] M. S. Kappes, M. Papathoma-Köhle, y M. Keiler, «Assessing physical vulnerability for multi-hazards using an indicator-based methodology», *Appl. Geogr.*, vol. 32, n.º 2, pp. 577-590, mar. 2012, doi: 10.1016/j.apgeog.2011.07.002.

[22] B. Russo *et al.*, «Improving Climate Resilience of Critical Assets: The ICARIA Project», *Sustainability*, vol. 15, n.º 19, p. 14090, sep. 2023, doi: 10.3390/su151914090.

[23] G. Zuccaro y M. F. Leone, «Building Resilient Cities: A Simulation-Based Scenario Assessment Methodology for the Integration of DRR and CCA in a Multi-Scale Design Perspective», *Procedia Eng.*, vol. 212, pp. 871-878, 2018, doi: 10.1016/j.proeng.2018.01.112.

[24] A. Turchi, R. Lumino, D. Gambardella, y M. F. Leone, «Coping Capacity, Adaptive Capacity, and Transformative Capacity Preliminary Characterization in a "Multi-Hazard" Resilience Perspective: The Soccavo District Case Study (City of Naples, Italy)», *Sustainability*, vol. 15, n.º 14, p. 10877, jul. 2023, doi: 10.3390/su151410877.

[25] ICARIA, «D2.1 Holistic Modeling multihazards», 2023.

[26] J. Zscheischler *et al.*, «Future climate risk from compound events», *Nat. Clim. Change*, vol. 8, n.º 6, pp. 469-477, jun. 2018, doi: 10.1038/s41558-018-0156-3.

[27] G. Zuccaro, D. De Gregorio, y M. F. Leone, «Theoretical model for cascading effects analyses», *Int. J. Disaster Risk Reduct.*, vol. 30, pp. 199-215, sep. 2018, doi: 10.1016/j.ijdrr.2018.04.019.

[28] R. Willows y R. K. Connell, *Climate adaptation: risk, uncertainty and decision-making*. Oxford: UK Climate Impacts Programme, 2003.

[29] C. M. Raymond *et al.*, «A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas», *Environ. Sci. Policy*, vol. 77, pp. 15-24, nov. 2017, doi: 10.1016/j.envsci.2017.07.008.

[30] S. A. Argyroudis, S. A. Mitoulis, L. Hofer, M. A. Zanini, E. Tubaldi, y D. M. Frangopol, «Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets», *Sci. Total Environ.*, vol. 714, p. 136854, abr. 2020, doi: 10.1016/j.scitotenv.2020.136854.

[31] Pescaroli, Gianluca y Alexander, David, «Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework», *Risk Anal.*, vol. 38, n.º 11, p. Pages 2245-2257, 2018, doi: https://doi.org/10.1111/risa.13128.

[32] C. B. Field, V. Barros, T. F. Stocker, y Q. Dahe, Eds., *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*, 1.ª ed. Cambridge University Press, 2012. doi: 10.1017/CBO9781139177245.

[33] J. Zscheischler *et al.*, «A typology of compound weather and climate events», *Nat. Rev. Earth Environ.*, vol. 1, n.º 7, pp. 333-347, jul. 2020, doi: 10.1038/s43017-020-0060-z.

[34] L. Ruangpan *et al.*, «Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits», *J. Environ. Manage.*, vol. 352, p. 119985, feb. 2024, doi: 10.1016/j.jenvman.2023.119985.

[35] S. O'Hogain y L. McCarton, «Hybrid Infrastructure: Local, Regional and Global Potential of Nature Based Solutions», en *A Technology Portfolio of Nature Based Solutions: Innovations in Water Management*, S. O'Hogain y L. McCarton, Eds., Cham: Springer International Publishing, 2018, pp. 105-113. doi: 10.1007/978-3-319-73281-7_6.

[36] J. Ballester *et al.*, «Heat-related mortality in Europe during the summer of 2022», *Nat. Med.*, vol. 29, n.º 7, pp. 1857-1866, jul. 2023, doi: 10.1038/s41591-023-02419-z.

[37] European Commission *et al.*, *European drought risk atlas*. Publications Office of the European Union, 2023. doi: 10.2760/608737.

[38] European Commission. Joint Research Centre., *Adapting to rising coastal flood risk in the EU under climate change: JRC PESETA IV project : Task 6.* LU: Publications Office, 2020. Accedido: 17 de julio de 2024. [En línea]. Disponible en: https://data.europa.eu/doi/10.2760/456870

[39] European Commission. Joint Research Centre., *Global warming and windstorm impacts in the EU: JRC PESETA IV project : Task 13.* LU: Publications Office, 2020. Accedido: 17 de julio de 2024. [En línea]. Disponible en: https://data.europa.eu/doi/10.2760/039014

[40] J. Ruffault *et al.*, «Increased likelihood of heat-induced large wildfires in the Mediterranean Basin», *Sci. Rep.*, vol. 10, n.º 1, p. 13790, ago. 2020, doi: 10.1038/s41598-020-70069-z.

[41] European Environment Agency, «Projected multi-hazard exposure for the 2020s, 2050s and 2080s». [En línea]. Disponible en: https://www.eea.europa.eu/data-and-maps/figures/projected-multi-hazard-exposure-for

[42] A. Garcia-Aristizabal, P. Gasparini, y G. Uhinga, «Multi-risk Assessment as a Tool for Decision-Making», en *Urban Vulnerability and Climate Change in Africa: A Multidisciplinary Approach*, S. Pauleit, A. Coly, S. Fohlmeister, P. Gasparini, G. Jørgensen, S. Kabisch, W. J. Kombe, S. Lindley, I. Simonis, y K. Yeshitela, Eds., Cham: Springer International Publishing, 2015, pp. 229-258. doi: 10.1007/978-3-319-03982-4_7.

[43] UN, «Sendai Framework for Disaster Risk Reduction 2015 - 2030», 2014.

[44] B. Evans *et al.*, «Mapping urban infrastructure interdependencies and fuzzy risks», *Procedia Eng.*, vol. 212, pp. 816-823, 2018, doi: 10.1016/j.proeng.2018.01.105.

[45] A. J. C. Gill *et al.*, «D1.2/Handbook of Multi-Hazard, Multi-Risk Definitions and Concepts», 2022.

[46] Hielkema L., Suidman J., y Jaime C., «Multi-Hazard Risk Analysis Methodologies». [En línea]. Disponible en: https://www.anticipation-hub.org/news/multi-hazard-risk-analysis-methodologies

[47] J. C. Gill, E. Hussain, y B. D. Malamud, «Workshop Report: Multi-Hazard Risk», 2020.

[48] C. Mbow, M. Van Noordwijk, E. Luedeling, H. Neufeldt, P. A. Minang, y G. Kowero, «Agroforestry solutions to address food security and climate change challenges in Africa», *Curr. Opin. Environ. Sustain.*, vol. 6, pp. 61-67, feb. 2014, doi: 10.1016/j.cosust.2013.10.014.

[49] D. Russi, «The Economics of EcosystemS anD Biodiversity for Water and Wetlands», 2013.

[50] J. Zedler y S. Kercher, «Wetland Resources: Status, Trends, Ecosystem Services, and Restorability», *Annu Rev Env. Resour*, vol. 15, pp. 39-74, nov. 2005, doi: 10.1146/annurev.energy.30.050504.144248.

[51] E. Cohen-Shacham, G. Walters, C. Janzen, y S. Maginnis, Eds., *Nature-based solutions to address global societal challenges*. IUCN International Union for Conservation of Nature, 2016. doi: 10.2305/IUCN.CH.2016.13.en.

[52] B. W. Griscom *et al.*, «Natural climate solutions», *Proc. Natl. Acad. Sci.*, vol. 114, n.º 44, pp. 11645-11650, oct. 2017, doi: 10.1073/pnas.1710465114.

[53] B. Locatelli, C. Pavageau, E. Pramova, y M. Di Gregorio, «Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs», *WIREs Clim. Change*, vol. 6, n.º 6, pp. 585-598, nov. 2015, doi: 10.1002/wcc.357.

[54] A. Balmford, J. Beresford, J. Green, R. Naidoo, M. Walpole, y A. Manica, «A Global Perspective on Trends in Nature-Based Tourism», *PLoS Biol.*, vol. 7, n.º 6, p. e1000144, jun. 2009, doi: 10.1371/journal.pbio.1000144.

[55] Ashley *et al.*, «It's not drainage any more; it's too valuable», *ICUD*, 2024.

[56] R. Vignola, B. Locatelli, C. Martinez, y P. Imbach, «Ecosystem-based adaptation to climate change: what role for policy-makers, society and scientists?», *Mitig. Adapt. Strateg. Glob. Change*, vol. 14, n.º 8, pp. 691-696, dic. 2009, doi: 10.1007/s11027-009-9193-6.

[57] IUCN, *Ecosystem based adaptation : knowledge gaps in making an economic case for investing in nature based solutions for climate change*. 2015.

[58] T. BenDor, T. W. Lester, A. Livengood, A. Davis, y L. Yonavjak, «Estimating the Size and Impact of the Ecological Restoration Economy», *PLOS ONE*, vol. 10, n.º 6, p. e0128339, jun. 2015, doi: 10.1371/journal.pone.0128339.

[59] C. Twohig-Bennett y A. Jones, «The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes», *Environ. Res.*, vol. 166, pp. 628-637, oct. 2018, doi: 10.1016/j.envres.2018.06.030.

[60] G. N. Bratman *et al.*, «Nature and mental health: An ecosystem service perspective», *Sci. Adv.*, vol. 5, n.º 7, p. eaax0903, jul. 2019, doi: 10.1126/sciadv.aax0903.

[61] Y. Tsunetsugu, J. Lee, B.-J. Park, L. Tyrväinen, T. Kagawa, y Y. Miyazaki, «Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements», *Landsc. Urban Plan.*, vol. 113, pp. 90-93, may 2013, doi: 10.1016/j.landurbplan.2013.01.014.

[62] K. V. Abhijith *et al.*, «Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review», *Atmos. Environ.*, vol. 162, pp. 71-86, ago. 2017, doi: 10.1016/j.atmosenv.2017.05.014.

[63] D. J. Nowak, S. Hirabayashi, A. Bodine, y E. Greenfield, «Tree and forest effects on air quality and human health in the United States», *Environ. Pollut.*, vol. 193, pp. 119-129, oct. 2014, doi: 10.1016/j.envpol.2014.05.028.

[64] C. Nesshöver *et al.*, «The science, policy and practice of nature-based solutions: An interdisciplinary perspective», *Sci. Total Environ.*, vol. 579, pp. 1215-1227, feb. 2017, doi: 10.1016/j.scitotenv.2016.11.106.

[65] L. Locatelli, M. Guerrero, B. Russo, E. Martínez-Gomariz, D. Sunyer, y M. Martínez, «Socio-Economic Assessment of Green Infrastructure for Climate Change Adaptation in the Context of Urban Drainage Planning», *Sustainability*, vol. 12, n.º 9, p. 3792, may 2020, doi: 10.3390/su12093792.

[66] T.-A. T. Le, K. Vodden, J. Wu, R. Bullock, y G. Sabau, «Benefits and risks from payments for ecosystem services programs across the globe», *Front. Environ. Sci.*.

[67] M. Guerrero-Hidalga *et al.*, «Methodology to Prioritize Climate Adaptation Measures in Urban Areas. Barcelona and Bristol Case Studies», *Sustainability*, vol. 12, n.º 12, p. 4807, jun. 2020, doi: 10.3390/su12124807.

[68] V. Meyer, N. Becker, y V. Markantonis, «Costs of Natural Hazards - A Synthesis».

[69] C. Veerkamp *et al.*, «Assessment Frameworks of Nature-based Solutions for Climate Change Adaptation and Disaster Risk Reduction», 2021, doi: 10.25424/CMCC/NBS_ASSESSMENT_APPROACHES.

[70] F. Koch y K. Krellenberg, «How to Contextualize SDG 11? Looking at Indicators for Sustainable Urban Development in Germany», *ISPRS Int. J. Geo-Inf.*, vol. 7, p. 464, nov. 2018, doi: 10.3390/ijgi7120464.

[71] B. Sowińska-Świerkosz y J. García, «A new evaluation framework for nature-based solutions (NBS) projects based on the application of performance questions and indicators approach», *Sci. Total Environ.*, vol. 787, p. 147615, sep. 2021, doi: 10.1016/j.scitotenv.2021.147615.

[72] European Commission. Directorate General for Research and Innovation., «Evaluating the impact of nature-based solutions: a handbook for practitioners.», Publications Office, LU, 2021. Accedido: 7 de marzo de 2024. [En línea]. Disponible en: https://data.europa.eu/doi/10.2777/244577

[73] N. Frantzeskaki, «Seven lessons for planning nature-based solutions in cities», *Environ. Sci. Policy*, vol. 93, pp. 101-111, mar. 2019, doi: 10.1016/j.envsci.2018.12.033.

[74] P. Kumar *et al.*, «An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards», *Earth-Sci. Rev.*, vol. 217, p. 103603, jun. 2021, doi: 10.1016/j.earscirev.2021.103603.

[75] S. Connop *et al.*, «Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure», *Environ. Sci. Policy*, vol. 62, pp. 99-111, ago. 2016, doi: 10.1016/j.envsci.2016.01.013.

[76] S. Narayan *et al.*, «The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences», *PLOS ONE*, vol. 11, n.º 5, p. e0154735, may 2016, doi: 10.1371/journal.pone.0154735.

[77] B. G. Reguero, M. W. Beck, D. N. Bresch, J. Calil, y I. Meliane, «Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States», *PLOS ONE*, vol. 13, n.º 4, p. e0192132, abr. 2018, doi: 10.1371/journal.pone.0192132.

[78] NASA, «California Wildfires». [En línea]. Disponible en: https://appliedsciences.nasa.gov/what-we-do/disasters/disasters-activations/california-fires-august-2020

[79] ESA, «Sentinels provide valuable support to International Disasters Charter». [En línea]. Disponible en: https://sentinel.esa.int/web/success-stories/-/sentinels-provide-valuable-support-to-international-disasters-charter

[80] ESA, «Copernicus Sentinel-1 maps floods in wake of Idai». [En línea]. Disponible en: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Copernicus_Sentinel-1_maps_floods_in_wake_of_Idai

[81] K. Jones, Y. Lanthier, P. Van Der Voet, E. Van Valkengoed, D. Taylor, y D. Fernández-Prieto, «Monitoring and assessment of wetlands using Earth Observation: The GlobWetland project», *J. Environ. Manage.*, vol. 90, n.º 7, pp. 2154-2169, may 2009, doi: 10.1016/j.jenvman.2007.07.037.

[82] H. Kim *et al.*, «Towards a better future for biodiversity and people: Modelling Nature Futures», *Glob. Environ. Change*, vol. 82, p. 102681, sep. 2023, doi: 10.1016/j.gloenvcha.2023.102681.

[83] IPBES, «Information on advanced work on scenarios and models of biodiversity and ecosystem functions and services», 2022.

[84] A. P. Durán *et al.*, «Bringing the Nature Futures Framework to life: creating a set of illustrative narratives of nature futures», *Sustain. Sci.*, may 2023, doi: 10.1007/s11625-023-01316-1.

[85] V. Eyring *et al.*, «Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization», *Geosci. Model Dev.*, vol. 9, n.º 5, pp. 1937-1958, may 2016, doi: 10.5194/gmd-9-1937-2016.

[86] Climate Europe, «Earth System Modeling, a definition». [En línea]. Disponible en: https://www.climateurope.eu/earth-system-modeling-a-definition/

[87] Nature Education, «Key features of climate models and earth system models: Earth system models gain complexity by considering the biological and chemical processes that feedback into the physics of climate».

[88] ICARIA, «D1.2-Climate-projections-and-hazard-scenarios_compressed.pdf», 2024.

[89] B. C. O'Neill *et al.*, «Achievements and needs for the climate change scenario framework», *Nat. Clim. Change*, vol. 10, n.º 12, pp. 1074-1084, dic. 2020, doi: 10.1038/s41558-020-00952-0.

[90] M. Meinshausen *et al.*, «The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500», *Geosci. Model Dev.*, vol. 13, n.º 8, pp. 3571-3605, ago. 2020, doi: 10.5194/gmd-13-3571-2020.

[91] K. Riahi *et al.*, «The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview», *Glob. Environ. Change*, vol. 42, pp. 153-168, ene. 2017, doi: 10.1016/j.gloenvcha.2016.05.009.

[92] A. Popp *et al.*, «Land-use futures in the shared socio-economic pathways», *Glob. Environ. Change*, vol. 42, pp. 331-345, ene. 2017, doi: 10.1016/j.gloenvcha.2016.10.002.

[93] European Comission, «ARSINOE». [En línea]. Disponible en: https://arsinoe-project.eu/

[94] V. Huber García, S. Meyer, K. Kok, P. Verweij, y R. Ludwig, «Deriving spatially explicit water uses from land use change modelling results in four river basins across Europe», *Sci. Total Environ.*, vol. 628-629, pp. 1079-1097, jul. 2018, doi: 10.1016/j.scitotenv.2018.02.051.

[95] «CLUEMONDO model scheme». [En línea]. Disponible en: https://www.earthinformatics.eu/tools/CLUEMONDO-projecting-land-use-future

[96] C. Brelsford, E. T. Coon, E. Moran, y M. Allen-Dumas, «Urban Scaling as Validation for Predictions of Imperviousness From Population», *Geophys. Res. Lett.*, vol. 47, n.º 23, p. e2020GL089742, dic. 2020, doi: 10.1029/2020GL089742.

[97] Z. J. Lyle, J. M. VanBriesen, y C. Samaras, «Drinking Water Utility-Level Understanding of Climate Change Effects to System Reliability», *ACS EST Water*, vol. 3, n.º 8, pp. 2395-2406, ago. 2023, doi: 10.1021/acsestwater.3c00091.

[98] H. Hewitt, B. Fox-Kemper, B. Pearson, M. Roberts, y D. Klocke, «The small scales of the ocean may hold the key to surprises», *Nat. Clim. Change*, vol. 12, n.º 6, pp. 496-499, jun. 2022, doi: 10.1038/s41558-022-01386-6.

[99] G. D. McCarthy y L. Caesar, «Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past?», *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 381, n.º 2262, p. 20220193, dic. 2023, doi: 10.1098/rsta.2022.0193.

[100] S. Drijfhout, «Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance», *Sci. Rep.*, vol. 5, n.º 1, p. 14877, oct. 2015, doi: 10.1038/srep14877.

[101] L. C. Jackson *et al.*, «Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM», *Clim. Dyn.*, vol. 45, n.º 11, pp. 3299-3316, dic. 2015, doi: 10.1007/s00382-015-2540-2.

[102] L. C. Jackson *et al.*, «Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project», *Geosci. Model Dev.*, vol. 16, n.º 7, pp. 1975-1995, abr. 2023, doi: 10.5194/gmd-16-1975-2023.

[103] K. Bellomo *et al.*, «Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model», *Clim. Dyn.*, vol. 61, n.º 7, pp. 3397-3416, oct. 2023, doi: 10.1007/s00382-023-06754-2.

[104] R. B. Alley *et al.*, «Abrupt Climate Change», *Science*, vol. 299, n.º 5615, pp. 2005-2010, mar. 2003, doi: 10.1126/science.1081056.

[105] V. Brovkin *et al.*, «Past abrupt changes, tipping points and cascading impacts in the Earth system», *Nat. Geosci.*, vol. 14, n.º 8, pp. 550-558, ago. 2021, doi: 10.1038/s41561-021-00790-5.

[106] N. Boers, M. Ghil, y T. F. Stocker, «Theoretical and paleoclimatic evidence for abrupt transitions in the Earth system», *Environ. Res. Lett.*, vol. 17, n.º 9, p. 093006, sep. 2022, doi: 10.1088/1748-9326/ac8944.

[107] S. Weldeab, R. R. Schneider, J. Yu, y A. Kylander-Clark, «Evidence for massive methane hydrate destabilization during the penultimate interglacial warming», *Proc. Natl. Acad. Sci.*, vol. 119, n.º 35, p. e2201871119, ago. 2022, doi: 10.1073/pnas.2201871119.

[108] Intergovernmental Panel On Climate Change (Ipcc), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*, 1.ª ed. Cambridge University Press, 2022. doi: 10.1017/9781009157964.

[109] T. M. Lenton *et al.*, «Tipping elements in the Earth's climate system», *Proc. Natl. Acad. Sci.*, vol. 105, n.º 6, pp. 1786-1793, feb. 2008, doi: 10.1073/pnas.0705414105.

[110] T. M. Lenton, D.I. Armstrong, y McKay, S. Loriani, J.F. Abrams, S.J. Lade, J.F. Donges, M. Milkoreit, T. Powell, S.R. Smith, C. Zimm, J.E. Buxton, E. Bailey, L. Laybourn, A. Ghadiali, J.G. Dyke (eds), «The Global Tipping Points Report 2023», University of Exeter, Exeter, UK, 2023.

[111] D. I. Armstrong McKay *et al.*, «Exceeding 1.5°C global warming could trigger multiple climate tipping points», *Science*, vol. 377, n.º 6611, p. eabn7950, sep. 2022, doi: 10.1126/science.abn7950.

[112] Q. Peng *et al.*, «Surface warming–induced global acceleration of upper ocean currents», *Sci. Adv.*, vol. 8, n.º 16, p. eabj8394, abr. 2022, doi: 10.1126/sciadv.abj8394.

[113] P. Ditlevsen y S. Ditlevsen, «Warning of a forthcoming collapse of the Atlantic meridional overturning circulation», *Nat. Commun.*, vol. 14, n.º 1, p. 4254, jul. 2023, doi: 10.1038/s41467-023-39810-w.

[114] R. M. Van Westen, M. Kliphuis, y H. A. Dijkstra, «Physics-based early warning signal shows that AMOC is on tipping course», *Sci. Adv.*, vol. 10, n.º 6, p. eadk1189, feb. 2024, doi: 10.1126/sciadv.adk1189.

[115] W. Weijer *et al.*, «Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis», *J. Geophys. Res. Oceans*, vol. 124, n.º 8, pp. 5336-5375, ago. 2019, doi: 10.1029/2019JC015083.

[116] University of Potsdam y S. Rahmstorf, «Is the Atlantic Overturning Circulation Approaching a Tipping Point?», *Oceanography*, 2024, doi: 10.5670/oceanog.2024.501.

[117] T. L. A. Dinh y F. Aires, «Revisiting the bias correction of climate models for impact studies», *Clim. Change*, vol. 176, n.º 10, p. 140, oct. 2023, doi: 10.1007/s10584-023-03597-y.

[118] K. Van Der Wiel, N. Wanders, F. M. Selten, y M. F. P. Bierkens, «Added Value of Large Ensemble Simulations for Assessing Extreme River Discharge in a 2 °C Warmer World», *Geophys. Res. Lett.*, vol. 46, n.º 4, pp. 2093-2102, feb. 2019, doi: 10.1029/2019GL081967.

[119] H. Hersbach, B. Bell, y P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee y J.-N. Thépaut, «ERA5 monthly averaged data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS)».

[120] R. Monjo *et al.*, «Estimation of future extreme rainfall in Barcelona (Spain) under monofractal hypothesis», *Int. J. Climatol.*, vol. 43, n.º 9, pp. 4047-4068, jul. 2023, doi: 10.1002/joc.8072.

[121] M. C. Casas-Castillo *et al.*, «On the consideration of scaling properties of extreme rainfall in Madrid (Spain) for developing a generalized intensity-duration-frequency equation and assessing probable maximum precipitation estimates», *Theor. Appl. Climatol.*, vol. 131, n.º 1, pp. 573-580, ene. 2018, doi: 10.1007/s00704-016-1998-0.

[122] R. Rodríguez *et al.*, «Influence of climate change on IDF curves for the metropolitan area of Barcelona (Spain)», *Int. J. Climatol.*, vol. 34, n.º 3, pp. 643-654, mar. 2014, doi: 10.1002/joc.3712.

[123] M. Drews, M. A. D. Larsen, R. Ludwig, y R. Wood, «D3.4 Common climate scenario baseline», 2023.

[124] M. R. Grose *et al.*, «A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia», *Clim. Serv.*, vol. 30, p. 100368, abr. 2023, doi: 10.1016/j.cliser.2023.100368.

[125] B. C. O'Neill *et al.*, «The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century», *Glob. Environ. Change*, vol. 42, pp. 169-180, ene. 2017, doi: 10.1016/j.gloenvcha.2015.01.004.

[126] European Comission, «Climate-ADAPT». [En línea]. Disponible en: https://climate-adapt.eea.europa.eu/en

[127] G. Pescaroli y D. Alexander, «Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework», *Risk Anal.*, vol. 38, n.º 11, pp. 2245-2257, nov. 2018, doi: 10.1111/risa.13128.

[128] J. Birkmann, Ed., *Addressing the challenge: recommendations and quality criteria for linking disaster risk reduction and adaptation to climate change*. en DKKV publication series, no. 38. Bonn: DKKV, 2009.

[129] M. G. Berman *et al.*, «Interacting with nature improves cognition and affect for individuals with depression», *J. Affect. Disord.*, vol. 140, n.º 3, pp. 300-305, nov. 2012, doi: 10.1016/j.jad.2012.03.012.

[130] M. keck y P. Sakdapolrak, «WHAT IS SOCIAL RESILIENCE? LESSONS LEARNED AND WAYS FORWARD», *Erdkunde*, vol. 67, n.º 1, pp. 5-19, 2013.

[131] L. Sterling y K. Taveter, *The Art of Agent-Oriented Modeling*. 2009. doi: 10.7551/mitpress/7682.001.0001.

[132] Carson, *Introduction to modeling and simulation*. 2004, p. 13 Vol.1.

[133] H. Stachowiak, *Allgemeine Modelltheorie*. 1973.

GLOSSARY

Adaptation: Process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects [3]. This can be specific to climate change, but also applicable to other challenges such as soil erosion, migration and structural economic changes. Adaptation can occur in autonomous fashion, for example through market changes, or as a result of intentional adaptation policies and plans at international, national, or local scale [10].

Adaptation measures (or actions): Technologies, processes, and activities directed at enhancing our capacity to adapt (building adaptive capacity) and at minimizing, adjusting to and taking advantage of the consequences of climatic change (delivering adaptation) [126]. Adaptation measures can be separated in i) hard and source-oriented measures, ii) hard and receptor-oriented measures, and iii) soft measures. In the context of European Guidelines (EU-GL), the term generally refers to the Actions reducing vulnerability to climate change and climate variability by preventing negative effects or by enhancing resilience to climate change [126].

Amenity: The quality of being pleasant, attractive, desirable and/or useful.

Assets: Natural or human-made resources that provide current or future utility, benefit, economic or intrinsic value to natural or human systems.

Biodiversity: The diversity of plant and animal life in the world, an area or a particular habitat – a high level of which is usually considered to be important or desirable.

Buffer: Something that helps reduce the scale of an impact.

Calibration: Model calibration can be defined as finding a unique set of model parameters that provide a good description of the system behavior and can be achieved by confronting model predictions with actual measurements performed on the system.

Capacity: Ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management. Capacity may include infrastructure, institutions, human knowledge skills, and collective attributes such as social relationships, leadership and management [9].

Cascading effect: Dynamics present in disasters, whereby a natural (originated by climate or geophysical conditions) or anthropogenic (originated by the failure of socioeconomic and/or technological systems) hazard generates a sequence of events and interactive causal chains with potential critical affection on different interdependent assets and services. Their repercussions on society and environment are particularly severe [42], [127]. For this reason, even circumscribed and low-intensity hazards could generate broad cascading effects over time and space. The domain of existing organizational, spatial, functional, physical interrelations between the environmental, socioeconomic, and technological systems that determine the occurrence of cascading effects are mostly associated with the vulnerability dimension and resulting in a non-linear disaster escalation process and potential cumulative impacts on exposed assets [27].

Caste Study: The combination of the NATALIE demonstration (demo) site and the follower site, if exists. When a demonstrator site does not have any follower, the case study and the demo site are equal terms.

Climate: Average weather, or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO).

The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate Change: Change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes [3].

Compound event: Specific category of extreme events due to their growing frequency and intensity. Compound events are the result of the combination of two or more natural events (causally correlated or not), that can i) occur simultaneously (i.e., compound coincident), ii) successively (i.e., compound consecutive), or iii) be combined with the evolutionary trends represented by the Shared Socioeconomic Pathways (SSPs) that drastically amplify their impact [1]. Compound events, which pertain to the natural environment and climate change domains, can be associated with the hazard dimension in its physical and statistical components [127]. Their analysis mostly involves physical modelling and forecasting activities.

Coping Capacity (CC): Strategies/measures adopted by individuals, organizations, and/or systems to handle abrupt adverse conditions, allowing them to absorb impacts and respond retroactively. CC manifests itself immediately, in the short-term, through all available resources with the aim of restoring the state of well-being prior to the crisis [7], [128], [129], [130]. It represents one of the key-components of resilience [24].

Co-benefits: The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefit.

Cost-Benefit Analysis (CBA): Analysis aimed at providing a structured process for integrating climate change risks and uncertainty into adaption options appraisal, with a view to selecting the "optimal" options that maximise the net benefits in terms of increased resilience to current and future climate. In the context of climate change, the focus widens to select not only efficient options but also those that perform robustly in the context of the uncertainties associated with future climate change.

Cost-effectiveness: Calculated by using a ratio by dividing costs of an investment (e.g., adaptation/mitigation measure) by units of effectiveness. The number of lives saved is an example of unit of effectiveness for risk adaptation/mitigation measure.

Damage (D): Distribution of damage occurred on one or more elements at risk (e.g., people, buildings, infrastructure, services, activities, etc.), expressed in number of damaged elements for each damage class and/or monetary value of their restoration.

Disaster: Serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacities, leading to one or more human, material, economic and environmental losses and impacts.

Disaster risk: Potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.

Disaster Risk Reduction (DRR): Policies and strategies/plans aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development.

Downscaling (climate data): Downscaling is performed to estimate higher resolution in climatic projections from global climate model outputs. Two different classes of models have been used in the past to perform downscaling: statistical and dynamic.

Dynamic Vulnerability (DV): "Procedure" that updates the vulnerability of one or more elements at risk, following a sequence of events of given intensities. Sequences of multiple events progressively increase the vulnerability of the elements in relation to the evolution process of damage. Implementing a dynamic vulnerability model means updating both exposure and vulnerability step-by-step, taking into account how each event could increase the vulnerability compared to the previous event. The vulnerability class is assigned proportionally to the level of damage, indicating the damage probability curves to be used when the next event occurs.

Drivers: Aspects which change a given system. They can be short term but are mainly long term. Changes in both the climate system and socioeconomic processes including adaptation and mitigation are drivers of hazards, exposure, and vulnerability. Drivers can, thus, be climatic or non-climatic. Climatic drivers include warming trend, drying trend, extreme temperature, extreme precipitation, precipitation, snow cover, damaging cyclone, sea level, ocean acidification, and carbon dioxide fertilization. Non-climatic drivers include land use change, migration, population and demographic change, economic development.

Ecology: The study of plants (flora) and animals (fauna) and the relationships between them and their physical environment.

Economic loss: Total economic impact that consists of direct economic loss and indirect economic loss. Direct economic loss is the monetary value of total or partial destruction of physical assets in the affected area, nearly equivalent to physical damage. Indirect economic loss is a decline in economic value added as a consequence of a direct economic loss and/or human and environmental impacts.

Ecosystem: A biological community and its physical environment.

Ecosystem services: The benefits provided by ecosystems that contribute to making human life both possible and worth living. Examples of ecosystem services include products such as food and water, regulation of floods, soil erosion and disease outbreaks, and non-material benefits such as recreational and spiritual benefits in natural areas.

Effectiveness: Ability to be successful and produce the intended results.

Exposure (E): Evaluation of the quantity, quality, and sensitivity of the elements at risk (e.g., people, buildings, infrastructure, services, activities, etc.) exposed to damage in hazard-prone areas, considering their spatial and temporal distribution. Exposure is usually combined with the vulnerability and capacities of the elements, in order to estimate the quantitative risks/impact associated with one or more hazards occurred.

Extreme weather event: Rare event in a particular place and time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th or 90th percentile of a probability density function estimated from observations.

Flood-prone Park: Communal recreational spaces that are intentionally designed to be flooded with minimal damage during storm or flood events. Flood-prone parks are often spaces which were previously developed – whether for industrial, commercial, or residential purposes – which have suffered repeated flood damage over time and whose original use no longer serves its function. While most commonly created by public entities, it is not uncommon for a private development to include the creation of a flood-prone park as a part of a larger site design. While most common along rivers, flood-prone parks can be employed in coastal areas as well. Also referred as Waterfront parks.

Forest management: Forest management is a branch of forestry concerned with overall administrative, legal, economic, and social aspects, as well as scientific and technical aspects, such as silviculture, protection, and forest regulation. This includes management for timber, aesthetics, recreation, urban values, water, wildlife, inland and nearshore fisheries, wood products, plant genetic resources, and other forest resource values. Management objectives can be for conservation, utilization, or a mixture of the two. Techniques include timber extraction, planting and replanting of different species, building and maintenance of roads and pathways through forests, and preventing fire.

Framework: Information architecture that comprises, in terms of software design, a reusable software template, or skeleton, from which key enabling and supporting services can be selected, configured, and integrated with application code.

Green-blue corridor: A strip of land in an urban area that can support habitats and allows wildlife to move along it. Typically includes cuttings, embankments, roadside grass verges, rights of way, rivers and canal banks.

Green (blue) Infrastructure: Broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.

Grey Infrastructure: Familiar urban infrastructure such as roads, sewer systems and storm drains are known as "grey infrastructure". Such conventional infrastructure often uses engineered solutions typically designed for a single function.

Hazard (H): Potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In the IPCC context, the term hazard usually refers to "climate-related physical events or trends or their physical impacts".

Hazardous event: Manifestation of a hazard in a particular place during a particular period of time.

Human behavior: People's response to a particular situation (e.g., climate-related event). The human behavior covers the range of actions by individuals, communities, organizations, governments at different level. It influences all factors of risk.

Impact: Probable spatial/temporal damage distribution according to a predefined scale of damage expected on the element at risk under consideration.

Impact scenario analysis: Choosing one or more significant events, among actually occurred past events or as a result of numerical hazard simulation models, it can be possible to obtain a damage evaluation following a specific event. The event chosen has, obviously, its own probability of occurrence to be considered.

Indicator: Single or aggregated parameters describing in a synthetic form the impact on the elements exposed involved in the study.

Land use: The main activity that takes places on an area of land based on economic, geographic or demographic use, such as residential, industrial, agricultural or commercial.

Losses: Amount of realized damages because of an occurred hazard. A typical subdivision of the type of losses is between direct losses (as consequences of the damage caused by adverse events) and indirect losses (business interruptions caused by an occurred hazard).

Mitigation: In the climate change domain, the term is used to indicate "a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)" [3], that are the source of climate change. More in general, it consists in the lessening or minimizing of the adverse impacts caused by a hazardous event [10], through actions that reduce hazard, exposure, and vulnerability [3].

Model: Hypothetical simplified description of a complex entity or process [131]. A model can be considered as “an abstract representation of a system or process” [132]. A model is a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process that has been designed for a specific purpose. Stachowiak [133] describes a model using three features: the mapping feature (reproduction of the original), the reduction feature (abstraction of the original) and the pragmatic feature (addressing a purpose for its user).

Multi-Criteria Analysis (MCA): Any structured approach used to assess overall preferences among alternative options, which are designed to fulfil several objectives. In MCA, predefined desirable objectives are delineated, and corresponding attributes or indicators are identified. The measurement of indicators does not necessarily need to be expressed in monetary terms. Rather, it often involves quantitative analysis through scoring, ranking, and weighting across a diverse array of qualitative impact categories and criteria. Known as multi-objective decision-making, the MCA serves as a decision analysis tool specifically well-suited for all those situations where a single-criterion approach (e.g., cost-benefit analysis) results inadequate. This is particularly evident when substantial environmental and social impacts cannot be easily quantified in monetary terms. In this sense, the MCA empowers decision makers to incorporate a comprehensive spectrum of criteria, spanning social, environmental, technical, economic, and financial considerations. Adaptation options can be ranked according to multiple criteria. MCA is useful to evaluate measures or interventions for which several criteria are deemed relevant and when is not feasible to quantify and assign them a monetary value in terms of costs and/or benefits. Using weighted criteria, an overall score can be determined for each adaptation option, facilitating the decision-making process to identify the most urgently needed option. The MCA prioritization process begins with a set of adaptation options, each expected to fulfil desired adaptation objectives. The primary goal is to prioritize these options based on the preferences of decision-makers or their representative proxies.

Multi-hazard: Selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, “cascadingly” or cumulatively over time, and taking into account the potential interrelated effects.

Multi-hazard assessment: To determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence.

Multi-risk assessment: To determine the whole risk from several hazards, taking into account possible hazards and vulnerability interactions (a multi-risk approach entails a multi-hazard and multi-vulnerability perspective). This would include the events occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event or hazard. This is mainly the case of cascading events or threatening the same elements at risk (vulnerable/exposed elements) without chronological coincidence.

Natural hazard: Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

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

Rainfall event: A single occurrence of rainfall before and after which there is a dry period that is sufficient to allow its effect on the drainage system to be defined.

Resilience: Ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management [10]. The resilience is also defined by IPCC as “the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation”.

Representative Concentration Pathways (RCPs): Based on IPCC report [7], “four RCPs produced from integrated assessment models are used in the Fifth and the Sixth IPCC Assessments for comparison, spanning the range from approximately below 2°C warming to high (>4°C) warming best-estimates by the end of the 21st century: RCP2.6, RCP4.5, RCP6.0 and RCP8.5.”

Risk (R): Potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented by the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction between hazard (H), exposure (E) and vulnerability (V), defined as the product (in terms of probabilistic convolution) of the three factors, according to the well-known relationship $R=H \times E \times V$ [3]. The risk therefore represents the probability that a given level of damage (e.g., on people, buildings, infrastructures, etc.), due to a hazard, will be reached in a given period of time, in a specific geographical area. Therefore, the risk must be understood as a cumulative assessment that considers the total potential damage that can be induced in the same area by several dangerous events (with different intensity or return periods) in a pre-set time window.

Risk analysis: Systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences.

Risk management: Policies and strategies/plans to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risk.

Risk perception: Subjective judgement that individuals make about the characteristics, likelihood, and severity of a risk [7]. It concerns how people perceive and interpret information regarding potential hazards, weighing factors such as uncertainty, potential consequences, and/or their own attitudes and beliefs.

Scenario: Plausible description of how the future may develop according to a coherent and internally consistent set of assumptions about key-driving forces (e.g., rate of technological change, prices) and relationships.

Shared Socioeconomic Pathways (SSPs): Based on what stated by the IPCC [1], “five SSP scenarios, namely SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5, were selected in the IPCC’s AR6 report to fill certain gaps identified in the RCPs. The first number in the label is the particular set of socioeconomic assumptions driving the emissions and other climate forcing inputs taken up by climate models, and the second number is the radiative forcing level reached in 2100.”

Stakeholder: Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity. Note: A decision maker can be a stakeholder.

Sustainable Urban Drainage System (SUDS): Drainage systems that are considered to be environmentally beneficial, causing minimal or no long-term detrimental impact.

Uncertainty: It comes out when we are not sure about the outcome of a process (like a measure of a physical quantity, or the occurrence of a destructive event). Several factors, acting simultaneously or separately, are responsible for the existence of uncertainty; we can group those factors in two groups: those due to the intrinsic stochasticity of the process (the so-called aleatory uncertainty), and those due to the lack of or imprecise knowledge of the process (epistemic uncertainty).

Urban: The categorization of areas as “urban”, carried out by government statistical departments, is generally based either on population size, population density, economic base, provision of services, or some combination of the above. Urban systems are networks and nodes of intensive interaction and exchange including capital, culture, and material objects. Urban areas exist on a continuum with rural areas.

Urban system: System of urban areas (Urban settlements from a systemic viewpoint).

Time periods: <u>Pre-industrial</u> period is the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST). The <u>‘modern’ period</u> is defined as 1995 to 2014 in AR6, while three <u>future periods</u> are used for presenting climate change projections, namely near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100), in both the AR6 WGI and WGII reports.

Transformative Capacity (TC): Encompasses the ability and potential of individuals, organizations and/or systems to access assets/funds and engage in decision-making process, aiming at defining shared pathways for preventing future adverse conditions, and radically transforming the functioning of communities involved. TC manifests gradually, in the long-term, enhancing the future well-being [7], [128], [129], [130]. Programs for emergency preparedness or strategic multi-stakeholder and civil society engagement concern the transformative side of resilience including operational tools organized within the framework of participation. It represents one of the key-components of resilience [24].

Variable: A variable is any characteristic, number, or quantity that can be measured and 'varies' between different respondents/units of measurements. The variables are used to define the indicators.

Vulnerability (V): The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to be harmed and lack of capacity to cope and adapt.

Vulnerability class: Categorization of the elements at risk, grouped according to selected properties (e.g., age, health status, crop resistance to droughts, maximum runoff capacity, etc.) able to identify a given behavior of the element under the hazardous action.

NATALIE

Accelerating and mainstreaming transformative NATure-bAsed solutions to enhance resiLIEence to climate change for diverse bio-geographical European regions

@NatalieProject

https://www.natalieproject.eu/

natalieproject@oieau.fr

Funded by the European Union

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

UK Research and Innovation