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Methodology for resilience assessment of key systems

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[1] PU = Public
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Disclaimer

Abbreviations

Abbreviation / Acronyms	Description
RCRFT	Regional Climate Resilience Footprint tool
WP	Work Package

Executive Summary

As regions and communities face the daunting challenges posed by climate change, there is an urgent need for tools that can effectively assess resilience factors and guide adaptation measures, as well as be used in the modelling and evaluation chain of decisions for the implementation of climate adaptation interventions. The policy term *resilience is of paramount importance*, and generally refers to the ability of systems to absorb and to adapt to emerging uncertain disturbances such as climate change. Although it remains a rather elusive term in the literature, defined in many different ways by scholars in a plethora of fields, its theory is valuable for assessing the baseline conditions of key systems in regions facing climate risks and evaluating the effectiveness of adaptation interventions.

In this task, we formalize an operationalizable definition of resilience and articulate a methodology for its assessment, to underpin the design problem of generating dynamic adaptation pathways across the key systems of the IMPETUS Demo Sites (T3.6). We employ as a definition the 'degree to which a region's key systems perform under progressively increasing disturbance'. By disturbance we mean future scenarios of climate change and other socio-economic parameters, and performance is quantified based on a multi-dimensional approach, utilizing the IMPETUS I&M framework as articulated in T3.2.

The resilience assessment methodology can be used also in a different way, without formulating future scenarios and system configurations; the upcoming Regional Climate Resilience Footprint Tool (RCRFT) fosters the initiation of conversation between a group of stakeholders, that engage in the quantification of the baseline resilience of the system, by leveraging the same methodological foundations.

IMPETUS

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1 Aim and scope of this document

1.1 IMPETUS project

In 2021, as part of the Green Deal, the European Commission adopted a new Adaptation Strategy that aims to increase and accelerate the EU's efforts to protect nature, people and livelihoods against the unavoidable impacts of climate change. As climate change progresses irrevocably, urgent measures are needed for building resilience and adaptive capacity. Climate action is at the heart of the European Green Deal, an ambitious package of measures ranging from ambitiously cutting greenhouse gas emissions, to investing in cutting-edge research and innovation, to preserving Europe's natural environment. As part of the emphasis on climate adaptation research efforts, IMPETUS is a European Union Horizon H2020 research and innovation programme, launched in October 2021, with the goal of accelerating Europe's climate adaptation strategy and meeting the European Union's ambition to become the world's first climate-neutral continent by 2050. IMPETUS aims to turn climate commitments into tangible, urgent actions to protect communities and the planet by bringing together 32 partners from 9 countries. Seven diverse demonstration sites will be the pilot cases for the innovative solutions of the project, that represent seven of Europe's eleven biogeographical regions[1], i.e., Continental (Berlin-Brandenbourg region), Coastal (Catalan coast), Mediterranean (Attica region), Atlantic (Zeeland province), Arctic (Troms and Finnmark County), Boreal (Zemgale region) and Mountains (Valle dei Laghi area). Multidisciplinary teams will work with policymakers, businesses and communities at local and regional levels and ensure that knowledge is created and shared together. Much of this activity will be centerered around 'Resilience Knowledge Boosters' (RKBs) based on each of the project's seven demonstration and testing sites. The RKBs provide a place for stakeholders to engage and create together; as a network, they will provide routes for knowledge flow and for successful climate adaptation approaches to reach other communities that need them. This approach will also improve risk assessment tools and models, facilitate better governance and economic decision-making, and achieve cost efficiencies in the successful solutions. In this way, IMPETUS will create pathways towards a climate-neutral and sustainable economy, while attaining fair and equitable solutions for all vulnerable parts of society. IMPETUS is divided into 8 work packages (WPs):

- WP1: Governance & Stakeholder Cocreation for Transformative Adaptation
- WP2: Digital and knowledge dimension of the Resilience Knowledge Boosters
- WP3: Exposure and Vulnerability Assessment
- WP4: Deployment of Solutions at demo sites
- WP5: IMPETUS Adaptation Pathways and Innovation Packages
- WP6: Boosting project impact
- WP7 Communication and dissemination
- WP8 Project management

1.2 Work Package 3: Exposure and Vulnerability Assessment

WP3 has a significant role in the IMPETUS project because its objective is to support strategic planning for the effective application of climate adaptation packages by developing and validating methodologies and tools for the assessment of European Regions and communities and their key system's exposure and vulnerabilities pertaining to climate change related risks. To this end, within WP3 there are six Tasks. Their activities include:

- Develop and demonstrate novel holistic metrics and indicators, as well as evaluation methods and tools for the identification of European regions or communities that are the most vulnerable and/or of low adaptive capacity to climate change impacts and the evaluation of their exposure to risks. Also, evaluation of vulnerability and prioritisation of key systems whose urgent protection would significantly improve the region's resilience.
- Develop and operationalise resilience assessment methods and tools for vulnerable regions and their key systems, before and after the implementation of climate adaptation measures.
- Demonstrate integrative systemic risk analyses and management approaches, considering multi-hazard and cascading effects, as well as interdependencies between key systems to assess potential hidden risks or unintended effects, resulting from the innovation packages

[1] https://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-in-europe-2

themselves, and identify parameters that need to be monitored (and their thresholds) as part of adaptation pathways.

- Develop and validate methodologies and tools to assess and improve the adaptive capacity and dynamic nature of adaptation pathways. Based on the parameters to be monitored and their thresholds provide the tools to build dynamic behaviour into the adaptation plans, including emerging problem inferences and contingency planning and support.

The six Tasks of WP3 are:

- Task 3.1: Generation of weather and climate data
- Task 3.2: Adopt and adapt indicators and metrics for climate change vulnerability, resilience assessment and pathway adaptation capacity
- Task 3.3: Identify and prioritise climate change ‘hot-spots’
- Task 3.4: Analyse and assess resilience of key systems
- Task 3.5: Analyse and assess costs, benefits and risks related to interventions
- Task 3.6: Strategic Resilience and Multi-Hazard Management tool for identifying dynamic adaptation pathways

1.3 Task 3.4: Analyse and assess resilience of key systems

In this task we develop an operationalizable methodology and a tool for application in the hot-spot regions (T3.3) that need urgent protection from climate impacts and risks. Our approach will allow system resilience to be assessed both before and after interventions (for the interventions ‘shortlisted’ in T3.5 and evaluated in T3.6 for the generation of adaptation pathways) allowing a quantification of the improvement in resilience from the application of climate adaptation measures, under significant uncertainty in future climate and socio-economic conditions, utilizing the flexible superset of indicators assembled in T3.2. Also, building on the work by Blues Cities this task will develop the Regional Climate Resilience Footprint Tool (RCRFT) which will allow regions and communities to perform a standardized self-assessment of their climate resilience (similar to the City Blueprint) as a conversation starter in the context of stakeholder engagement in WP1. This report focuses on the methodology articulation for assessing resilience in key systems, and another deliverable will follow in M30 of the project, focusing on the RCRFT, which is currently under development.

2 Resilience for key systems

2.1 The emergence of resilience in policy discourse

Resilience is a term that has been dominating the policy discourse and the scientific literature (Hillmann and Guenther 2021; Meerow et al. 2016), on the topic of ‘future proofing” a range of systems that includes practically everything from the energy and water sectors, to urban communities, and organizations (Rockstrom et al. 2014). The explosion of popularity of the term can be visualized in Figure 2.1, which shows the number of scientific publications per year.

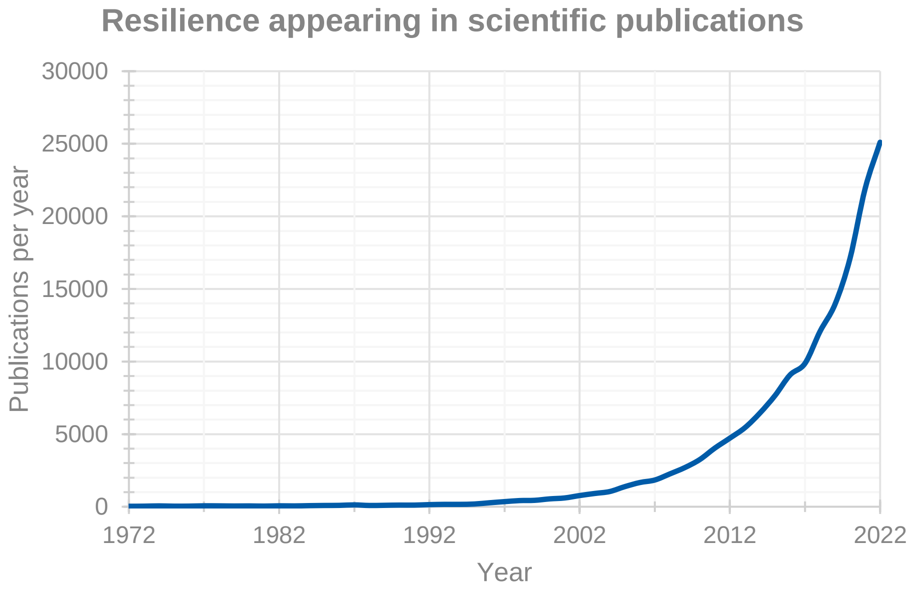

Figure 2.1: The trend of the term resilience in scientific literature (data from Scopus).

There can be many explanations for this rise (Meerow and Newell 2015); one of the main reasons is that resilience provides insights about complex socio-ecological systems and their sustainable management (Folke 2006), especially under the emerging threat of climate change (Leichenko 2011; Pickett et al. 2004; Solecki et al. 2011; Zimmerman and Faris 2011). Resilience theory in general recognizes that nonlinear change, shocks, disturbances and uncertainty affect systems, so it is very relevant in climate studies (Tyler and Moench 2012). It is also strongly linked (and sometimes confused) with other similar policy terms like sustainability, vulnerability and adaptation (Meerow and Newell 2019)

Nonetheless, ever since its introduction, resilience has remained a rather elusive term because there is a conceptual fuzziness to it (Meerow et al. 2016). The fuzziness stems from it being abstract and malleable enough to be involved in everything from research to governmental policies (Walker and Cooper 2011). The term functions both as a “boundary object” between scientific domains, allowing interpretive flexibility and definition negotiations (van Pelt et al. 2015) - and as a “bridging concept” which actively links fields and stimulates communication and collaboration, fostering interdisciplinarity and transdisciplinarity (Baggio et al. 2015; Davoudi et al. 2012; Deppisch and Hasibovic 2013). A significant portion of research condemns this vagueness in definition, stating that it can make resilience difficult to operationalize and develop general indicators or metrics (e.g., Gunderson 2000; Pizzo 2015; Vale 2014). Even so, policy makers around the world have widely adopted the term, risking, as some scholars mainly in the social sciences domain note, turning the term into a “policy buzzword” (Davoudi et al. 2012; Hammond 2014; Schwarz 2018; Vale 2014; Weichselgartner and Kelman 2015). The main issue is the general lack of attentiveness in applications and agendas to social structures, politics, power and equity concerns (Cote and Nightingale 2012; Cretney 2014; Evans 2011).

In the context of IMPETUS, the focus is on the support of local stakeholders with complex strategic and transdisciplinary decision-making; therefore, resilience should be defined in a clear and transparent manner, taking into consideration the complex socio-economic, socio-ecological and bio-physical interactions within urban regions and their key systems.

2.2 Resilience roots

Etymologically, the origin of the word stems from the Latin verb *resilio*, which means “to jump back” (Klein et al. 2003). The term resilience has been used extensively in the field of mechanics and material science, since the late 1800s (e.g., (Merriman 1885; Thurston 1874) to today, as the ability of a material “to store strain energy and deflect elastically under a load without breaking or being deformed” (Gordon 1978). Also, another metaphorically similar use of the term is in use in the mental health psychology domain, starting from the 1950’s as the ability of children exposed to traumatic events to cope and attain normal adulthood (Bloch et al. 1956; Clarke et al. 1958), expanded in recent years to the ability of adults who experience extraordinary events to cope and maintain relatively stable psychological and physical functioning (Bonanno 2004).

Since the 1970s, however, the term resilience has been used extensively used outside the mechanics/material and psychology domains, stemming from the work of the theoretical ecologist Holling (Holling 1973), then in the context of ecological systems in phase space returning to an equilibrium state, after a perturbation. Resilience in that work was defined as “the measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables”; This ecological definition, sparked an upsurge of interest in the term and its applications, as it encapsulates system analysis and system thinking for the first time (Klein et al. 2003; Pickett et al. 2004) and since its inception, in numerous variations has been referenced in virtually all related resilience literature (Francis and Bekera 2014), including the largest influence in the urban resilience field (Meerow et al. 2016).

Holling suggested in this early work that resilient ecological systems differ from stable ones, because very stable systems (defined as exhibiting low variability of species densities over time) may not be able to cope with sudden large variations in population densities after significant perturbations, in contrast with systems that exhibit unstable behaviour with wide variability, as these may withstand severe shocks. Moreover, Holling illustrated the existence of multiple stability domains (“basins of attraction”) that form after perturbations, in contrast with the single equilibrium state that was the understanding at the time, which conceived ecosystems as inherently stable and predictable (Clements 1936), thus always able to return to equilibrium after human stressors were removed from the environment (Folke 2006).

Fiering and Holling (Fiering and Holling 1974) explored stability versus resilience in engineering resource systems and suggested that specifying standards for the system to strictly adhere to, for example completing design objectives with probabilities close to unity, in a “fail-safe” notion, could end up restraining the system with high misallocated costs. The reason is that systems can be exposed to unknown threats, for which no probability of occurrence can be assigned, pertaining to the uncertainty problem for the future provision of systems performance. For a long time, however, the literature, continued to focus on the study of systems that return to a single stable state (Folke 2006) for long, creating an interpretation of resilience as the return speed to this single equilibrium after disturbance (O’Neil et al. 1994; Pimm 1984). Holling subsequently proposed that (Holling 1996) there are two different interpretations of resilience, the “engineering resilience”, which focuses on the return speed (because it is a common goal in designing fail-safe engineering systems) and the “ecological resilience” which focuses on “maintaining existence of function”, acknowledging the fact that disturbances can force systems to flip between various different equilibrium states, and the goal is for an ecological system to be ‘safe-to-fail’ (to re-organize and adapt). Ecological resilience evolved from the 1973 definition to account for the emergence of different stability domains after perturbation as the “ability to adapt to change by exploiting instabilities” (Walker et al. 1981) and not just absorb the disturbances, and as scientific research progressed, resilience thinking evolved into concepts that include the possibility that the system may experience a lasting effect after perturbations. One such definition of resilience is “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” by Walker et al. (Walker et al. 2004).

The concept of ‘ecological resilience’ soon transformed into an interdisciplinary work about societal (human) – ecological (biophysical) interactions, in what is called socio-ecological systems (SES) (Gallopín 1991). In SESs, the focus shifts to the ‘adaptive cycle’, which is viewed as another very important component of resilience and reflects the learning aspect of the system behaviour (Carpenter et al. 2001; Folke et al. 2004; Gunderson 2000; Gunderson et al. 1995; Gunderson and Holling 2002; Nelson et al. 2007; Walker et al. 2004). In that sense, in most of the works dealing with systems where there is interaction between humans and the environment, learning and building adaptive capacity are included in the formulation of the definition of resilience (Adger 2006; Carpenter et al. 2001; Wong and Brown 2009). The theory of the adaptive cycle is the notion that dynamic systems (such as ecosystems, societies, organizations, regions and other SESs), do not tend toward some stable or equilibrium condition, because of the constant changes in their environment. Instead, systems pass through the following four characteristic phases; rapid growth and exploitation (r), conservation (K), where system dynamics are predictable, collapse or release (Ω), following a perturbation, and renewal or reorganization (α), where a different version of the system emerges (Carpenter et al. 2001), as shown schematically in Figure 2.2.

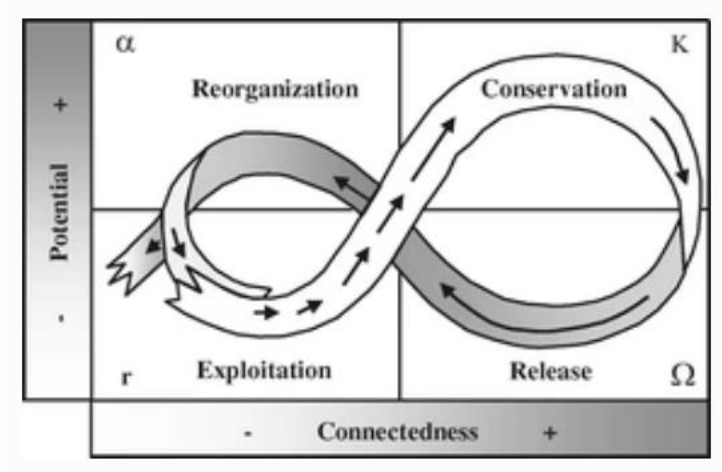

Figure 2.2: The four phases of the adaptive cycle (Carpenter et al. 2001)

2.3 Resilience sprawl to other fields

Resilience theory and its applications were not limited to the ecological or SES field; it rapidly extended to numerous other domains that deal with systems undergoing changes, disturbances or stresses including:

- Natural disasters and urban/community resilience (Bruneau et al. 2003; Comfort et al. 2010; Cutter et al. 2008; Rose 2007);
- Climate change adaptation (Leichenko 2011; Nelson et al. 2007; Solecki et al. 2011; Tyler and Moench 2012; Wardekker et al. 2010);
- Infrastructural systems (Cai et al. 2018; Vugrin et al. 2010);
- Water systems (Butler et al. 2014; Diao et al. 2016; Fiering 1982; Hashimoto et al. 1982; Sweetapple et al. 2018; Todini 2000);
- Electric power or microgrids (Chen et al. 2016; Gholami et al. 2016; Kinney et al. 2005; Lei et al. 2019; Panteli and Mancarella 2015);
- Supply chain resilience (Fahimnia and Jabbarzadeh 2016; Gunasekaran et al. 2015; Ponomarov and Holcomb 2009; Torabi et al. 2015);
- Organizational or enterprises' resilience (Bhamra et al. 2011; Fiksel 2003; Fiksel et al. 2015; Hamel and Välikangas 2003; Home and Orr 1997; Kendra and Wachtendorf 2003; Mallak 1998)

Figure 2.3 depicts the co-citation network (created with the software VOSviewer) generated from the top 1% of publications recovered from the SCOPUS database (www.scopus.com) that use 'resilience' in the title or abstract. The node size property in Figure 3.2 is set to be relevant to link strength, i.e., connections to this publication, and clusters are formed by these co-citation networks. The clusters include works about resilience of SES, in many different fields such as the aforementioned. By running a term co-occurrence analysis on the same dataset, we can observe the terms that occur most frequently along resilience, i.e., network, stress, ecosystem, application, climate change, species, outcome, performance, individual, and intervention, outlining the different fields where resilience thinking is applied.

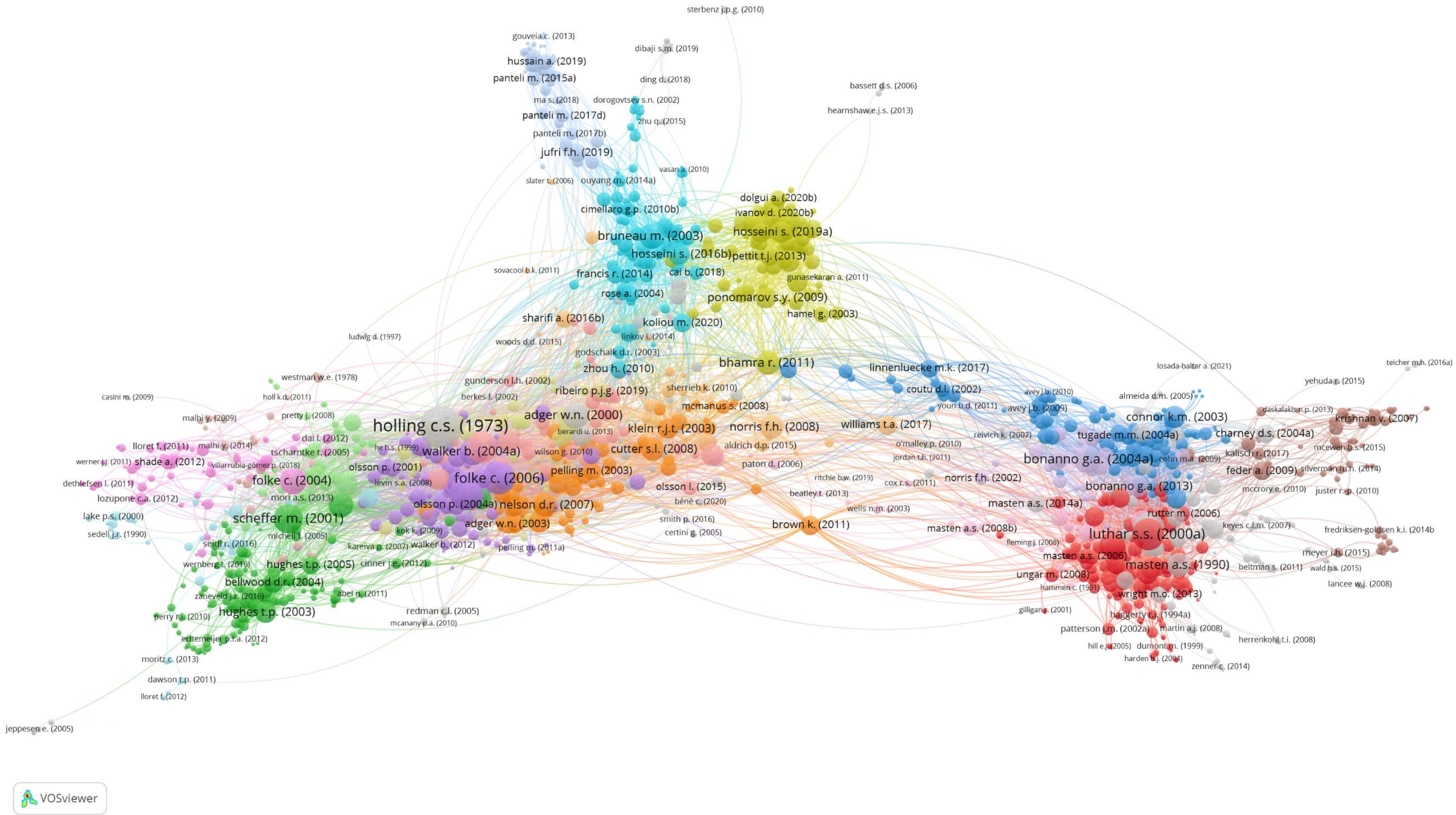

Figure 2.3: The co-citation network from the top 1% of publications by subject area featuring resilience in title or abstract (source: SCOPUS).

Resilience, however, has been employed in different ways across all these domains, starting with a variety of different definitions; Table 2.1 presents some definitions of resilience from a variety of domains to contextualize it.

Table 2.1: Definitions of resilience in various domains.

Definition	Domain	Source
A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables	Ecological systems	(Holling 1973)
The return time of variables towards their equilibrium after a perturbation, in a stable system	Ecological systems	(Pimm 1984)
The magnitude of disturbance that a system can absorb before its structure is redefined by changing the variables and processes that control behaviour	Ecological systems	(Gunderson 2000)
Resilience is characterized by these properties: (a) the amount of change the system can undergo and still remain within the same domain of attraction (i.e., retain the same controls on structure and function); (b) the degree to which the system is capable of self-organization and (c) the degree to which the system can build the capacity to learn and adapt.	Socio-ecological systems	(Carpenter et al. 2001)
Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels.	Critical infrastructure resilience	(Vugrin et al. 2010)
Resilience is the capacity of systems to buffer shocks and stresses	Agricultural systems' resilience	(Pretty 2008)
Resilience is the capacity of an SES to sustain a desired set of ecosystem services in the face of disturbance and ongoing evolution and change	Socio-ecological systems	(Biggs et al. 2012)
Resilience is the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.	System analysis	(Haimes 2009)
Resilience is the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin	Water systems	(Scott et al. 2012)
Resilience is the capability to maintain functions and structure when subjected to internal and external change and to degrade gracefully when it must	Natural disasters	(Allenby and Fink 2005)
Resilience is the joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation	Critical Infrastructure	(Ouyang 2014)
Resilience is the ability of an urban system, as well as all its constituent socio-ecological and socio-technical networks across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity	Urban resilience	(Meerow et al. 2016)
Resilience is the physical, biological, personality, social, and cultural systems' capability to effectively absorb, respond to, and recover from an internally or externally induced set of extraordinary demands.	Disaster management	(Aguirre 2006)

The ability of an actor to cope with or adapt to hazard stress	Community resilience	(Pelling 2003)
The capacity of an enterprise to survive, adapt, and grow in the face of turbulent change	Organizational resilience	(Fiksel 2006)

Our literature review reveals multiple overlapping and sometimes divergent themes in how resilience is defined and understood. These can be broadly grouped into those focusing on recovery speed after disturbances and those emphasizing adaptability to change. Here are the key points distilled from the literature:

- Resilience is frequently framed as either an inherent ability of a system or as a capacity that can be developed. This distinction is crucial for systems built with natural resilience versus those that can evolve or be engineered for it.
- Some definitions adopt a quantitative viewpoint, identifying resilience as something that can be measured, making it particularly applicable in specialized fields.
- A common aspect is the system's ability to recover or 'bounce back' to a functional state following disturbances, sometimes under the term 'engineering resilience.'
- Many definitions indicate that resilient systems are capable of mitigating or absorbing the impact of external stressors.
- The ability to proactively plan for, prepare, and anticipate potential stressors is often emphasized, revealing a forward-looking aspect of resilience, especially in engineered or infrastructural systems.
- The literature also points to the preference for systems that experience gradual degradation rather than sudden, catastrophic failure, emphasizing the value of some sustained, long-term functionality as failure events unfold or stressful conditions manifest.

2.4 Properties of resilient systems

The literature identifies multiple traits that contribute to a system's resilience, although these traits can vary depending on the context and scientific domain. The following list attempts to outline common patterns that enhance resilience across various fields, including socio-ecological, engineering, and organizational systems.

- Robustness: An important trait for resilient systems is described as an entity’s ability to withstand a given level of stress without any degradation or loss of function.
- Buffering capacity: This trait is referred to the capacity excess of a system that can be utilized when in an emergency, thus being more resilient (Butler et al. 2014). In social systems (a society, a governance system), buffering capacity and robustness refer to their capacity to deal with shocks (such as climate impacts), from a socioeconomic dimension.
- Stability: This trait refers to systems’ ability to manage disruptions and return to a stable state, thereby improving reliability and thus, resilience. However, systems that are not inherently stable can also demonstrate high levels of resilience.
- Safe failure (or soft failure): The capacity to handle abrupt impacts or the gradual buildup of stress without experiencing a devastating failure, even when the situation falls outside of the design parameters, is important for resilience (Tyler and Moench 2012).
- Agility/rapidity: The systems’ ability to promptly accumulate all the required resources in order to maintain functionality or escape cascading effects and future interruptions (Bruneau et al. 2003; Sharifi and Yamagata 2016).
- Redundancy: Having multiple interchangeable components with similar or overlapping functions adds a reserve capacity to a system, acting as a form of "insurance" against total failure when a single component breaks (Liao 2012; Wardekker et al. 2010). A related idea is modularity, which not only involves substitutable components but also offers multiple ways for a system to deliver its service (Tyler and Moench 2012).
- Flexibility: The system attribute to maintaining several options and configurations, thus being able to adapt to short term out-of-system alterations (Liao 2012; Sharifi and Yamagata 2016). In water systems for example, the capability to use alternative sources for water supply, enables

the system to be less vulnerable to ‘unforeseen’ threats and failures. Characteristics like flexibility, diversity, refers to the extent to which a system can employ multiple, distinct functions concurrently (Liao 2012; Wardekker et al. 2010). This enhances resilience by providing the system with a broader range of functionalities, enabling it to better cope with disturbances.

- Independence/autonomy: The ability of system components to operate independently without external support enhances resilience and availability, especially when other parts are hindered (Godschalk 2003). While autonomy strengthens resilience, the traits of interdependence and interconnectedness can have mixed effects (positive or negative), potentially causing cascading failures in critical systems (Chang et al. 2007). For example, a blackout in an energy system could negatively impact a connected water supply system.
- Cohesion: The presence of cohesive connections and interactions between various system components and variables is highlighted (Fiksel 2003). In social systems, cohesion refers to the robustness of social bonds and the community's sense of unity.
- Resourcefulness: Refers to the system's resources for preparation, response, and recovery from disturbances, encompassing both material assets and the human capacity for planning and action (Bruneau et al. 2003; Cutter et al. 2008).
- Coordination capacity: A system with effective coordination among key managerial stakeholders is better equipped for rapid recovery from disturbances, as it allows for more organized and well-planned actions (Tyler and Moench 2012).
- Foresight capacity: Systems that assess future conditions in advance and analyze various scenarios for preparation tend to be more resilient (Sharifi and Yamagata 2016). Similar concepts found in the literature include preparedness (Cutter et al. 2008) and anticipation (Fiksel et al. 2015).
- Collaboration: The continuous participation of stakeholders who share the same opportunities and incentives for solving problems (Sharifi and Yamagata 2016).
- Adaptability: A system’s ability to alternate it’s responses based on unforeseen effects (Fiksel 2003), while also ‘build’ on new pressures and apply new knowledge to enhance it’s capacity for future events (Carpenter et al. 2001; Gunderson 2000; Nelson et al. 2007).
- Self-organization: Self-organized systems exhibit resilience due to their decentralized nature, allowing for quicker responses and adaptability to events (Krasny and Tidball 2009; Liao 2012). These systems also have strong social and institutional memory for dealing with change (Folke et al. 2005). In social contexts, self-organization enables local communities to independently respond to disruptions and fosters better decision-making through both horizontal and vertical institutional connections (Cutter et al. 2008). The term "flatness" refers to systems with less hierarchy, leading to greater flexibility and resilience (Wildavsky 1988). Similarly, in technical systems, distributed or decentralized designs have been shown to enhance resilience (Ahern 2011; Bouziotas et al. 2019, 2023).
- Creativity/innovation capacity: A system's ability to view disruptions as opportunities for beneficial growth is crucial for resilience. This suggests that the system has and applies its innovative capacities (Sharifi and Yamagata 2016). Innovation reinforces resilience by enhancing the system's capability for transformation (Folke 2006). This idea of benefiting from adversity is also referred to 'antifragility' in existing literature (Taleb 2012).
- Efficiency: Efficiency is considered an important trait for resilient systems in various contexts such as energy, economics, and organizational resilience (Fiksel 2003; Mafabi et al. 2012). However, resilience can sometimes conflict with efficiency, as traits like redundancy and flexibility may reduce efficiency in terms of economics or resource usage (Meerow and Newell 2015). Hyper-efficient systems may be less resilient due to their narrow optimization focus (Walker and Salt 2006).
- Equity/fairness: In social systems, equity and fairness are key elements of resilience and are frequently discussed in the context of socio-ecological systems, community resilience, and climate resilience (Cote and Nightingale 2012; Gunderson and Holling 2002). Equity should be present both in decision-making processes and outcomes, affecting institutions' fairness and

the distribution of vulnerabilities within a population (Nelson et al. 2007). This increases social cohesiveness by enhancing a community's ability to recover from shocks (Sharifi and Yamagata 2016).

2.5 Resilience and other related concepts

Over the years, the academic community has worked to establish a common understanding of resilience, its definitions, and its relationships with other related terms, particularly sustainability. The challenges posed by the Anthropocene era, including human-made disturbances and the growing complexity of global social-ecological systems, necessitate a focus on resilience at the planetary level. Resilience is viewed as essential to achieving sustainable development, a concept popularized by the 1987 Brundtland Report (WCED 1987) describing it as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In this context, resilience helps maintain the stability of Earth's systems and is therefore considered a key aspect of sustainability. There is broad academic consensus on the relationship between resilience and sustainability. As an example, transitioning from centralized to decentralized designs in the water sector is seen as a move that enhances both resilience and sustainability.

While both resilience and sustainability are key concepts in systems thinking, they diverge in their approaches to dealing with change and uncertainty. Resilience focuses more on adaptation, aiming to maintain essential system functions through adjustments. Sustainability, on the other hand, leans towards transformation, calling for a more radical reorganization of systems when conditions become untenable (Redman 2014). In terms of achieving sustainable development, three broad views exist according to Rees (1995): (i) maintaining the "status quo", that can be defined as preserving the structures as they are, (ii) opting for "reform" within existing structures but with essential deviations, or (iii) seeking radical "transformation" to the economic and power society structures.

In the context of social sciences including urban resilience, disaster management, and climate change adaptation, the term "resilience" has gained attention and criticism. Some scholars (Davoudi et al. 2012; Harris et al. 2017) argue that the term is overused in political discourse and often disconnected from analytical concepts, similar to how "sustainability" has been treated in the past. Questions also arise about whether resilience is always a positive or useful concept, particularly when it comes to social systems and their interaction with the environment. As noted by Anderies et al. (2013) and Carpenter et al. (2001), resilience is not a normative concept as it is not inherently linked with positive or negative connotations. For example, a dictatorship might be considered "resilient" if it can withstand various changes and challenges, but that doesn't make it desirable. Therefore, it is generally stated that resilience is a descriptive concept that in order to assess "good" or "bad," additional frameworks are essential (Matyas and Pelling 2015).

The concept of resilience has been critiqued for its broad nature and lack of focus on political power structures, scale, and social equity. Critics argue that this generality can lead to interpretations of resilience that align with neoliberal agendas and preserve systemic inequalities like poverty and social injustice. Even systems that adapt in cycles resiliently may sustain an unjust "status quo" without addressing the root causes of crises. Scholars have proposed alternative frameworks to address these issues:

- The "Five W's" approach (Meerow and Newell 2019) suggests that resilience policies should be structured by asking: for whom, what, when, where, and why. This helps clarify potential trade-offs between stakeholders, the entity being made resilient, the type of threat, the temporal and spatial scales, and the political context.
- "Negotiated resilience" (Harris et al. 2017) reframes resilience as an active negotiation between various stakeholders and actors rather than a definitive goal set by a political agenda, taking into account different time and governmental scales.

In the last years the term resilience has been gradually altered towards a process-oriented undertaking rather than an outcome-oriented procedure (Matyas and Pelling 2015). Both these perspectives aim to tackle any abstractions, clarify the specific objectives and identify how stakeholders are involved or impacted.

In systems analysis literature, resilience and risk are frequently discussed together in management analyses, yet they differ fundamentally (Aven 2016). Risk focuses on quantifiable hazards (Lowrance 1976), exposures, and vulnerabilities and often assumes known or measurable probabilities on plausible scenarios. Resilience, on the other hand, is more concerned with a system's ability to adapt to or recover from unexpected, uncertain events. While risk can sometimes be measured using statistical models, many future events fall under the category of "deep uncertainty" (Lempert et al. 2004), where probabilities cannot be easily assigned. These could include extreme disastrous and unpredictable events. Resilience is thus seen as an intrinsic property that helps systems adapt to a wide range of uncertain conditions, rather than being highly specialized for specific, known risks. In this manner, resilience-oriented analyses aim to ‘build’ systems as interactive and holistic entities that can resist unknown threats (Fiksel 2003).

In studies related to natural disasters and hazards, resilience and vulnerability are closely related concepts. Vulnerability can be broadly defined as the potential for loss (Cutter 1996) or susceptibility to harm (Adger 2006) but, like resilience, has other various interpretations as well. In policy and development planning for social, socio-ecological, or socio-technical systems, resilience has been increasingly favored over vulnerability due to its more positive connotation. The components of vulnerability often include exposure to hazards, sensitivity to perturbations, and adaptive capacity. However, there is debate within the literature about the relationship between resilience and vulnerability:

- Some view resilience as the opposite of vulnerability.
- Others see resilience as a component of vulnerability.
- Some consider resilience and vulnerability as two distinct but interconnected properties of a system.
- The key sub-components of vulnerability, such as exposure to hazards and sensitivity, have areas of overlap with both resilience and risk concepts.

Hazards are threats to a system and can be either abrupt changes called perturbations or more continuous pressures known as stress. There's a debate on whether these pressures are internal or external to the system (Gallopín 2006). Sensitivity is defined as how much a system changes or is affected when exposed to these pressures or perturbations. While some argue that sensitivity and exposure are nearly inseparable and determine a system's vulnerability, others consider sensitivity as an inherent attribute of the system, distinct from exposure.

In policy design, understanding both exposure and sensitivity is crucial for mitigating vulnerability (Adger 2006). For example, the Natanz nuclear plant was sensitive to cyber-attacks but was thought to be secure because it was not exposed to external networks. However, it was compromised through an infected USB stick, demonstrating that it was, in fact, vulnerable due to its sensitivity and actual exposure. It's important to note that levels of exposure and sensitivity are often unknown beforehand, leading to "deep uncertainty." This emphasizes the role of resilience theory and analysis in preparing systems for unpredictable hazards (Smit and Wandel 2006).

There is a relationship between robustness and resilience in the context of system analysis, drawing from multiple academic sources. Robustness originated from statistical analysis and is traditionally understood as a system's insensitivity to deviations in its design parameters. It is considered a desirable quality that enables a system to withstand stress without degrading or losing function. Resilience, on the other hand, is related but distinct, focusing on a system's ability to adapt to uncertain changes and recover from them.

The two concepts are often correlated: a robust system is typically resilient because it can absorb shocks. However, a resilient system isn't necessarily robust. In engineering terms, robustness refers to the stress a system can absorb before failing, while resilience relates to how the system behaves or performs under disturbances, including failure states. Robustness and resilience come into play in discussions about how systems behave during failures or outside their design specifications.

2.6 Antifragility

Of particular interest in the research undertaken in IMPETUS is the concept of antifragility, as we are dealing with the study of climate adaptation interventions. In its original definition, antifragility (formalized as a system-wide property) “refers to when a system benefits from the variability” of the surrounding environment. It is opposite to fragility, that is “related to how a system suffers” from the same variability “beyond a certain pre-set threshold” (Taleb 2012).

After facing an adversity, three distinct outcomes can be identified as opposite to fragility (Munoz et al. 2022): resilience (as in *recovery* after performance degradation – note that as previously discussed resilience can be defined in many ways), robustness (insensitivity to adverse events) and antifragility (beneficial gains in performance). Antifragility is a distinct enough property from resilience as it focuses on the possibility of a system to enhance its functionalities, prosper and upgrade after experiencing perturbations and disturbances. In that sense, antifragile systems are also resilient, but the opposite does not hold true.

To assess if something is fragile, robust, resilient or antifragile means to examine its possible responses to different perturbations (Blečić and Cecchini 2020) and assess if the system is disrupted (fragile), not affected (robust), degraded but still functioning and then recovered (resilient), or if it gains benefits (antifragile).

Over time, the concept of antifragility has been explored to assess its implication for managing different types of adversities, including those related to climate change, under deep uncertainties. Indeed, climate change adaptation, if thought as a continuous process opposed to a process with a pre-set end point, can lead to anti-fragile systems, with net benefit gains for the environment and for society. In antifragile systems, projected adverse events are treated as opportunities, instead of threats, for improvement, growth and development. Indeed, in antifragile systems, disturbances can trigger adaptation processes that are not aimed at returning the system to the same pre-disturbance level, but rather, to generate reorganization, removal of weakness points, allowing the systems to evolve toward a better state. The average performance of an antifragile system increases as perturbations trigger selection and removal of underperforming system features, while the strongest features survive (Adelhart Toorop et al. 2023). According to some authors (Blečić and Cecchini 2020), preparedness (learning capacity), adaptability (being flexible), and transformability (being innovative), are salient features of antifragility, although sometimes they are attributed to resilience.

Transformational adaptation is a key concept for achieving antifragility to climate change (Ziervogel et al. 2016). Transformational adaptation is often introduced as further evolution from autonomous adaptation and incremental adaptation.

Autonomous adaptation, also referred to as coping adaptation or reactive adaptation (Chhetri et al. 2019), occurs when individuals or communities routinely respond to social and climatic stimuli independent of outside intervention. Autonomous adaptation is generally led by individuals or communities and lacks planning explicitly or consciously focused on addressing climate change (IPCC 2021).

Incremental adaptation involves planning and is implemented with the goal of identifying solutions to the consequences of climate change. It aims to improve the efficiency of existing infrastructure and schemes, without providing a radical change of their attributes (Chhetri et al. 2019).

Transformational adaptation changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts, including altered goals or values and addressing the root causes of vulnerability. Though having multiple definitions, transformational adaptation is commonly referred to as a deep change as opposed to minor, marginal or incremental change (IPCC 2021). Other conceptions of transformational adaptation characterize it as a fundamental reconsideration of human-environment relations resulting in the long-term sustainability of the system being transformed.

In the IPCC AR6 transformational adaptation is seen as a component of “climate resilient development” in which adaptation, mitigation and development solutions are pursued together to exploit synergies and reduce trade-offs among these actions.

Literature on antifragility in the context of climate change suggests that urban systems deserve particular attention, exploring the transition from smart cities to resilient cities and finally to antifragile cities (Hespanhol 2017). In urban systems, water management is extremely challenging due to climate change induced alteration of hydrological conditions and to the increasing demand of water resources. This leads both to situations of water scarcity and to more frequent and severe floods. Urban areas can become antifragile when they seek to learn from shocks; this requires careful infrastructure and urban spatial planning. For example, an anti-fragile infrastructure (such as a water supply system) can be characterised by redundancy (not reliant upon a single source of water) or by diffuse complementary interventions (multiple drainage systems, green roofs and porous pavements (Blečić and Cecchini 2020). In urban planning, antifragility could be a meaningful goal for planning, distinct from resilience.

The antifragility approach was explored as a new lens to study and address the vulnerability of agricultural systems to external driving forces, including climate change. Adaptation options like agroecology and conservation agriculture are recognised as systems to reduce the vulnerability of the system to climate change and these systems may be also regarded as antifragile responses (Adelhart Toorop et al. 2023).

Paradoxically, disasters, like floods, are seen as learning opportunities for livelihood enhancement. Flood-related knowledge, besides specific changes in flood management, could also prompt wider changes such as institutional, social, or economic changes (Kuang and Liao 2020). Therefore, following the concept of antifragility, disasters are opportunities that could trigger transformational adaptation able to evolve the system to a better state.

A core property of antifragility seems to be optionality, which means having multiple (redundant) options, allowing the system to benefit from unpredicted and unpredictable opportunities. Optionality also means diversification of economic activities, so as to spread out risks in case of climatic disasters. To achieve this goal, transformation and adaptation of policies may be required.

Finally, a decisive enabling factor for achieving antifragility is governance, since transformational adaptation requires transformation of governance systems themselves. (Babovic et al. 2018).

2.7 Climate resilience assessment tools

Besides the existence of a large body of literature where the broad concept of resilience is discussed in depth, a growing collection of tools is available online, with high potential for supporting the practical evaluation of resilience to climate change in different sectors, ecosystems and regions.

These tools can be divided into two broad groups: (i) composite indexes that compose the information coming from different indicators in a single score and (ii) decision support tools, that assist users through the process of evaluating resilience and planning adaptation by providing resources, examples, and a portfolio of adaptation options. Some of these indexes are not specifically designed for climate resilience but include an increasingly diverse range of natural and man-made pressures that include, beside climate change, rapid urbanization, terrorism, and increasing vulnerability to natural hazards.

Not intending to offer an exhaustive inventory of all available tools, the following text describes some examples providing inspiration for the elaboration of the Regional Climate Resilience Footprint Tool, developed within the Impetus Project.

2.7.1 Climate Resilience composite indexes

The City Blueprint (https://www.watershare.eu/tool/city-blueprint/) is a practical communicative tool that can help enable cities to evolve towards sustainable water-wise cities. The tool is currently hosted on the Watershare website, a worldwide network of water research organisations and utilities dedicated to delivering equitable water solutions for all.

The City Blueprint consists of three complementary frameworks: the Trends and Pressures Framework (TPF) to assess the challenges of cities; the City Blueprint® Framework (CBF), to assess how cities are managing their water cycle; and the Governance Capacity Framework (GCF) where cities can improve their water governance.

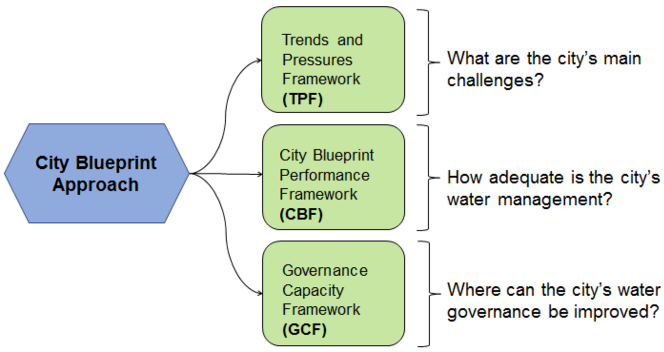

Figure 2.4: City Blueprint approach.

The Trends and Pressure framework is organised in 12 descriptive trends and pressure indicators equally covering social, environmental and financial categories, based on key information from international organizations.

The CBF provides a clear overview of Integrated Water Resources Management (IWRM) performance and its bottlenecks in municipalities and regions. The CBF consists of 25 indicators divided into 7 broad categories providing a full picture of the entire urban water cycle. The information is used to calculate the indicator scores on a scale of 0 (low performance) to 10 (high performance). The Blue City Index is the geometric mean of the values of the 25 indicators and also varies between 0 and 10.

The GCF has been developed as a further extension to CBF, to address governance challenges that are increasingly recognised as barriers or enablers for the implementation of urban water management solutions. The GCF focuses on the most reccurring water-related issues that are expected to steadily increase in importance due to global trends of climate change and urbanization.

Table 2.2: *The three complementary frameworks of the City Blueprint tool*

Framework	**Categories**
Trends and Pressures Framework (TPF)	Social
	Environmental
	Financial
City Blueprint® Framework (CBF)	Water quality
	Solid waste
	Basic water services
	Wastewater treatment
	Water Infrastructure
	Climate adaptation
	Plans and actions
Governance Capacity Framework (GCF)	Awareness
	Useful knowledge
	Continuous learning
	Stakeholder engagement process
	Policy ambition
	Agents of change
	Mukti-level network potential
	Financial viability
	Implementing capacity

The City Blueprint has been currently applied to 125 cities in xx countries of the world before undergoing critical revision based on the learning experiences obtained during this process (Dieperink et al. 2023; Grison et al. 2023).

The City Resilience Index (CRI, https://www.cityresilienceindex.org) was developed by Arup with the support from The Rockefeller Foundation.

The resilience of a city is assessed according to four key dimensions, described in the following table. The index centers around 12 goals and 52 indicators. Each indicator is assessed using a set of qualitative questions that can be answered through quantitative metrics. For example, within the Goal Health and Wellbeing, the metric “Number of homeless people per 100,000 population” is the metric corresponding to the qualitative question “To what extent does the city have an adequate supply of safe and affordable housing?” related to indicator 1.1.: Safe and affordable housing.

Moreover, the Rapid Resilience review tool is designed to carry out a quick and rapid resilience assessment of cities’ urban systems according to the 12 goals of resilience. Qualitative questions can be answered through a semi-qualitative score: from 1 (worst case) to 5 (best case).

Table 2.3: The dimension and goals of the city Resilience Index

Dimension	**Goals**
Health and Wellbeing	Goal 1: Minimal human vulnerability
	Goal 2: Diverse livelihood and employment
	Goal 3: Effective safeguards to human health and life
Economy and Society	Goal 4: Collective identity and community support
	Goal 5: Comprehensive security and rule of law
	Goal 6: Sustainable economy
Infrastructure and ecosystems	Goal 7: Reduced exposure and fragility

	Goal 8: Effective provision of critical services
	Goal 9: Reliable mobility and communications
Leadership and strategy	Goal 10: Effective leadership and management
	Goal 11: Empowered stakeholders
	Goal 12: Integrated development planning

Source: https://www.cityresilienceindex.org/#/

The **Climate Resilience Screening Index** (CRSI, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100SSN6.txt), has been developed by the Environmental Protection Agency of the USA (US-EPA), as an endpoint for characterizing county and community resilience outcomes that are based on risk profiles and responsive to changes in governance, societal, built and natural system characteristics. The Climate Resilience Screening Index (CRSI) framework serves as a conceptual roadmap showing how acute climate events impact resilience, by evaluating the factors that influence vulnerability and recoverability.

The index is a composite measure comprised of five domains (Risk, Governance, Society, Built Environment, and Natural Environment), represented by 20 indicators, calculated from 117 metrics. CRSI has been run and its results provided for almost all counties of the United States. These available results can provide broad scale comparisons of large areas across the United States

Table 2.4: The dimension and indicators of the Climate Resilience Screening Index

Dimension	Indicators
Built environment	Communication Infrastructure
	Housing Characteristics
	Transportation Infrastructure
	Utility infrastructure
	Vacant Structures
Governance	Community preparedness
	Natural Resource Conservation
	Personal preparedness
Natural Environment	Condition
	Extent of Ecosystem Types
Risk	Exposure
	Loss
Society	Demographics
	Economic Diversity
	Health Characteristics
	Labor and trade services
	Safety and Security
	Social Cohesion
	Social Services
	Socio-Economics

2.7.2 Decision support systems

The **Adaptation Support Tool (AST)** available in the Climate-ADAPT platform (https://climate-adapt.eea.europa.eu/en/knowledge/tools/adaptation-support-tool) aims to assist policy makers and coordinators on the national level in developing, implementing, monitoring and evaluating climate change adaptation strategies and plans. The AST is based on the adaptation policy cycle, composed of the following steps:

1. Preparing the ground for adaptation
2. Assessing climate change risks and vulnerabilities

3. Identifying adaptation options
4. Assessing adaptation options
5. Implementing Adaptation
6. Monitoring and Evaluating Adaptation

For each of these steps, the AST provides specific guidance, tools and further information sources.

Moreover, the Climate-ADAPT urban adaptation support tool (UAST, https://climate-adapt.eea.europa.eu/en/knowledge/tools/adaptation-support-tool) and the Regional Adaptation Support Tool developed within the EU Mission on Adaptation to climate change (https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data/regional-adaptation-support-tool/step-2-assessing-climate-change-risks-and-vulnerabilities) offer more specific guidance to implementing the adaptation process at the urban and regional level respectively.

The **U.S. Climate Resilience Toolkit (**https://toolkit.climate.gov/) is a step-by-step procedure to assess resilience. The tool was developed by a partnership of federal agencies and hosted by NOAA's Web Operation Center. The toolkit offers several resources (e.g., case studies, tools, relevant reports) and downloadable spreadsheets to record input as users move through the steps. Users can explore data and projections of climate change (mapping interfaces) and find vulnerability indexes. All resources are organised around the following steps:

- assess exposure,
- assess vulnerability and risks,
- identify adaptation options,
- prioritise and plan,
- take action.

The **EPA Climate Resilience Evaluation and Awareness Tool (CREAT) Risk Assessment Application for Water Utilities (**https://www.epa.gov/crwu/climate-resilience-evaluation-and-awareness-tool-creat-risk-assessment-application-water) is a tool, made available by the Environmental Protection Agency of the USA (USEPA), that assists water sector utilities in assessing climate-related risks to utility assets and operations. Throughout CREAT's five modules, users explore climate impacts and identify adaptation options to increase resilience. The modules are:

- Climate Awareness: Provide basic utility information; increase awareness of climate impacts;
- Scenario Development: Understand utility risk; design scenarios of threats based on climate data;
- Consequences and Assets: Outline potential consequences; catalog critical assets;
- Adaptation Planning: Inventory current actions that provide resilience; design adaptation plans; and
- Risk Assessment: Assess risk from a changing climate; compare risk reduction of adaptation plans.

At the conclusion of each of the first four modules, users may generate interim reports to inform utility planning and decision making. In particular (as reported in the CREATE methodology guide), the tool provides assistance in managing several climate-related threats for water resources, as reported in the following table.

Table 2.5: Specific threats addressed by the Climate Resilience Evaluation and Awareness Tool

Dimension	Threats
Water Supply Management	drought
	seasonal demand
	snowpack
	reservoir storage
	low streamflow conditions
Peak Service Challenges	stormwater runoff
	seasonal demand
	discharge under low receiving water flow conditions
Water Quality Management	runoff

	treatment
	violations
	saltwater intrusion
	water turbidity
	algal blooms
Natural Disasters	fires
	floods
	tornadoes
	ice storms
Ecosystem/Landscape Management	coastal erosion
	wetland loss
	endangered species protection
Population/Demographic Changes	customer base
	land use
	workforce availability
Sector Water/Service Needs	agriculture
	energy sector
	health services
	local industries
Interdependent Sector Reliability	power sector
	transportation
	chemical suppliers
Sea Level Rise	saltwater intrusion
	coastal storm surge

The **Climate Resilient City Tool** (https://www.deltares.nl/en/software/climate-resilient-city-tool/), developed by Deltares (CRCTool) contains a database of over 50 adaptation measures, descriptions, pictures of best practices and references for further reading. The CRCTool consider the use of Nature Based Solutions to increase urban climate resilience. Traditional grey measures are included to enable comparison.

Based on properties of the project area such as soil type, land use, scale and relevant climate hazards, the tool presents a selection of adaptation measures, ranked by their applicability and expected effectiveness in that area.

The **CRCTool** supports the collaborative planning of climate adaptation measures and strategy formulation to make cities more resilient and attractive. It is developed to support this first exploratory and conceptual phase of the adaptation process. It can be used to facilitate stakeholder's collaboration during workshops or to support the preliminary analysis of a project area. The results of the CRCTool can be also used to inform urban designers and water managers on which adaptation measures are supported by the stakeholders and where they can be implemented.

The **ADAPT2CLIMA** tool (developed within the LIFE ADAPT2CLIMA project, https://tool.adapt2clima.eu/en/home/#content) was designed to enhance the understanding of climate change and its impacts on agriculture in order to support farmers, policy makers and other relevant stakeholders (agronomists, the agribusiness industry, etc.) in adaptation planning. It was applied in Italy, Greece and Cyprus. It is based on the following components: (i) Climatic indicators, (ii) hydrologic indicators, (iii) agronomic indicators, (iv) socio-economic indicators and (v) adaptation measures. Each adaptation measure is assessed according to different criteria, including their efficiency, urgency for implementation, usefulness irrespectively of climate change, technical issues etc.

3 IMPETUS Resilience Assessment Methodology

3.1 Outline

The methodology presented here will be used to analyze and assess the resilience of key systems (e.g., the water, energy, health sectors), within the climate change 'hot-spot' regions identified (link to the work done within IMPETUS task 3.2). These hotspots will need climate adaptation interventions (link to task 3.5 and T3.6) in order to improve the overall resilience of the region or community. Hence, resilience assessment will be performed with two distinct ways, but based on the same general principles:

- The *general climate resilience assessment* for a region's key systems, for configurations of said systems before and after climate interventions, using multiple metrics and indicators (adapted from the IMPETUS I&M (indicators and metrics) framework developed in T3.2), against future scenarios that account for multiple uncertainties inherent in climate change and socio-economic drivers; this method essentially quantifies the improvement in resilience from the application of climate adaptation measures and will be part of the toolkit assembly for the generation of dynamic adaptation pathways in T3.6.
- The *baseline resilience self-assessment* for a region's key systems, based on their current (baseline) state, employing a plethora of metrics, and engaging stakeholders to collaborate on assessing resilience as a conversation starter for the identification of suitable I&Ms, intervention measures, climate risks, etc. The baseline resilience self-assessment is supported by a specific tool developed within T3.4, the Regional Climate Resilience Footprint Tool (RCRFT).

For both methods, the I&Ms selected have a pivotal role, and a brief description of the outcomes of the supporting task T3.2 is presented in the next section.

3.2 Indicator and metrics

To support local stakeholders with complex strategic and transdisciplinary decision-making, a flexible framework of indicators has been identified in the early stages of the project. This framework has been designed to undertake resilience assessments, evaluate climate vulnerability and climate adaptation measures and pathways. The proposed IMPETUS indicator framework (referenced in deliverable report D3.1 Metrics for climate change, vulnerability, resilience, and adaptation) consists of two complementary kinds of indicators:

1. Core indicators: These indicators are relevant for most demonstration sites and are related to climate vulnerability and climate adaptation. The core set of indicators is considered essential for the demonstration sites, taking into account Europe's diverse bio-geographical regions which range from continental, coastal, Mediterranean, and Atlantic, to arctic, boreal, and mountainous.
2. Additional indicators: These indicators are more specific to certain contexts or bio-geographical regions. They apply to a limited number of demonstration sites or bio-geographical regions.

Additionally, a third group of indicators, called supportive metrics, complements the overall IMPETUS indicator framework. Supportive metrics are meant to complement the information provided by the core indicators.

To ensure that practitioners can use the indicators effectively, both within the IMPETUS demonstration sites and beyond, they have been designed to be easily understood, timely, relevant, and user-oriented. I**n total, 69 core indicators (supported by 12 further indicators for their calculation) and 43 additional indicators have been proposed (see D3.1).**

The proposed IMPETUS indicator framework provides a structure for climate-sensitive strategic decision-making and serves as a repository of indicators. Depending on the specific case, different indicators can be selected from the categories and subcategories, potentially supplemented by other location-based indicators. Therefore, the proposed set of indicators is not exhaustive but serves as a meaningful starting point for a continuous learning-by-doing process. Please refer to the figure below for a brief overview of the IMPETUS indicator framework.

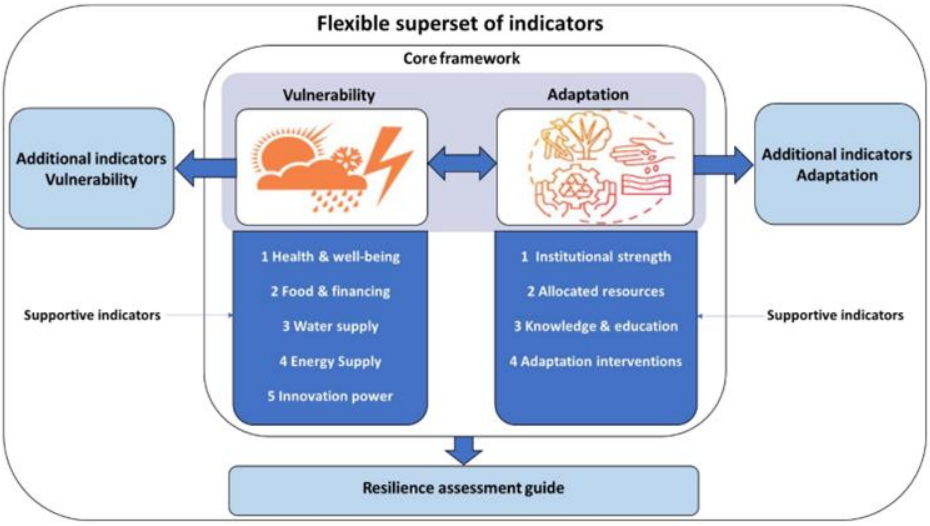

Figure 3.1: Schematic of the flexible IMPETUS I&M framework

The categories, subcategories, and indicators have been derived from a wide literature inventory, different monitoring, reporting, and evaluation initiatives at the global, European, and national scale. They have also been complemented by stakeholders' feedback. Accordingly, climate vulnerability indicators are classified into five categories:

1. Health & well-being: This category considers climate-related health risks, vulnerability of health infrastructure, and overall socio-economic well-being.
2. Security of food & shelter: Both basic needs can be threatened by climate extremes, such as heatwaves, water scarcity, floods, or lack of adaptive capacity.
3. Water: This category focuses on the delivery of water services and the availability of water resources, which are key vulnerabilities for many regions in Europe.
4. Energy supply: This category includes energy demand and energy provision, which are critical in reducing vulnerabilities to climate extremes, particularly for marginalized communities.
5. Innovation power: This category refers to the economic, human, and institutional capacity necessary to develop and apply innovations, which is considered essential to address climate vulnerabilities.

Similarly, climate change adaptation indicators are categorized into four categories:

1. Institutional strength: This category includes coordination, strategies, plans, policies, laws, and regulations that strengthen climate adaptation.
2. Allocated resources: This category considers the application of instruments to provide financial incentives, insurance, and risk sharing.
3. Knowledge and education: This category focuses on climate information, adaptation tools, awareness, and capacity-building, as key elements of successful climate adaptation.
4. Adaptation interventions: This category assesses the progress in the actual implementation of green measures.

This flexible superset of core indicators will ultimately need to adequately meet the needs at the local scale, which are crucial to adopting effective strategies for vulnerability assessment and implementing adaptation measures. These “local” indicators are essential providers of valuable insights into the specific risks and challenges faced by local communities, helping stakeholders make informed decisions and tailor adaptation strategies to local needs. In particular this kind of indicators allow:

- Tailored Assessments: Local vulnerability and adaptation indicators enable a comprehensive understanding of the unique challenges faced by specific regions or communities. By focusing on local contexts, these indicators provide a more accurate picture of vulnerabilities, taking into account factors such as geography, socio-economic conditions, and infrastructure. This tailored approach ensures that adaptation measures are precisely targeted and aligned with the specific needs of the community.

- Effective Decision-making: The use of local indicators enhances decision-making processes related to climate change adaptation. These indicators offer valuable data and insights that enable stakeholders to prioritize actions based on the most pressing vulnerabilities. By understanding local risks, decision-makers can allocate resources effectively, implement appropriate adaptation strategies, and maximize the impact of limited resources. This approach leads to more efficient and sustainable outcomes.
- Community Engagement and Empowerment: Engaging local communities in the process of vulnerability assessment and adaptation planning is crucial for successful outcomes. Local indicators facilitate community participation by making the assessment process more accessible and understandable to stakeholders. When communities have a clear understanding of their vulnerabilities and the available adaptation options, they become empowered to actively contribute to decision-making processes, ensuring that solutions are practical, acceptable, and culturally relevant.
- Resilience Building: Building resilience at the local level is essential for withstanding climate change impacts. Local vulnerability and adaptation indicators provide a foundation for designing and implementing targeted resilience-building measures. By identifying and addressing specific vulnerabilities, communities can develop adaptive capacity, enhance their ability to absorb shocks, and recover more effectively from climate-related events. This proactive approach fosters long-term sustainability and reduces reliance on reactive and ad-hoc measures.
- Monitoring and Evaluation: Local indicators also play a crucial role in monitoring and evaluating the effectiveness of adaptation measures over time. By tracking changes in vulnerability levels, the success and impact of implemented strategies can be assessed. This feedback loop allows for adaptive management, ensuring that adjustments can be made to improve the efficiency and efficacy of ongoing adaptation efforts.

3.3 Formulating a general climate resilience assessment methodology for a region's key systems

The wider the system boundaries and the longer term the thinking, as in the case of climate-proofing a region, the more important and challenging it is to formally conceptualize the difference between design alternatives (Makropoulos 2017), i.e., the selection and implementation of climate adaptation interventions in the context of the IMPETUS project. Moreover, the existence of multiple key systems within a region increases the complexity of resilience-based applications. We suggest that an internally consistent, theoretically valid, and computationally robust way to assess different aspects of the overall region's performance under long-term, or *deep* uncertainty (Hallegatte 2009; Hallegatte et al. 2012), so that the various options can be better understood and evaluated by stakeholders in the process of strategic planning, in the search for climate adaptation pathways.

As discussed in Section 2, there are various definitions on resilience, which, revolve around two main central themes:

- The return time of a water system from a shock or disturbance to normal operation (or the recovery speed to a stable state in general, being it degraded or even upgraded for antifragile systems) – an 'engineering' type of resilience.
- The ability/capacity of a water system to maintain a level of function coping or adapting to disturbance, or similarly the amount of disturbance the system can handle before significantly (usually below a threshold) changing its form, structure, or (self-organized) procedures – an 'ecological' type of resilience.

For an operationalizable definition of resilience suitable for the needs of this task, we argue that a definition closer to the notion of 'ecological resilience' can assess systems' integrity given an uncertain regime of future unforeseeable stressors better than the return-time types, as climate change and the other socio-economic stressors are not acute, but rather chronic in nature, evolving through large timeframes. That is not to say that climate change may not induce short-term acute shocks like extreme flooding events or heatwaves; but rather that the focus is on building the adaptation capacity to increase resilience in the long term, under a multitude of future world views.

As such, hereafter we adopt (and adapt) the definition of resilience given in the works of Makropoulos et al. (2018), Nikolopoulos et al. (2019) and Nikolopoulos et al. (2022), originally made for urban water systems, but generalizable to other contexts as well. Thus, resilience is the “degree to which a system continues to perform under progressively increasing disturbance”.

To be able to operationalize this definition in a different context there need to be defined (through the interactions and engagement of relevant stakeholders) and computed its component terms: notably *performance* as a function of *disturbance*. Performance is quantified via the usage of various suitable metrics for different aspects; in the case of a region with more than one key systems, at least one indicator should be selected for each one. In the special (easier to conceptualize and comprehend) case of a single system with a single performance indicator, we can define a ‘reliability metric’ in a generic and expanded way, to describe the ability of the system to consistently deliver its objectives, considered over a specified timespan. With the quantification of the reliability metric, it is possible to map the impact any stressor has on the resilience of a system.

Disturbance is modelled through scenarios, which are narratives comprised of various changing parameters through the specified timeframe and constitute complete future world views. These scenarios are formulated dependent on the choice of stakeholders and expert opinion regarding their magnitude and impacts, according to the examined case study. Scenarios can vary between mild to extreme cases, but nonetheless should stress the system in question outside of normal expected ‘inputs’. In the case of IMPETUS regions, scenarios should include climatic variables and other socio-economic drivers; a large body of work already exists that formulates such scenarios for important variables, like the Shared Socioeconomic Pathways (SSPs) (O’Neill et al. 2017; Riahi et al. 2017), which eases the burden and complexity of formulating scenarios, as well subjectivity, allowing a level of standardization between assessments for different regions, of scenario formulation. The SSP narratives describe a set of alternative plausible trajectories of societal development, which are based on hypotheses about which societal elements are the most important determinants of challenges to climate change mitigation and adaptation. According to each of the five SSP narratives, a plethora of climate change “Representative Concentration Pathways” (RCPs) scenarios can be combined, describing different levels of greenhouse gases and other radiative forcings that produce different conditions for global circulation models that generate future climate projections (based on the application of models, to be further discussed in subsequent sections).

With performance and disturbance defined, we need to visualize how the system behaves over time. The graphical expression of performance quantified through any metric of reliability, can be seen in Figure 3.2, which constitutes a special type of graph, termed resilience profile graph (Makropoulos et al. 2018). This graph is essentially a univariate stress-strain diagram, where the resilience of the system under increasing disturbance is communicated through the area under the curve. Each point of the graph is a calculation of reliability of a given objective being met (y-axis), under the conditions specified by a particular stress scenario (x-axis). These points are typically acquired by simulation of the system for each particular scenario. The x-axis of the resilience profile graph is constructed as an ordinal series of progressively more extreme disturbances in the form of scenarios. Therefore, it is not a nominal scale, and the scenario-space does not constitute a continuous space. Robustness quantification is also present in the figure, defined as the ‘degree to which the system’s performance is unchanged under disturbance’ (Makropoulos et al. 2018).

To scale resilience and robustness to maximum of 1, we propose that the area under the curve is divided by the area of the ideal, ‘completely robust’ system. and that robustness is divided with the number of points in the resilience profile diagram, which is the number of scenarios analyzed in the study. Essentially, using this scaling the area of the curve transforms into the average of the curve points in the y-axis, therefore the actual mean value (or the *expected value*) of the performance or reliability metric across all the scenarios. As formulated, the increased strain (resulting from increased scenario stress) is depicted as a decrease in reliability; This representation has the advantage of allowing larger areas under the curve to represent increased resilience which is a visually intuitive result. Note, that with this methodology of stress-testing systems through a specific set of scenarios, the value of resilience obtained is relative and used to compare with other system designs or configurations (e.g., with a different set of climate adaptation interventions) against the same scenario set.

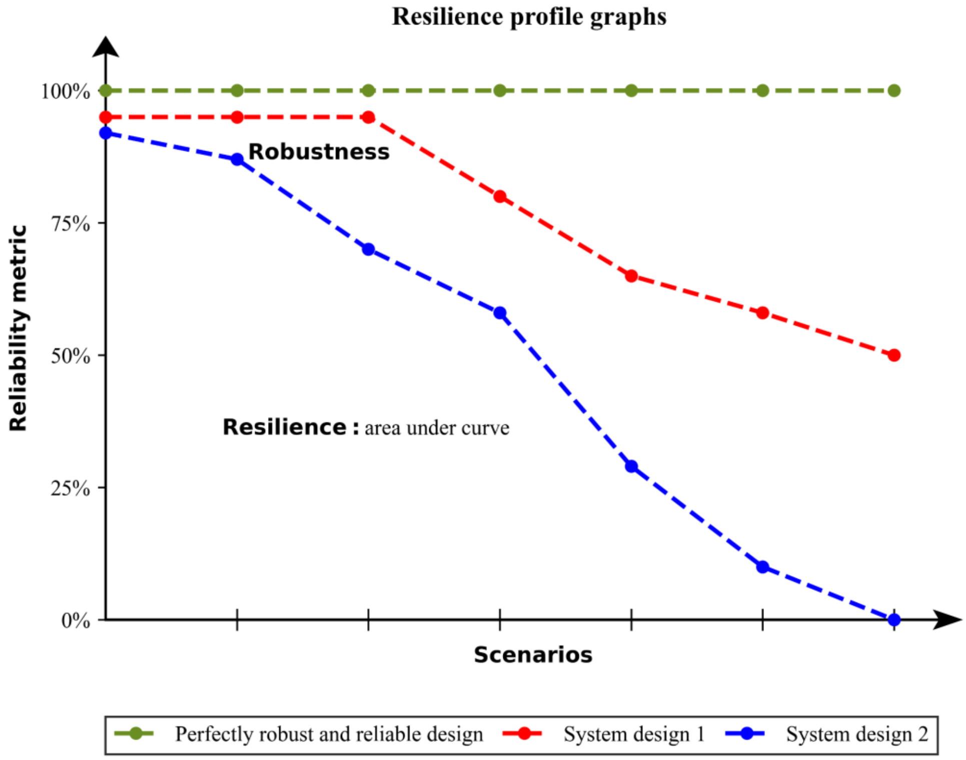

Figure 3.2: Resilience profile graph for a single reliability indicator, for the ideal system and two other systems, where one is more resilient and robust than the other. Figure adapted from Nikolopoulos et al (2022).

As discussed above, the problem formulation is rather static, with deterministic scenarios. For the cases where scenarios can have multiple realizations (such as different models creating a plethora of future climate projections, based on the same conditions e.g., same SSP-RCP combination) and/or stochastic elements, there does not exist a single performance curve describing the systems performance under disturbance. The different world views that are built during the scenario formulation procedure can be considered as 'scenario types", and can have variations in their realization, hence a cloud of performance points is generated. With multiple samples generated from each scenario, statistical properties, such as quantiles, can be calculated. Using the points from each scenario that correspond to a particular quantile, we can generate a curve that corresponds to a confidence interval (CI), encapsulating uncertainty in the resilience metric estimation per se. Figure 3.3 demonstrates this concept.

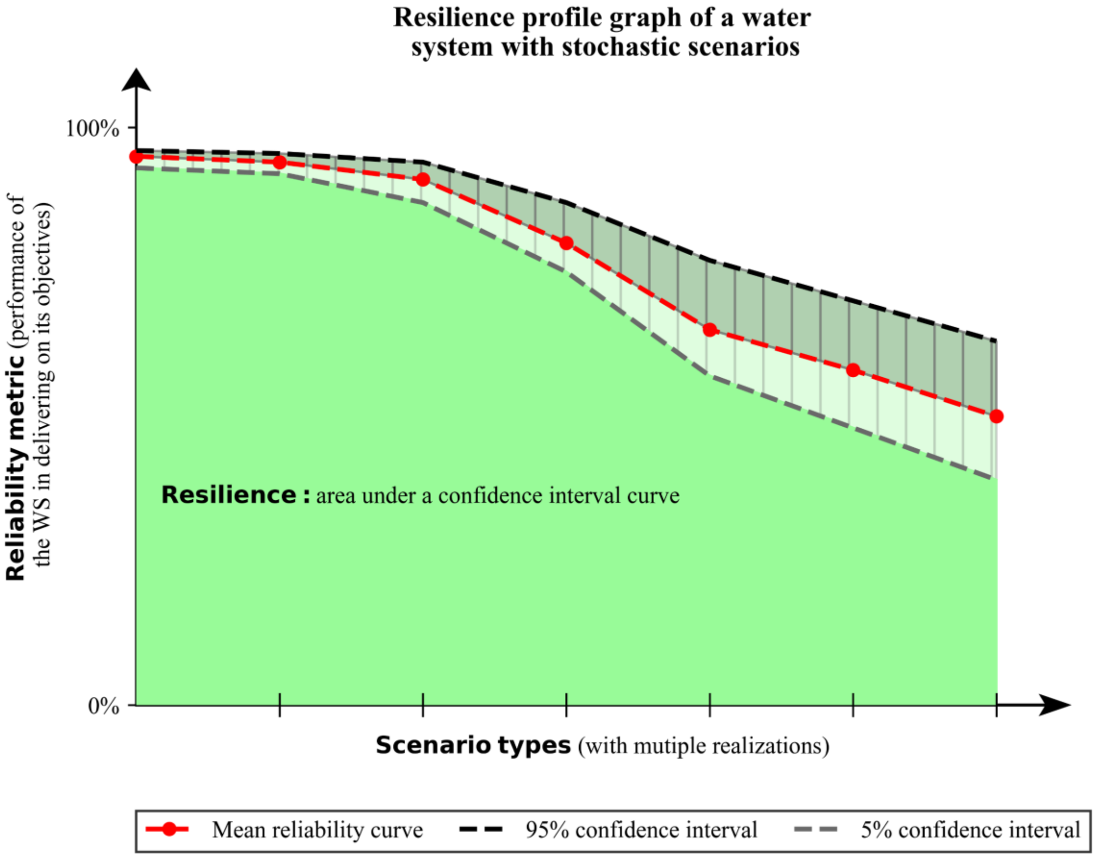

Figure 3.3: Resilience profile graphs for specific confidence intervals, for a single reliability indicator, under scenario types that have multiple realizations. Figure adapted from Nikolopoulos et al (2022).

In the general case where the system is evaluated using multiple indicators, a similar procedure can be followed, but the multidimensional aspect needs a different visualization. We propose the usage of a 'radar' chart per scenario (or scenario type, when there are multiple realizations) as shown in *Figure 3.3*, with axes evaluating a reliability metric for each indicator selected by stakeholders that assesses a region (i.e., scaled from 0% to 100%). For each scenario and confidence interval if there are multiple realizations, the ratio between that area of the indicators compared to the full area of the chart is the aggregated metric, i.e., the average value of indicators. For the aggregation across all scenarios, in a similar manner to the 'area' of the univariate resilience graph, we need the 'volume' across the stacked charts representing scenarios in increasing disturbance order. Essentially, we calculate the expected value for a specific confidence interval across all scenarios to assess resilience in this multi-dimensional expression.

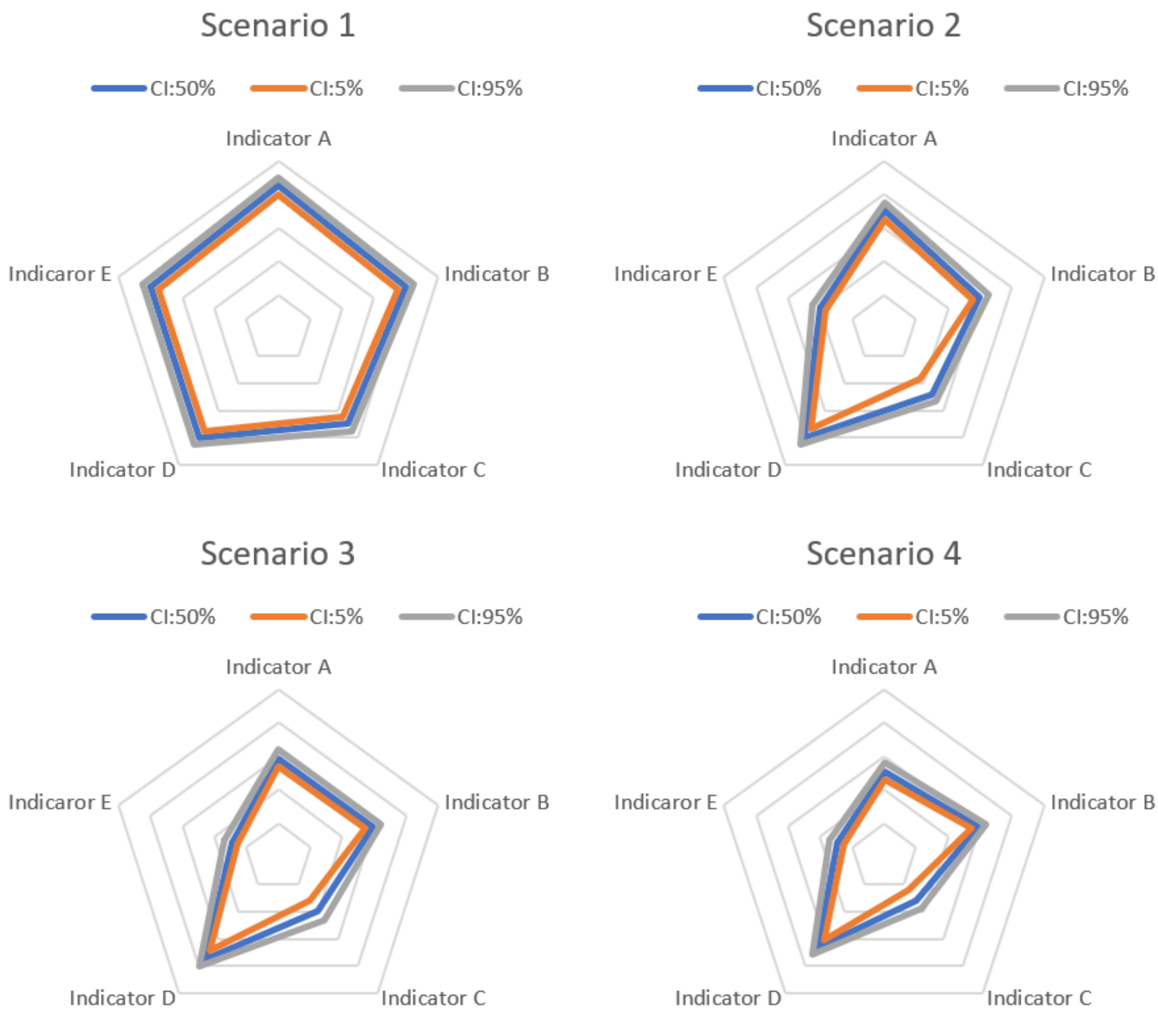

Figure 3.4: Multidimensional radar charts per scenario type, for a specific confidence interval stemming from multiple realizations.

3.4 Regional Climate Resilience Footprint Tool brief description

In this section, a brief introduction to the RCRFT is presented, as a thorough accompanying report will follow the deliverable of the tool in M30 (D3.4 Regional Climate Resilience Footprint Tool)

The RCRFT draws significant inspiration from the Horizon 2020 project BlueSCities (https://bluescities.eu), which facilitated a coordinated approach to integrating water and waste sectors into smart city planning, emphasizing local solutions for global issues. The RCRFT leverages similar strategies to provide a standardized self-assessment framework for regions and communities, serving as a catalyst for stakeholder engagement in resilience-building.

Like the CITY BLUEPRINT and CITY AMBERPRINT initiatives under BlueSCities that offered baseline assessments of water management, energy, transport, and ICT in cities, the RCRFT allows baseline regional resilience assessment, thereby quantifying the threats from climate risks. The tool's application to the IMPETUS Demo Sites, will contribute to the broader evaluation of the creation of dynamic adaptation pathways.

Drawing from the successful implementation of City Blueprints under the BlueSCities project, the RCRFT provides a standardized self-assessment framework. This tool is designed to allow regions and communities to conduct an assessment of their climate resilience, serving as a conversation starter for stakeholder engagement. Also, The RCRFT emphasizes the need to involve stakeholders at all levels. By integrating the tool into broader conversations about climate resilience, it fosters a culture of dialogue and proactive discourse around climate change adaptation, leading to more informed decision-making processes.

3.4.1 Platform Structure and User Accessibility

The RCRFT tool leverages an extensive set of indicators and metrics as developed in T3.2, designed to provide stakeholders with an actionable understanding of their resilience landscape.

RCRFT is currently under development as an online platform that will be accessible to a broad spectrum of stakeholders, ranging from citizens and NGOs to government agencies and ministries. Each stakeholder group will be provided with unique login credentials, ensuring that their inputs are both secure and categorized for analytical purposes.

<u>Indicator Selection and Customization</u>

Upon accessing the tool, users are presented with a comprehensive list of pre-established indicators and metrics that are grounded in Report 3.1 "Metrics for climate change, vulnerability, resilience, and adaptation". In addition to these, users have the flexibility to input their own indicators and metrics, thereby customizing the tool to the unique climate challenges and opportunities specific to their region.

<u>Quantifying Current Resilience Landscape</u>

Stakeholders assign reference values to each selected indicator, capturing the current state of a specific domain—be it health infrastructure, energy capacity, or any other pertinent area. For instance, the vulnerability of health infrastructure could be quantified using the number of available hospital beds. Furthermore, stakeholders are prompted to define the lower and upper limits for each indicator, allowing for a nuanced interpretation of the indicator's current performance, or to compare with the EU average and range. This feature aids in normalizing the indicators across different stakeholders' submissions by stack, providing a comparable picture of the system resilience across indicators with different normative or ordinal scales, as for example in the work of Garcia et al 2017 where regional indicators were rescaled to a common scale.

<u>Belief Functions on Certainty Level</u>

Each stakeholder is required to indicate their level of certainty in their input, that is for each indicator they fill in a level from 1 (intuition) to 5 (expert knowledge) (see Table 3.1). This feature acknowledges that different stakeholders possess varying levels of expertise and information quality. For example, a government ministry might have high-certainty data, while a citizen's input could be considered lower in terms of certainty.

Table 3.1: Stakeholders' level of certainty with their respected values

Level of Certainty	Value

Intuition	1
Informed	2
Domain knowledge	3
Administrative knowledge	4
Expert knowledge	5

Data Processing and Visualization

Stakeholders have the option to save a draft of their inputs, providing the flexibility to revisit and revise their data before final submission. Upon submission, each indicator is normalized based on the defined lower and upper limits, and the levels of certainty are recorded.

For each stakeholder's submission, a radar graph is generated that captures the dimensions of their selected indicators. Confidence intervals, derived from the level of certainty, will be on these radar graphs to quantify the uncertainty of the resilience indexes. With multiple submissions from the stakeholders, these radar graphs will be finally overlaid to calculate a final volume, representing a composite measure of the degree of resilience in the specified region or community. Finally, the degree of resilience can be visualized per stakeholder type, e.g., by aggregating only the submissions from citizens (or any other stakeholder type) with their respective uncertainty levels. This categorization will enable to examination of the uncertainty levels of each type more clearly.

Resilience Over Time

Given that resilience is not static but changes over time, the tool could include a temporal tracking feature that allows stakeholders to assess how different metrics of resilience have evolved. This historical data can serve as a powerful tool for policymakers to judge the impact of implemented interventions and plan future interventions more effectively.

4 Linkage with T3.6 and the creation of adaptation pathways

4.1 A brief explanation of the T3.6 tools for the adaptation pathways

The tools developed in T3.6 aim to support long-term resilience and risk management, focusing on climate adaptation pathways. The objective is to furnish stakeholders with tools that enable a long-term perspective on resilience and multi-hazard risk management, specifically within the context of the actual deployment of climate adaptation pathways (T5.1.4). This entails a detailed focus on potential risks and contingencies that might arise from embracing these pathways and executing intervention packages. Key components of this endeavor include the creation of a scenario planner tool, which is instrumental in operationalizing longer-term risks in association with WP5. It is pivotal to discern and continually monitor crucial parameters intrinsic to the adaptation pathways, establishing alarm thresholds that actuate critical decision points. Furthermore, there is an emphasis on innovating a **Risk and Emerging problems Inference Engine** tailored for adaptive pathways for the threshold designation. Complementing this, the formulation of a **Dynamic Contingency Response tool** will be crafted to bolster stakeholders in their contingency planning actions, rooted in exhaustive contingency roadmaps. These advanced tools and approaches are set to be showcased at a DS level.

<u>Conceptualization of Task 3.6</u>

More specifically, in Task 3.6, our objective is to assess and evaluate the system performance under varying system parameters and a set of interventions. The process can be broken down as follows:

- The Risk and Emerging problems Inference Engine will aggregate all the socioeconomic and climatic data and set alarm thresholds for each system variable based on a statistical analysis and expert judgement.
- The Dynamic Contingency Response (DCR) tool can be explained and be 'separated' into the following actions:
    - Selection of Intervention: From the available set of interventions defined for each DS, we choose an appropriate intervention, each with their appropriate characteristics (e.g., relative and actual cost, scaled quantified benefit, hidden risks) to be applied in the system.
    - Scenario Modification: The scenario parameters of a particular DS are altered based on the socioeconomic and climatic variables of the system model.
    - Performance Evaluation: Once the parameters of the scenario have been adjusted, the system's performance is then assessed using system indicators. This assessment helps in contrasting the modified system's performance against a baseline.
    - Repetition: This entire process, from the selection of an intervention in any timestep to performance evaluation, is reiterated for every available intervention. Furthermore, the procedure is repeated across all defined scenarios.
    - The temporal continuation of the DS indicators and metrics based on all the different options of interventions will be designed in a tree graph-based approach where nodes are the system conditions and edges are the decisions (interventions or do-nothing approach) that contain a generalized cost (balance of positive/negative aspects of the decision) as shown in Figure 4.1. The optimal pathway is assumed to be the path with the least (generalized) cost from start to end.
    - In total, the purpose of the DCR tool is to comprehensively understand the impact of different interventions on the system across various scenarios, thereby offering insights into the most effective interventions in the most effective timestamp for optimal system performance.

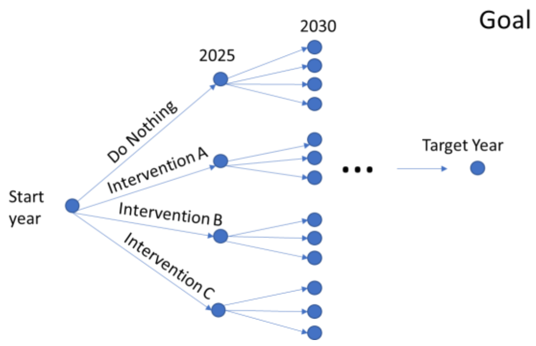

Figure 4.1: Visualization of the tree-graph based approach for the DCR tool.

4.2 Linkage of climate resilience assessment methodology with the adaptation pathways

The climate resilience assessment methodology described in Section 3.3 will be used as the basis to evaluate the formulation of adaptation pathways in T3.6. Each particular set of climate adaptation interventions (pathway) form a system configuration; this configuration is stress tested against scenarios of climate and socio-economic parameters. For each realization per scenario type (i.e., each set of variation of projections of the socioeconomic and climatic variables for a given scenario), the values of the indicators will be visualized in a radar chart (its axes evaluating a reliability metric for each indicator). For many scenarios, stacked radar charts will depict the overall performance of the system across scenarios that range from mild to extreme future disturbance. At each radar chart, the ratio between the area of the indicators compared to the full area of the chart will culminate in the aggregated performance metric, i.e., the expected value of indicators. By using statistical properties of these points, such as quantiles, it is possible to generate curves that correspond to a confidence interval (CI), encapsulating uncertainty in the resilience metric estimation per se across all stacked scenarios. By calculating the actual mean value (or the expected value) of the reliability metric across all the realizations, and across the scenarios we will estimate a total resilience score of the key systems per Demo Site, given the set of adaptation interventions selected.

The effect of interventions that promote the indicators to greater values than baseline conditions even in the most stressful scenarios provide antifragility capacity to the systems, allowing us to identify which solutions and interventions build antifragility.

Note that the resilience value obtained is a relative measure that is used to compare the different pathways of interventions that emerge, dependent on the scenarios and indicators selected. However, across different pathways, with this assessment we are able to *identify the most resilient pathway*. This score can be the objective function on which to optimize the generation of pathways using the DCPT. The specific procedure of determining the most resilient pathway through optimization is still open to changes, as Task 3.6 is ongoing, to be delivered in M42.

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5 Conclusions & future work

The methodology for climate resilience assessment presented here, builds on the vast amount of work in the literature on the topic, and presents a generic, model-agnostic, indicator-flexible, uncertainty-wise framework for key systems in regions that are under severe climate risks, and in need of adaptation interventions. The methodology is part of a continuous effort in IMPETUS WP3: Exposure and Vulnerability Assessment, and conceptually follows the development of the indicator and metrics framework for climate vulnerability and adaptation capacity (I&M) in T3.2 and the development of the regional climate change hot-spot identification and prioritization service (HIPS) in T3.3.

Utilizing certain aspects of this methodology, the regional climate resilience footprint tool (RCRFT), upcoming in M30, will help bridge the gap between models and tools and stakeholder engagement (WP1). The tool will bring together a variety of people with different roles to evaluate the baseline conditions of the region, possibly identifying weak links and aiding in the policy discourse about future implementation of climate adaptation interventions.

Furthermore, the methodological proposition will be used to assess the resilience of adaptation pathways in the IMPETUS Demo Sites (T5.2) which will be supported by the tools developed in T3.6.

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