Ref. Ares(2024)2372259 - 31/03/2024

The ARSINOE Multi-System Dynamic Modelling Framework

D3.8 (Task3.5)

WP3: Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework

Authors: Navonil Mustafee (UNEXE), Otto Chen (UNEXE), Barry Evans (UNEXE), Georgios-Alexandros Chatzistefanou (KWR&UNEXE), Qian Li (UNEXE), Mehdi Khoury (UNEXE), Albert S. Chen (UNEXE), Lydia Vamvakeridou-Lyroudia (KWR&UNEXE)

Date: 8 Mar 2024

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101037424.

Deliverable Number and Name	D3.8- The ARSINOE Multi-System Dynamic Modelling Framework
Work Package	WP3 – Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework
Dissemination Level	Confidential till M42 then review further demand (to publish the innovative content), then Public
Author(s)	Nav Mustafee (UNEXE), Otto Chen (UNEXE), Qian Li (UNEXE), Georgios-Alexandros Chatzistefanou (KWR&UNEXE), Barry Evans (UNEXE), Mehdi Khoury (UNEXE), Albert S. Chen (UNEXE), Lydia Vamvakeridou-Lyroudia (KWR&UNEXE)
Primary Contact and Email	Otto Chen, c.chen2@exeter.ac.uk
Date Due	31/03/2024 (M30)
Date Submitted	31/03/2024
File Name	ARSINOE_D3.8
Status	Final
Reviewed by (if applicable)	Martin Drew (DTU), Giannis Adamos (UTH), Slobodan Djordjević (UNEXE)
Suggested citation	Mustafee, N., Chen, O., Li, Q., Evans, B., Chatzistefanou, G., Khoury, M., Chen Albert and Vamvakeridou-Lyroudia L.S. (2024). The ARSINOE Multi-System Dynamic Modelling Framework. ARSINOE Deliverable 3.8, H2020 grant no. 101037424

This document has been prepared in the framework of the European project ARSINOE. This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 101037424.

TABLE OF CONTENTS

List of abbreviations

ABS	Agent Based Simulation
CI	Critical Infrastructure
CS	Case Study
DES	Discrete Event Simulation
DMRM&AF	Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework
EA	Environment Agency
M&S	Modelling and Simulation
MSDMF	Multi System Dynamic Modelling Framework
OR/MS	Operations Research and Management Science
REM	Resilience Enhancement Measure
SD	System Dynamics

List of figures

List of tables

Executive summary

This report presents the ARSINOE Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework (DMRM&AF), as part of deliverable **D3.8**, due M30. The modelling framework, also referred to as the ARSINOE wheel, is designed to be sufficiently generic as an instrument to be applied by all the case studies in the ARSINOE project. The framework has been applied in the work presented as part of **D3.5** (Two simulation models developed using Operations Research/Management Science techniques to evaluate resource allocation among permutable services), where the ARSINOE Wheel framework was used in developing the simulation models for Athens metropolitan area case study (CS#1) and the Torbay case study (CS#8), respectively.

The first part of the report provides context and motivation, while the second part gives a brief overview of climate resilience. The third section describes the development of the state-of-the-art DMRM&AF (ARSINOE Wheel), followed by a section providing the application of the framework to each case study.

Contribution to EU policies related to climate change adaptation and/or resilience to climate change: This report presents innovative modelling approach, which may lead to new incentives and governance measures and initiatives that could bring enhanced resilience to climate-related hazards, hence also enhancing the adaptation to climate change. Most importantly, the work presents innovative governance approaches through the case studies' response to climate-related hazards, by demonstrating the usefulness of system thinking and allocation of resources in times of crises.

Related Deliverables: The modelling framework has reported intermediate work **MS10** (The ARSINOE MultiSystem Dynamic Modelling Framework-M21) in Task3.5. It is directly related to **D3.9** (Two distributed simulation models developed using the IEEE1516 standard and implementing the ARSINOE MultiSystem Dynamic Modelling Framework-M42), **D4.1** (Visualisation Dashboard for Codesigning Solutions/Scenarios for Digital Twin-M36), **D4.2** (The ARSINOE Serious Game-M42), and **D4.3** (Two Digital Twins - Torbay case study + 1 case study-M48).

1 Introduction

There is ample evidence that the intensity and frequency of occurrence of extreme hazards such as floods, droughts and heat waves will continue to increase due to climate change, even in the low or optimistic end of the global warming scenarios (Aghakouchak et al., 2020; IPCC, 2021). Meanwhile, transformations in the global landscape, such as population growth, decreasing food security and rapid urbanization may further alter the exposure and vulnerability, and amplify climate-induced risks (Fünfgeld, 2010). Therefore, building climate-resilience for regions and communities has become one of the major challenges of the 21st century, a fact that is reflected in many national and international policies and government strategies.

The United Nations Office for Disaster Risk Reduction (UNDRR) defines resilience as the "*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management*" (United Nations General Assembly, 2016). In addressing resilience, a variety of actors are involved, adding extra dimensions to the inherent complexity of it, while a continuous cycle of preparedness, mitigation, response, adaptation and recovery actions based on previous knowledge is implied, as shown in Figure 1.1.

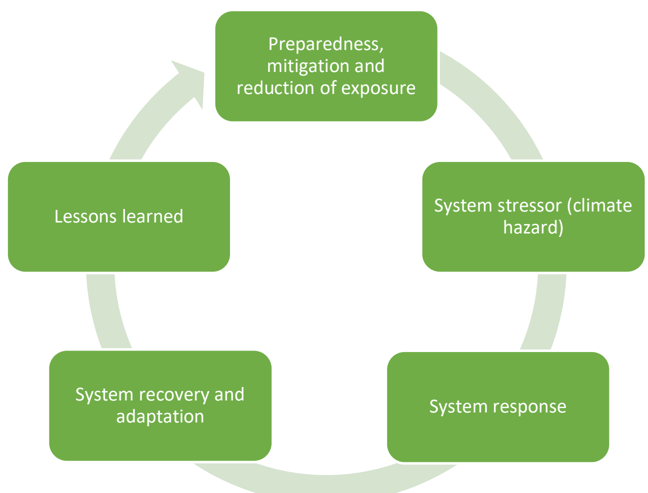

Figure 1.1 Continuous cycle of building resilience to climate hazards

In this context, stakeholders and decision makers require the means to understand the complex aspects that influence resilience to specific climate hazards for the unique characteristics of the system they manage, to assess potential strategies and pathways to improve it. Resilience assessments can be used to that extent and be the basis for the development of local climate resilience enhancement strategies. Moreover, they can be used to raise awareness among the affected parties and to inform already implemented strategies. To this end, ARSINOE has developed the Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework (DMRM&AF) (Task 3.5), by integrating a set of tools, techniques and methods from a variety of academic disciplines, co-created and co-designed with the stakeholders and tailored to each case study (CS). Each CS will apply its own suite of models and tools, to assess climate resilience and delineate resilience enhancement strategies.

2 Concept of Resilience

Enhancing resilience in regions and communities and investigating how resilience thinking can be operationalised in the face of increasing climate stressors are at the core of the ARSINOE project. Resilience itself is a broad and multifaceted concept, with definitions ranging across various disciplines. Thus, understanding the concept and evolution of resilience throughout various scientific disciplines is critical to put it into practice and develop tangible tools for applications , such as resilience assessment tools. This section aims to provide an overview of the existing literature regarding resilience, including its characteristics and assessment approaches with emphasis on climate and natural disaster resilience, and the development of the ARSINOE DMRM&AF, which will provide stakeholders and relevant practitioners the means to conduct resilience assessments.

2.1 Definition and evolution of the concept of resilience

Resilience is a term that has increasingly been used in various scientific disciplines, including ecology, psychology, health-related and social sciences, engineering and business administration amongst numerous others (Folke, 2006; Haimes, 2009; Hosseini et al., 2016; Koliou et al., 2018), as well as in mainstream science literature (e.g. Rifkin, 2022), with *Time Magazine* characterizing it as "the environmental buzzword of 2013" (Walsh, 2018). While these multi-disciplinary studies share this term, the underlying principles and concepts often differ to various extents, as its applications range from the study of single components of engineered systems to complex socio-ecological systems or communities. Table 2.1 provides a number of various definitions of resilience, focusing on the engineering, infrastructure and climate- and disaster resilience literature, which is the main scope of the presented work within this deliverable.

Table 2.1 Summary of definitions of resilience in the scientific literature

Publication	Definition
Holling (1973)	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
Pimm (1984)	The speed at which a system variable returns to its reference condition (equilibrium) following a perturbation
Adger (2000)	The ability of communities to withstand external shocks to their social infrastructure
Bruneau et al. (2003)	The ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimise social disruption and mitigate the effects of future earthquakes.
Poland (2009)	The ability of the city to remain safe and usable after a major earthquake. A resilient city is able to contain the effects of earthquakes when they occur, carry out recovery activities in ways that minimise social disruption, and rebuild following earthquakes in ways that mitigate the effects of future earthquakes.
Vugrin et al., (2010)	The ability to reduce efficiently both the magnitude and the duration of the deviation from targeted system performance levels

Publication	Definition
Djordjević et al. (2011)	The capacity of a system, community or society, potentially exposed to hazards, to adapt by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure.
Arctic Council (2016)	The capacity of people to learn, share and make use of their knowledge of social and ecological interactions and feedbacks, to deliberately and effectively engage in shaping adaptive or transformative social-ecological change
Nan & Sansavini (2017)	The ability of a system to resist the effects of a disruptive force and to reduce performance deviations
IPCC (2022)	The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure

One of the first and most influential definitions of the term "resilience" is often credited to the ecologist C.S. Holling (1973), who introduced a multiple-equilibria perspective regarding the stability and states of ecological systems, which may possess multiple stability domains that are influenced by ecological processes, random events, disturbances, and heterogeneity of temporal and spatial scales. Within each stability domain, the system variables may fluctuate to varying degrees, but if the system tends to remain within the boundaries of that domain, it is characterised as resilient. Resilience was thus defined as "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". A detailed review of this concept can be found in Folke (2006). Within this context, two types of resilience can be discerned, namely engineering and ecological resilience (Holling, 1996). More specifically, engineering resilience refers to conditions near a single equilibrium steady state, where the resistance to a perturbation and the speed of return to the equilibrium are used to measure the property, while ecological resilience refers to conditions far from any equilibrium steady state, where instabilities can flip a system into another regime or stability domain. These terms are not domain-exclusive, meaning for example that an engineered system can have multiple steady states as or that resilience in ecological systems may be defined differently (e.g., Pimm's definition (1984) on ecological resilience which focuses on the speed of recovery).

Community and infrastructure system resilience, including critical services networks such as healthcare or governance, is currently perceived from both perspectives. In the seminal work on social system resilience (with a strong focus on infrastructure systems and within the context of earthquake engineering) of Bruneau et al. (2003), resilience was defined as the ability of a system to reduce the chances of a perturbation, mitigate or absorb its impacts, recover quickly, and lower future impacts via learning and adaptation. In their definition, four properties of resilience were identified (commonly referred to as the 4R's), namely **Robustness** (the ability of a system to withstand stresses without losing performance), **Redundancy** (the existence of alternative elements that are able to satisfy functional requirements in case of interruptions or loss of functionality), **Resourcefulness** (the ability to mobilise resources to establish priorities and goals) and **Rapidity** (the ability to meet priorities in a timely manner to contain losses). This temporal and multi-partite view of resilience is reflected in many studies to varying degrees. For example, Ouyang and Dueñas-Osorio (2012) defined resilience as the joint ability of infrastructure systems to resist (prevent and withstand) different possible hazards, absorb the initial damage, and recover to normal operation. Alternatively, Nan and Sansavini (2017) defined resilience as the ability of a system to resist the effects of a disruptive force and to reduce performance deviations, and considered three fundamental resilience capabilities, namely absorptive capacity (similar to robustness), adaptive capacity and restorative capability.

While definitions of resilience in the scientific literature are nuanced or differ to a greater extent based on the scope of each study, it can be seen that the focus is placed to all temporal dimensions, namely pre-, during- and post-event dimensions, especially when examining resilience to hazardous events (or abrupt perturbations). This is reflected to the definitions of several organizations that aim to promote resilience to climate-related stresses, such as IPCC's (2022) definition on resilience as "the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure" or UNDRR's (United Nations General Assembly, 2016) definition as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management". It is worth mentioning that the IPCC adopts the notion that resilience is a positive attribute when it maintains the capacity for adaptation, learning and/or transformation (Arctic Council, 2016). Finally, building resilience, especially due to the ongoing climate change, is receiving widespread attention, as resilience and its accompanying definitions are addressed in many national documents such as Government of Canada (2022) and UK Cabinet Office (2022).

In summary, resilience has been used in a plethora of scientific fields with varying definitions as a result of its widespread applications. Over time, definitions evolved to consider a multitude of dimensions, including pre-, during- and post-event dimensions and to consider it as a cyclical process involving preparedness, mitigation, response, adaptation and recovery actions (refer to Figure 1.1.). Thus, resilience can be thought of as synthesis of distinct (but often overlapping) capacities or capabilities spanning the whole temporal scale of a system subject to stresses rather than a single trait. However, this widespread use of the term has given rise to a number of challenges or research gaps. First of all, there is lack of consensus regarding a universal definition of resilience. The used definitions are often subject to the specific applications and systems (including different system boundaries and scales) that they are being applied, with the risk of undermining important universal concepts. Moreover, different researchers hold different views on certain attributes of resilience (e.g. the notion of bouncing back has been criticised as reproducing vulnerabilities (Doorn, 2015) and that recovery should incorporate a learning element as well). Adding to the confusion is the use of common terms to describe different attributes or of different terms that refer to the same resilience dimension (e.g. robustness, absorptive capacity or resistance). As a result, operationalizing or putting resilience to practice in concrete settings (e.g. for critical infrastructure (CI) operators) becomes challenging. Additionally, resilience definitions tend to be highly theoretical or convoluted and resilience attributes are often confused with resilience enhancement measures or strategies (e.g. robustness and redundancy), which impose additional barriers to its operationalization. Finally, the differences of the applications of the term may pose barriers to interdisciplinary dialogue (Olsson et al., 2015). It is thus apparent, that a concise and unifying definition that facilitates its application to practice is needed. To that end, ARSINOE will provide a concise and practical definition of resilience as part of its DMRM&AF.

2.2 Resilience attributes and indicators: Moving from risk management to resilience

Based on the literature review presented in section 2.1 of the present document, the concept of resilience is similar to concepts such as vulnerability management, risk management and disaster risk reduction. Risk is usually defined in scientific literature as the consequence of interaction between a hazard and the characteristics that make people and places vulnerable and exposed to said hazard (United Nations General Assembly, 2016), expressed as the product of these components, as seen in Figure 2.1. As such, traditional risk management focuses on minimizing risk by reducing the aforementioned risk factors. Minimizing risk contributes consequently to increased resilience. Similarly, reducing vulnerabilities by comprehensive vulnerability assessments can also be seen as a means to improve resilience.

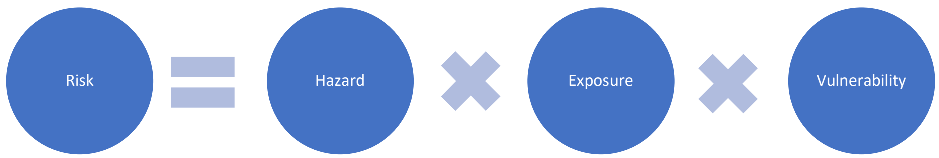

Figure 2.1 Disaster risk estimation formula (Kron, 2002)

However, resilience implies more attributes including preparedness, recovery and flexibility. As such, resilient systems are expected to have agile structures that enable some level of continuation of functionality during an event and rapid recovery thereafter, which is typically not a topic of risk management. Moreover, while traditional risk management focuses on specific hazards, resilient systems must possess the ability to cope with unexpected or extreme events. Efficient and adaptive response to a perturbation is also a key element of a resilient system. Finally, it is evident that resilience entails a plethora of attributes that enhance a system's ability to cope with stresses. The definitions and identification of these attributes vary between scholars, but may include Robustness, Redundancy, Resourcefulness and Rapidity (Bruneau et al., 2003), Buffering capacity, Flexibility, Margin and Tolerance (Woods, 2012) or others. A comprehensive review of resilience attributes and corresponding indicators can be found in Dillard (2021).

In the context of engineered systems, resilience is often understood as a function of a certain measure of performance or functionality versus time before, during and after an event or stress. Figure 2.2 presents a typical system performance curve. The y-axis represents the measure of functionality, while the x-axis represents time. Functionality can refer to the number of customers served, the connectivity of a network, economic activities or others, depending on the definition and the specific case at hand. A disruptive event is assumed to take place at time t_0, and the functionality starts dropping after time t_1. At t_2 recovery of the system is assumed to start before reaching a recovered state at time t_3. Based on this temporal response of a system, different scholars have suggested different attributes of the system. For example, Nan and Sansavini (2017) defined system susceptibility, absorptive capability, adaptive capability and restorative capability as attributes of the graph, while Kong and Simonovic (2018) defined robustness, resourcefulness, redundancy, rapidity, proactive adaptive capacity and reactive adaptive capacity. The synthesis of these attributes provides an indication about the resilience of a system.

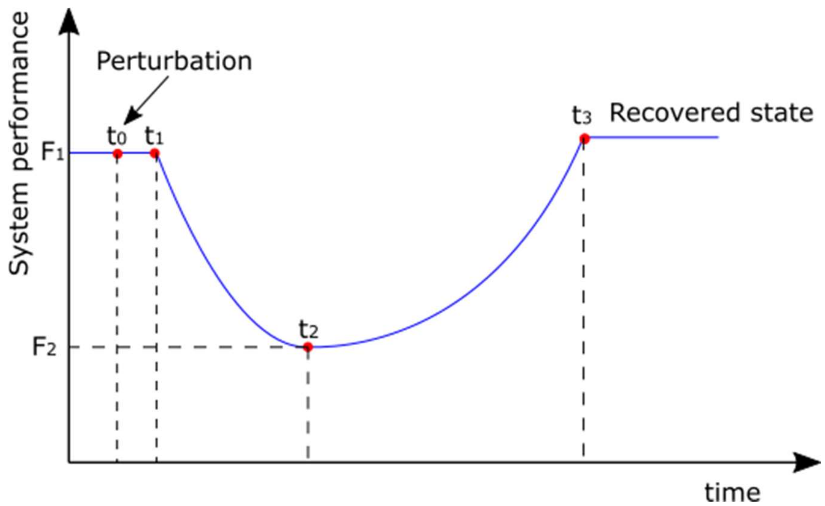

Figure 2.2 System performance as a function of time

Finally, resilience needs to be thought of as a property of a system, to be approached by a system's perspective, rather than focusing on individual components, as the interactions between the various components greatly affect system performance and response. For example, in the case of resilient regions and communities, various actors such as governance institutions, infrastructure assets, businesses, people and the surrounding environment among others and their interactions need to be taken into account when evaluating the system resilience.

3 Development of Dynamic Multi-System Resilience Modelling and Assessment Framework (DMRM&AF)/ARSINOE Wheel

3.1 Introduction

Modelling and simulation (M&S) techniques are frequently used to model human and natural systems. A plethora of M&S techniques exists to model such systems. Taking the example of a human-based system (e.g., queuing systems of service facilities such as hospitals, stock and flow systems related to demand and supply), there are numerous examples of the application of simulation approaches such as d*iscrete-event simulation (DES)*, *agent-based simulation (ABS)* and *system dynamics (SD)*. In the case of nature-based systems, for example, simulation of climate change, *climate models* consist of *mathematical equations* that are based on the laws of physics and fluid motion, and which model the exchange of matter and energy within three-dimensional computational meshes of the Earth's surface (Climate.gov, 2023). For systems that comprise both human and nature-based elements, for example, the effects of flooding on critical human infrastructure, a hybrid M&S approach using different M&S techniques could be used. An example of this is a hybrid model comprising of (a) *hydrological models* of flood-affected catchments, (b) *ABS models* of traffic within catchments, and (c) *queuing/DES models* of resources geared towards system response and recovery could potentially be used to investigate the resilience of road networks to flooding. Hybrid modelling approaches aiming to improve resilience to climate change have been used in other recent Horizon 20202 projects, e.g. in RESCCUE (Velasco et al., 2020).

The M&S techniques, whether they are conventional single-technique implementation or a combined (hybrid) approach, have been developed in diverse fields of scientific enquiry. The ARSINOE project, for example, involves researchers that consider disciplines such as Climate Change, Environment and Ecology, Water Engineering, Operations Research and Management Science (OR/MS), etc. as the fundamental core of their work. M&S as a technique for computational modelling thrives in each discipline. Thus, for the ARSINOE project, the integrated use of simulation techniques takes an interdisciplinary focus.

A key objective of ARSINOE is to investigate the interaction of natural and man-based systems using hybrid M&S approaches that have been developed in various academic disciplines and using discipline-specific methods, tools and techniques. Towards the realisation of this objective, we defined the following two aims. **Aim 1** is to develop an overarching conceptual framework that weaves the discipline-specific M&S approaches towards the realisation of the synergy of techniques for resilience modelling and assessment. The aim is realised through the development of the *DMRM&AF, also referred to as ARSINOE Wheel*. **Aim 2** is operationalising ARSINOE Wheel through multiple ARSINOE case studies. This report presents the work that was undertaken in realisation of Aims 1 and 2. In terms of modelling methodology and disciplinary anchoring, the ARSINOE Wheel framework builds on hybrid M&S and cross-disciplinary research respectively. These are discussed next.

- Hybrid Simulation: M&S techniques have often conventionally been used in isolation. This prevented realising synergies by leveraging the strengths of individual techniques. The current state-of-the-art, therefore, proposes the combined application of different simulation techniques - which is referred as Hybrid Simulation (Brailsford et al., 2019) that is now a distinct area of research within the field of M&S.
- Hybrid Modelling: Hybrid modelling is the combined application of research methods, frameworks, tools and techniques that have existed (and flourished) in multiple academic

disciplines, with a view to enabling cross-disciplinary research (Tolk et al., 2021). Unlike hybrid simulation, which is mostly restricted to M&S approaches, hybrid modelling aims to combine intellectual, implementational, empirical and other artefacts that have been developed in diverse scientific disciplines. For example, *distributed computing* is acknowledged as a distinct area of research in Computer Science. Novel methods, frameworks and standards from computer science and distributed computing thus enable the synchronised execution of simulation models developed in Engineering, Climate Science, Environment and Ecology, OR/MS and other scientific fields. Thus, simulation models that employ distributed computing techniques are an example of a hybrid model since its objective is to realise synergies by combining methods across disciplines.

- Cross-disciplinary research: There are three different forms of cross-disciplinary research, namely, multidisciplinary, interdisciplinary and transdisciplinary research. From the perspective of computational modelling, multidisciplinary research is often enabled through the integration of infrastructures, and which allows for data exchange (Tolk et al., 2021). For example, the simulations developed by discipline A output results, and which are used as inputs for discipline B (Figure 3.1). However, ARSINOE extends the current state-of-the-art as it explores synergies in the use of modelling methods realised through "interoperability of implementation" (defined as interdisciplinary research) and further towards composability of conceptualisation to enable systematic integration of not only tools and methods, but also underlying research paradigms and theories (this is defined as transdisciplinary research).

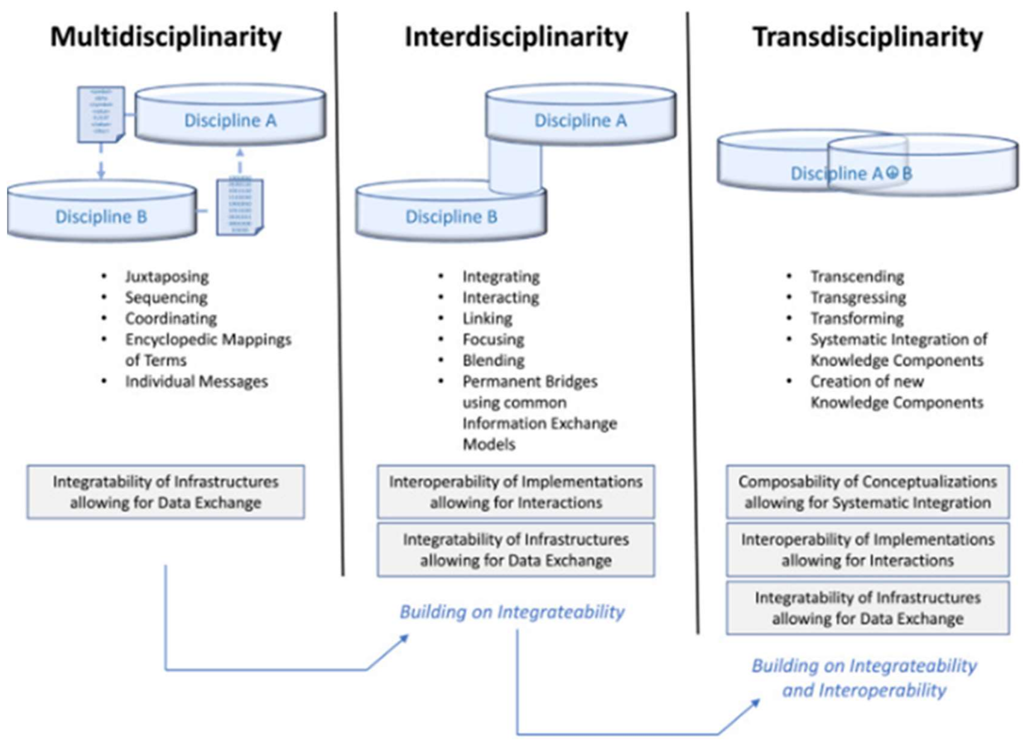

Figure 3.1 ARSINOE explores synergies in the use of modelling methods with a focus on multidisciplinary and interdisciplinarity. The Figure is from Tolk et al. (2021).

3.2 Definitional aspects of the framework

The Modelling Work Package (WP 3) of ARSINOE aimed to further cross-disciplinary research in hybrid simulation and hybrid modelling by developing the DMRM&AF (the ARSINOE Wheel). The framework supports the modelling of both human and nature-based elements and the interaction between these systems. Towards this, ARSINOE Wheel has conceptualised the application of computational models for resilience modelling. As mentioned earlier, the models used to represent specific elements of these man-based and natural systems are developed in distinct fields of study and often comprise climate change models, models of ecology, hydrological models, agent-based and other forms of OR/MS models. The framework was developed by investigating the underlying approach to computational modelling; these were related to modelling methodology (e.g., continuous or discrete-time, model resolution), application development (e.g., data requirements, conceptual model development, stakeholder involvement), technical aspects (e.g., model reusability, APIs for input-output and control of the simulation program) and efficacy of results implementation (e.g., whether methods focus on case studies or the objective is to inform policy). Thus, the goal of ARSINOE Wheel was for the project partners from diverse application domains to converge at a unified view of the cross-disciplinary modelling methods.

A total of six requirements were identified and selected as the main definitional elements of the *framework.* These requirements were presented at the ARSINOE's first General Assembly which took place in Tenerife, 4th-6th October 2022.

- *Requirement 1* – **The need for a <u>dynamic</u> framework for modelling**: The framework should support dynamic modelling methods, i.e., computation methods that capture changes over time (e.g., simulated time for computer simulations, wall-clock time for digital twins)
- *Requirement 2* – **The need for a <u>multi-sectoral</u> framework**: The framework should support modelling and assessment requirements from stakeholders from a multitude of sectors. For example, stakeholders from critical infrastructures (electricity, gas and water supply); transport sector (highways agencies, train operators); healthcare sector (including social care); stakeholders from environment and ecology sectors; banking and insurance sectors; local communities. The framework should be *extensible to incorporate modelling and assessment requirements from new stakeholders*, as and when these are identified through Living Labs.
- *Requirement 3* – **A framework for <u>resilience modelling and assessment</u>**: Computational methods proposed by the framework for resilience modelling and assessment should appreciate the plethora of methods that exist (including a hybrid of these approaches) and requirements that may be specific to the case studies. As such, the proposed list of methods and their combinations should not be seen as exhaustive. It follows, therefore, that the *framework is also extensible in its articulation of computational methods*.
- *Requirement 4* – **A framework that is <u>conceptual</u>**: As per Requirement 3, the framework does not define a specific set of computational methods and is extensible. Thus, the framework is conceptual rather than prescriptive, i.e., it does not prescribe specific modelling methods. The choice of methods is based on the requirements of ARSINOE case studies. The conceptualisation is only at a high-level. For specific case-studies, the framework includes more detail.
- *Requirement 5* – **A framework that is <u>cross-disciplinary</u>**: Cross-disciplinary research can be classified as multidisciplinary, interdisciplinary and transdisciplinary research. ARSINOE explores synergies in the use of modelling methods with a focus on *multidisciplinary* and *interdisciplinarity.* This has been discussed in section 3.1 (also refer to Figure 3.1). *DMRM&AF* is cross-disciplinary in terms of incorporating modelling techniques from different disciplines.
- *Requirement 6* – **A framework that defines <u>modelling linkages at the application and the tool level</u>**: As per Requirement 4, the high-level conceptualisation aims to provide an integrative view

of modelling methods from multiple disciplines. However, at an *application level*, there will need to be modelling linkages, i.e., the output of one model can be the input for other models, or indeed, multiple modelling techniques used in a synergistic approach for the realisation of the objectives of a case study. An example of the latter is hybrid simulation (Brailsford et al., 2019). The realisation of Requirement 6 is also fulfilled by establishing linkages at the *tool level*, and which is at a higher abstraction compared to the application level. In ARSINOE, tools are defined as commercial or open-source software which are used for the implementation of well-defined applications. Tools developed in different disciplines and which allow for data exchange are critical for enabling multidisciplinary research (Figure 3.1). The applications developed using these tools thus benefit from modelling linkages that are researched, designed and implemented at the tool level and which enable faster development of applications with multidisciplinary character. As shown in Figure 3.2, cross-disciplinary linkages at the methods-levels (interdisciplinary research) are more challenging.

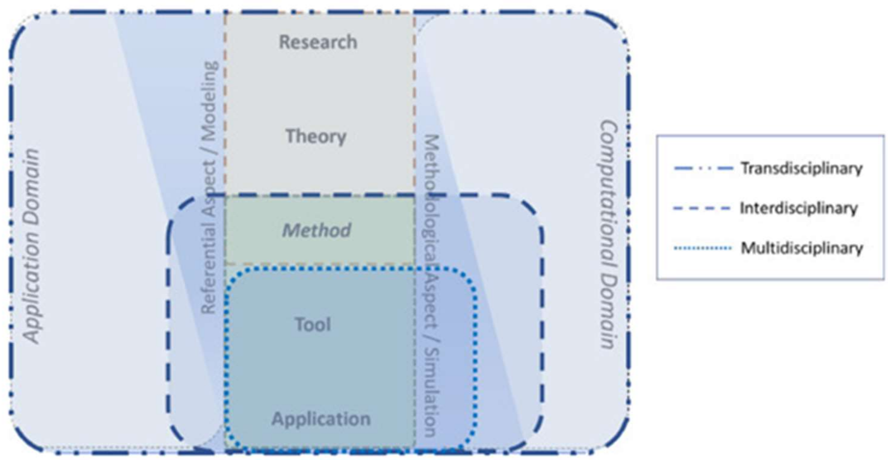

Figure 3.2 The ARSINOE DMRM&AF defines cross-disciplinary modelling linkages in the tool and application levels. The Figure is from Tolk et al. (2021)

Following the feedback received at the Tenerife ARSINOE general assembly (Oct, 2022), the team at Exeter made several changes to the framework. The co-creation approach is presented next.

3.3 Development of the ARSINOE Wheel through Co-creation approach

As already stated, ARSINOE is an interdisciplinary research project that comprises scientific disciplines such as climate, environment and ecology, engineering, social science, economics, and operations research. A key objective of ARSINOE is to investigate the interaction of natural and human-based systems (socio-environmental systems) using different modelling approaches developed in these disciplines and through discipline-specific methods, tools, and techniques. A crucial element in the approach followed by ARSINOE is the co-creation in different levels, and which was similarly employed for the development of the ARSINOE Wheel:

(i) identification of challenges (through the Living Lab workshops),

(ii) modelling of the bio-physical and socio-economic systems (through participatory modelling and data collection with citizen science tools),

(iii) vision, hindcasting, scenarios and solutions design (through the co-creation of adaptation pathways within the Living Labs and the choice experiments for assessment of willingness to pay), and

(iv) implementation of co-created solutions (through the tender calls).

(i), (ii) and (iii) are relevant to the modelling and assessment steps of ARSINOE, and thus, the focus of the workshop and the request for information relate to all three.

The modelling approaches employed by ARSINOE could be qualitative or quantitative, or a mixed-methods approach could be implemented. Computational modelling is a key element of quantitative modelling; it enables experimentation of future scenarios, including the effect of climate change on vulnerable regions.

Following the co-creation approach, the next iteration of the ARSINOE Wheel framework was presented as the 2023 ARSINOE General Assembly, which was held in KWR in The Netherlands. Here all the case studies engaged with the framework and identified how the different modelling elements could be represented through the wheel conceptualisation, and identify opportunities for linking models. Figures 3.3 and 3.4 show the case studies working on the ARSIONE wheel that were specific to individual studies.

Figure 3.3 Prof Mustafee (UNEXE) presented the ARSINOE Wheel framework in the workshop

Figure 3.4 Case study partners under group discussion for the co-creation of ARSINOE Wheel Framework (DMRM&AF)

Following the workshop in The Netherlands, the case studies completed their individual ARSINOE Wheel conceptualisation of the modelling activities undertaken as part of the project and also completed the information capture templates. These case study artefacts were studied by researchers in University of Exeter, and a framework draft for each case study was prepared; the objective here was to ensure consistency as much as possible. The documents then iterated between the Exeter team and the respective case studies, and a final version was agreed, and which is included in Section 4 of the document. The information capture templates are included as Appendix A.

In summary, the ARSINOE Wheel is a co-created framework and engaged all the case study partners to create a consensus on modelling methods for resilience assessment. It is being implemented by all case study partners. The ARSINOE Wheel and its different tiers are presented next.

3.4 The ARSINOE Wheel

In ARSINOE, **nine case studies** are selected in regions that are vulnerable to the consequences of climate change, either gradual changes or as expressed through extreme weather and climate events. The overarching objective is to assess their resilience towards these stressors and offer systemic solutions and innovations towards their transformation into more climate-resilient regions. In the case studies, different modelling techniques from across disciplines are combined to assess the resilience of specific domains. This is also referred to as hybrid modelling (Tolk et al. 2021). Thus, some case studies implement individual models for resilience assessment, whereas other case studies leverage the strengths of various modelling techniques. The mix of modelling methods is unique to a case study and is based on its objectives.

ARSINOE has proposed an overarching conceptual modelling framework to support the modelling initiatives the case studies undertake. This synthesis weaves the discipline-specific approaches and ensures comparability across different settings. The framework is called the *ARSINOE Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework (DMRM&AF)*, also called the *ARSINOE Wheel* (Figure 3.5).

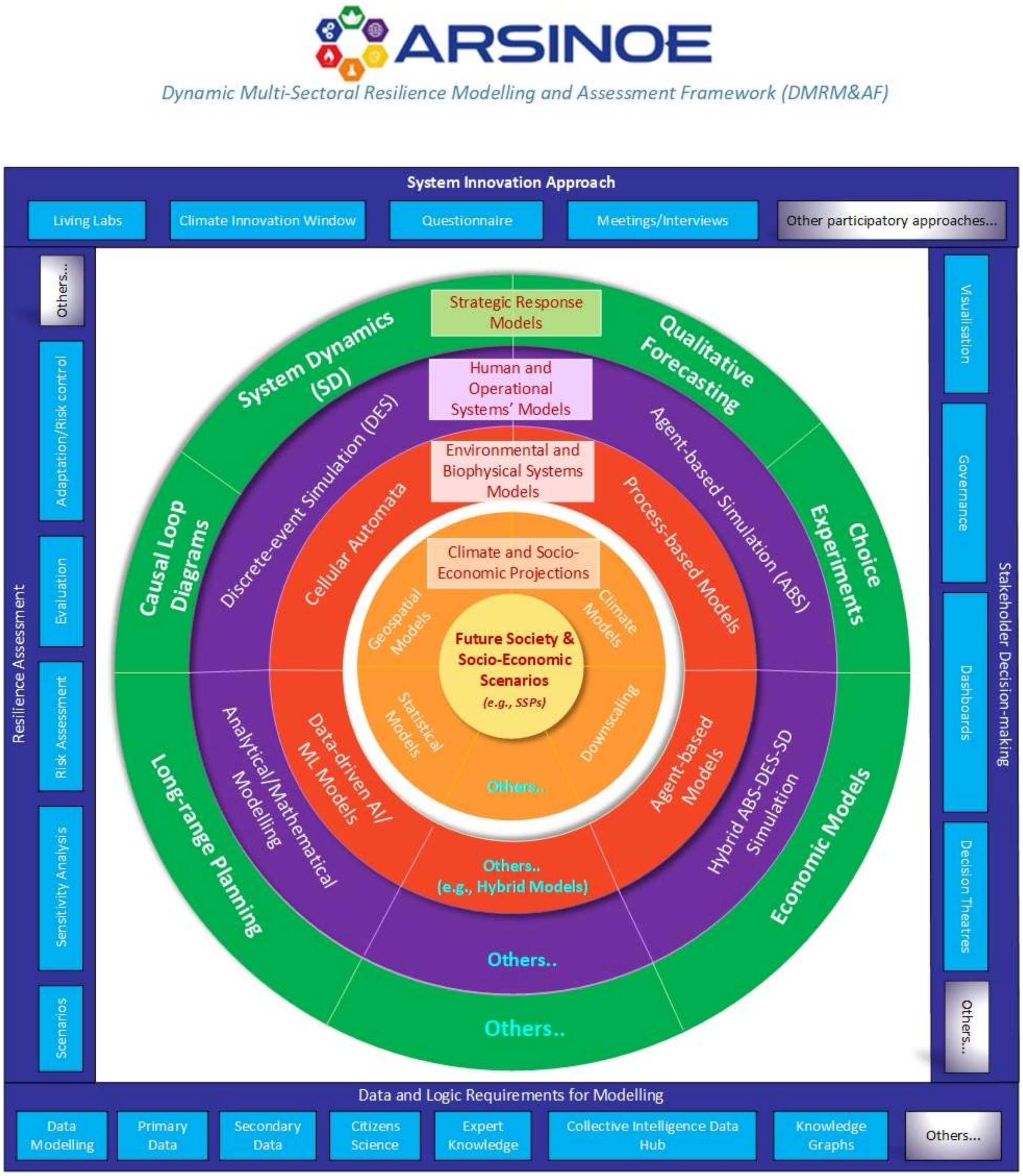

Figure 3.5 The ARSINOE Dynamic Multi-Sectoral Resilience Modelling and Assessment Framework (DMRM&AF)

DMRM&AF is a hybrid modelling framework since its objective is to provide an integrated conceptualisation of resilience assessment methods aimed at realising synergies by combining discipline-specific methods. It comprises five tiers, which are aligned to disciplinary-specific modelling methods. The tiers are illustrated through concentric circles. **The Modelling methods illustrated in the wheel are extensible** (shown as “Others” in Figure 3.5)**;** the methods implemented will be based on the requirements of a specific study. Also, **Modelling methods could be used across different tiers.**

The conceptualisation of the circle is as follows (refer to Table 3.1 for the definitional elements of the individual tiers):

- **Tiers 1 and 2 are the shared ARSINOE climate baseline for all case studies:** The innermost circle (Tier 1; Future Society and Socio-Economic Scenarios) represents the Shared Socioeconomic Pathways and Representative Concentration Pathways (SSP-RCPs) scenarios. SSP1-2.6 and SSP3–7.0 will be mandatory for all case studies. Tier 2 (Climate and Socio-Economic Projections) are mostly the *downscaled* Global Climate Models (GCM) which provide projections on Earth’s climate. Downscaling of GCM is necessary because the impacts of changing climate will lead to adaptation strategies on regional and local scales. Thus, Tier 2 will employ Empirical Statistical Downscaling (ESD) techniques and provide, for each case study, the regional downscaled data from three representative CORDEX Regional Climate Model (RCM) simulations. Case studies may also develop their regional Tier 2 models (e.g., Case Study 1 – Weather Research & Forecasting Model (WRF)). Tier 2 regional climate models will be mandatory for all case studies. Case studies can supplement Tier 1/2 with other scenarios/models based on national guidelines.
- **Tier 3 models (Environmental and Biophysical Systems Models) are for environmental-ecological impact assessment and evaluation of human intervention/interaction on environment and ecology.** The outputs from climate simulations (downscaling global models forced by the Tier 1 scenarios) will inform subsequent resilience modelling initiatives (which are dependent on the aims and objectives of the individual case studies). The ARSINOE climate baseline scenario is described in Deliverable D3.4. Examples of modelling methods in this tier include process and data-driven models, and agent-based models (the brief introduction of each modelling approach please see Table 3.2). The outputs from Tier 3 models may be available for subsequent use as inputs to the models in other tiers (including Tier 3 models).
- **Tier 4 (Human and Operational Systems) represents a detailed level modelling approach, to enable stakeholders better and more informed decision-making**. These methods are mostly used in Operations Research, Decision Science and Mathematics. Table 3.1 (last column) lists a sub-set of approaches to model operational systems that represent real-world processes and their interaction with human resources such as technicians, first responders, and machinery (water pumps, flood barriers). Both analytical/mathematical modelling and simulation approaches are widely used. Hybrid Simulation (Figure 3.5), wherein multiple simulation methods (e.g., agent-based simulation, discrete-event simulation, system dynamics) are applied to realise the objectives of a single simulation study, is used to capture the increasing complexity of underlying systems (the brief introduction of each modelling approach please see Table 3.2). Modelling methods could be used across different tiers. For example, agent-based models can be developed for both Tiers 3 and 4. Similarly, system dynamics can be a part of a hybrid simulation in Tier 4, but it can be used for strategic decision-making in Tier 5.
- **Tier 5 represents modelling methods that are generally used for strategic decision-making.** The methods could be qualitative, for example, Causal Loop Diagrams (Qualitative System Dynamics), The Delphi Method/Qualitative Forecasting, Hindcasting and System Thinking, or quantitative approaches such as Stock and Flow models in System Dynamics (the brief introduction of each modelling approach please see Table 3.2).

Table 3.1 The definitional elements of the five tiers of the ARSINOE DMRM&AF

Tier#	Tier Name	Description	Discipline	Examples of Modelling Methodologies
Tier 1	Future Society and Socio-Economic Scenarios	**SSP-RCPs** to analyse the feedback between climate change and socioeconomic factors, such as world population growth, economic development, and technological progress.	Climate Science, Socio-Economics	SSP-RCP scenarios
Tier 2	Climate and Socio-Economic Projections	Climate and socio-economic projections at the relevant scales. Typically based on numerical models (climate models, geospatial and statistical models, downscaling of all of the previously mentioned model types, if needed). Climate models (and analyses derived thereof) provide projections of essential climate variables, stressors, and extremes: temperature, precipitation, wind, soil moisture, heatwaves, storms, storm surges, river runoff, extreme rains, etc. Tier 1 provides the scenarios that are used by Tier 2.	Climate Science, Natural and Technical Sciences	Climate Models, Statistical Models, Geospatial Models, Dynamical and statistical downscaling models and methods
Tier 3	Environmental and Biophysical Systems Models	Environmental-ecological impact assessment and evaluation of human intervention/interaction on environment and ecology. For example, flood modelling with/without adaptation, crop models and hydrological models including human activities (e.g., groundwater pumping and artificial recharge to control land subsidence, hydrological changes under different land-use scenarios), compound and cascading effects models.	Conservation Ecology, Environmental Sciences, Engineering	Process-based and data-driven (AI/ML) models, Cellular Automata, Agent-based Models, models integrating multiple methods (Hybrid Models)

Tier 4	Human and Operational Systems Models	Models for decision-making usually involve human-induced processes. Modelling objectives frequently include efficient use of resources. For example, resource allocation model using discrete-event simulation.	Operations Research, Decision Sciences, Mathematics	ABS, Agent-based Social Simulation (ABSS), Discrete-Event Simulation, Hybrid Simulation, Analytical/ Mathematical modelling methods (e.g., Network Optimisation, Linear Programming, Dynamic Programming)
Tier 5	Strategic Response Models	Holistic-level models for strategic decision-making.	Operations Research, Economics, Planning and Governance	Qualitative approaches such as Causal Loop Diagrams (QSD) and The Delphi Method, System Dynamics (Stock and Flow models), Long-Range Planning, Hindcasting, Choice Experiments, Economic models

Yet another element of the ARSINOE DMRM&AF are the four pillars related to **System Innovation Approach**, **Data and Logic**, **Resilience Assessment** and **Stakeholder Decision-Making**, and on which the four concentric circles rest. Similar to the modelling methods depicted in the ARSINOE Wheel, the specific tools and techniques shown in the pillars are extensible and are based on the requirements of a specific study. The pillars are briefly discussed next:

- **System innovation approach** – Stakeholder requirements can be captured through Living Labs, Climate Innovation Window (CIW), interviews and questionnaires, expert opinion, and a wider array of participatory approaches such as Soft Systems Methodology (SSM). It is expected that the stakeholder engagement will clarify the aim, objectives and conceptualisation of a modelling study, help define the data needs, etc.
- **Data and logic requirements for modelling** – Most models require an underpinning methodology, which is usually discipline-specific. In addition, there is a requirement for data and modelling logic. Primary and secondary data are well understood. In ARSINOE, a source of primary data is citizen science. With data, comes the requirement of data storage and retrieval of information. Knowledge Graph is based on NoSQL Graph Database which enables users to query multiple linked graphs. The collective intelligence hub will also be an important element for sourcing data.
- **Resilience assessment** – Specific methods for resilience assessment are extensible and based on the individual objectives of the case study. For example, for the Torbay Case Study, the focus is on infrastructure resilience. However, two approaches that are expected to be uniformly applied to all the case studies are risk assessment and sensitivity analysis.
- **Stakeholder decision-making** – The primary objective of modelling is to enable informed decision-making. Methods such as visualisation and dashboards enable stakeholders to fully engage with the output and results of a modelling study.

Table 3.2 The introduction of example modelling approaches in the Tiers

Modelling approach	Introduction
Process-based models & **Data-driven models**	**Process-based or physically- or physics-based models** are based on a detailed understanding of the underlying mechanisms and processes driving system behaviour. These models represent the system's dynamics through mathematical equations or algorithms that simulate the interactions and transformations occurring within the system. Process-based models often require expert knowledge and domain-specific understanding to develop numerical procedures and algorithms required for solution of partial differential equation, and calibrate and validate the models. They are commonly used in fields such as physics, engineering, and ecology to simulate physical processes, chemical reactions, and biological systems. **Data-driven models**, on the other hand, rely on empirical data to capture patterns, correlations, and relationships within the system. These models are constructed using statistical techniques, machine learning algorithms, or other data analysis methods to identify and extrapolate from observed data. Data-driven models do not require detailed knowledge of underlying processes and can often handle complex, high-dimensional data sets. They are widely used in fields such as finance, marketing, and healthcare for forecasting, prediction, and decision support. The main difference between process-based models and data-driven models lies in their underlying principles and the types of information they rely on. Process-based models prioritise mechanistic understanding and theoretical principles, whilst data-driven models focus on empirical observations and statistical patterns. Each approach has its own advantages and applications. Process-based models are well-suited for understanding system mechanisms, exploring hypothetical scenarios, and testing theoretical hypotheses. They provide insights into underlying processes and can be used to simulate complex systems under different conditions. Data-driven models, on the other hand, excel at capturing patterns and relationships in large, complex data sets. They are useful for prediction, forecasting, and decision-making when detailed knowledge of underlying mechanisms is not available or when dealing with uncertain or noisy data.
Agent-based Simulation (ABS), Discrete-Event Simulation (DES), System Dynamics (SD), and Hybrid Simulation	**Agent-based Simulation (ABS)** models individual agents within a system, each with its own characteristics, behaviours, and decision-making processes. These agents interact with each other and their environment, often leading to emergent phenomena and complex system behaviour. ABS is particularly useful for studying social dynamics, market behaviour, traffic flow, and ecological systems, where individual-level interactions play a significant role in shaping overall outcomes. **Discrete-Event Simulation (DES)** focuses on modelling the sequence of events and activities that occur within a system over time. It tracks changes in system state at discrete points in time, typically in response to specific events or triggers. DES is widely used in manufacturing, logistics,

	healthcare, and service industries to optimize processes, improve resource utilization, and evaluate alternative scenarios. **System Dynamics (SD)** is a modelling approach that combines qualitative and quantitative methods to simulate the behaviour of dynamic systems over time. It focuses on feedback loops, stocks and flows, and the accumulation of changes within a system. System Dynamics models help stakeholders understand the long-term implications of decisions, identify policy interventions, and test strategies for system improvement. **Hybrid Simulation** combines elements of ABS, DES, and SD simulation to capture the strengths of each approach and address the limitations of individual techniques. By integrating agent-based models of individual behaviour, discrete-event models of system processes, and system dynamics models of feedback loops and accumulations, hybrid simulation offers a more comprehensive and flexible tool for studying complex systems. This approach is particularly useful for exploring dynamic systems with multiple levels of abstraction, such as supply chains, energy systems, and socio-technical systems.
Cellular Automata	**Cellular automata (CA)** is a computational modelling approach that simulates complex systems by breaking them down into simple components organised in a grid-like structure. At its core, a cellular automaton consists of a grid of cells, each of which can be in a finite number of states. The state of a cell evolves over discrete time steps according to a set of rules based on the states of neighbouring cells. These rules determine how each cell's state changes based on its current state and the states of its neighbours. One of the key characteristics of cellular automata is their ability to exhibit complex behaviour emerging from simple rules. This property makes them useful for modelling and studying systems that display self-organisation, emergence, and other complex phenomena. Cellular automata can capture a wide range of phenomena, from simple patterns and structures to chaotic behaviour and phase transitions. Researchers use cellular automata to model various phenomena, such as population dynamics, traffic flow, flooding, pattern formation, and the behaviour of physical systems at a microscopic level. By adjusting the rules and initial conditions of the automaton, scientists can explore how different factors influence the overall behaviour of the system.
Long-range Planning	**Long-range planning** modelling approach, is a strategic method employed by organisations to anticipate and prepare for future scenarios, typically over an extended period. Unlike short-term planning, which focuses on immediate goals and actions, long-range planning considers broader trends, uncertainties, and potential challenges that may emerge over the long term. At its core, long-range planning involves forecasting future conditions, setting objectives, and devising strategies to achieve those objectives.

	This approach requires careful analysis of various factors, including market trends, technological advancements, regulatory changes, and socio-economic developments. Long-range planning models typically utilise quantitative techniques, such as mathematical modelling, scenario analysis, and simulation, to evaluate different scenarios and assess the potential outcomes of strategic decisions. By simulating various future scenarios, organisations can identify potential risks and opportunities, allocate resources effectively, and make informed decisions to achieve their long-term objectives.
Analytical and Mathematical modelling (e.g., Network Optimisation, Linear Programming, and Dynamic Programming)	Analytical and mathematical modelling methods, including techniques such as Network Optimisation, Linear Programming, and Dynamic Programming, are fundamental tools within the field of operational research. These methods provide systematic approaches to problem-solving and decision-making, particularly in complex and dynamic systems. **Network Optimisation** involves the analysis and optimisation of networks, such as transportation, communication, or supply chains. It aims to improve the efficiency and effectiveness of these networks by determining the best routes, schedules, or allocations of resources. This method is vital in industries where efficient network operations are critical, such as logistics, telecommunications, and urban planning. **Linear Programming** is a mathematical method used to optimise resource allocation in situations where there are linear relationships between variables. It involves formulating a mathematical model of the problem, typically involving constraints and an objective function, and then finding the optimal solution that maximises or minimises the objective while satisfying the constraints. Linear Programming is widely applied in areas like production planning, resource allocation, and financial management. **Dynamic Programming** is a method for solving complex problems by breaking them down into simpler subproblems and systematically finding optimal solutions to each subproblem. It is particularly useful in problems with overlapping substructures or sequential decision-making processes. Dynamic Programming is applied in various fields, including engineering, economics, and computer science, to solve problems such as resource management, project scheduling, and optimisation of control systems.
Qualitative modelling approaches, including Causal Loop Diagrams (QSD), the Delphi Method, Hindcasting, and Choice Experiments	Qualitative modelling approaches are essential tools within operational research, offering methodologies for understanding complex systems, gathering expert opinions, and exploring future scenarios. These methods rely on qualitative data, expert judgment, and conceptual frameworks to gain insights into system behaviour and inform decision-making processes. **Causal Loop Diagrams (CLDs),** a core component of **Qualitative System Dynamics (QSD)**, are graphical representations of causal relationships

	between variables within a system. CLDs help identify feedback loops, delays, and nonlinear relationships, enabling analysts to understand system dynamics and anticipate unintended consequences of interventions. QSD provides a qualitative framework for exploring system behaviour, identifying leverage points, and formulating strategies for system improvement. **The Delphi Method** is a structured approach for gathering and synthesising expert opinions on complex issues. It involves iterative rounds of surveys or interviews with a panel of experts, who provide anonymous feedback and revise their opinions based on group consensus. The Delphi Method is valuable for forecasting, decision-making under uncertainty, and exploring diverse perspectives on complex problems. **Hindcasting** is a scenario-based approach for planning and decision-making that starts with a desired future outcome and works backward to identify actions and policies needed to achieve that outcome. Unlike forecasting, which extrapolates current trends into the future, hindcasting encourages creative thinking, stakeholder engagement, and the exploration of alternative futures. **Choice Experiments** are a method for eliciting preferences and values from stakeholders by presenting them with hypothetical scenarios and asking them to make choices. This approach is commonly used in market research, environmental valuation, and policy analysis to understand consumer preferences, estimate willingness to pay, and inform resource allocation decisions.

Table 3.3 Listing of variables for the ARSINOE WHEEL information capture template

Variable	Description	Comments (if any)
Case Study (CS) Perspective		
CS Overall Objective	What is the overall objective of the ARSINOE Case Study (CS) concerning the use of modelling methods to transform the (vulnerable) case study region towards a more climate-resilient region?	Please consider the ARSINOE tagline – "Climate-resilient Regions through systemic solutions and innovations".
Extreme Event Type	What is the extreme event type that concerns the case study? (or potential hazard)	Examples include flood, heat waves, drought, etc.
Phase	Phases of extreme events that the CS assessment and strategy covers/targets	Phases include preparedness, response, recovery, etc.
Resilience Target	What is the main target aspect(s) to be assessed by the CS to improve regional climate resilience?	Examples include infrastructure resilience, community resilience, natural environment resilience, crop resilience, etc.
Why is the target critical?	As the climate resilience of a region consists of many aspects, whilst in your CS only some target aspects are selected and considered, why they are critical?	
Related Aspects	Some aspects are not the main targets but are involved in the CS assessment or modelling.	
Information on Individual Models *A list of the models being developed and the ARSINOE Tiers that they represent.*		
Tier #	Tier number	Tiers 1-5 (refer to Figure 3.5)
Tier Name	Tier name	Name of the tier (Figure 3.5)
Model Name + **Modelling Methodology**	The name of the model and the modelling methodology	Mention as "others" if the modelling methodology is not identified in the ARSINOE wheel.
Pillar 1 System Innovation Approach (SIA)	Please include SIA techniques employed by CS for the specific model. Provide a short description, if needed.	Mention as "others" if the technique for SIA is now shown in the ARSINOE wheel.
Pillar 2 Data and Logic	Please include a short description of the data (and logic) used for modelling.	Mention as "others" if techniques used by CS are not shown in the ARSINOE wheel.
Pillar 3 Resilience Assessment	Please include a short description of resilience assessments being undertaken through the modelling activity.	Mention as "others" if the resilient assessment approach is not identified in the ARSINOE wheel.
Pillar 4 Stakeholder Decision Making	Please enter approached being used to aid stakeholder decision-making.	Mention as "others" if the modelling methodology is not identified in the ARSINOE wheel.
Comments		As needed.

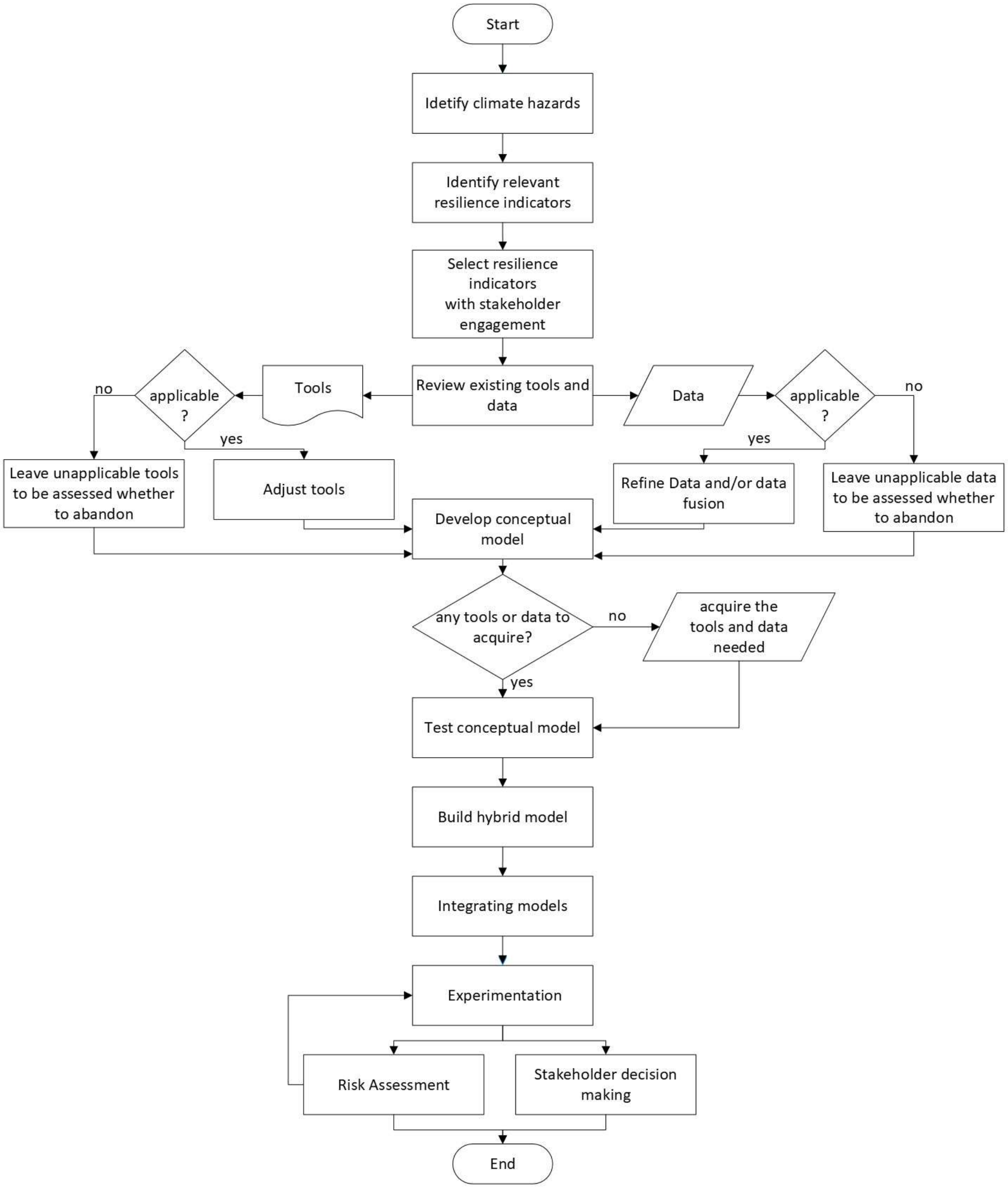

Figure 3.6 The workflow for climate hazards applying DMRM&AF for resilience assessment

4 Application of the ARSINOE Wheel framework (DMRM&AF) to Case Studies (CS)

Nine case studies outlined below encompass a broad geographical scope across the European Continent, spanning from Spain to the Black Sea and from Greece to Denmark, as illustrated in Figure 4.1. These studies delve into diverse systems complexities, encompassing sectors such as health, energy, transport, forests, fisheries, farmland, and wetlands. These systems confront a myriad of challenges including biodiversity loss, floods, water scarcity, and escalating severity of heatwaves, varying according to the specific region under consideration.

All case studies are planned to do resilience assessment along the short (present + 30 years = 2050) and a long (2100) time horizon – at least modelling-wise – to facilitate a structured intercomparison of regional differences in climate change impacts and responses across Europe (for details please see D3.4). However, some case studies will work with their own time horizons in modelling on top of this.

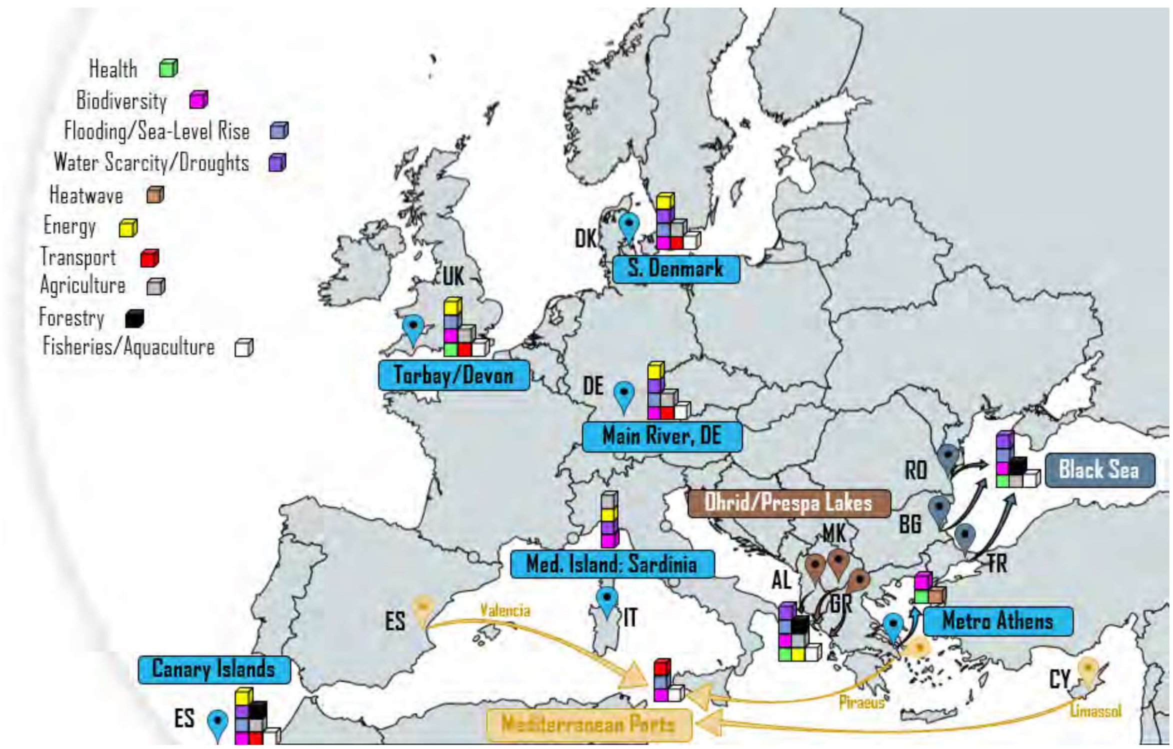

Figure 4.1 Case Studies mapping and Key Systems addressed

4.1 Case Study #1 – Athens Metropolitan Area CS

The case study is dedicated to a comprehensive assessment of urban resilience against heatwaves and their related cascading impacts. It primarily focuses on heatwaves and associated human-induced factors like air pollution, biodiversity loss, landscape fragmentation, and accessibility to green and blue spaces. The evaluation is structured across various phases, encompassing preparedness, response (leveraging digitisation and tools), and recovery, with a special emphasis on Nature-Based Solutions (NBS) targeted towards the long-term heat mitigation. The overarching resilience targets revolve around community health and well-being, anthropogenic natural environment resilience, and sustainability. Recognising heatwaves as significant hazards affecting health, well-being, economy, and ecosystems underscores the criticality of the outlined resilience targets.

The case study investigates a spectrum of interconnected aspects, including urban heat island (UHI), land uses/cover in the urban context, vulnerability indices, socioeconomics, landscape fragmentation, accessibility to green and blue spaces, biodiversity, awareness, citizen engagement, and citizen science, to enable holistic resilience assessment. The CS is working in close collaboration with stakeholders to focus on the 2050 time horizon, which is for many the most appropriate planning dimension. However, some models are developed and applied to simulate up to 2100, in order to consider possible long-term developments.

The models developed in Case Study 1 are now discussed under the specific tiers of the DMRM&AF (Arsinoe Wheel). The content in this section should be read alongside Figure 4.2, which is the ARSINOE Wheel (AW) visualisation for the Athens case study, and Table 4.1 in the appendix. The AW pillars that support the realisation of the individual models, namely, stakeholders, data and logic, systems innovation and resilience assessment, are listed in Table 4.1.

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** The scenarios are commonly used in all case studies to provide climate change prediction based on given socio-economic contexts and scenarios. The information from the projections can influence subsequent models.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climatic Model (WRF Model):** Based on statistical downscaling (highlighted in orange in Tier-2 of the AW), it translates global climate projections into local climate parameters, providing critical inputs for other subsequent models.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Urban Heat Island Model (UHI Model):** This process-based model simulates physical processes of impact due to urban heat island effect, offering insights into temperature variations across urban landscapes. An urban heat island (UHI) is a metropolitan area that is warmer than its surrounding rural areas, due to the change in land cover and materials, and the accumulation of waste heat from human activities. UHIs can have negative impacts on air quality, water quality, biodiversity, and human health. It applies data-driven AI/ML approach, particularly complex network analysis, to understand intricate relationships within the urban environment related to urban heat island effects.
  - **Biodiversity Assessment Model (BA Model):** Based on data-driven AI/ML approach, the model employs clustering techniques to assess and understand biodiversity patterns. Thus, it creates spatial clusters that constitute different types of urban habitats.
  - **Landscape Fragmentation Model (LF Model):** It is a process-based model based on GIS application. The model evaluates landscape fragmentation and connectivity of protected areas, identifying vulnerable zones and potential cascading effects.
  - **Air Quality model (AQ Model):** The model Integrates process-based understanding and numerical simulations to provide a comprehensive view of air quality and pollution, considering the impact of heatwaves. It is designed to treat complex atmospheric chemistry in urban areas and improve the near-field dispersion representation. It can present air pollution conditions, identify hotspot/intervention areas, and impact assessment of simulated mitigation/adaptation scenarios on urban air pollution.

- **Socio-Economic Vulnerability Index Model (VI Model):** It is a data-driven model, which identifies socio-economic vulnerabilities and incorporates demographics, economic indicators, and community resilience.

- Tier 4: Human and Operational Systems Models:
  - **Heat Event Response Model (HER Model):** A hybrid simulation approach consisting of agent-based simulation, discrete-event simulation, and system dynamics simulation approach is applied to build this model. The model has been developed by the University of Exeter as part of joint research work for WP3 (D3.9). It simulates human and operational responses to extreme heat events from a resource perspective, aiding in understanding infrastructures and community reactions and response effectiveness. The model also plays a critical role in the distributed modelling of the case study. It serves as a platform model to integrate other individual models, transforming static limitations into dynamic features in the distributed simulation. Please refer to section 1.1.1 which provides further information on linking models.

- Tier 5: Strategic Response Models:
  - **Nature-Based Solutions Selection (NBS):** By using WRF model on a regional scale, coupled with urban modelling, the modelling utilises numerical models informed by data to select NBS and understand their impact on microclimates, considering their efficacy under various climate scenarios.
  - **Willingness to Pay Model (WtP Model):** Applying choice experiments via VR assesses the community's willingness to pay for resilience measures and contributes to informed decision-making.
  - **Risk Hotspot Model (RH Model):** Applying System Dynamics and Long-Range Planning, the modelling identifies risk hotspots and formulates strategic responses.

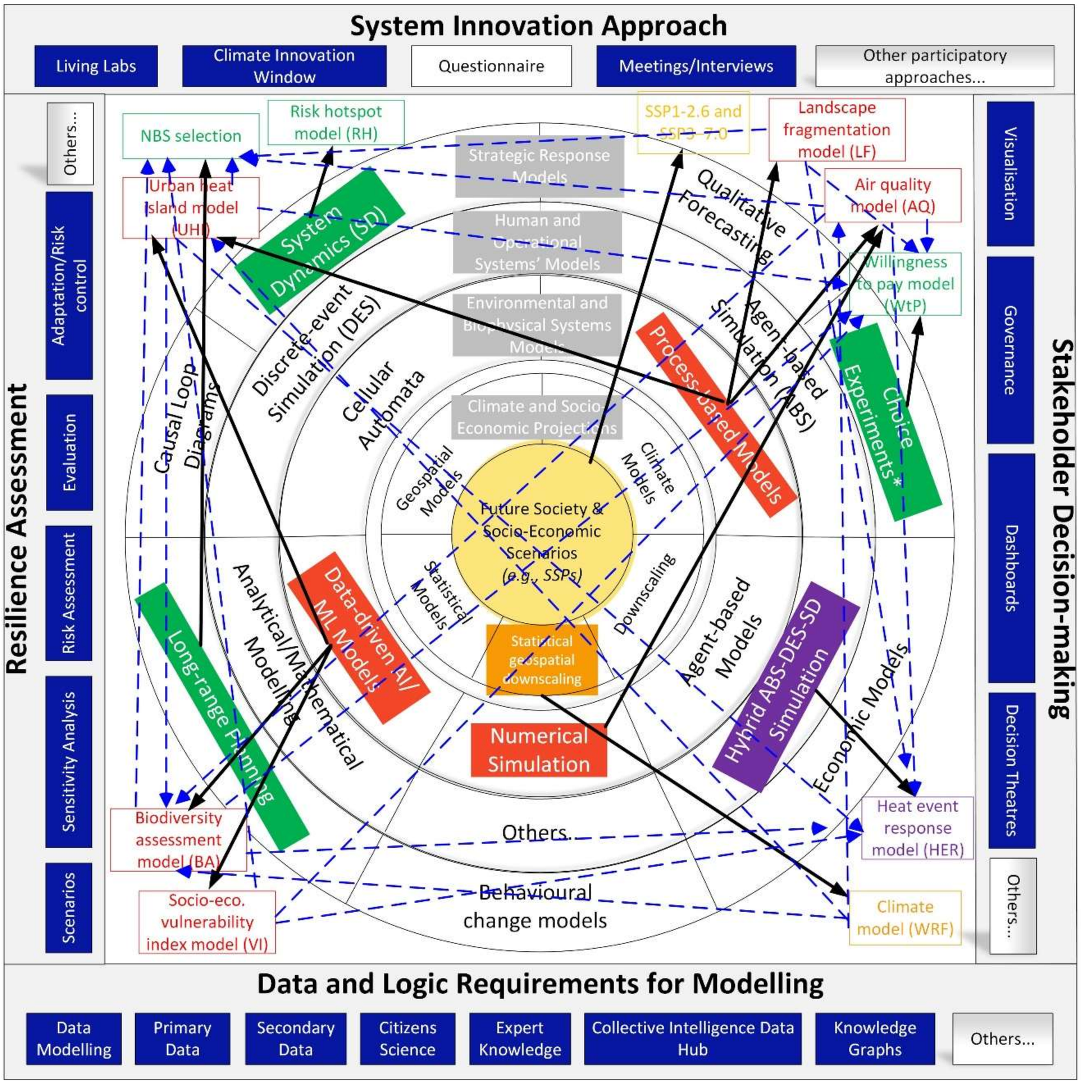

Figure 4.2 The ARSINOE Wheel visualisation for CS#1 Athens Metropolitan Area

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

Linking existing models enhances the comprehensiveness of the resilience assessment. The integration of models is visualised using the AW framework. For example, Figure 4.2 uses dashed arrows to show the Input/Output relationship of the *Heat Event Response model (HER Model)* with the X Model, Y Model, Z Model etc. By integrating these existing models through a distributed simulation (M11 and D3.9), the interactions between socio-economic, environmental, and human systems can be dynamically captured. This approach provides a more holistic understanding of urban resilience against heatwaves and cascading hazards, enhancing the representation of the complex system and supporting the development of targeted strategies for urban resilience.

The connections and interactions between individual models in the distributed simulation can be seen in Figure 4.2, focusing on the impact of heatwaves on both the build environment and ecosystem, as follows (for more information about the distributed model, please see M11 and D3.9):

- **Urban Heat Island Model (UHI Model):** This model can simulate heat distribution within the urban environment, identifying areas with higher temperatures due to urbanisation factors such as buildings and pavement. Some simulation outcomes, e.g., temperature, can be used as input in the BA Model, HER Model, and WtP Model (the input-output interrelation is presented with a blue dashed line in Figure 4.2). The changes in the landscape fragmentation model may also interact with the simulation of UHI model.
- **Air Quality model (AQ Model):** The output of the downscaling microclimate simulation can serve as input to the Air Quality model, as higher temperatures in urban areas can exacerbate air pollution, leading to increased concentrations of pollutants such as ozone and particulate matter. The output of AQ Model can be the input of the BA Model, NBS selection, and WtP Model.
- **Biodiversity Assessment Model (BA Model):** The output of the downscaling microclimate simulation can be utilised as input to assess the impact of microclimate on biodiversity, particularly sensitive species or habitats. The output of the BA Model can be the input of HER Model, WtP model, and NBS section.
- **Socio-Economic Vulnerability Index Model (VI Model):** This model is static, whilst the outputs can be used in the platform model, i.e., Extreme Heat Event Response model (EHSR), to analyse how vulnerable populations within the urban area are dynamically affected by heatwaves, considering factors such as income, access to healthcare, and infrastructure. The output of the VI Model can be the input of HER Model, WtP model, and NBS section.
- **Heat Event Response Model (HER Model):** the model serves as the platform model to integrate other individual models into the distributed simulation. The distributed model evaluates the effectiveness of response strategies during extreme heat events, such as heatwave risk maps, long-term mitigation strategy and land use and biodiversity, and emergency mitigation resource preposition. In Figure 4.2, we use dashed arrows to show the Input/Output relationship of the *Extreme Heat Event Response model (HER Model)* with the BA Model, VI Model, AQ Model etc.

By employing the AW framework on the Athens Case Study, we thus gain a comprehensive understanding of resilience to heatwave impacts on both the city of Athens and its ecosystem. It allows for the integration of various factors, such as urban heat islands, air quality, biodiversity, and socio-economic vulnerability, into a holistic assessment framework. This approach enables decision-makers to identify priority areas for intervention, develop targeted adaptation strategies, and enhance overall resilience to heatwaves within complex urban systems.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, the Urban Heat Island Model (UHI Model) of Tier 3 used approaches from all the four pillars. For SIA methods, Living Lab was applied for discussion with stakeholders about past heatwave impacts. As for the data and logic pillar, data modelling, primary, secondary data, and knowledge expert are needed. As for the resilience assessment pillar, uncertainty analysis and hazard component of the Risk Assessment equation are utilised. As for the decision-making pillar, governance, visualisation of UHI maps in dashboard are applied. Further information on the specific methods that were used by CS#1 is included in Appendix 1.

4.2 Case Study #2 – Mediterranean Ports CS

The focal point of this case study is the resilience assessment of port infrastructure and operations against heatwaves, wind/waves, and extreme weather events. The case study covers three ports, namely Piraeus (Greece), Limassol (Cyprus), and Valencia (Spain). It aims to enhance the resiliency strategy by incorporating many seaport dimensions, including environment, operations, energy, core infrastructure, socioeconomic and safety. The resilience assessment indicates the relevant climatic variables and how these impacts directly or indirectly affect the port operations and infrastructure by considering several other factors (e.g. other sectors as shipping or Energy Demand). This comprehensive evaluation spans preparedness and response phases, with the overarching resilience target aimed at ensuring the robustness of the entire port value chain, encompassing nearby municipalities and communities. The criticality of this target is underscored by the potential impacts associated with high operational costs, traffic disruptions in ports, user and worker health concerns, and safety issues.

To attain a holistic understanding, the case study investigates various related aspects, including transportation, safety, education (specifically upskilling and reskilling), and energy efficiency. These aspects are crucial components of the port's overall resilience, contributing to its ability to withstand and recover from diverse climatic stressors. The horizon of our future narratives are 2040-2060.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.3; further information about related Pillar approach can be seen in Table 4.2):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** The projections are commonly used in all case studies to provide climate change prediction based on given socio-economic contexts and scenarios. The information from the projections can influence subsequent models.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projections (CSP):** To conduct port operations and infrastructure vulnerability assessment, the Climate and Socio-Economic Projections are utilised to assess the vulnerability of port operations and infrastructure to climate and socio-economic changes, offering insights into potential stressors and challenges. The projections apply climate model and statistical model approach. It should be noted that there are models involved in Tier2 whilst this case study only lists the projections (CSP). The models and modelling activities involved for producing the projections (CSP) include global climate and Earth system models that take the Tie1 scenarios (SSP-RCPs) as input and simulate in a course spatio-temporal resolution, as well as regional climate models for downscaling (both requiring supercomputers). In ARSINOE project we just take the projections as given, e.g. in the CMIP archives. Most of the case studies only use these projections without further conducting modelling activities in Tier2 (e.g., WRF model in CS1). For more details about the background modelling activities for producing the climate projections, please see D3.4 and D3.5.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Wave Model:** The advanced Wave Model Maris HMS (developed by Scientia Maris, 2022) was used, which is responsible for simulating the wave propagation and transformation from offshore to nearshore, the wave penetration into the port basin and the wave disturbance (Chondros et al., 2022, 2024). It is a nonlinear irregular wave model based on mild-slope equations, capable of simulating accurately all the dominant phenomena, i.e., shoaling, reflection, diffraction, refraction and breaking.” This information is crucial for assessing the impact of wave-related stressors on port infrastructure and operations. The model applies data-driven model and process-based modelling approach.

- Tier 4: Human and Operational Systems Models:
  - **Hybrid Reporting Model (HR Model)** for Ports: The model integrates human and operational system factors, offering a comprehensive view of how human activities and operational processes contribute to the resilience of port infrastructure. It is based on analytical/mathematical modelling approach.
- Tier 5: Strategic Response Models:
  - **Strategic Response Model (SR Model)** for Mediterranean Ports: The model captures the dynamic interplay of various factors affecting Mediterranean ports, enabling a strategic response to mitigate risks and enhance resilience. By incorporating economic model, system dynamics, and choice experiments approach (discrete choice modelling), the model assesses decision-making scenarios, aiding in the selection of strategic responses for the Mediterranean ports.

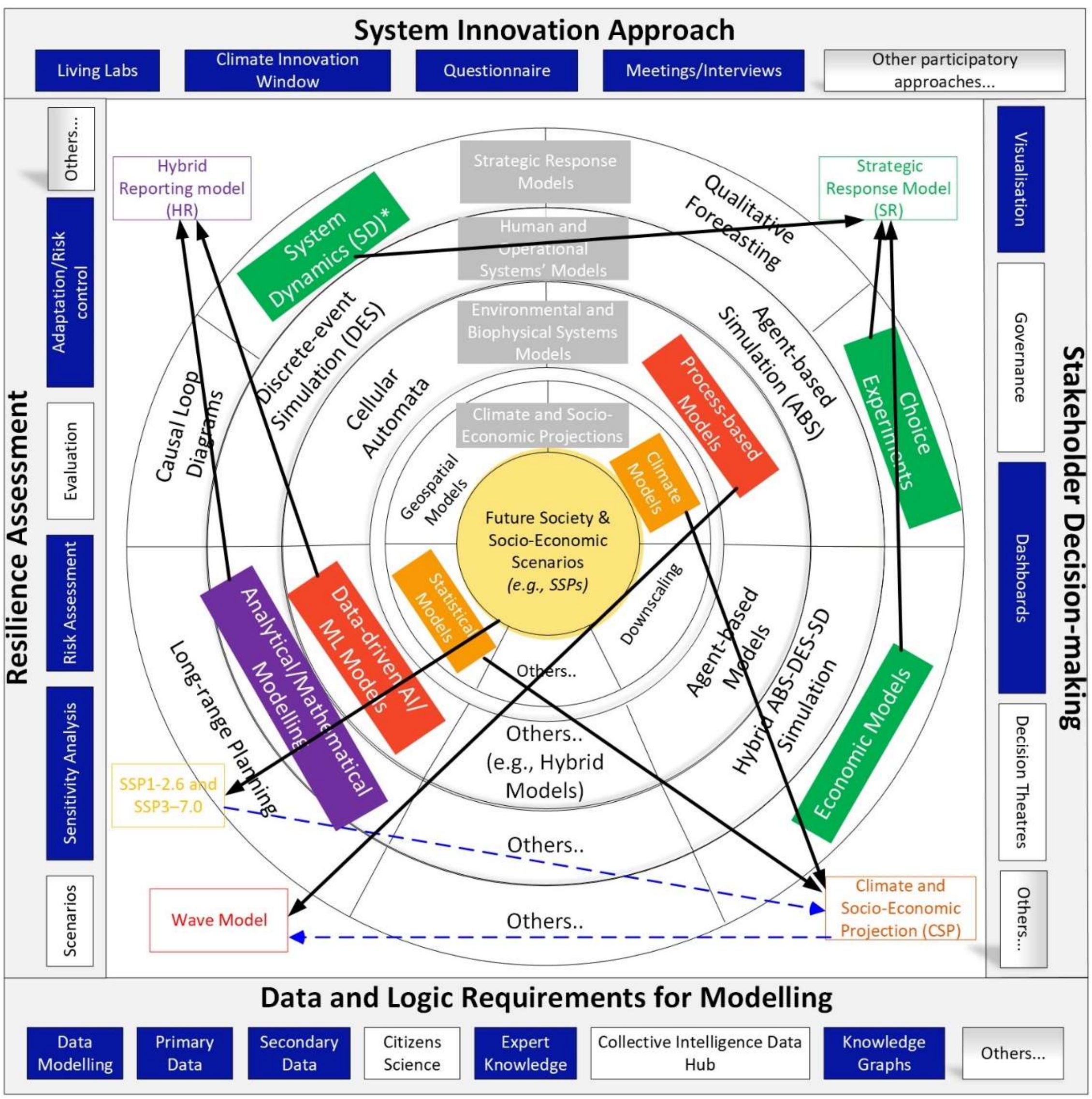

Figure 4.3 The ARSINOE Wheel visualisation for CS#2 Mediterranean Ports

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

In the context of this resilience assessment, there exist opportunities to integrate existing models through DMRM&AF. This integration spans different tiers, each focusing on specific aspects of the port infrastructure and operations resilience framework. The input-output interrelations between individual models are presented with blue dash line in Figure 4.3, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to RCM model to produce regional climate projection.
- **Climate and Socio-Economic Projections (CSP):** The projections serve as inputs for the downstream wave model.

By interlinking these existing models through the modelling framework, there is potential for the resilience assessment to gain a more nuanced and comprehensive perspective. This approach allows for a dynamic understanding of the interactions between societal, environmental, and operational elements within the port infrastructure and operations, ultimately facilitating the development of targeted strategies for bolstering resilience in the face of heatwaves, wind/waves, and extreme weather events.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, the Hybrid Reporting Model (HR Model) used approaches from all the four pillars. For SIA methods, Stakeholders Validate the material issues and the list of KPIs to be included in the analysis. As for the data and logic pillar, secondary data, indicators at the port Level including emissions, air pollution, logistics are needed. As for the resilience assessment pillar, monitoring port performance against long term targets and SDGs is utilised. As for the decision-making pillar, ESG and SDG through dashboards are applied. Further information on the specific methods that were used by CS#2 is included in Appendix 1.

4.3 Case Study #3 – Main River Basin CS

The Main River basin is located in the centre of Europe and Germany. The overarching objective of this case study is to enhance resilience to climate change and land/water use changes within the water and energy sectors. The study focuses on various extreme events, including pluvial floods, droughts, heatwaves, and fluvial floods. The resilience-building process spans prediction/projection, response, and adaptation phases, with a targeted emphasis on ensuring water and energy security. The critical nature of this target is evident due to the anticipation that existing conflicts will intensify under climate change, coupled with rising demands for water and energy resources.

The case study delves into various related aspects critical to the resilience of the water and energy sectors, including city utilities (specifically drinking water supply), agriculture, forestry, and hydropower. Understanding the dynamics of these aspects is crucial for formulating effective strategies to mitigate the impacts of extreme events. The CS is working in close collaboration with stakeholders to focus on the 2050 time horizon, which is for many the most appropriate planning dimension. However, the land surface response tools are developed and applied to simulate up to 2100, in order to consider possible long-term developments.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.4; further information about related Pillar approach can be seen in Table 4.3):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These scenarios provide insights into future climatic, societal and socio-economic conditions, influencing subsequent models to understand the potential impacts on water and energy security.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projections (CSP):** Regional climate model data from Euro-CORDEX and own ClimEx-data; land use projections for the Main river, refined from the ClimEx project. These projections offer critical information on the future climate, including extreme events, guiding subsequent models in assessing the vulnerability of water and energy systems. The model utilises geospatial model and downscaling approach.
- Tier 3: Environmental and Biophysical Systems Models:
  - **WaSiM and SWAT Model (WS Model):** The process-based model simulates the hydrological and water quality aspects, offering insights into the impacts of extreme events on water resources. WaSiM is a physically based and spatially distributed hydrological model; it is the main tool to analyse the water availability under current and future climate conditions. This model not only delivers simulated river discharge at specified gauges, but also delivers gridded spatial outputs that can be used to assess changes in the different storage components of the water balance as well as the physical states during extreme dry or wet conditions. Main outputs include evapotranspiration, soil moisture in the root zone and the full soil column, snow storage, groundwater depth, and groundwater recharge.
  - **Water Temperature and Quality Model (WTQ Model):** A machine learning approach LSTM-CNN is employed for predicting water temperature and quality, providing a detailed understanding of the environmental conditions.
- Tier 4: Human and Operational Systems Models:
  - **Land Use Model (LU Model):** This model (iCLUE) focuses on land use changes, playing a pivotal role in understanding the human-induced impacts on water and energy resilience. It applies a hybrid modelling approach.
  - **Resource Management Model (RM Model):** Potential integration of a resource management model with AnyLogic may provide a platform for simulating operational systems regarding

resource allocation, contributing to the overall resilience assessment. The model is based on hybrid ABS-DES-SD simulation approach.

- Tier 5: Strategic Response Models:
  - **Strategic Response Model (SR Model):** Based on system dynamics, long-range planning, and qualitative forecasting approach, this model captures the dynamic interactions between environmental, socio-economic, and operational factors, offering a strategic response framework for the Main Area.

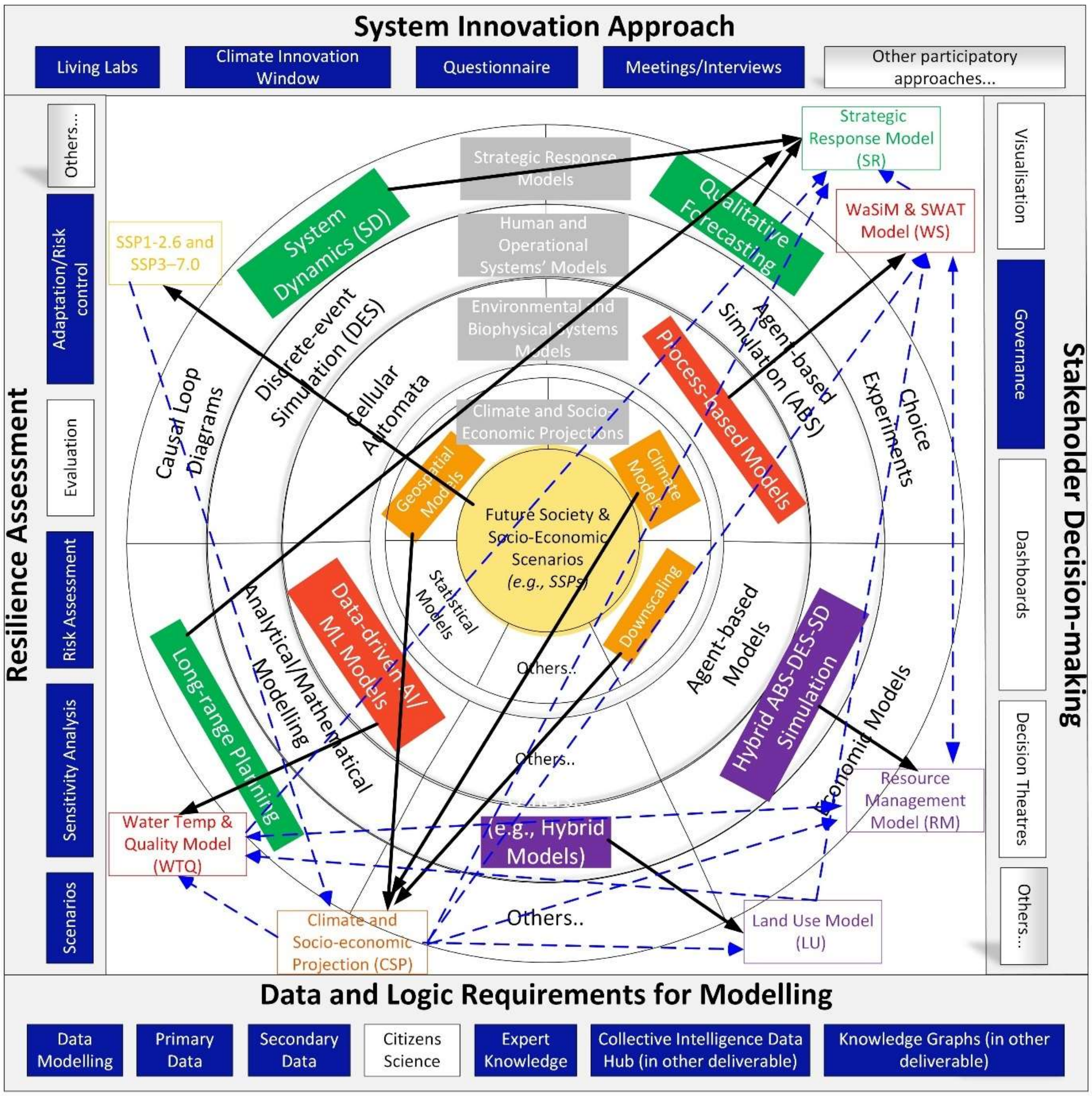

Figure 4.4 The ARSINOE Wheel visualisation for CS#3 Main River Basin

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

In order to conduct a comprehensive resilience assessment, existing models may be integrated through the modelling framework. The possible way of integration is structured across different tiers, each addressing specific aspects of the water and energy sector's resilience framework. The input-output interrelations between individual models are presented with blue dash line in Figure 4.4, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the RCM model.
- **Climate and Socio-Economic Projections (CSP):** The models provide regional climate projections, which serve as inputs for all the downstream models in Tier 3, 4, and 5.
- **WaSiM and SWAT Model (WS Model):** Delivers hydroclimatic inputs for the models in Tier 4 and Tier 5.
- **Water Temperature and Quality Model (WTQ Model):** Delivers hydroclimatic inputs for the models in Tier 4 and Tier 5.
- **Land Use Model (LU Model):** Delivers feedback to Tier 3.
- **Resource Management Model (RM Model):** Delivers feedback to Tier 3 models.

By interlinking these existing models through the modelling framework, the resilience assessment may gain a more holistic perspective. This approach facilitates a dynamic understanding of the interactions between climate, land use, water use, and the water and energy sectors, enabling the development of targeted strategies to enhance resilience in the face of floods, droughts, heatwaves, and flash floods.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Water Temperature and Quality Model (WTQ Model, with temperature prototyped and quality to be implemented) uses approaches from three pillars. For SIA methods, discussion with experts on land, energy and water use and demand are needed. As for the data and logic pillar, reference land use, current water extraction and use rates are needed. As for the decision-making pillar, visualisation and dashboard are applied to facilitate decision-making. Further information on the specific methods that were used by CS#3 is included in Appendix 1.

4.4 Case Study #4 – Ohrid and Prespa Lakes CS

The Region of Ohrid and the Prespa Lakes, situated in south-western Europe. The primary objective of this case study is to enhance the climate resilience of environmental, social, and economic sectors, all of which are dependent on water availability. The focus is on mitigating the impacts of droughts, which induce water scarcity. The resilience-building process is organised across preparedness and response (adaptation) phases, targeting the social sector (households), economy sectors (industry, agriculture, tourism), and the energy sector (cascade Hydropower Plants - HPPs). The criticality of this target lies in the essential role of water for the survival and sustainable development of the included sectors, making it imperative to address the challenges posed by drought-induced water scarcity.

In the pursuit of improved climate resilience, the case study considers the interconnected aspects of environmental ecosystems. Understanding the dynamics of environmental ecosystems is crucial for formulating effective strategies to mitigate the impacts of water scarcity on social, economic, and energy sectors.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.5; further information about related Pillar approach can be seen in Table 4.4):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3-7.0:** These scenarios provide insights into future societal and socio-economic conditions, influencing subsequent models to understand the potential impacts on water and energy security.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate indicators:** Based on downscaling approach, the regional climate indicators are produced. These projections offer critical information on the future climate, including extreme events, guiding subsequent models in assessing the vulnerability of water and energy systems.
  - **Economic indicators:** Based on downscaling approach, the regional economic indicators are produced.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Integrated Water Management Model (IWAMM):** This model incorporates hydro-climate, socio-economic, and water consumption modelling of sectors based on Water-Energy-Food (WEF) nexus principles. It provides a comprehensive understanding of the complex interactions between water availability, climate, and socio-economic factors. The model utilises hybrid modelling approach.
- Tier 4: Human and Operational Systems Models:
  - **Watershed Hydrological Model (WH Model):** The model projects water consumption by economy, energy, and social sectors under selected SSP scenarios. The identification of trans-sectoral and transboundary trade-offs is based on users' prioritisation, recognising the interdependence of water use across various sectors. It applies analytical modelling approach.
  - **Energy Generation Model (EG Model):** The model plays a critical role in enhancing the understanding and resilience of water management practices by assessing energy requirements, simulating multi-sector interactions, optimising adaptation strategies, integrating renewable energy solutions, and informing policy decisions. It applies analytical modelling approach.
- Tier 5: Strategic Response Models:
  - **Water Allocation Model (WA Model):** The model simulates the effects of considered adaptivity (response) measures and their influence on freshwater consumption. It aids in understanding the potential effectiveness of different adaptation strategies optimise the allocation of water per user, based on WEF nexus principles, considering the

interconnectedness of water, energy, and food systems. The model also considers the cross-sectoral integration of water management, emphasising the interdependencies between different sectors and their collective impact on water resources. It is based on long-range planning approach.

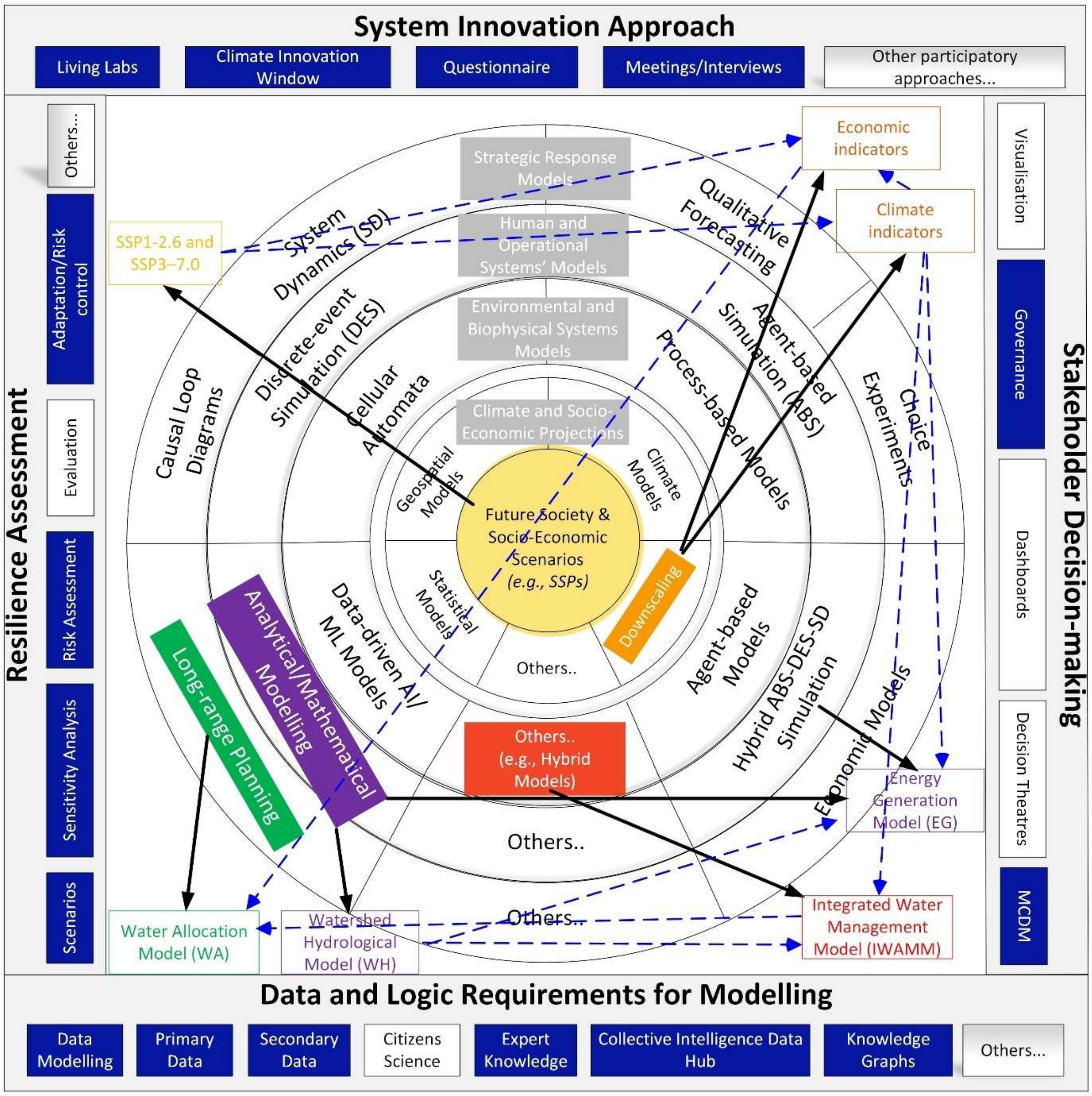

Figure 4.5 The ARSINOE Wheel visualisation for CS#4 Ohrid and Prespa lakes

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The possible integration of existing models through the modelling framework is essential for a comprehensive resilience assessment. The integration is structured across different tiers, each addressing specific aspects of the climate resilience framework. The input-output interrelations between individual models are presented with blue dash line in Figure 4.5, as follows:

- **SSP1-2.6 and SSP5–8.5**: Input to the climate indicators and economic indicators in Tier2.

- **Climate indicators:** They serve as inputs for the downstream Integrated Water Management Model (IWAMM), as well as to energy generation model.
- **Economic indicators:** Input to water allocation model in Tier5.
- **Integrated Water Management Model (IWAMM):** Input to water allocation model in Tier5.
- **Watershed Hydrological Model (WH Model):** It serves as inputs for the Integrated Water Management Model (IWAMM), as well as to energy generation model.

By interlinking these existing models through DMRM&AF, the resilience assessment gains a holistic perspective. This approach enables a dynamic understanding of the interactions between climate, water availability, and the social, economic, and energy sectors, fostering the development of targeted strategies to enhance resilience in the face of drought-induced water scarcity.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Water Allocation Model (WA Model) used approaches from two pillars. For SIA methods, communication with specific target groups including sector operators, experts, and policy makers. As for the decision-making pillar, MCDM techniques, development of a long-term cross-sectoral water management plans, are leveraged by policy recommendations. Further information on the specific methods that were used by CS#4 is included in Appendix 1.

4.5 Case Study #5 –Canary Island CS

One of the primary objectives of Project ARSINOE in the Canary Islands (Spain) is to develop a 3D geological model for the island of El Hierro and La Palma. This model aims to enhance the management of the island's aquifer and, for the first time, provide accurate values for natural recharge. Natural recharge is expected to be influenced by climate change, as any alterations in the amount or frequency of precipitation will impact the volume of water infiltrating the subsurface, ultimately affecting the calculation of natural recharge. The 3D geological model for the islands of El Hierro and La Palma was created using GeoModeller software. GeoModeller facilitates the construction of complex 3D geological models by utilizing geological data from both surface and subsurface sources. It then applies a geo-statistical algorithm to produce the 3D geological model.

The core objective of this case study is to model the island aquifer in La Palma and El Hierro, aiming to calculate the natural recharge of the aquifer more accurately. Additionally, the study focuses on modelling sea level rise in selected cities on these islands. The extreme events considered are related to groundwater quality and quantity as well as sea level rise. The primary phase involves improving current decision-making information for policymakers. The resilience targets include groundwater resilience and infrastructure resilience. The criticality of these targets stems from the essential role of groundwater in the viability of life in the Canary Islands, increased dependence on desalination, and the potential compromise of infrastructure due to sea level rise. The time horizon for modelling is 2100, whilst for the Living Lab is 2050.

The case study takes into account several related aspects crucial for resilience, including the salinisation of aquifer water due to sea level rise, reduced land availability, and the potential impact on real estate and the community. These aspects highlight the intricate relationships between hydrological systems, land use, and societal well-being.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.6; further information about related Pillar approach can be seen in Table 4.5):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These scenarios provide insights into future societal and socio-economic conditions, influencing subsequent models to understand potential impacts on groundwater and infrastructure resilience.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projections (CSP):** Numerical modelling, as well as geospatial model, downscaling is employed in this tier to project regional climate and socio-economic conditions, contributing to the assessment of groundwater and infrastructure resilience under different scenarios.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Groundwater Model:** The model focuses on simulating the island aquifer, providing a detailed understanding of groundwater dynamics, recharge, and quality. Data-Driven AI/ML model approach is utilised for understanding complex interactions between groundwater dynamics and sea level rise, enhancing the accuracy of predictions.
  - **Sea Level Rise Model (SLR Model):** The model projects sea level rise in selected cities, considering the potential impacts on aquifers and infrastructure. Data-Driven AI/ML model approach is utilised for understanding complex interactions between groundwater dynamics and sea level rise, enhancing the accuracy of predictions.
- Tier 4: Human and Operational Systems Models:

- Groundwater Model: It is noted that the groundwater model in Tier3 also applies analytical/mathematical modelling approach from Tier4 to address operational aspect.

- Tier 5: Strategic Response Models:
  - **Strategic Response Model (SR Model):** The model applies long-range planning approach, which helps formulate strategic responses to the challenges identified in the previous tiers, aiding policymakers in developing sustainable and resilient strategies.

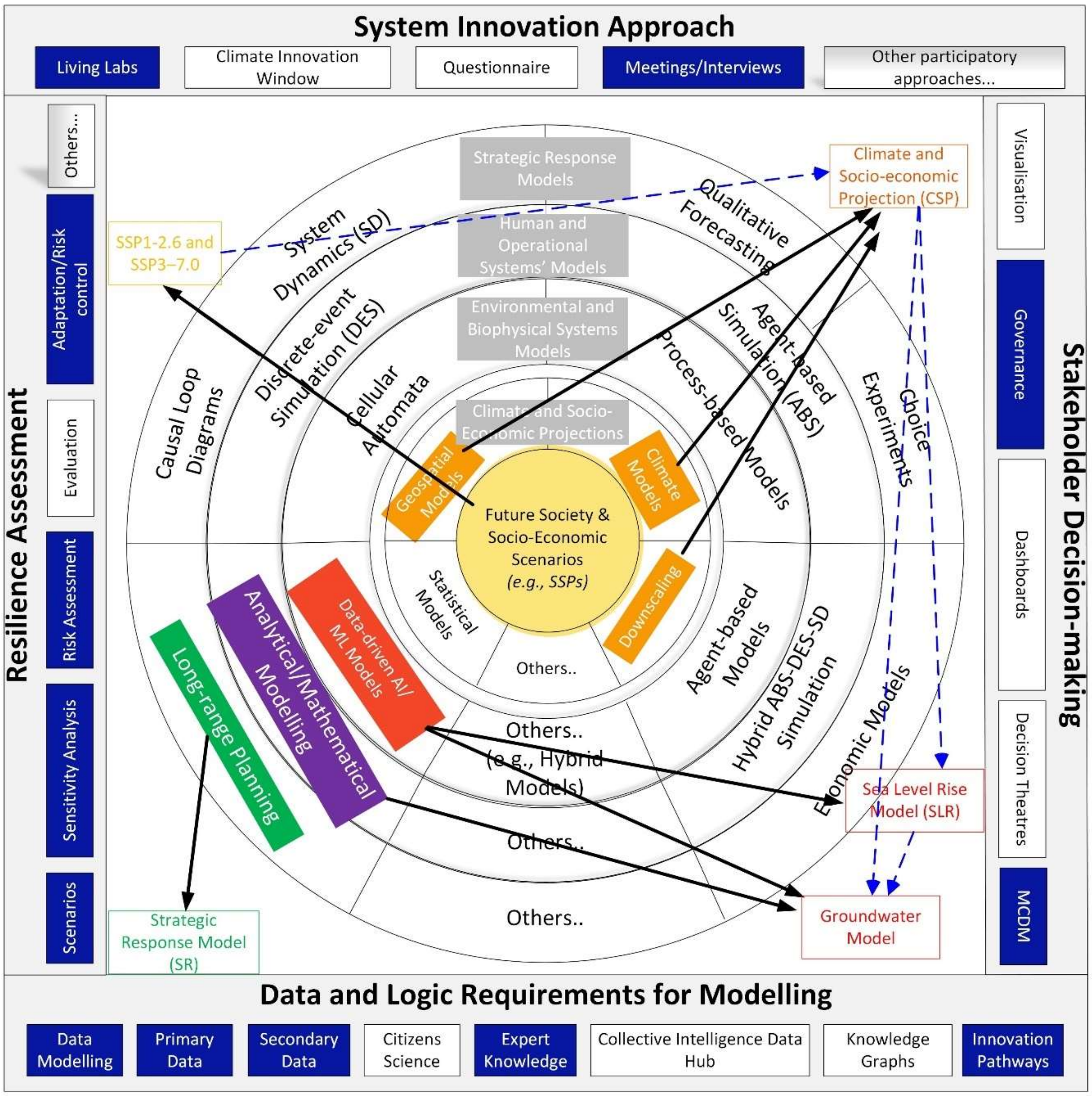

Figure 4.6 The ARSINOE Wheel visualisation for CS#5

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

To comprehensively address the resilience of the aquifer and infrastructure, existing models are integrated through a distributed simulation concept, structured across different tiers. The input-output interrelations between individual models are presented with blue dash line in Figure 4.6, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the climate and socio-economic indicators in Tier2.
- **Climate and Socio-Economic Projections (CSP):** They serve as inputs for the downstream groundwater model and sea level rise model.
- **Sea Level Rise Model (SLR Model):** Input to the Groundwater Model.

By integrating these models through a distributed simulation concept, the case study gains a comprehensive understanding of the interactions between climate, groundwater, sea level rise, and infrastructure resilience in La Palma and El Hierro. This approach facilitates the development of targeted and informed strategies to enhance the resilience of the aquifer and infrastructure in the face of changing environmental conditions.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Groundwater Model used approaches from all the four pillars. For SIA methods, meeting and interviews with local policy makers are conducted. As for the data and logic pillar, primary data from sensors, as well as secondary data including data from water authorities (series) are needed. As for the resilience assessment pillar, scenarios are utilised. As for the decision-making pillar, water management proposals are applied to improve the decision making regarding hydrological plans. Further information on the specific methods that were used by CS#5 is included in Appendix 1.

4.6 Case Study #6 – Black Sea CS

There are **four** sub-cases in the CS#6, located in Bulgaria, Greene, Romania and Turkey, as follows:

I. Sub-case: Bulgaria – Ropotamo activities

The Bulgarian team, Team BG, embarked on a comprehensive fieldwork and mission in August 2022 as part of their resilience assessment in the Ropotamo region. This initiative involves a spatial analysis of the territory, utilising data from national and international platforms. Additionally, climate projections for the next 50 years (RCP 4.5 and RCP 8.5) were prepared using a regional climate model with high spatial resolution. The team actively participated in working groups and international forums. Automated monitoring missions were initiated in October 2022, with plans for drone monitoring, and a final field mission is scheduled for February/March 2024.

Upcoming activities in 2024 include an analysis to determine the locations of ground sensors and the development of a scheme for their installation within the reserve. The team aims to finalise an integrated GIS application, incorporating various datasets related to the protected area, mapped habitats, land cover/land use, archival orthophoto images, and geographic base information.

The case study's focus extends to spatial analysis, climate projections, ecosystem services, and the integration of diverse datasets through GIS applications. Monitoring, sensor deployment, and strategic responses are crucial components of the resilience assessment.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.7; further information about related Pillar approach can be seen in Table 4.6):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These scenarios provide insights into future societal and socio-economic conditions, guiding subsequent models to understand potential impacts on resilience factors in the Ropotamo region.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projections (CSP):** Regional climate modelling approach is employed to project regional climate conditions, contributing to future resilience assessments.

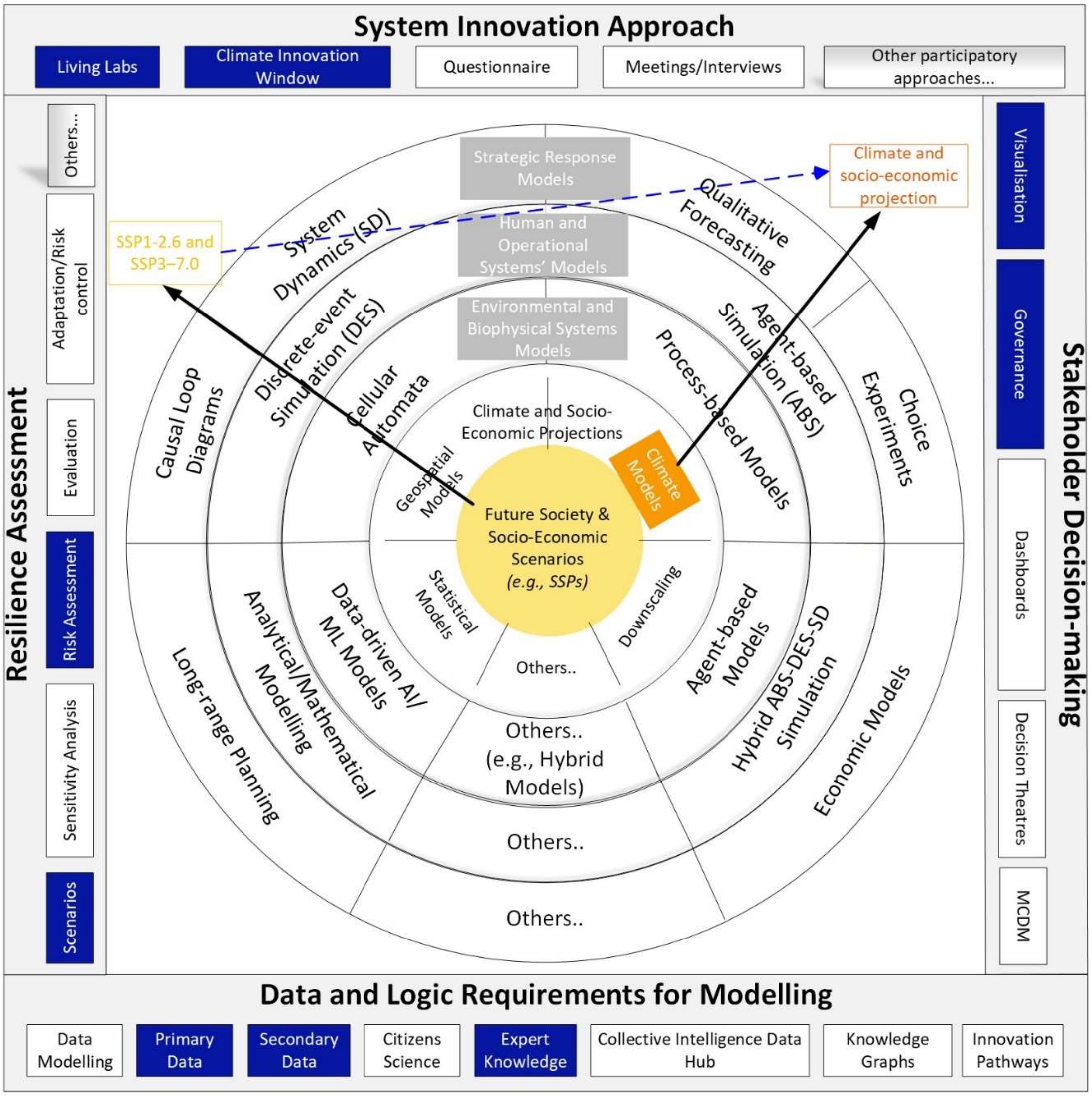

Figure 4.7 The ARSINOE Wheel visualisation for CS#6-BG Ropotamo

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The integration of existing models is critical for a comprehensive resilience assessment, structured across different tiers. The input-output interrelations between individual models are presented with blue dash line in Figure 4.7, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the RCM in Tier2.
- **Climate and Socio-Economic Projections (CSP):** It serves as inputs for the GIS database activities and assessments to support future decision-making on operational and strategic response level.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. Further information on the specific methods that were used by CS#6 is included in Appendix 1.

II. CS6-RO sub-case: Romania

The Romanian research team's work revolves around analysing the adaptive capacity of microbiota in the Danube Delta branches, with a specific focus on climate change-induced eutrophication resulting from alternating drought and heavy rainfall periods. Their multi-tiered approach encompasses four key pillars. Team_RO employ the SSP1-2.6 and SSP3–7.0 scenarios for modelling and focus on Social Impact Assessment (SIA) methods, data and logic, resilience assessment, and decision making. Next, climate and socio-economic projections are made, while environmental and biophysical systems modelling is initiated. Digital Twin Application and innovative farming models on salted soils in the Danube Delta are utilised. This tier combines focus groups, discussions, and scientific research activities involving experts and stakeholders, along with the integration of big data and data interoperability. The evolution of soil microbiota during plant development is investigated, and output data from the Metaverse are obtained. The land surface models are projected to simulate up to 2100.

Team_RO also focuses on human and operational systems models, employing a Living Lab for co-creation and co-design of innovative solutions, alongside focus group meetings and online consultations. Outputs from Environmental and Biophysical Systems Models, questionnaires, interviews, and collective decision-making bodies, such as local council sessions and public debates, play a vital role in shaping the research.

Finally, the Strategic Response Models centre on strategic planning and response, coordinated by key authorities like the Danube Delta Reserve Administration and Tulcea County Council. Specific planning methods guide these strategies, using the insights and results of Environmental and Biophysical Systems Models and Human and Operational Systems Models for effective response planning. The implementation results of the strategic plan are evaluated, actively disseminating scientific-evidence information, and engaging in debates, validation, and co-creation of solutions with local communities. Notably, the Danube Delta Reserve operates within a distinctive legal framework for its functioning, administration, and decision-making.

This multi-tiered approach ensures a holistic understanding of the adaptive capacity of the Danube Delta microbiota in the context of climate change and supports the development of effective strategies to safeguard this critical ecosystem.

The respective ARSINOE Information Capture Table for CS6-RO sub-case is presented in the Table 4.7, while the respective CS6-RO ARSINOE wheel is presented in Figure 4.8.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.8; further information about related Pillar approach can be seen in Table 4.7):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** They provide insights into future societal and socio-economic conditions, guiding subsequent models.
- Tier 2: Climate and Socio-Economic Projections:

- **Climate and Socio-economic Projection (CSP):** The projection provides regional climate conditions, contributing to the assessment of resilience and subsequent modelling under different scenarios.

- Tier 3: Environmental and Biophysical Systems Models:
  - **Digital Twin Application (DT):** Using Metaverse technology and choosing experiment approach, the process-based DT model monitors the impact of climate change processes on biofiltration capacity of water ecosystem in the Danube branches and lakes.
  - **Biofiltration Capacity Model (BC):** The mathematical model also applies system dynamics and causal loop diagrams approach to simulation biofiltration capacity.

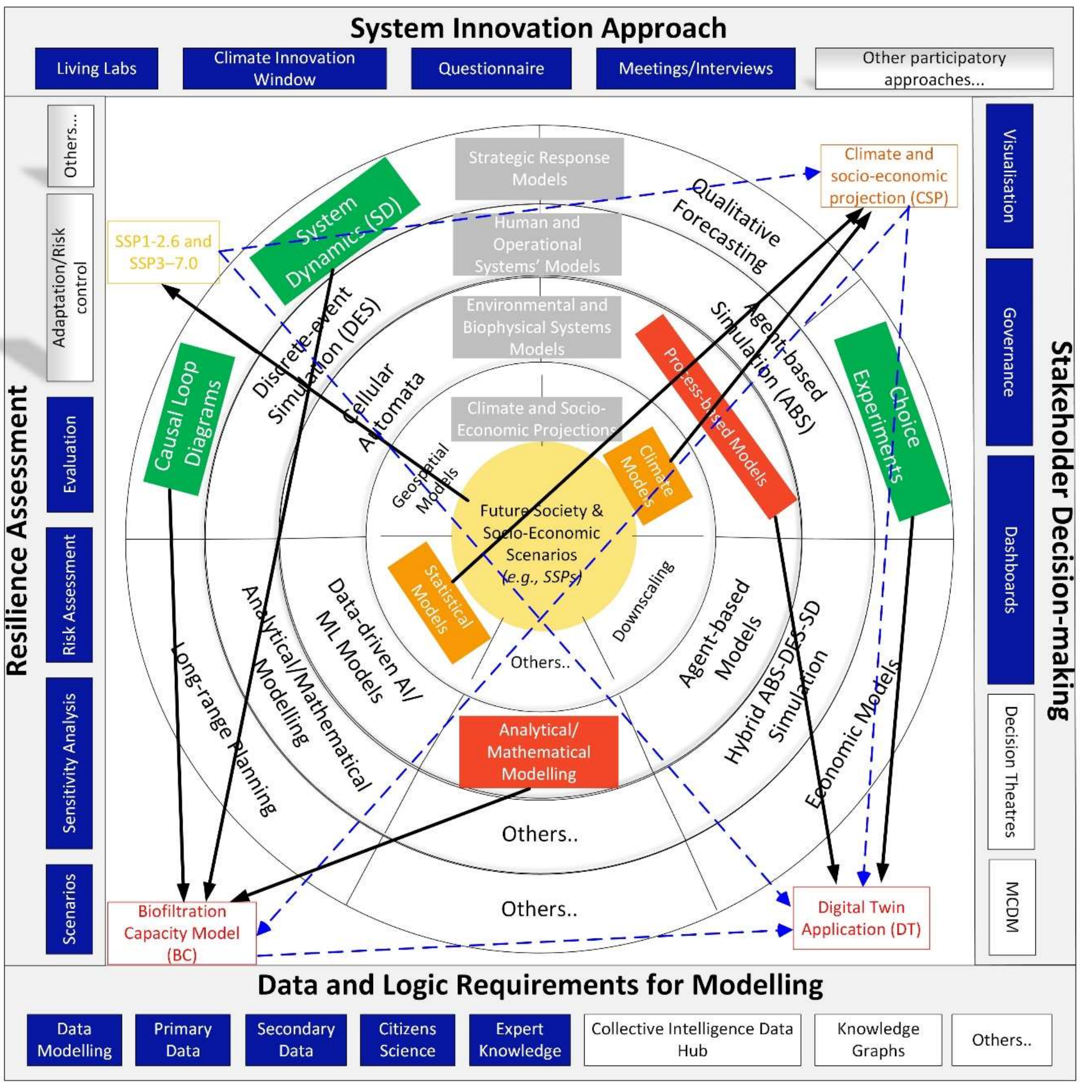

Figure 4.8 The ARSINOE Wheel visualisation for CS#6--RO

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The input-output interrelations between individual models are presented with blue dash line in Figure 4.8, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the Climate and Socio-economic Projection (CSP) in Tier2.
- **Climate and Socio-economic Projection (CSP):** It serves as inputs for the subsequent Digital Twin model and Biofiltration Capacity Model, as well as assessments to support future decision-making.
- **Digital Twin Application (DT)** and **Biofiltration Capacity Model (BC)** have mutual input-output relation. These models are interconnected, allowing for the assessment of environmental and biophysical impacts on microbiota.
- The **Living Lab** serves as a platform for co-creation and co-design of innovative solutions. This activity incorporates outputs from Digital Twin Model and Biofiltration Capacity Model, alongside questionnaires, interviews, and collective decision-making bodies.
- **Strategic planning activity** is developed and coordinated by key authorities such as the Danube Delta Reserve Administration, Tulcea County Council, and ITI Delta Dunarii. These plans are guided by insights and results from Digital Twin Model and Biofiltration Capacity Model and Living Lab, ensuring a strategic response to safeguard the Danube Delta microbiota. The implementation of the strategic planning is evaluated, emphasising active engagement with local communities through debates, validation, and co-creation of solutions.

The Romanian research team is conducting a comprehensive study on the adaptive capacity of microbiota in the Danube Delta branches, specifically focusing on climate change-induced eutrophication resulting from alternating drought and heavy rainfall periods. This multi-tiered approach encompasses Social Impact Assessment (SIA), climate and socio-economic projections, environmental and biophysical systems modelling, human and operational systems modelling, and strategic response models. The research is designed to provide a holistic understanding of the adaptive capacity of the Danube Delta microbiota and develop effective strategies for safeguarding this critical ecosystem. The case study considers the dynamic interactions between climate change, eutrophication, microbiota, and human activities in the Danube Delta. It also highlights the importance of stakeholder engagement, data interoperability, and the legal framework within which the Danube Delta Reserve operates.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Digital Twin Model (DT) used approaches from all the four pillars. For SIA methods, focus groups, discussions and scientific research activities involving experts, stakeholders and other interested parties are applied. As for the data and logic pillar, big data processing, and interoperability of data with the available models are needed. As for the resilience assessment pillar, sensitivity analyses and forecasting of the evolution of quality of water are utilised. As for the decision-making pillar, visualization and dashboard are applied to facilitate decision-making. Further information on the specific methods that were used by CS#6 is included in Appendix 1.

III. CS6-TR sub-case: Türkiye

The respective ARSINOE Information Capture Table for CS6-TR sub-case is presented in Table 4.8, while the respective CS6-TR ARSINOE wheel is presented in Figure 4.9.

The case study aims to analyse factors contributing to a vulnerable state and distorting seawater quality, particularly focusing on mucilage events. The study targets marine biogeochemical cycles, emphasising the importance of understanding these cycles for sustaining the properties of seawater. The analysis includes considerations of land-sea interactions, climate change, and fisheries as related aspects. The approach involves a multi-tiered framework, incorporating societal, climatic, environmental, and operational factors.

The case study's scope extends to understanding land-sea interactions, climate change impacts, and the role of fisheries in the context of mucilage events. These aspects are crucial for assessing the vulnerability and resilience of marine biogeochemical cycles.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.9; further information about related Pillar approach can be seen in Table 4.8):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These scenarios provide insights into future societal and socio-economic conditions, influencing subsequent models to understand the potential influences on seawater quality.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projection (CSP):** The projection is essential for understanding the climatic factors influencing seawater quality and mucilage events.
  - **NEMO-TURSEM Coupled Model (NT)**: The model is essential for understanding the climatic factors influencing seawater quality and mucilage events. This involves simulating the dynamics of marine biogeochemical cycles under different conditions, with a focus on mucilage events. It applies downscaling, statistical model, and geospatial model approach from Tier2. It also applies process-based model, data-driven model, and hybrid model approach from Tier3 (Environmental and Biophysical Systems Models).

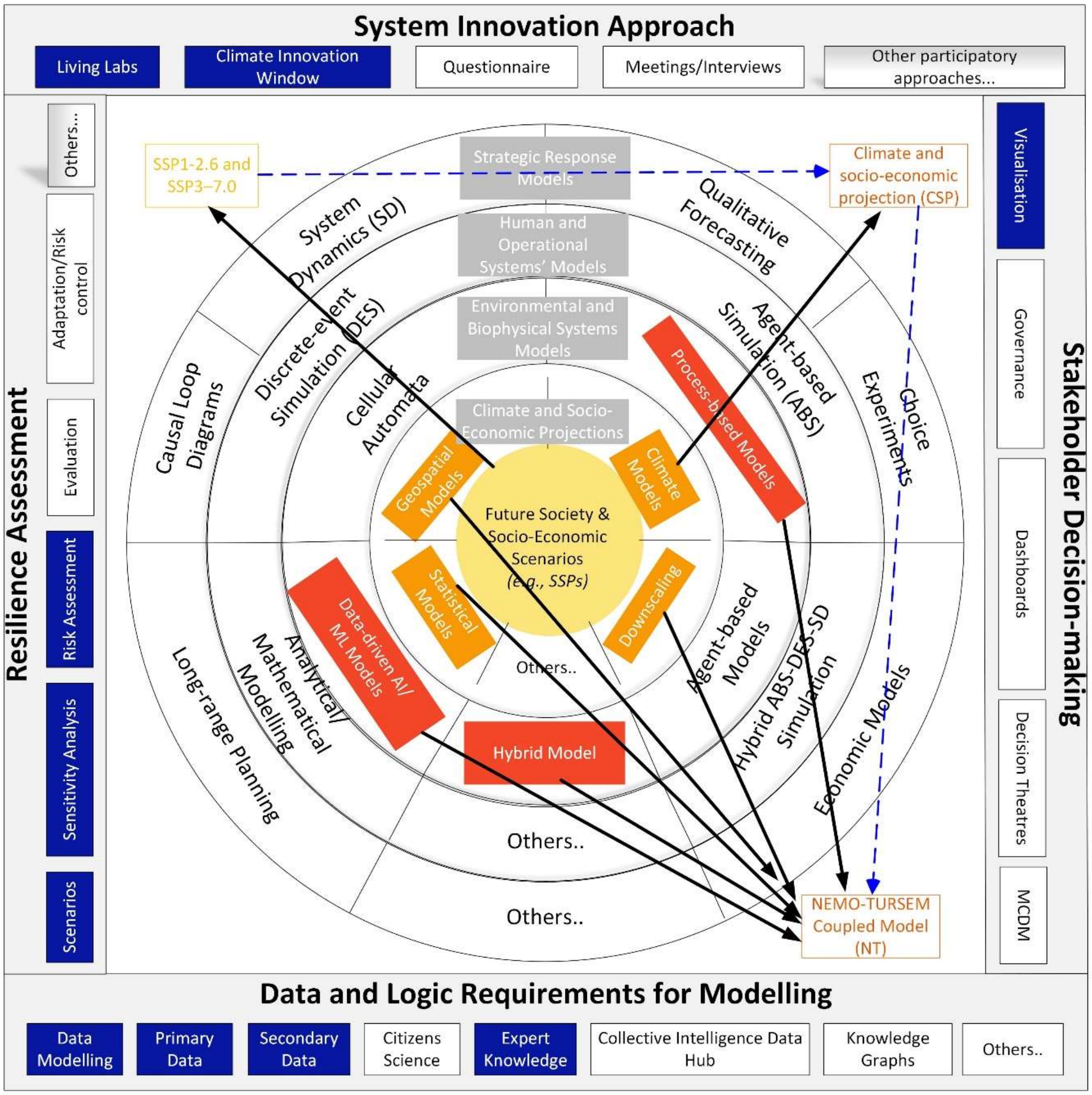

Figure 4.9 The ARSINOE Wheel visualisation for CS#6--TR

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The input-output interrelations between individual models are presented with blue dash line in Figure 4.9, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the Climate and Socio-economic Projection (CSP) in Tier2.
- **Climate and Socio-economic Projection (CSP):** It serves as inputs for the subsequent NEMO-TURSEM Coupled Model, as well as assessments to support future decision-making.

By integrating these models through a distributed simulation concept, the case study achieves a comprehensive understanding of the factors contributing to seawater quality vulnerability and mucilage events. The interconnectedness of the tiers ensures a holistic consideration of societal, climatic, environmental, and operational factors, contributing to effective strategies for response and recovery in marine ecosystems.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, NEMO-TURSEM Coupled Model in Tier 3 used approaches from all the four pillars. For SIA methods, living lab approach is applied. As for the data and logic pillar, input parameters including wind, radiation, temperature, humidity, precipitation, and snowfall data from ERA5, and initial temperature and salinity from WOA 2018, rivers from PERSEUS Project, and Bathymetry from GEBCO are needed. As for the resilience assessment pillar, scenarios are run and the output parameters are evaluated to understand whether the system limits are reached. As for the decision-making pillar, living labs to identify tools, technologies, and policies required to improve resilience in the CS area. Further information on the specific methods that were used by CS#6 is included in Appendix 1.

IV. CS6-GR sub-case: Greece – Aliakmonas river basin

The sub-case of Aliakmonas aims at creating a Digital Twin of the sub-basin of Aliakmonas downstream the Asomata dam. As far as Future Society and Socio-Economic Scenarios are concerned, Team_GR will utilise the SSP1-2.6 and SSP3-7.0 data, provided by the corresponding partners. These will be used as input for the Climate and Socio-Economic Projections, using MED-CORDEX downscaled open data, focused on sub-case CS6-GR. If the SSP1-2.6 and and SSP3–7.0 are not available, CMIP5: RCP2.6 and RCP8.5 CORDEX regional climate model will be used. Living Labs for knowledge transfer, citizens' and stakeholders' engagement in research and innovation framework, as well as discussion with stakeholders about the "Land and Sea" Interactions will enhance the process. The discussion's conclusions may be applicable to every sub-case of CS6.

The above output data will be used as input data for the Environmental and Biophysical Systems Model. In CS6-GR, the Digital Twin includes two models, one for hydrological (1) and one for hydraulic (2) simulations, coupled with an optimisation tool (3): Mod1. Hydrological/Meteorological model HEC-HMS (USACE); Mod2. Hydraulic Model HEC-RAS 1D (USACE) (will only be implemented if the equipment for real-time flow-meter measurements is timely acquired or/and there is access to other parties' real-time data); Mod3. Optimization tool: Genetic Algorithms for automated calibration/parameter estimation of Models 1 & 2. The data will be refined by discussion sessions with local stakeholders about historical/recent extreme flood events in the Aliakmon Riverine environment. The input parameters of the 3 models are:

- Input1. Hydrometeorological data: Wind, radiation, temperature, humidity, precipitation data from ERA5, initial temperature
- Input2. Topography: DEM and geospatial data from Hellenic Cadastre (5m or 2m resolution)
- Input3. Geology and Soil data: Soil map of Greece (OPEKEPE, 2015) and Hydrolithological map of Greece (RBMP, 2017)
- Input4. Land uses: CORINE (2018)
- Input5. Precipitation data: IDF curves and RBMP (2017)
- Input6. Measured data: a) river surface elevation and flow rates from ELGO-DEMETER (ref?), Public Power Company (www.dei.gr/en/ppc-group/ppc/), b) gauges (Deep Learning

assisted cameras, radar/flow-meters, cheap circuit Arduino-based DIY river surface elevation gauges) installed in the framework of ARSINOE project

- Input7. Data for parameter estimation, validation and Verification: a) Historical flood records (local authorities, press, social media), b) Satellite images/data (e.g. Copernicus, Sentinel), c) crowd sourcing data (citizen-based data, e.g. https://floods-crowdsourcing.diae.uth.gr, Tegos et al., 2022)

Scenarios of extreme events in the intake of the studied Aliakmonas sub-basin, the Agia Varvara Restructuring Project (including Earth Dam, Reservoir, Spillway, Water Intake, and Small Hydroelectric Station). Simulations will be implemented to investigate the flood dynamics in the studied downstream area. For the ease of decision making, identification of tools and new technologies (e.g. low-cost sensors) will be implemented in order to improve monitoring and enhance climate change impact mitigation in the sub-CS area.

Living Labs will be held in order to discuss anthropogenic impacts and drivers on water resources, in the framework of Human and Operational Systems Models.

The respective ARSINOE Information Capture Table for CS6-GR sub-case is presented in the following Table 4.9, while the respective CS6-GR ARSINOE wheel is presented in Figure 4.10.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.10; further information about related Pillar approach can be seen in Table 4.9):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These scenarios serve as the foundational baseline for the study, providing insights into future societal and socio-economic conditions. They guide subsequent models, influencing decision-making processes related to climate change impacts on the Aliakmonas sub-basin.

- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-economic Projection (CSP):** Downscaling is employed (MED-CORDEX) to project regional climate conditions, providing essential data for understanding the climatic factors affecting hydrological and hydraulic systems in the sub-basin.

- Tier 3: Environmental and Biophysical Systems Models:
  - **Digital Twin Model (DT):** It consists of three models, including a Hydrological/Meteorological model (HEC-HMS), a Hydraulic Model (HEC-RAS 1D), and an optimisation tool by Genetic Algorithms approach (from Tier 4). The integrated model forming the Digital Twin Model, simulating hydrological and hydraulic dynamics and considering various input parameters such as hydrometeorological data, topography, geology and soil data, land uses, and measured data from multiple sources. Living Labs and stakeholder discussions contribute to refining these models. The model also applies long-range planning and qualitative forecasting modelling approach from Tier 5.

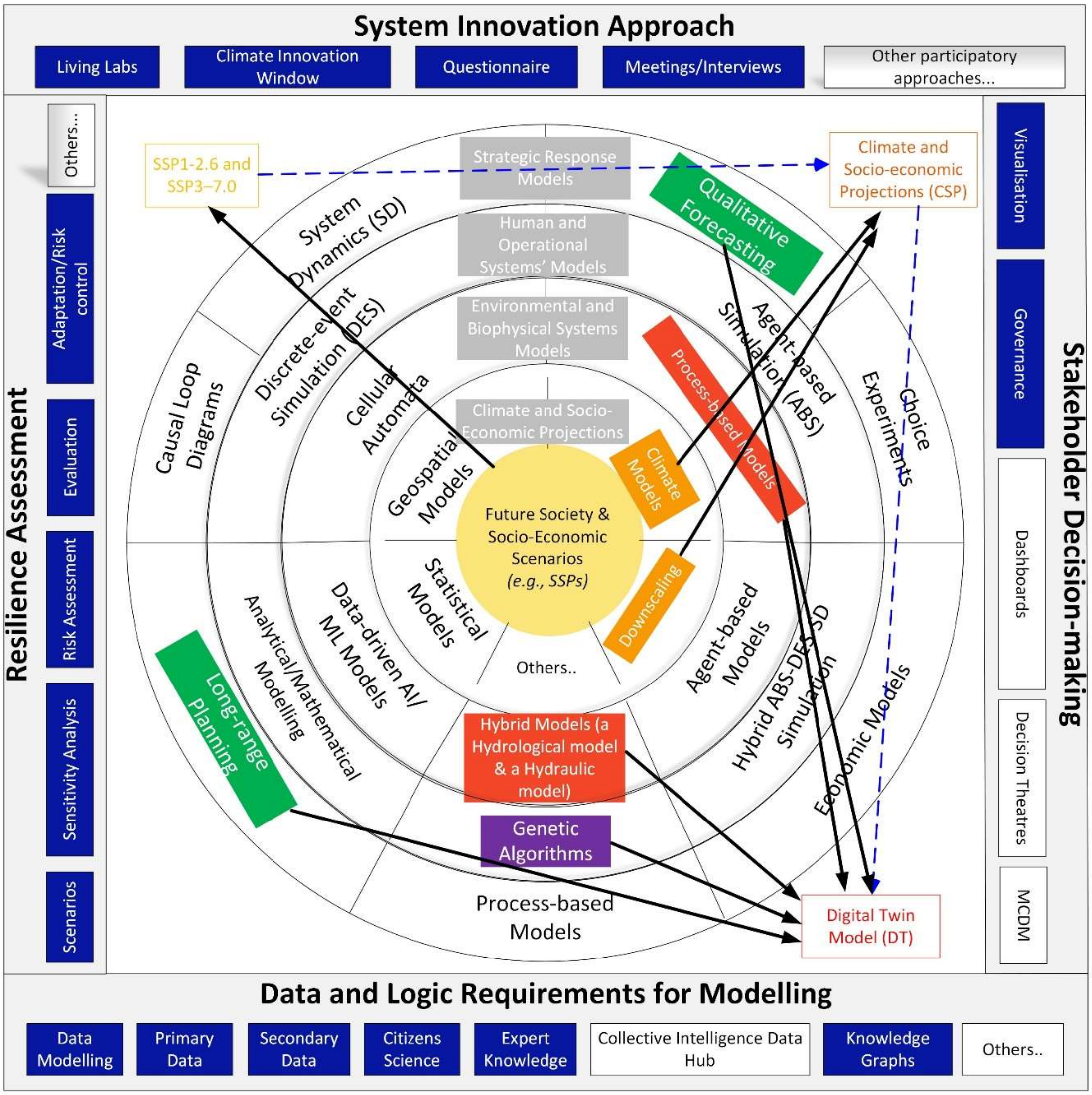

Figure 4.10 The ARSINOE Wheel visualisation for CS#6-- GR Aliakmonas

<u>Using the ARSINOE Wheel framework to visualise the linkages between existing models:</u>

The input-output interrelations between individual models are presented with blue dash line in Figure 4.10, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the Regional Climate Model (RCM) in Tier2.
- **Regional Climate Model (RCM):** It serves as inputs for the subsequent Digital Twin Model (DT).
- **Digital Twin Model (DT):** The optimization tool applying Genetic Algorithms has mutual input-output relation with the Hydrological Model (HEC-HMS) and Hydraulic Model (HEC-RAS), for automated calibration/parameter estimation.

The case study achieves an integrated understanding of the Aliakmonas sub-basin's dynamics, incorporating climate projections, environmental models, and stakeholder engagement. The interconnectedness of the tiers ensures a holistic consideration of climatic, environmental, human, and strategic factors, contributing to effective decision-making for climate resilience and flood mitigation in the studied area.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Digital Twin Model (DT) used approaches from all the four pillars. For SIA methods, discussion with local stakeholders about historical/recent extreme flood events in the Aliakmon Riverine environment is needed. As for the data and logic pillar, hydrometeorological data, topography geology and soil data, land use data, precipitation data, and measured data are needed. As for the resilience assessment pillar, scenarios of extreme events in the intake of the studied Aliakmonas sub-basin are utilised. As for the decision-making pillar, identification of tools and new technologies (e.g. low-cost sensors) to improve monitoring and enhance climate change impact mitigation in the sub-CS area are needed to facilitate decision-making. Further information on the specific methods that were used by CS#6 is included in Appendix 1.

ARSINOE CS6 Virtual Watershed: Conceptual interconnection of all CS6 sub-cases

The hydraulically/simulation-wise autonomous sub-cases of CS6 can be conceptually interconnected into a single unified virtual watershed. The interconnections can be of a data transfer nature ("my input is your output") or of a know-how transfer nature. While the know-how transfer applies both ways for all couples of research teams/countries, the data transfer is one way for some couples, as shown in Table 4.10. All interconnections that constitute the ARSINOE CS6 Virtual Watershed are graphically presented in Figure 4.11.

Table 4.10 One-way data transfer interconnections between CS6 research teams/sub-cases/countries

Data transfer				
from \ to	GR	BG	RO	TR
GR	–	✗	✓	✓
BG	✓	–	✓	✓
RO	✗	✗	–	✓
TR	✗	✗	✗	–

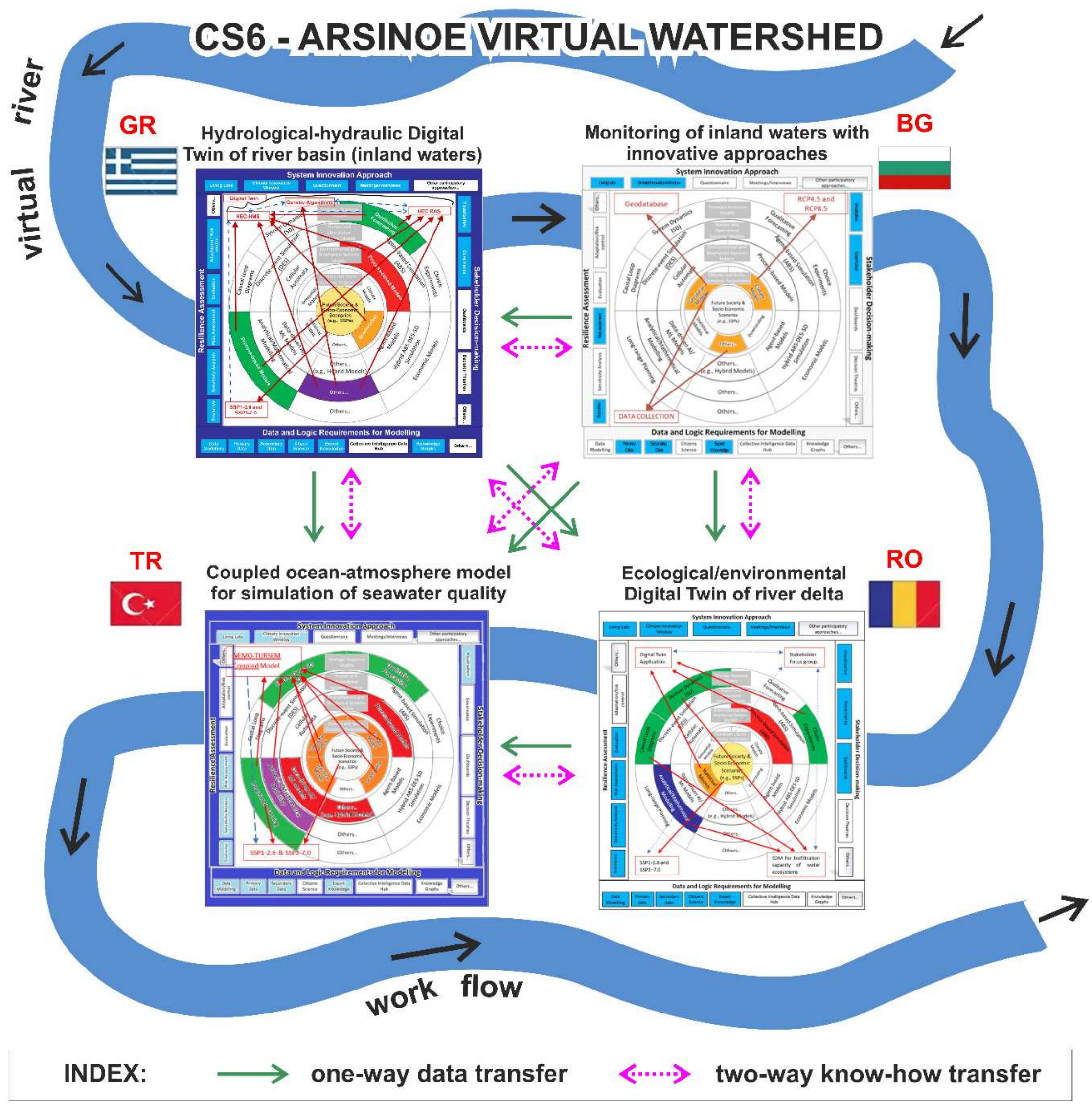

Figure 4.11 "Wheel of Wheels": graphical representation of the conceptual interconnections of the CS6 sub-cases (wheels), forming altogether the ARSINOE CS6 Virtual Watershed

4.7 Case Study #7 – Esbjerg City and Port CS

The case study focuses on the resilience assessment of Esbjerg city and port (southern Denmark) against various water-related challenges. More generally, it explores the interrelated climate challenges related to water (coastal flooding, pluvial flooding, fluvial flooding, rising groundwater, drought, compound events) across all the four municipalities and the Wadden Sea region in the southern part of Jutland using Esbjerg city and port as a demonstrator. In this more general scope, the case study also involves sectoral and ecosystem challenges - with a focus on agriculture - and ecosystems/biodiversity related to water resources (drought, salinisation caused by intruding sea water) and floods in the open land. The objective of the modelling element of the case study is to enhance resilience to current and future climate risks, addressing vulnerabilities in the community, urban infrastructure, and socio-economic activities. The urgency stems from the city's susceptibility to various water-related hazards, necessitating comprehensive knowledge development, local investments in climate change adaptation, and improved emergency preparedness. The key aspects of the case study include community and civil society engagement, urban development, climate adaptation, and emergency preparedness. The holistic approach aims to fill knowledge gaps, drive local development, and facilitate investments in climate change adaptation, aligning with improved emergency preparedness measures.

The models developed in Case Study 7 are discussed next under the specific tiers of the DMRM&AF framework (the framework is referred to as the **Arsinoe Wheel**, or AW for short). The content in this section should be read alongside Figure 4.12, which is the AW visualisation for the Esbjerg case study, and Table 4.11 (included in the appendix), which presents a comprehensive narration of the models and the AW pillars that support the realisation of the individual models, namely, stakeholders, data and logic, systems innovation and resilience assessment.

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** These socio-economic scenarios are used in all case studies as a baseline for climate change projections using Earth System Models. The contextual information from the scenarios can influence subsequent models. SSP1-2.6 describes a world somewhat aligned with the Paris Agreement with low. SSP3-7.0 represents a high-warming, un-mitigated world.
- Tier 2: Climate and Socio-Economic Projections:
  - **Earth System Models (ESM):** They provide global climate projections. These global climate models are implicit input to the CORDEX Regional Climate Models.
  - **Regional Climate Models (RCM**): They provide regional climate projections.
  - **Precipitation Downscaling**: From RCMs, it is employed using empirical-statistical downscaling approaches.
  - **Sea Level Rise Projection (SLR**, from CMIP6): It is based on a statistical/geospatial modelling approach. The SLR projection is produced by the Intergovernmental Panel on Climate Change (IPCC).
  - **Extreme Sea Level Model (ESL Model):** It is based on a statistical/geospatial modelling approach.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Coastal Flood Model (CF Model):** The SFINCS model (Super-Fast INundation of CoastS), a new reduced-complexity engine recently developed by Deltares capable of simulating compound flooding, is planned to be used as the CF Model. It simulates coastal flood scenarios and is a process-based model. It includes planned urban development/climate change adaptation options (e.g. a sea wall and a major storm surge barrier) in Esbjerg.
  - **Overland Flood Model (OF Model):** The model is a process-based model. It includes planned urban development/climate change adaptation options (e.g. a sea wall and a major storm surge barrier) in Esbjerg.

- **Groundwater Model (GW Model**): It utilises data-driven approaches. The national DK-model, hydrological information and prediction (HIP) is planned to be used as the GW Model.
- **Drought Indicator Model (DI Model):** Machine learning/data-driven approach may be used. The indicators will employ RCM data.
- **Stream Flow Model (SF Model):** It utilises machine learning/data-driven approaches.

- Tier 4: Human and Operational Systems Models:
  - **Damage Cost Model (DC Model):** It is the main tool used in CS7 to assess the (economic) risks related to flooding under current and future physical conditions, different socio-economic scenarios, including the effects of different climate change adaptation options. The model applies a discrete-event simulation approach. It is a micro-economic and spatially explicit GIS-based tool that integrates a number of damage cost curves inferred from statistical and physical data using econometric modelling. The model estimates economic losses based on detailed flood maps (flood depth) at varying scales and complexity but is usually used at scales corresponding to individual buildings and assets. It facilitates multi-risk, multi-sector analyses, and adaptation assessments.
  - **Vulnerability Model (VB Model):** It utilises agent-based modelling. The model assesses the economic impact of hazards and vulnerabilities in human and operational systems.

While these are labelled as analyses in the AW, they contribute to strategic responses by providing insights into long-term measures for enhancing climate resilience, urban development, and overall community well-being. We will consider different adaptation, urban planning, and risk management pathways, including a new flood wall, planned green infrastructure (i.e. "Havnestrøget" which will be established ca. 2050-60). They will be framed in current and expected future policy objectives in terms of DK2020, SDGs, etc.

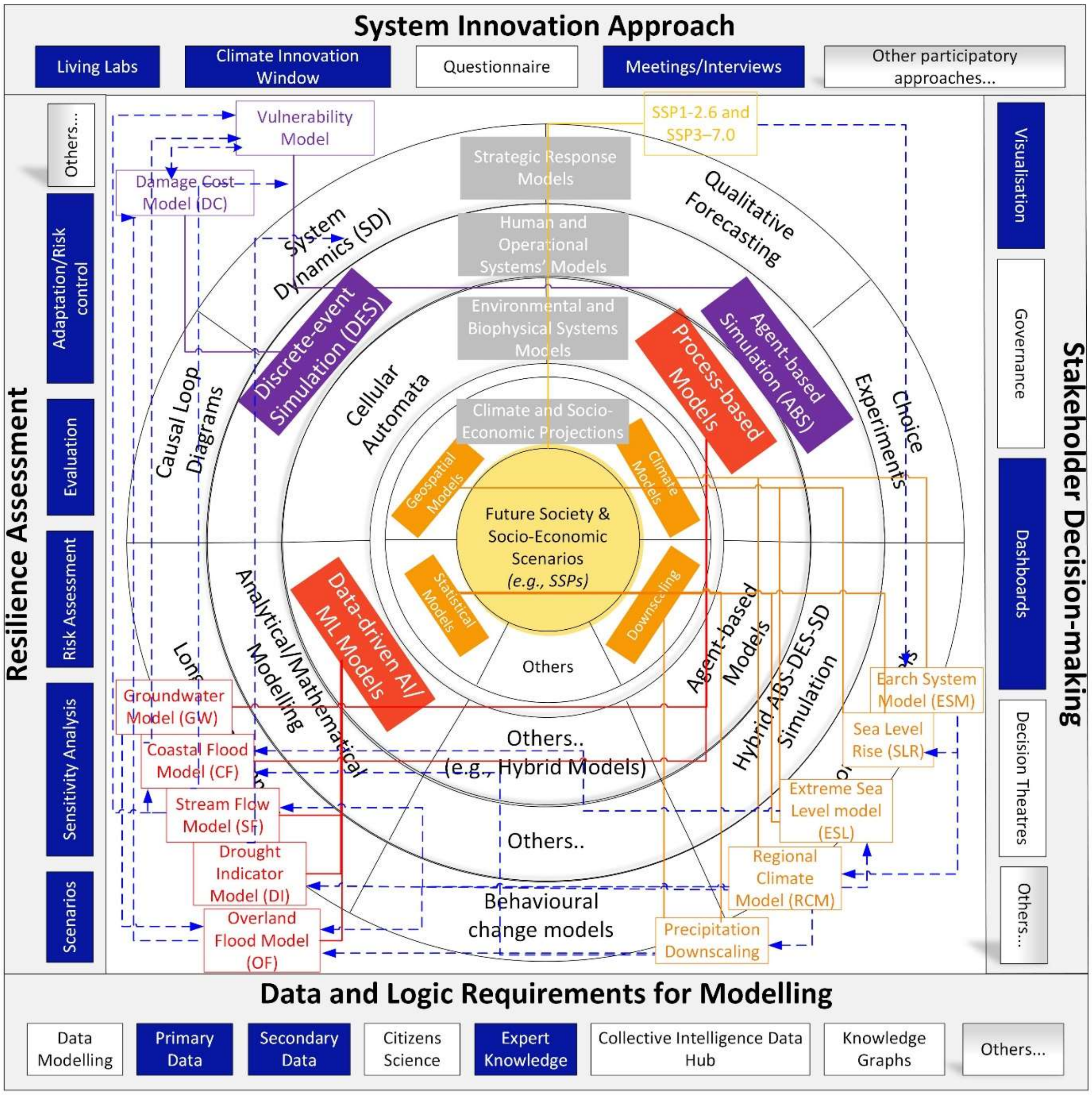

Figure 4.12 The ARSINOE Wheel visualisation for CS#7 Esbjerg city and port

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

Through the modelling framework, the case study integrates information from future scenarios, climate projections, environmental models, and human and operational system models. This interconnected approach ensures a comprehensive understanding of the vulnerabilities and resilience of Esbjerg city and port, facilitating informed decision-making for climate adaptation and long-term planning. The input-output interrelations between individual models are presented with a blue dashed line in Figure 4.12.

- **Earth System Model (ESM):** These global climate models are implicit input to the CORDEX RCMs and sea level rise.
- **Regional Climate Model (RCM):** The models provide regional climate projections, which serve as inputs for downstream models, including Drought indicators and Streamflow model.
- **Sea Level Rise Projection (SLR):** Input to flood models (Tier 3), and the extreme sea level model.
- **Extreme Sea Level Model (ESL):** Input to the coastal and overland flood models (Tier 3).
- **Precipitation downscaling**: Input to the coastal and overland flood models (Tier 3).
- **Drought Indicator Model (DI):** It receives outputs from the Regional Climate Model (RCM).
- **Coastal Flood Model (CF):** Input to Damage Cost model and vulnerability model.
- **Stream Flow Model (SF):** Input to Coastal flood model and Overland flood model, and to Vulnerability model.
- **Damage Cost Model (DC)** and **Vulnerability Model** are mutually interacting with input and output. They both provide the quantitative foundation for Tier 5 analyses (i.e., Climate change adaptation, Urban planning, and Resilience assessment)

<u>**Implementation of the AW Pillars in the case study:**</u>

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Damage Cost Model used approaches from all the four pillars. For SIA methods, discussion with stakeholders about their priorities, requirements for the model, data needs, cost assessment, dissemination of results. As for the data and logic pillar, flood maps including rain events, coastal events, and flooding from streams, damage costs curves or indicators for multi-sectors, statistical data on population, municipal adaptation plans are needed. As for the resilience assessment pillar, scenarios, risk assessment, evaluation, adaptation/risk control are utilised. As for the decision-making pillar, visualization and uncertainty assessment are applied to facilitate decision-making under deep uncertainty. Further information on the specific methods that were used by CS#7 is included in Appendix 1.

4.8 Case Study #8 – Torbay

Located in the English Channel in Devon, South West England, the case study focuses on the resilience assessment of infrastructure impacted by flood events. The overall objective is to evaluate and enhance the resilience of critical infrastructure, with a specific emphasis on flood response and recovery. The target of this resilience assessment is infrastructure resilience, given the significant impact of service reduction during extreme climate events. Related aspects include transportation, community well-being, and the protection of built assets. The future projection CS8 is looking at are 2070 (50 years of climate change) and 2120 (100 years of climate change).

The models developed in Case Study 8 are discussed next under the specific tiers of the DMRM&AF framework (the framework is referred to as the **Arsinoe Wheel**, or AW for short). The content in this section should be read alongside Figure 4.13, which is the AW visualisation for the Torbay case study, and Table 4.12 (included in the appendix), which presents a comprehensive narration of the models and the

AW pillars that support the realisation of the individual models, namely, stakeholders, data and logic, systems innovation and resilience assessment.

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0:** The projections are commonly used in all case studies to provide climate change prediction based on given socio-economic contexts and scenarios. The information from the projections can influence subsequent models.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and Socio-Economic Projections (CSP):** Based on downscaling, it translates global climate projections into local climate parameters, providing critical inputs for other subsequent models.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Flood Model:** The CAFlood model simulates flood scenarios in Torbay and is a process-based model. It utilises Cellular Automata for flood hazard analysis. This model contributes to understanding the environmental dynamics and hazard patterns associated with floods, laying the foundation for subsequent resilience assessments.
- Tier 4: Human and Operational Systems Models:
  - **Resource Allocation Model (RA Model):** It is the main tool used in CS8 to assess the resource utilisation for emergency response related to flooding under current and future physical conditions, different socio-economic scenarios, including the effects of different climate change adaptation options. The model applies hybrid simulation approach, encompassing discrete-event simulation (DES), agent-based simulation (ABS), and system dynamics (SD) approach. It is also a spatially explicit GIS-based model. The model simulates resource allocation, exploring how resource sharing amongst multiple sectors of emergency responders can play a critical role for better addressing resource limitation and efficiency.
  - **Flood Impact Assessment Model (FIA Model):** The model (called **CORFU** model) utilises GIS tool as well as flood prediction from the Flood Model. It assesses the economic impact of hazards and vulnerabilities of assets in the case study area.
  - **Traffic Model:** The model uses the open-source SUMO software to assess potential disruptions to traffic flows during flood scenarios. This model enhances understanding of the impacts on transportation infrastructure. It utilises agent-based modelling. The model simulates traffic conditions and flows affected by flood events in the area.
  - **Cascading Failure Model (CF Model):** It is developed in Julia Programming Language and applies Artificial Neural Networks approach. The model simulates cascading failures. This model helps analyse the potential domino effects on critical infrastructure following flood events, which investigates how cascading effects between regional labour who work for or are related to critical infrastructures and the operation of the infrastructures, due to the impact of flood events in Torbay. It also addresses the cascading failure effects between critical infrastructures caused by flood.
- Tier 5: Strategic Response Models:
  - **Strategic Response Model (SR Model)**: It is based on system dynamics (SD) approach. The model focuses on long-term planning and strategic decision-making. It synthesises information from lower tiers, providing insights for developing comprehensive strategies to enhance resilience at the regional level. It explores the potential of resource sharing and allocation strategy between towns and cities in Devon area, as a regional strategic response for flood mitigation. It can also be used as a resilience assessment tool.

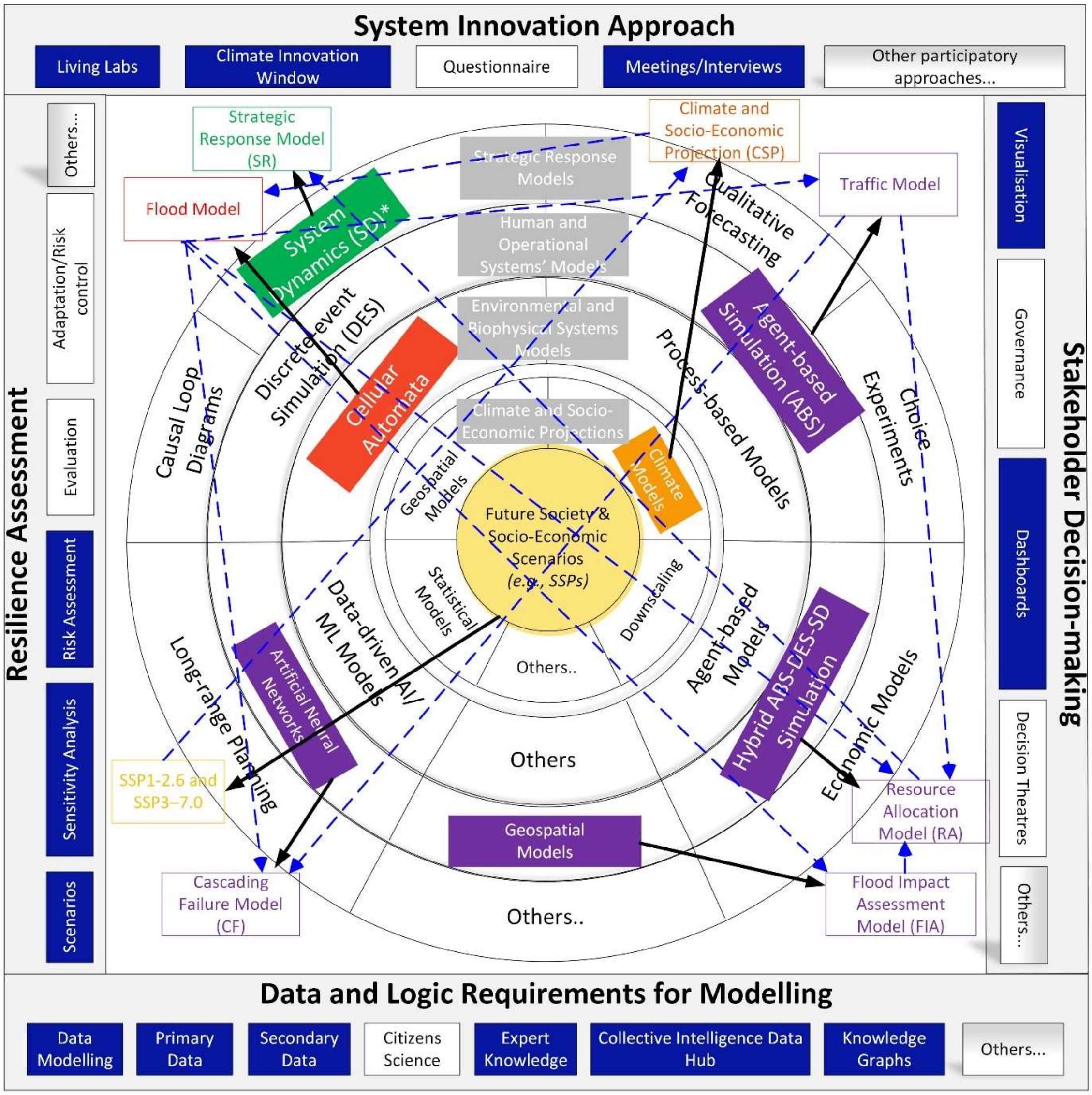

Figure 4.13 The ARSINOE Wheel visualisation for CS#8 Torbay

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The input-output interrelations between individual models are presented with blue dash line in Figure 4.13, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the Regional Climate Model to produce the projections in Tier2.
- **Climate and Socio-Economic Projections (CSP):** It serves as inputs for the subsequent flood model in Tier3.
- **Flood Model:** The model provides inputs to all the models in Tier 4, including RA model, FIA model, traffic model, and CF model.
- **Traffic Model**: It serves as inputs for RA model and CF model in the same tier.

- **Flood Impact Assessment Model (FIA Model):** The output of the model can serve as inputs for the RA model.
- **Resource Allocation Model (RA Model):** It provides inputs to the SR Model of Tier 5.

These tiers interconnect to provide a comprehensive understanding of the resilience of infrastructure during flood events. The integration of future scenarios, climate projections, environmental models, and human and operational system models facilitates informed decision-making for strategic response planning and long-term infrastructure resilience.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Cascading Failure Model (CF) used approaches from all the four pillars. For SIA methods, discussion with experts familiar with historical events in the region that have caused disruption are implemented. As for the data and logic pillar, secondary data from council and ordnance survey data containing GIS positions of critical services nodes; ordnance survey data showing statistics on residents (i.e. commuting distance, industry of employment) are needed. As for the resilience assessment pillar, scenarios, risk assessment, evaluation, adaptation/risk control are utilised. As for the decision-making pillar, visualization and dashboard are applied to facilitate decision-making under deep uncertainty. Further information on the specific methods that were used by CS#8 is included in Appendix 1.

4.9 Case Study #9 – Sardinia CS

The case study, located in the region of southern Sardinia, Italy, focuses on assessing alternative durum wheat crop managements as adaptation strategies to cope with climate change. The overall objective is to utilise field experiments, crop modelling, and climate change projections to inform adaptation planning for durum wheat cultivation. The study employs tiered models to integrate future scenarios, climate projections, environmental considerations, and human-operational systems, providing comprehensive insights into potential adaptation strategies.

Soil, weather and crop data from field experiments conducted by Agris in the Ussana experimental farm, as well as literature review and expert knowledge, will be used to calibrate crop simulation models (e.g. Aquacrop and/or DSSAT) for new durum wheat varieties in both rainfed and irrigated conditions.

Climate Change projections under SSP1-2.6 and SSP3-7.0 scenarios will be downscaled for the Sardinian CS area (Ussana experimental farm) and used to feed the crop simulation models and simulate durum wheat under different climate and management scenarios. Expected anomalies in terms of crop growth and production as well as crop water requirement and nutrient balances will be provided. In addition, alternative agronomic options (changes in crop calendars, cultivars, crop management, etc.) will be to explore their effects as potential adaptation strategies to reduce climate change impacts on durum wheat in Mediterranean areas and inform adaptation planning. A specific focus on irrigation and crop water requirements will be given. The option of extending the analysis to a larger area - or the whole Sardinia - will be evaluated according to the CS9 needs. The climate projections in the case study are focused on the 2035-2065 period and centred upon 2050. This 30-year time span was taken into account as a reference during the Living Lab meetings with stakeholders. However, the time horizon is flexible and is constrained only by the availability of the Cordex scenario data.

Model description (each model and its applied modelling approach in the DMRM&AF can be seen in Figure 4.14; further information about related Pillar approach can be seen in Table 4.13):

- Tier 1: Future Society and Socio-Economic Scenarios:
  - **SSP1-2.6 and SSP3–7.0**: These scenarios establish the foundational framework for the study, outlining future societal and socio-economic conditions. The selected Shared Socioeconomic Pathways (SSPs) guide subsequent models, shaping the assessment of alternative durum wheat crop managements.
- Tier 2: Climate and Socio-Economic Projections:
  - **Climate and socio-economic projections (CSP)**: Downscaled climate change projections under SSP1-2.6 and SSP3-7.0 scenarios specifically cater to the Sardinian CS area.
- Tier 3: Environmental and Biophysical Systems Models:
  - **Environmental and Biophysical Systems Model (EB Model):** The CERES-Wheat model will be applied to simulate durum wheat growth and productivity in Sardinia under present and projected climate conditions. The available calibrations of CERES-Wheat model for Sardinia into the **Crop Growth Simulation Model (CG Model)** will be updated including new durum wheat cultivars and experimental data in irrigated conditions that is collected in ARSINOE. The CG model simulates growth, development, and yield as a function of the soil-plant atmosphere dynamics. It can be integrated with process-based modelling approach of Tier3 into an Environmental and Biophysical Systems Model (EB Model) to provide a better understanding of: (1) the impact of climate change on wheat production and the environment; (2) the interactions amongst crops,

soils, water, climate as well as ecological and environmental dynamics in order to achieve a holistic view of the systems as a whole.

- Tier 4: Human and Operational Systems Models:
  - **Human and Operational Systems Model (HO Model): Crop Growth Simulation Model (CG Model),** e.g., AquaCrop model, is a crop growth model developed by FAO's (Food and Agricultural Organization of United Nation) Land and Water Division to address food security and assess the effect of the environment and management on crop production (https://www.fao.org/aquacrop). AquaCrop simulates the yield response of herbaceous crops to water and is particularly well suited to conditions in which water is a key limiting factor in crop production. AquaCrop has been widely used in the literature to simulate durum wheat yield production, especially in arid and semi-arid countries but needs to be calibrated for the local conditions in the Case Study area. Using CG Model outputs as inputs to integrate with modelling approaches, including analytical/mathematical modelling and discrete-event simulation (DES) approach in this Tier into Human and Operational Systems Model (HO Model) can contribute to better understand the impact of agriculture on human societies and operational systems. This approach could enable the design of policies and strategies aimed at promoting sustainability and resilience in agricultural systems, with a special focus on: food security; water resource management; environmental health; land use; territorial planning.
- Tier 5: Strategic Response Models:
  - **Strategic Response Model (SR Model):** A strategic response model based on system dynamics and long-range planning approach, synthesises information from lower tiers to provide a holistic understanding of the potential adaptation strategies for durum wheat cultivation. The model aids in long-term planning and decision-making, aligning with the overall objective of informing adaptation planning.

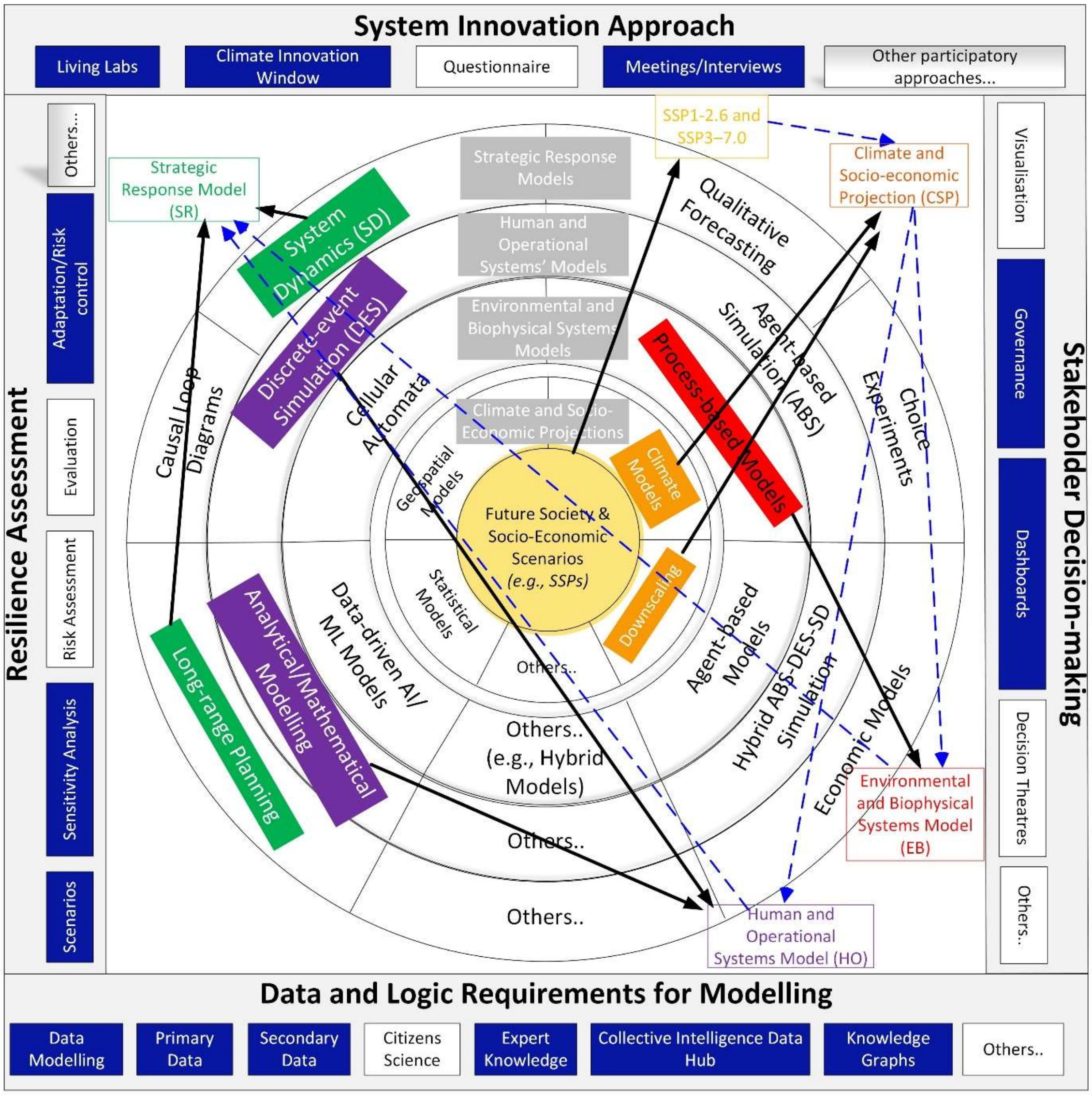

Figure 4.14 The ARSINOE Wheel visualisation for CS#9 Sardinia

Using the ARSINOE Wheel framework to visualise the linkages between existing models:

The input-output interrelations between individual models are presented with blue dash line in Figure 4.14, as follows:

- **SSP1-2.6 and SSP3–7.0:** Input to the climate and socio-economic indicators in Tier2.
- **Climate and socio-economic projections:** They serve as inputs for the downstream Crop Growth Simulation Model (CG model AquaCrop).
- **Crop Growth Simulation Model (CG Model):** May be the input to the Strategic Response Model SR Model).

Through the modelling framework, these tiers are interconnected, allowing for a comprehensive assessment of alternative durum wheat crop managements. The integration of future scenarios, climate projections, environmental and human-operational models ensure a well-informed approach to adapt durum wheat cultivation to the challenges posed by climate change in Mediterranean areas.

Implementation of the AW Pillars in the case study:

The case study has identified specific approaches related to SIA methods, data capture and logic development, resilience assessment, and decision making (the four AW pillars) that were used in the implementation of their models. For example, Crop Growth Model used approaches from three pillars. With regard to the data and logic pillar, primary data including soil, weather, and crop from field observations; secondary data includes literature data; expert knowledge is also needed. As for the resilience assessment pillar, scenarios, sensitivity analysis, changes in crop management to simulate crop adaptation response are utilised. As for the decision-making pillar, we will demonstrate the effectiveness of different measures and discuss with stakeholders for possible solutions. Further information on the specific methods that were used by CS#9 is included in Appendix 1.

5 Conclusions

The ARSINOE project is a comprehensive interdisciplinary research initiative aimed at understanding the complex interactions between natural and human systems, particularly focusing on climate change and its impacts. It brings together various scientific disciplines such as climate science, engineering, social sciences, economics, and operations research. A key aspect of the project is the co-creation approach, which involves active participation from stakeholders in different stages of the research process.

The project utilises diverse modelling approaches, both qualitative and quantitative, to assess the resilience of vulnerable regions to climate change. Computational modelling plays a crucial role in simulating future scenarios and understanding the potential effects of climate change on these regions. The ARSINOE Wheel framework (DMRM&AF) developed through this deliverable, serves as a conceptual model for integrating different modelling techniques and ensuring consistency across various case studies. It was developed through a collaborative process and is being implemented by all nine case study partners. The framework facilitates the conceptualisation of modelling activities undertaken within the project, ensuring comparability and coherence across different settings. It supports the assessment of resilience and the development of systemic solutions for transforming regions into climate-resilient areas.

Overall, the ARSINOE Wheel framework (DMRM&AF) demonstrates a holistic and integrated approach to studying climate change impacts and fostering resilience in vulnerable regions through interdisciplinary collaboration and co-creation.

Acknowledgements

The data for the modelling in CS#8 were obtained with the participation of the Torbay Council, emergency planning office, and the Westcountry Rivers Trust, whilst in CS#1 were collected by the Athens case study partners.

Appendix

Table 4.1 The ARSINOE WHEEL information capture for CS#1 Athens Metropolitan Area

CS Overall Objective	Assessment of Urban Resilience against heatwaves and cascading hazards
Extreme Event Type	main: heatwaves cascading: air pollution, biodiversity loss, landscape fragmentation, accessibility to green and blue
Phase	preparedness, response (through digitisation and tools), recovery (through NBS targeted to heat mitigation)
Resilience Target	community health and well-being, anthropogenic natural environment resilience, sustainability
Why is the target critical?	heatwaves are considered as a major hazard affecting health, well-being, economy, and ecosystems
Related Aspects	urban heat island, land uses/cover at the urban context, vulnerability indices, socioeconomics, landscape fragmentation, accessibility to green and blue, , biodiversity, awareness, citizen engagement, citizen science

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	

Tier 2	Climate and Socio-Economic Projections	**climatic parameters statistical downscaling** geospatial/statistical/downscaling	Living Lab: discussion with stakeholders about past heatwave impacts definition of case study geographical boundaries and grid	data modelling climate expert knowledge CIDH.	Scenarios for uncertainty analysis		Input to Urban Heat Island Model;
Tier 3	Environmental and Biophysical Systems Models	**Urban Heat Island** a) process based models & b) Data driven AI/ML model (complex network analysis)	Living Lab: discussion with stakeholders about past heatwave impacts definition of case study geographical boundaries and grid	data modelling, primary, secondary data, knowledge expert, CIDH	uncertainty analysis & hazard component of the Risk Assessment equation	governance, visualisation of UHI maps in dashboard	Input-output relation: from climatic parameters statistical downscaling
Tier 3	Environmental and Biophysical Systems Models	**biodiversity assessment** Data driven AI/ML model clustering techniques	Living Lab: biodiversity loss is indicated as relevant hazard to heatwaves and biodiversity is indicated as an interlinked subsytem by the LL	data modelling, primary data: biodiversity (fauna & habitats) secondary data (heatwave, air pollution, noise), citizen science, expert knowledge, CIDH	uncertainty analysis & hazard component of the Risk Assessment equation evaluation, adaptation risk control	governance, visualisation of urban habitats for biodiversity maps in dashboard	Input-output relation: from Urban Heat Island; connectivity of protected areas, landscape fragmentation (MSPA); air quality

				citizen science data are used to enhance existing primary biodiversity data sets for calibration/validation of the model			
Tier 3	Environmental and Biophysical Systems Models	**connectivity of protected areas, landscape fragmentation (MSPA)** process-based model (GIS)	Living Lab: fragmentation is indicated as relevant hazard to heatwaves	primary & secondary data (green spaces and protected areas) & expert knowledge, CIDH satellite data	uncertainty analysis & hazard component of the Risk Assessment equation evaluation, adaptation risk control	governance, visualisation of accessibility to green, connectivity, frafmentation maps, dashboards	
Tier 3	Environmental and Biophysical Systems Models	**air quality** hybrid process based and numerical	Living Lab: discussions with stakeholders on the cascading impact on health and well-being of bad air quality and heatwaves validation of air quality parameters selection	primary & secondary data (land cover, climatic, traffic data) & expert knowledge, CIDH	uncertainty analysis & hazard component of the Risk Assessment equation evaluation, adaptation risk control	governance, visualisation of air quality hotspots maps, dashboards	

Tier 3	Environmental and Biophysical Systems Models	**socio-economic vulnerability** Data driven AI/ML model clustering technique	Living Lab definition of vulnerability and drivers	primary & secondary data (social deprivation, age, income, house ownership, house size, house age, profession, nationality, unemployment, population density) & expert knowledge, CIDH	uncertainty analysis and vulnerability & exposure components of the Risk Assessment equation evaluation, adaptation risk control	governance, visualisation of vulnerability & exposure maps, dashboards	
Tier 4	Human and Operational Systems Models	**extreme heat event response*** Agent-based Simulation & DES	interviews of all involved agents	primary data (adaptation plans and response strategies of agents), secondary data (vulnerability and exposure maps as simulated in tier 3) & expert knowledge, CIDH	adaptation/risk control	visualisation, governance, ABM tool	Input-output relation: from Urban Heat Island; biodiversity assessment; connectivity of protected areas, landscape fragmentation (MSPA); air quality; socio-economic vulnerability;

Tier 5	Strategic Response Models	**NBS selection-urban modelling & microclimate WRF*** regional climate model data driven numerical long range planning	Living Lab the tested NBSs come out of co-creation iterations	primary (air temperature, precipitation, humidity, surface temperature, soil moisture, PBL height, etc), secondary data (simulated risk maps in Tier 3), modelling, expert knowledge, collective intelligence data hub	scenarios, sensitivity analysis, urban (green and blue) capacity assessment for risk hotspots, adaptation	governance, visualisation of resilience maps and increased urban capacity, dashboards	Input-output relation: from Urban Heat Island; biodiversity assessment; connectivity of protected areas, landscape fragmentation (MSPA); air quality; socio-economic vulnerability;
Tier 5	Strategic Response Models	**assessment of willingness to pay*** choice experiments via VR	Living Labs & wider audience	data modelling, secondary data, expert knowledge	scenarios, pathways	Virtual Reality, Augmented Reality, decision theatres	Input-output relation: from Urban Heat Island; biodiversity assessment; connectivity of protected areas, landscape fragmentation (MSPA); air quality;

							socio-economic vulnerability; NBS selection-urban modelling & microclimate WRF;
Tier 5	Strategic Response Models	**SDM for risk hotspots maps *** SDM and Long-range planning	Living Lab the structure of the SDM is developed through an iterative process for capturing the LL's mental map.	secondary data, collective intelligence data hub, Knowledge graph	scenarios, sensitivity analysis, risk assessment, evaluation	dashboards, governance, visualisation	
Note: *Future work is identified with a star (*)*							

Table 4.2 The ARSINOE WHEEL information capture for CS#2 Mediterranean Ports

CS Overall Objective	Resilience Assessment of Port Infrastructure and Operations affected by Heatwaves, Wind/Waves and Extreme Weather Events
Extreme Event Type	Heatwaves, Wind/Waves and Extreme Weather Events
Phase	preparedness, response

Resilience Target	Ensure the resilience of the entire port value chain, including nearby municipalities and communities
Why is the target critical?	Important Impacts associated with high costs from operations reduction, traffic in ports, health of users and workers, safety issues
Related Aspects	Transportation, Safety, Education (Upskilling Reskilling) and Energy Efficiency

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	Port Operations and Infrastructure Vulnerability Assessment	Stakeholders Validate the climate variables (Heatwaves, Wind/Wave, Extreme Weather Events) which have the most significant impact on ports assets	Structured Interviews and Surveys on the port	Assess the level of the impact	X	

Tier 3	Environmental and Biophysical Systems Models	Wave Models	X	Copernicus Data: Wave height, Wind speed, and others	Assess the Infrastructural Resilience	X	
Tier 4	Human and Operational Systems Models	Hybrid Reporting Model for Ports	Stakeholders Validate the Material Issues and the list of KPIs to be included in the analysis	Secondary data: KPIs – Indicators at the port Level, including Emissions, Air pollution, Logistics etc.	Monitor Port Performance Against Long Term Targets and SDGs	ESG and SDG Dashboards	Will use output from Tier 1, 2 and 3
Tier 5	Strategic Response Models	Strategic response model for Mediterranean Ports - **System Dynamics**	To be confirmed	To be confirmed	To be confirmed	To be confirmed	SD model is future work
		Choice Experiments	Stakeholders Participate in Survey , Survey using VR equipment	Primary Data, Secondary Data	X	Willingness to Pay for Adaptation actions	
Note: *Future work is identified with a star (*)*							

Table 4.3 The ARSINOE WHEEL information capture for CS#3 Main River Basin

CS Overall Objective	increasing resilience to climate and land/water use change in the water and energy sector
Extreme Event Type	flood, drought, heat, flash flood
Phase	prediction/projection, response, adaptation

Resilience Target	water security, energy security
Why is the target critical?	present day conflicts (already in existence) are expected to exacerbate under climate change and increasing water and energy demand
Related Aspects	City utilities (drinking water supply), agriculture, forestry, hydropower

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	Regional climate model data from Euro-CORDEX and own ClimEx-data; land use projections for the Main river, refined from the ClimEx project	Discussion with stakeholders about past and future expected impacts of extremes; screening of relevant literature	Reference data provided from public meteorological surveys Bias correction Downscaling to hydrological model scale	Scenarios for experimentation, Risk and Resilience assessment (evaluate the changes of extremes dynamics and their impact)	demonstrate the effectiveness of different measures and discuss with stakeholders for possible solutions	Regional Climate Model data drives all projections; delivers climate services for Tier 3 (all models), 4, and 5
Tier 3	Environmental and Biophysical Systems Models	1: WaSiM [, SWAT]	Discussion with stakeholders about past and future	Collect data from public surveys	Scenarios for experimentation,	demonstrate the effectiveness of different measures	Delivers hydroclimatic

			expected impacts of extremes; screening of relevant literature	Use model parameterizations and results from previous model applications Update of model information	Risk and Resilience assessment (evaluate the changes of extremes dynamics and their impact; testing mitigation and adaptation options)	and discuss with stakeholders for possible solutions	services for Tier 4 and Tier 5
		2: CNNs for water temperature and water quality*	Discussion with stakeholders; screening literature	Collect data from public surveys (temperature, oxygen, pH, runoff for selected reference stations); train CNN and attempt to apply with projected hydroclimatic data from Model group 1	Scenarios for experimentation, Risk and Resilience assessment (evaluate the changes of extremes dynamics and their impact; testing input factors for relevance)	demonstrate the effectiveness of different measures and discuss with stakeholders for possible solutions	Delivers hydroclimatic services for Tier 4 and Tier 5
Tier 4	Human and Operational Systems Models	iCLUE Land Use Model [AnyLogic, to be confirmed]	Discussion with Experts on land, energy and water use and demand	Reference land use; current water extraction and use rates	No direct risk/resilience assessment; assessment via feedback and iteration of Tier 3 models	Visualisation, Dashboard*	Delivers feedback to Tier 3
Tier 5	Strategic Response Models	Strategic response model for Main Area* - **System Dynamics**	To be confirmed	To be confirmed	To be confirmed	To be confirmed	Future work

Note: *Future work is identified with a star (*)*

Table 4.4 The ARSINOE WHEEL information capture for CS#4 Ohrid and Prespa lakes

CS Overall Objective	Improving climate resilience of environmental, social and economy sectors, dependant on water availability
Extreme Event Type	Droughts, inducing water scarcity
Phase	Preparedness, response (adaptation)
Resilience Target	Social sector (households), economy sectors (industry, agriculture, tourism) and energy sector (cascade HPPs)
Why is the target critical?	Water is essential for survival and sustainable development of all included sectors
Related Aspects	Environmental ecosystems

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP5–8.5	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE

		Note: In the second stage (M30 – M42),: SSP1-2.6 and SSP3–7.0, as per CMIP6, will be implemented					climate baseline for all CS We have considered RCP8.5 for two reasons: 1) this scenario has ben envisaged by the Government Report on climate changes by 2100 (North Macedonia, March 2020) and 2) this is the most severe scenario in aspect of availability of water and, as such, was found relevant for the water availability assessment
Tier 2	Climate and Socio-Economic Projections	Climate indicators: Based on downscaling approach, the regional climate indicators are produced. These projections offer critical information on the future	1. Discussion with stakeholders about the lakes' status in the recent past, causes and consequences thereof; 2.SIA implementation, resulting in the	Primary data: Observed (measured) data for: 1) the two watersheds hydrology, 2) selected (relevant) climate change indicators (sum of monthly	Water balance calculation by 2100, resulting in projections of lakes' water level on mean monthly basis; enabling assessment of availability of water for included sectors	Development of adaptivity (response) measures to be discussed with stakeholders on their feasibility and effectiveness *	* To be carried out in the second stage

		climate, including extreme events, guiding subsequent models in assessing the vulnerability of water and energy systems. Economic indicators: Based on downscaling approach, the regional economic indicators are produced.	future vision of the sectors and region, along with innovation pathways co-creation	precipitations, mean monthly air temperature); 3) water use per sectors Secondary data : Available studies, reports, plans in the filed, in all the three countries included in the CS4			
Tier 3	Environmental and Biophysical Systems Models	IWAMM – Integrated water management model – includes hydro – climate, socio - economic and water consumption modelling of sectors, based on WEF nexus principles	Discussion with relevant stakeholders, during workshops and LLs, on the subject of biodiversity dependence of water scarcity	Secondary data – environmental management studies and plans, including bio systems affected by water scarcity; stakeholders' observations	Indirect assessed; through evaluation of impacts of water level decrease on environmental systems	Development of adaptivity measures to be discussed with stakeholders on their feasibility and effectiveness *	* In the second stage (M35 – M42)
Tier 4	Human and Operational Systems Models	Watershed Hydrological Model (WH Model)	Discussion with stakeholders, during workshops and LLs;	Primary data: Water amounts used by sectors on monthly and annua	Evaluation of availability of water (water level, as a quantitative status	Creation of measures to reduce fresh water use in sectors;	* In the second stage (M30 – M40)

		Energy Generation Model (EG Model) Projections of consumption of water by economy, energy and social sectors, under selected SSP scenarios; identification of trans sectoral and transboundary trade offs based on users prioritization	Introducing CIW to stakeholders, for co -creation and deployment of innovations	basis; establishing sectoral trade offs Secondary data – water management plans, including bio - systems affected; along with stakeholders'' observations	of sources of water, based on water balance simulations)	reduction of water losses in distribution infrastructure *	
Tier 5	Strategic Response Models	Water Allocation Model (WA Model) Simulation of effects of considered adaptivity (response) measures and their influence on fresh water consumption; optimization of allocation of water per users, based on WEF nexus principles;	Communication with specific target groups: sector operators, experts and policy makers *	To be confirmed	To be confirmed	MCDM techniques; Development of a long tern cross sectoral water management plans, leveraged by policy recommendations *	* in the second stage (M35 – M42)

		cross sectoral integrated water management						
Note: *Future work is identified with a star (*)*								

Table 4.5 The ARSINOE WHEEL information capture for CS#5

CS Overall Objective	Modelling of the island aquifer in La Palma and El Hierro, in order to be able to calculate the natural recharge of the aquifer in an adjusted way. Modelling sea level rise in two selected cities on La Palma and El Hierro.
Extreme Event Type	Groundwater quality and quantity Sea Level Rise
Phase	Improve current decision-making information to policy makers
Resilience Target	Groundwater resilience; Infrastructure Resilience
Why is the target critical?	The availability of groundwater marks the viability of life in the Canary Islands and the increase in dependence on desalination, together with the increase in energy dependence in this case. Due to the rise in sea level, real estate and other infrastructures may be compromised.
Related Aspects	Salinisation of aquifer water due to sea level rise (interaction between the two models)

	Reduced land availability Impact on real estate and the community

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	**Others** (Numerical modelling)	Living Labs	Secondary data: Climate and weather variables	Scenarios for experimentation, Risk and Resilience assessment	**Others** (Discussion with stakeholders)	The outcomes of the process followed in the Living Lab have been foundational in identifying where there might be a gap that could be filled through innovation contracted via WP5. In our case, we will have climate data for the Canary Islands

							at a manageable scale and in accordance with the 6th IPCC Report.
Tier 3	Environmental and Biophysical Systems Models	Groundwater Sea level rise **Data-driven AI/ML Models**	Meeting and interviews with local policy makers	Primary data: sensors; Secondary data: Data from water authorities (series)	Climate scenarios (ICCP)	**Others** (Water management proposals, to improve the decision making regarding the Hydrological Plans)	The two models interact with each other; the output from the sea level rise model will serve as input for the groundwater model, as the objective is to determine whether the rising sea levels in the Canary Islands will cause saline intrusion into the aquifers of La Palma and El Hierro Island. Moreover, the output data from the groundwater model will be provided to the Canary Islands Water Council for use in decision-

							making for the next Hydrological Plan.
Tier 4	Human and Operational Systems Models						
Tier 5	Strategic Response Models	**Long range planning**	Meetings/Interviews	Primary and Secondary data	Tbc	Tbc	The output data from model will be sent to the relevant authorities to be taken into account during decision-making on the islands
Note: *Future work is identified with a star (*)*							

Table 4.6 The ARSINOE WHEEL information capture for CS6-BG Ropotamo

CS Overall Objective	Effect of Climate Change on the Ropotamo Reserve
Extreme Event Type	Floods/droughts
Phase	preparedness
Resilience Target	natural environment resilience, crop resilience, infrastructure resilience
Why is the target critical?	The Ropotamo Reserve and the Ropotamo River are extremely important habitats and protected areas. The importance of the area is the reason for its protection under both national and foreign categorizations - it is a national reserve that has been declared a Ramsar site, an ornithologically important Special Protection Area (SPA), and a site of Community Importance (SCI) under the NATURA 2000 network.
Related Aspects	climate change, collection of monitoring data using innovative approach for the reserve (static sensors and UAS)

Tier #	Tier Name	Model Name - Modelling Methodology	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	Living labs to generate a future narrative, and identify milestones and innovation pathways	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	X	WG discussions on climate related risks for the area	Medcordex project database of climate projections (RCP4.5 and RCP8.5)	X	X	Data to be included in a geodatabase to support future decision-making processes on resilience

Tier 3	Environmental and Biophysical Systems Models						
Tier 4	Human and Operational Systems Models	X	X	X	X	LL to determine the best ways to support the resilience of the area	X
Tier 5	Strategic Response Models	X	X	X	X	X	X
Note: *Future work is identified with a star (*)*							

Table 4.7 The ARSINOE WHEEL information capture for CS6-RO

CS Overall Objective	Analysing the adaptive capacity to climate change of the microbiota from the Danube Delta branches
Extreme Event Type	Fostering of Eutrophication caused by the alternation of large periods of drought and heavy rainfalls
Phase	Awareness building for protecting and restoring water-related ecosystems
Resilience Target	Biofiltration capacity and alternative agriculture on salted soils and marshes
Why is the target critical?	Due to the rapid alteration with significant changes of parameters of the ecosystems functioning, the water quality in the Danube Delta water ecosystems is worsening due to low adaptation capacity of the water microbiota complex.
Related Aspects	Climate change, Fishery/Aquaculture, Water quality, Water Quantity

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections						Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 3	Environmental and Biophysical Systems Models	1. Digital Twin Application using Metaverse technology and SDM for monitoring the impact of climate change processes on biofiltration capacity of the aqueous biota in the Danube branches and related lakes 2. Innovative farming models on salted soils in Danube Delta	Focus groups, Discussions and scientific research activities involving experts, stakeholders and other interested parties	Big data processing and data inputs for System Dynamic Models Interoperability of data with the available models For Innovative Farming: data inputs from ERANet project (HALOSYS)	Input parameters for Digital Twin Application: 1) on-site measurement data - Physical Data Logger demonstration with 6 parameters: salinity, temperature, turbidity, oxygen concentration and oxygen saturation, chlorophyll-a, sound velocity	Output data from Metaverse	(1) The Living Lab serves as a platform for co-creation and co-design of innovative solutions. This activity incorporates outputs from Digital Twin Model and Biofiltration Capacity Model. (2) Strategic planning activity is developed and coordinated by key authorities such as the Danube Delta Reserve Administration,

					2) Data for parameter estimation, validation and verification: - satellite data from existing data lake - historical meteo data records 3) Similar data on hydrographic, composition and microbiology parameters of water in the Danube Delta 4) Data processing and modelling tools and platforms that could relate available data with observable properties, sensitivity analyses and forecasting of the evolution of quality of water		Tulcea County Council, and ITI Delta Dunarii. These plans are guided by insights and results from Digital Twin Model and Biofiltration Capacity Model and Living Lab, ensuring a strategic response to safeguard the Danube Delta microbiota.

					Investigation of the evolution of the soil microbiota during the plant development		
Tier 4	Human and Operational Systems Models						
Tier 5	Strategic Response Models						
Note: *Future work is identified with a star (*)*							

Table 4.8 The ARSINOE WHEEL information capture for CS6-TR

CS Overall Objective	Analysing the factors that create a vulnerable state and distort seawater quality
Extreme Event Type	Mucilage
Phase	Response, recovery
Resilience Target	Marine biogeochemical cycles
Why is the target critical?	The biogeochemical cycles are important to sustain the existing properties of the seawater
Related Aspects	Land-sea interaction, climate change, fisheries

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	NEMO-TURSEM Coupled Model		CMIP5: RCP2.6 and RCP8.5 CORDEX regional climate model	X	X	
Tier 3	Environmental and Biophysical Systems Models	NEMO-TURSEM Coupled Model	Living labs	Input parameters 1) Wind, radiation, temperature, humidity, precipitation, and snowfall data from ERA5, 2) Initial temperature and salinity from WOA 2018, 3) Rivers from PERSEUS Project, Bathymetry from GEBCO	*Simulation scenarios are run and the output parameters are evaluated to understand whether the system limits are reached. The output parameters are Output Parameters 1) Sea surface temperature, sea surface height, salinity, and currents (u-v-w) 2) Phytoplankton, zooplankton, nutrients (nitrate,		*Land input is expected from the other CSs around the Black Sea. If available, the upstream data will be used in our NEMO-TURSEM Coupled Model to facilitate a basin-wide approach.

					nitrite, phosphate, silicate), oxygen, hydrogen sulphide, POM, DOM, dissolved iron, and dissolved manganese		
Tier 4	Human and Operational Systems Models						
Tier 5	Strategic Response Models						
Note: *Future work is identified with a star (*)*							

Table 4.9 The ARSINOE WHEEL information capture for CS6-GR Aliakmonas

CS Overall Objective	Resilience Assessment of infrastructure affected by flood event
Extreme Event Type	Flood
Phase	Prediction, Response, Recovery
Resilience Target	Infrastructure Resilience

Why is the target critical?	Flood events severely impact lives of residents, irrigation and water supply of hundreds of thousands
Related Aspects	Transportation, community, built assets, irrigation, water supply

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3-7.0	X	X	X	Living Labs for knowledge transfer, citizens' and stakeholders' engagement in research and innovation framework	Tier 1 + 2 comprise our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	MED-CORDEX downscaled open data, focused on CS	Discussion with stakeholders about the "Land and Sea" Interactions → Applicable to every sub-CS	SSP1-2.6 and SSP3–7.0 (if available), otherwise CMIP5: RCP2.6 and RCP8.5 CORDEX regional climate model	X	X	Tier 1 + 2 comprise our shared ARSINOE climate baseline for all CS. Climate and Socio-Economic Projections' resulting data will be provided to AUTH by the corresponding partners.
Tier 3	Environmental and Biophysical Systems Models	**DIGITAL TWIN of Aliakmonas sub-basin:** 1. Hydrological/Meteor	Discussion with local stakeholders about historical/recent extreme flood events in the	**Input parameters 1.** Hydrometeorological data: Wind, radiation, temperature,	Scenarios of extreme events in the intake of the studied Aliakmonas sub-basin, the Agia Varvara	Identification of tools and new technologies (e.g. low-cost sensors) to improve monitoring and enhance climate	HEC-HMS output is input for HEC-RAS

		ological model **HEC-HMS** (USACE) 2. Hydraulic Model **HEC-RAS 1D** (USACE) (will only be implemented if the equipment for real-time flow-meter measurements is timely acquired or/and there is access to other parties' real-time data) 3. Optimization tool: **Genetic Algorithms** for automated calibration/parameter estimation of Models 1 & 2.	Aliakmon Riverine environment.	humidity, precipitation data from ERA5, initial temperature **2.** Topography: DEM and geospatial data from Hellenic Cadastre (5m or 2m resolution) **3.** Geology and Soil data: Soil map of Greece (OPEKEPE, 2015) and Hydrolithological map of Greece (RBMP, 2017) **4.** Land uses: CORINE (2018) **5.** Precipitation data: IDF curves and RBMP (2017) **6.** Measured data: a) river surface elevation and flow rates from ELGO-DEMETER (ref?), Public Power Company (www.dei.gr/en/ppc	Restructuring Project (including Earth Dam, Reservoir, Spillway, Water Intake, and Small Hydroelectric Station). Simulations will investigate the flood dynamics in the studied downstream area.	change impact mitigation in the sub-CS area.	

				-group/ppc/), b) gauges (Deep Learning assisted cameras, radar/flow-meters, cheap circuit Arduino-based DIY river surface elevation gauges) installed in the framework of ARSINOE project **7.** Data for parameter estimation, validation and Verification: a) Historical flood records (local authorities, press, social media), b) Satellite images/data (e.g. Copernicus, Sentinel), c) crowd sourcing data (citizen based data, e.g. https://floods-crowdsourcing.diae.			

				uth.gr, Tegos et al., 2022)			
Tier 4	Human and Operational Systems Models						
Tier 5	Strategic Response Models						
Note: *Future work is identified with a star (*)*							

Table 4.11 The ARSINOE WHEEL information capture for CS#7 Esbjerg city and port

CS Overall Objective	Resilience assessment for Esbjerg city and port towards floods and other water-related challenges.
Extreme Event Type	Flooding (rain, sea), compound flooding (rain, sea, groundwater, streams), droughts
Phase	Climate adaptation, Prevention/Preparedness/Response/Recovery
Resilience Target	Community (urban)

Why is the target critical?	The city of Esbjerg is subject to water-related challenges from all sides: from coastal floods and storm surges, extreme rains, rising groundwater levels, riverine floods, and even droughts. Sometimes these hazards even compound. To enhance resilience to current and future climate risks, and abate their consequences for people, infrastructure, the port and other socio-economic activities, and vulnerable natural systems, there is an urgent need for filling key knowledge gaps as well as for extensive local development and investments in climate change adaptation, which needs to go hand-in-hand with improved emergency preparedness.
Related Aspects	Community / civil society, urban development, climate adaptation, emergency preparedness

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections	Earth System Models (ESMs) – CMIP6 **Climate models**	NA NA	NA <u>Secondary data:</u> CMIP5/6 global climate projections	NA Scenarios, sensitivity analysis, risk assessment	NA **Others** (uncertainty assessment; facilitate decision-	These global climate models are implicit input to the CORDEX RCMs and to sea level rise scenarios. Present and future projections of key climate variables e.g. precipitation at ca.

		Regional Climate Models (RCMs) – CMIP5/6- CORDEX **Climate models** IPCC projected sea level rise (CMIP6) **Statistical/geospatial models** Extreme sea level model **Statistical/geospatial models** Precip. Downscaling* (empirical-statistical downscaling approach and/or scaling approach)	Discussion with key stakeholders and experts (DCA, Esbjerg municipality) Elicitation with key stakeholders and experts (DCA) NA	(initially: CMIP5; final: CMIP6) <u>Secondary data:</u> Sea level rise projections (IPCC, DMI) <u>Secondary data:</u> Observed sea levels; reanalysis, e.g. ERA5, DANRA, UERRA; RCM wind fields; output from full hydrodynamic simulations <u>Secondary data:</u> Precipitation from RCMs (daily) – see above; time series from rain gauges, scaling factors, etc.	Scenarios, sensitivity analysis, risk assessment Scenarios, sensitivity analysis, risk assessment NA	making under deep uncertainty) **Others** (uncertainty assessment; facilitate decision-making under deep uncertainty) **Others** (uncertainty assessment; facilitate decision-making under deep uncertainty) NA	11 km horizontal grid resolution Input to flood models (**Tier 3**), extreme sea level model, downscaling Input to extreme sea level model. Explicitly modelled (DTU) and/or authoritative values used (DCA) Input to the coastal and overland flood models (**Tier 3**). Explicitly modelled and/or authoritative values used.

		Downscaling (method tbd.)					
Tier 3	Environmental and Biophysical Systems Models	Coastal flood model – SFINCS (DCA). Alternatively MIKE, SCALGO, … **Process-based model**	Discussion with stakeholders about coastal flood risk	<u>Secondary data:</u> Results from **Tier 2** Digital elevation / landscape model	Scenarios, risk assessment, evaluation	**Others** (uncertainty assessment; facilitate decision-making under deep uncertainty), **Visualization**	Receives input from other **Tier 2** and **Tier 3** models This provides input to DamageCost and vulnerability model
		Overland flood model(*) – TBD (SCALGO, …) **Process-based model**	Elicitation with key stakeholders and experts (Esbjerg municipality, …)	<u>Secondary data:</u> Downscaled precipitation, results from ground-water model, stream-flow model (see below) Digital elevation / landscape model	Scenarios, risk assessment, evaluation	**Others** (uncertainty assessment; facilitate decision-making under deep uncertainty), **Visualization**	To be decided; partially overlaps the coastal flood model
		Groundwater model(*) – HIP?	Expert elicitation (e.g. GEUS, Esbjerg municipality)	<u>Secondary data:</u> HIP (process-based model), potentially direct measurements	Risk assessment	NA	Model data provided externally (or via a data-driven model similar to the streamflow model)

		(externally provided data) **Others** Drought indicators* (calculated by DTU/LMU based on RCM data) **ML/Data-driven model** Streamflow model (DTU/DMI PhD project) **ML/Data-driven model**	Discussion with stakeholders about drought risks Expert elicitation (e.g. GEUS, DMI, Esbjerg municipality) Decision on what streams to model.	NA Secondary data: Observations of discharge from relevant/select streams, reanalysis, e.g. ERA5, DANRA, UERRA; RCM data	Scenarios, sensitivity analysis, risk assessment, evaluation Scenarios, sensitivity analysis, risk assessment, evaluation	**Others** (facilitate decision-making under deep uncertainty) **Others** (uncertainty assessment; facilitate decision-making under deep uncertainty)	Complements the streamflow modelling High and low flows; soil moisture (tbc), / Matthew Newell, DTU
Tier 4	Human and Operational Systems Models	Skadesøkonomi / DamageCost model **Discrete event simulation**	Discussion with stakeholders about their priorities, requirements for the model, data needs, cost	Secondary data: Flood maps (flood depth): rain events, coastal events, flooding from streams, damage	Scenarios, risk assessment, evaluation, adaptation/risk control	**Visualization, Others** (uncertainty assessment; facilitate decision-making under deep uncertainty)	Facilitates multi-risk, multi-sector analyses, adaptation assessments; provides the quantitative

		DCA/FD vulnerability model **Agent-based model**	assessment, dissemination of results Discussion with stakeholders, dissemination of results	costs curves or indicators for multi-sectors (embedded in the model), statistical data on population, income, etc. (Statistics Denmark), municipal adaptation plans e.g. “Havnestrøget” (implemented into flood modelling tools) (**Tier 3**) <u>Secondary data:</u> Flood maps, … (tbc)	Scenarios, risk assessment, evaluation	**Visualization, Others** (facilitate decision-making under deep uncertainty)	foundation for **Tier 5** analyses Provides the foundation for **Tier 5** analyses Tbc.
Tier 5	Strategic Response Models	Climate change adaptation* (analysis – not a model) Long-term planning Urban planning* (analysis – not a model) Long-term planning	Discussions with select stakeholders, co-production (CS7 partners) Discussions with select stakeholders, co-production (CS7 partners)	<u>Secondary data: Results from relevant models (see above)</u> <u>Secondary data: Results from relevant models (see above)</u>	Scenarios, adaptation/risk control Scenarios, adaptation/risk control	**Others (uncertainty assessment; facilitate decision-making under deep uncertainty)** **Others (uncertainty assessment; facilitate decision-making under deep uncertainty)**	We will consider different adaptation, urban planning, and risk management pathways, including a new flood wall, planned green infrastructure (i.e. “Havnestrøget” which will be established ca. 2050-60). They will be framed in current

		Resilience assessment* (analysis – not a model) Long-term planning	Discussions with select stakeholders, co-production (partners)	<u>Secondary data: Results from relevant models, SDG targets/indicators</u>	Scenarios, sensitivity analysis, risk assessment, evaluation	**Others (uncertainty assessment; facilitate decision-making under deep uncertainty)**	and expected future policy objectives in terms of DK2020, SDGs, etc.
Note: *Future work is identified with a star (*) Abbr. DCA = Kystdirektoratet (Danish Coastal Authority), DMI = Danish Meteorological Institute, GEUS = Geological Survey of Denmark and Greenland*							

Table 4.12 The ARSINOE WHEEL information capture for CS#8 Torbay

CS Overall Objective	Resilience Assessment of infrastructure affected by flood event
Extreme Event Type	Flood
Phase	Response, Recovery
Resilience Target	Infrastructure Resilience
Why is the target critical?	Service reduction is the biggest impact during an extreme climate event
Related Aspects	Transportation, community, built assets

In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	
Tier 2	Climate and Socio-Economic Projections	Climate and Socio-Economic Projections	X	X	X	X	
Tier 3	Environmental and Biophysical Systems Models	CAFlood Flood Hazard Analysis Model - **Cellular Automata**	Discussion with stakeholders about past flood impacts.	Secondary data: (1) LiDAR data from the Environmental Agency (EA); (2) Rain gauge observations from Torbay Council, EA and Met Office; (3) Radar data from Met Office; (4) Land cover data from Ordnance Survey; (5) Historical flood records from Torbay Council).	Scenarios for experimentation (simulate the change of flood dynamic of various interventions)	**Others** (demonstrate the effectiveness of different measures and discuss with stakeholders for possible solutions)	

Tier 4	Human and Operational Systems Models	Model 1: Resource Allocation Model for Torbay area for flood emergency response - **Hybrid Simulation using ABS, DES and SD**	Discussion with infrastructure and response experts familiar with historical events in the region that have caused disruption.	Secondary data: (1) Flood model outputs (Tier 3; CAFlood) are used to change parameters of flood depth to critical infrastructure nodes (i.e., reduce the critical services delivered in some areas); (2) Traffic model results (Tier 4 - Model 2; ABS) are used to enter the integrity of "road" critical service for each area.	Scenarios for experimentation, Risk and Resilience Assessment, Others**:** (1) For selected modelled Scenarios: Quantify disruption to critical services. (2) Risk and Resilience assessment: Analyse resource utilisation and the mitigation of critical service capacity decrease towards baseline capacity. (3) Analyse disruption to specific services i.e. emergency responders. (4) Adaptation and Risk control: Based on resilience analysis, determine which critical services need priority and greater protection and what soft measures such as resource allocation of staff or equipment could be employed to minimise disruption.	Visualisation, Dashboard*	Model 1 use output from the **Tier 3** flood model and T**ier 4 Model 2***
		Model 2: Traffic flow Modelling - **Micro-scale ABS model**	Discussion with experts familiar with historical events in the	Secondary data: (1) Road network data from OpenStreetMap;	Scenarios for experimentation, Risk and Resilience Assessment, Others:	Visualisation, Dashboard*	Model 2 will use output from **Tier 3** flood model*

		Micro-Scale Traffic modelling using open-source modelling software SUMO software to analyse potential disruption to traffic flows from flood scenarios.	region that have caused disruption.	(2) Traffic count data for the region from local authority used to define daily "dry weather" baseline flows; (3) Flood model outputs (Tier 3; CAFlood) used to change parameters of the road network (i.e. reduce speeds or close sections) within the traffic simulation).	(1) For selected modelled Scenarios: Quantify disruption to traffic flows in terms of accumulated delays in journeys; (2) Risk and Resilience assessment: Analyse time of recovery for the network to return towards baseline behaviour; (3) Analyse disruption to specific vehicles and routes i.e. emergency responders; (4) Adaptation and Risk control: Based on resilience analysis, determine which roads need greater protection from flooding and what soft measures such as traffic re-routing could be employed to minimise disruption.		
		<u>Model 3</u>: Cascading Failure Engine developed in Julia Programming Language - **Others (Artificial Neural Networks)**	Discussion with experts familiar with historical events in the region that have caused disruption.	Secondary data: (1) Council and ordnance survey data containing GIS positions of critical services nodes; (2) Ordnance Survey data showing statistics	Scenarios for experimentation, Risk and Resilience Assessment, Others: (1) For selected modelled Scenarios: Quantify disruption to critical services;	Visualisation, Dashboard*	Model 3 will use output from **Tier 3** flood model* and **Tier 4 Model 2***

				on residents (i.e. commuting distance, industry of employment…); (3) Traffic model results (Tier 4 - Model 2; ABS) results used to enter the integrity of "road" critical service for each area; (4) Flood model outputs (Tier 3; CAFlood) are used to change parameters of damage to critical infrastructure nodes (i.e., reduce the critical services delivered in some areas).	(2) Risk and Resilience assessment: Analyse time of recovery for network to return towards baseline behaviour; (3) Analyse disruption to specific services i.e. emergency responders; (4) Adaptation and Risk control: Based on resilience analysis, determine which critical services need greater protection and what soft measures such as resource allocation of staff or equipment could be employed to minimise disruption.		
		CORFU Flood Impact Assessment Tool to evaluate the direct and indirect damage caused by flood - **Others (Numerical Model)**	Discussion with stakeholders about past flood impacts.	Secondary data: (1) Building use and critical infrastructure from National Receptor Dataset from Defra/Environmental Agency. Others: (1) Multi-coloured Handbook from Middlesex University.	Scenarios for experimentation, Risk and Resilience assessment (evaluate the changes of flood impact with different resilience measures)	**Others** (demonstrate the effectiveness of different measures and discuss with stakeholders for possible solutions)	CORFU Flood Impact Assessment Tool to evaluate the direct and indirect damage caused by flood - **Others (Numerical Model)**

Tier 5	Strategic Response Models	Strategic response model for Devon Area* - **System Dynamics**	To be confirmed	To be confirmed	To be confirmed	To be confirmed	SD model is future work
Note: *Future work is identified with a star (*)* ***Note:*** *Model outputs that are used as inputs for other models are indicated as secondary data.*							

Table 4.13 The ARSINOE WHEEL information capture for CS#9 Sardinia

CS Overall Objective	Assessment (through field experiments and crop modelling) of alternative durum wheat crop managements as adaptation strategies to cope with climate change
Extreme Event Type	Drought, extreme temperatures
Phase	Response
Resilience Target	Crop resilience
Why is the target critical?	Wheat production is of strategic importance for Sardinia and Mediterranean areas for food security and socio-cultural identity (e.g. local traditional bread, pasta and cous cous).
Related Aspects	Local food supply chain
In the table below, please list the models being developed and the ARSINOE Tiers that they represent (columns 1-2). Add information pertaining to the modelling methodology and the name of the model (column 3), and information related to the four tiers (columns 4-7). Include comments (including "future work") in the last column (column 8).	

Tier #	Tier Name	Model Name - **Modelling Methodology**	Pillar 1 SIA Methods	Pillar 2 Data and Logic	Pillar 3 Resilience Assessment	Pillar 4 Decision Making	Comments
Tier 1	Future Society and Socio-Economic Scenarios	SSP1-2.6 and SSP3–7.0	X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 2	Climate and Socio-Economic Projections		X	X	X	X	Tier 1 + 2 comprises our shared ARSINOE climate baseline for all CS
Tier 3	Environmental and Biophysical Systems Models	Crop modelling (e.g. Aquacrop, DSSAT)		Primary data: soil, weather, crop, from field observations Secondary data: literature data Expert knowledge	Climate change scenarios* Sensitivity analysis* Changes in crop management to simulate crop adaptation response *		
Tier 4	Human and Operational Systems Models	Crop modelling (e.g. Aquacrop, DSSAT)		Primary data: soil, weather, crop, from field observations	Climate change scenarios* Sensitivity analysis*	**Others** (demonstrate the effectiveness of different measures	

				Secondary data: literature data Expert knowledge	Changes in crop management to simulate crop adaptation response *	and discuss with stakeholders for possible solutions)	
Tier 5	Strategic Response Models	System Dynamics *	To be confirmed	To be confirmed	To be confirmed	To be confirmed	SD model is future work
Note: *Future work is identified with a star (*)*							

References

Adger, W. N. (2000). Social and ecological resilience: are they related? *Progress in Human Geography*, *24*(3), 347–364. https://doi.org/10.1191/030913200701540465

Aghakouchak, A., Chiang, F., Huning, L. S., Love, C. A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S. M., Ragno, E., & Sadegh, M. (2020). Climate Extremes and Compound Hazards in a Warming World. *Annual Review of Earth and Planetary Sciences*, *48*, 519–548. https://doi.org/10.1146/ANNUREV-EARTH-071719-055228

Arctic Council. (2016). *Arctic Resilience Report* (M. Carson & G. Peterson, Eds.). Stockholm Environment Institute and Stockholm Resilience Centre. http://www.arctic-council.org/arr.

Australian Government. (2018). *Security of Critical Infrastructure Act 2018* .

Brailsford, S. C., Eldabi, T., Kunc, M., Mustafee, N., & Osorio, A. F. (2019). Hybrid simulation modelling in operational research: A state-of-the-art review. *European Journal of Operational Research*, *278*(3), 721–737. https://doi.org/10.1016/j.ejor.2018.10.025

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

Climate.gov. (2023). *Climate Models | NOAA Climate.gov*. https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-models

Dillard, M. (2021). *Inventory of Community Resilience Indicators & Assessment Frameworks*. https://doi.org/https://doi.org/10.18434/mds2-2297

Djordjević, S., Butler, D., Gourbesville, P., Mark, O. and Pasche, E. (2011). New policies to deal with climate change and other drivers impacting on resilience to flooding in urban areas: the CORFU approach, *Environmental Science & Policy,* 14(7), 864-873. https://doi.org/10.1016/j.envsci.2011.05.008

Doorn, N. (2015). Resilience indicators: opportunities for including distributive justice concerns in disaster management. *Journal of Risk Research*, *20*(6), 711–731. https://doi.org/10.1080/13669877.2015.1100662

European Commission. (2005). *Green Paper: On a European Programme for Critical Infrastructure Protection*.

Fekete, A. (2019). Critical infrastructure and flood resilience: Cascading effects beyond water. *Wiley Interdisciplinary Reviews: Water*, *6*(5). https://doi.org/10.1002/WAT2.1370

Fisher, R. A., & Koven, C. D. (2020). Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems. *Journal of Advances in Modelling Earth Systems*, *12*(4). https://doi.org/10.1029/2018MS001453

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. https://doi.org/10.1016/J.GLOENVCHA.2006.04.002

Fünfgeld, H. (2010). Institutional challenges to climate risk management in cities. *Current Opinion in Environmental Sustainability*, *2*(3), 156–160. https://doi.org/10.1016/J.COSUST.2010.07.001

Gibson, M. J., Chen, A. S., Khoury, M., Vamvakeridou-Lyroudia, L. S., Stewart, D., Wood, M., Savić, D. A., & Djordjević, S. (2020). Case study of the cascading effects on critical infrastructure in Torbay coastal/pluvial flooding with climate change and 3D visualisation. *Journal of Hydroinformatics*, *22*(1), 77–92. https://doi.org/10.2166/HYDRO.2019.032

Government of Canada. (2009). *National Strategy for Critical Infrastructure*.

Government of Canada. (2022). *Government of Canada Adaptation Action Plan*.

Haimes, Y. Y. (2009). On the Definition of Resilience in Systems. *Risk Analysis*, *29*(4), 498–501. https://doi.org/10.1111/J.1539-6924.2009.01216.X

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/ANNUREV.ES.04.110173.000245

Holling, C. S. (1996). Engineering Resilience versus Ecological Resilience. In P. Schulze (Ed.), *Engineering Within Ecological Constraints* (pp. 31–44). National Academies Press. https://doi.org/10.17226/4919

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety*, *145*, 47–61. https://doi.org/10.1016/J.RESS.2015.08.006

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Cambridge University Press* (Issue In Press). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds.). Cambridge University Press.

Khoury, M., Bullock, S., Fu, G., & Dawson, R. (2015). Improving measures of topological robustness in networks of networks and suggestion of a novel way to counter both failure propagation and isolation. *Infrastructure Complexity 2015 2:1*, *2*(1), 1–20. https://doi.org/10.1186/S40551-015-0004-9

Koliou, M., van de Lindt, J. W., McAllister, T. P., Ellingwood, B. R., Dillard, M., & Cutler, H. (2018). State of the research in community resilience: progress and challenges. *Sustainable and Resilient Infrastructure*, *5*(3), 131–151. https://doi.org/10.1080/23789689.2017.1418547

Kong, J., & Simonovic, S. P. (2018). A model of interdependent infrastructure system resilience. *International Journal of Safety and Security Engineering*, *8*(3), 377–389. https://doi.org/10.2495/SAFE-V8-N3-377-389

Kron, W. (2002). Flood risk = hazard x exposure x vulnerabilty. In B. Wu (Ed.), *Second International Symposium on Flood Defence* (pp. 82–97). International Association for Hydraulic Research, International Research and Training Center on Erosion and Sedimentation.

Linstone, H. A., & Turoff, M. (Eds.). (1975). The delphi method (pp. 3-12). Reading, MA: Addison-Wesley.

Little, R. G. (2010). Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures. *Journal of Urban Technology*, *9*(1), 109–123. https://doi.org/10.1080/106307302317379855

Mishra, A. K., & Singh, V. P. (2011). Drought modelling – A review. *Journal of Hydrology*, *403*(1–2), 157–175. https://doi.org/10.1016/j.jhydrol.2011.03.049

Nan, C., & Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering & System Safety*, *157*, 35–53. https://doi.org/10.1016/J.RESS.2016.08.013

Olsson, L., Jerneck, A., Thoren, H., Persson, J., & O'Byrne, D. (2015). Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Science Advances*, *1*(4), e1400217. https://doi.org/10.1126/SCIADV.1400217

O'rourke, T. D. (2007). Critical Infrastructure , Interdependencies , and Resilience. *The Bridge - National Academy of Engineering*, *37*(1), 22–29.

Ouyang, M. (2014). Review on modelling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety*, *121*, 43–60. https://doi.org/10.1016/J.RESS.2013.06.040

Ouyang, M., & Dueñas-Osorio, L. (2012). Time-dependent resilience assessment and improvement of urban infrastructure systems. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *22*(3), 033122. https://doi.org/10.1063/1.4737204

Pederson, P., Dudenhoeffer, D., Hartley, S., & Permann, M. (2006). *Critical Infrastructure Interdependency Modelling: A Survey of U.S. and International Research*.

Pescaroli, G., & Alexander, D. E. (2015). A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. *Planet@Risk* , *3*(1), 58–67.

Pimm, S. L. (1984). The complexity and stability of ecosystems. *Nature*, *307*(5949), 321–326. https://doi.org/10.1038/307321a0

Poland, C. (2009). *Defining Resilience: What San Francisco needs from its seismic mitigation policies*.

Rifkin, J. (2022). *The age of resilience: Reimagining existence on a rewilding planet*. St. Martin's Press.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, *21*(6), 11–25. https://doi.org/10.1109/37.969131

Rogers, C. D. F., Bouch, C. J., Williams, S., Barber, A. R. G., Baker, C. J., Bryson, J. R., Chapman, D. N., Chapman, L., Coaffee, J., Jefferson, I., & Quinn, A. D. (2012). Resistance and resilience – paradigms for critical local infrastructure. *Proceeding of the Institution of Civil Engineers - Municipal Engineer*, *165*(2), 73–84. https://doi.org/10.1680/MUEN.11.00030

Sun, W., Bocchini, P., & Davison, B. D. (2021a). Policy-based disaster recovery planning model for interdependent infrastructure systems under uncertainty. *Structure and Infrastructure Engineering*, *17*(4), 555–578. https://doi.org/10.1080/15732479.2020.1843504

Sun, W., Bocchini, P., & Davison, B. D. (2021b). Overview of Interdependency Models of Critical Infrastructure for Resilience Assessment. *Natural Hazards Review*, *23*(1), 04021058. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000535

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., & Hall, J. W. (2019). Infrastructure for sustainable development. *Nature Sustainability 2019 2:4*, *2*(4), 324–331. https://doi.org/10.1038/s41893-019-0256-8

The Economist Intelligence Unit Ltd. (2019). *The critical role of infrastructure for the Sustainable Development Goals*. https://content.unops.org/publications/The-critical-role-of-infrastructure-for-the-SDGs_EN.pdf

Tolk, A., Harper, A., & Mustafee, N. (2021). Hybrid models as transdisciplinary research enablers. *European Journal of Operational Research*, *291*(3), 1075–1090. https://doi.org/10.1016/j.ejor.2020.10.010

UK Cabinet Office. (2022). *The UK Government Resilience Framework*. https://www.gov.uk//government/publications/the-uk-government-resilience-framework

United Nations General Assembly. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. https://digitallibrary.un.org/record/852089

United Nations Office for Disaster Risk Reduction (UNDRR). (n.d.). *Sendai Framework for Disaster Risk Reduction 2015 - 2030*. Retrieved November 29, 2021, from https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

U.S. Department of Homeland Security. (2013). *National Infrastructure Protection Plan 2013 : Partnering for Critical Infrastructure Security and Resilience* .

Vamvakeridou-Lyroudia, L. S., Chen, A. S., Khoury, M., Gibson, M. J., Kostaridis, A., Stewart, D., Wood, M., Djordjevic, S., & Savic, D. A. (2020). Assessing and visualising hazard impacts to enhance the resilience of Critical Infrastructures to urban flooding. *Science of The Total Environment*, *707*, 136078. https://doi.org/10.1016/J.SCITOTENV.2019.136078

Velasco, M., Russo, B., Monjo, R., Paradinas, C., Djordjević, S., Evans, B., Martínez-Gomariz, E., Guerrero-Hidalga, M., Cardoso, M.A., Brito, R.S. and Pacheco, D. (2020). Increased urban resilience to climate change – key outputs from the RESCCUE project, *Sustainability,* 12(23), 9881. https://doi.org/10.3390/su12239881

Vugrin, E. D., Warren, D. E., Ehlen, M. A., & Camphouse, R. C. (2010). A framework for assessing the resilience of infrastructure and economic systems. In K. Gopalakrishnan & S. Peeta (Eds.), *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modelling, and Intelligent Engineering* (pp. 77–116). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-11405-2_3/COVER

Walsh, B. (2018, January 8). Adapt or Die: Why the Environmental Buzzword of 2013 Will Be Resilience. *Time : Science & Space*. https://science.time.com/2013/01/08/adapt-or-die-why-the-environmental-buzzword-of-2013-will-be-resilience/#ixzz2JeE6rFwE

Woods, D. D. (2012). Essential characteristics of resilience. In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience Engineering: Concepts and Precepts* (pp. 21–34). Ashgate Publishing Ltd. https://doi.org/10.1201/9781315605685-4/ESSENTIAL-CHARACTERISTICS-RESILIENCE-DAVID-WOODS

Yao, B. H., Xie, L. L., & Huo, E. J. (2004). A comprehensive study method for lifeline system interaction under seismic conditions. *Acta Seismologica Sinica*, *17*(2), 211–221. https://doi.org/10.1007/BF02896935

Systems Innovation Approach (SIA) addresses the growing complexity, interdependencies and interconnectedness of modern societies and economies, focusing on the functions of the cross-sectoral system as a whole and on the variety of actors. The Climate Innovation Window (CIW) is the EU reference innovations marketplace for climate adaptation technologies. ARSINOE shapes the pathways to resilience by bringing together SIA and CIW, to build an ecosystem for climate change adaptation solutions. Within the ARSINOE ecosystem, pathways to solutions are co-created and co-designed by stakeholders, who can then select either existing CIW technologies, or technologies by new providers (or a combination) to form an innovation package. This package may be designed for implementation to a specific region, but its building blocks are transferable and re-usable; they can be re-adapted and updated. In this way, the user (region) gets an innovation package consisting of validated technologies (expanding the market for CIW); new technologies implemented in the specific local innovation package get the opportunity to be validated and become CIW members, while the society (citizens, stakeholders) benefits as a whole. ARSINOE applies a three-tier, approach: (a) using SIA it integrates multi-faceted technological, digital, business, governance and environmental aspects with social innovation for the development of adaptation pathways to climate change for specific regions; (b) it links with CIW to form innovation packages by matching innovators with end-users/regions; (c) it fosters the ecosystem sustainability and growth with cross-fertilization and replication across regions and scales, at European level and beyond, using specific business models, exploitation and outreach actions. The ARSINOE approach is show-cased in nine widely varied demonstrators, as a proof-of-concept with regards to its applicability, replicability, potential and efficacy.

ARSINOE

CLIMATE-RESILIENT REGIONS THROUGH SYSTEMIC SOLUTIONS AND INNOVATIONS

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101037424.