HUMAN CENTRED CLIMATE SERVICES

Deliverable D4.1

Preliminary report on causal mechanisms between climate change, climate service information, and socio-economic behaviour

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Innovating Climate services through Integrating Scientific and local Knowledge

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Author(s):	Riccardo Biella, Lotte Muller, Maurizio Mazzoleni, Giuliano Di Baldassarre
Contributing Authors(s):	
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Executive Summary

More than 100 million people per year are affected by climate-related extremes, such as floods and droughts. The frequency and the impact of these extreme events are expected to increase in many regions of the world due to global warming and socio-economic changes. Climate services (CS) have been used over last decades to support decision making processes and reduce risk associated with climate-related extremes. However, the role of CS information in shaping decisions planning about adaptation options, such as climate-resilience pathways achieving a zero-emission pathway by 2050, remains largely unexplored. In this preliminary report (D4.1), we describe different methods used in this project for unpacking the causal mechanisms between climate change, CS data, socio-economic behaviours, which are expected to pave the way for the upcoming analyses of human-climate interactions (T4.2, T4.3, and T4.4).

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1 Introduction

Over the last 50 years, climate-related hazards such as droughts, floods, and wildfires (Centre for research on the epidemiology of disasters (CRED), 2019), have caused about USD 1.5 trillion in economic losses and more than 1 million death worldwide, with their severity expected to increase in many regions of the world because of climatic and socio-economic changes (Hoegh-Guldberg et al., 2018; Swain et al., 2018). Just recently, Europe experienced one of the worst droughts of the last 500 years during the 2022 summer (Toreti et al., 2022), with 47% and 17% of the territory in warning and alert conditions, respectively (see Figure 1). Over the last 75 years, increasing trends of deficits in precipitation, soil moisture, and runoff have been observed in Europe, leading to economic losses of more than 50 billion EUR (Naumann et al., 2021). On the other hand, flood events occurred in Pakistan during August 2022 leading to devastating consequences and more than 1000 fatalities. Recent climate projections show that in the future we will experience more of such extreme events, with Europe affected by increasing drier and warmer springs and summers due to global anthropogenic warming. This will expose farmers, households, and ecosystems to severe water shortages, food and economic losses, and environmental degradation (Bastos et al., 2020; Mohammed et al., 2022; Quinton et al., 2022; Webber et al., 2018).

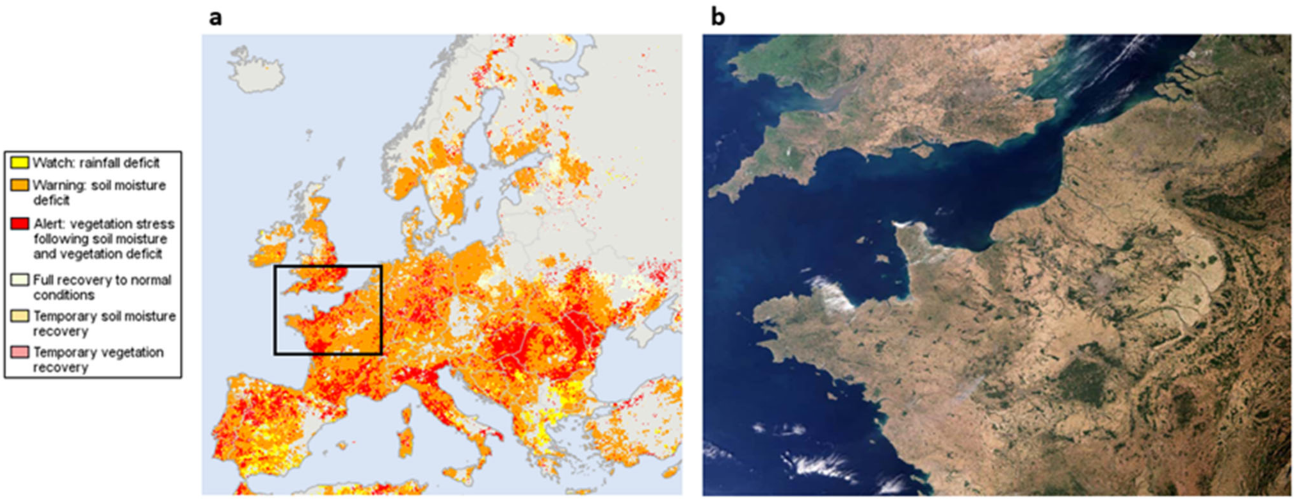

Figure 1. (a) Drought conditions in the August 2022 expressed as combined drought indicator (Toreti et al., 2022). (b) Satellite image from 9 August showing the effect of drought in northern France and southern England (European Union, Copernicus Sentinel-3).

Improving risk management and adaptation strategies will allow stakeholders and end-users to adapt and reduce droughts and floods impacts in the future. Over the years, numerous monitoring and prediction systems have been developed by exploiting observations from in-situ networks and remote sensing within advanced statistical approaches (e.g. multivariate analysis) and numerical models (Hao et al., 2017). For example, short- and long-term weather forecasts have been used as input for land surface and hydrological models to provide both soil moisture and streamflow prediction and continuous monitoring of crucial hydrologic variables for drought and flood characterization (Lidard et al 2021).

Climate Services (CS) have been successfully implemented and used for mitigation and adaptation in view of the consequences of climate change. The concept of CS includes, but is not limited to, climate sciences and weather services provide individually tailored information for risk management by decision-makers. The European Research and Innovation Roadmap for Climate Services describes CS (European Commissions, 2015) as: "*the transformation of climate-related data — together with other relevant information into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other* *service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster risk management*".

A number of CS have been developed over the last years for better representing the atmospheric, oceanic, cryosphere, and land surface phenomena and their interactions over different time horizons (from days to decades) and spatial scales (from local to global) and over regions, from highly localized to the entire planet. Examples of CS includes past climate data, historic reanalysis data, forecasts and predictions, among others. CS are essential in building climate resilience and for climate risk management as a basis for adequate decision-making (Brasseur and Gallardo, 2016). The argument for the benefit of CS is that knowledge about the consequences of climate change is needed for risk management to avoid arbitrary decisions and inadequate preparedness for climate disasters (Lemos et al., 2012). Moreover, it has been demonstrated that CS such as early warning system used for flood forecasting can lead to potential monetary benefits in reducing flood (Pappenberger et al., 2015).

Despite these benefits of CS, it is still not clear how effectively CS can aid decision-making for risk adaptation and mitigation purposes, which format CS need to have to do so, and how the information provided by CS influence user behaviour and consequent adaptation actions to extreme events. While the physical and social links between climate change and adaptation actions have been widely analysed, the feedbacks generated by the availability of climatic information and adaptation actions are seldom considered. For example, a CS can provide information on the future water availability for a certain region and end-users could decide to adopt tailored adaptation strategies based on that information. On the other hand, the same end-user could decide upon different actions if limited climatic/hydrological information is available. Those adaptation actions may in turn affect other end-users and shape their future actions and goals.

This deliverable focuses on identifying the dynamics explaining the emergence of different feedbacks between climate change, CS data, socio-economic behaviour, and adaptation measures aimed at building a resilient pathway in the I-CISK living labs. This will be achieved by first exploring the interplays between CSs, human behaviour, and decision-making (section 2). We will then focus on the methods used to represent CS-human interplays (section 3) and their links with the different living labs of the I-CISK project (section 4). Finally, we will summarize the results obtained and provide an outlook of future research activities.

2 Interplays between climate services, human behaviour, and decision-making

Additional to the numerous benefits provided by CS to users, the dynamics between CS, human behaviour and decision-making represents an important aspect for the design of resilient adaptation actions. There are several channels through which human behaviour can cause/contribute to feedbacks. For example, Wens et al. (2019) describe a framework to extend traditional risk modelling to include two-way feedbacks between adaptation and drought exposure, vulnerability and hazard. Figure 2 shows an adaptation of the framework developed by Wens et al. (2019) to include climate services. To make the figure explicitly relevant, we have included climate services explicitly as input to adaptive action (blue box with CS). Figure 2A shows the influence of adaptation on drought risk, yet does not include feedback mechanisms. While Figure 2B-D highlight channels through which human behaviour can cause/contribute to feedbacks. Namely, Figure 2B shows a bi-directional influence between adaptation and risk, Figure 2 shows the influence of adaptation on risk across spatiotemporal scales and lastly Figure 2D the influence of risk on individual decision-making behaviour. For further details, see work by Wens et al. (2019). To understand potential feedback channels shown in Figure 2B-D (red arrows), first Figure 2A must be clearly understood. Understanding behavioural responses to climate services is essential to consequently understanding possible feedback mechanisms.

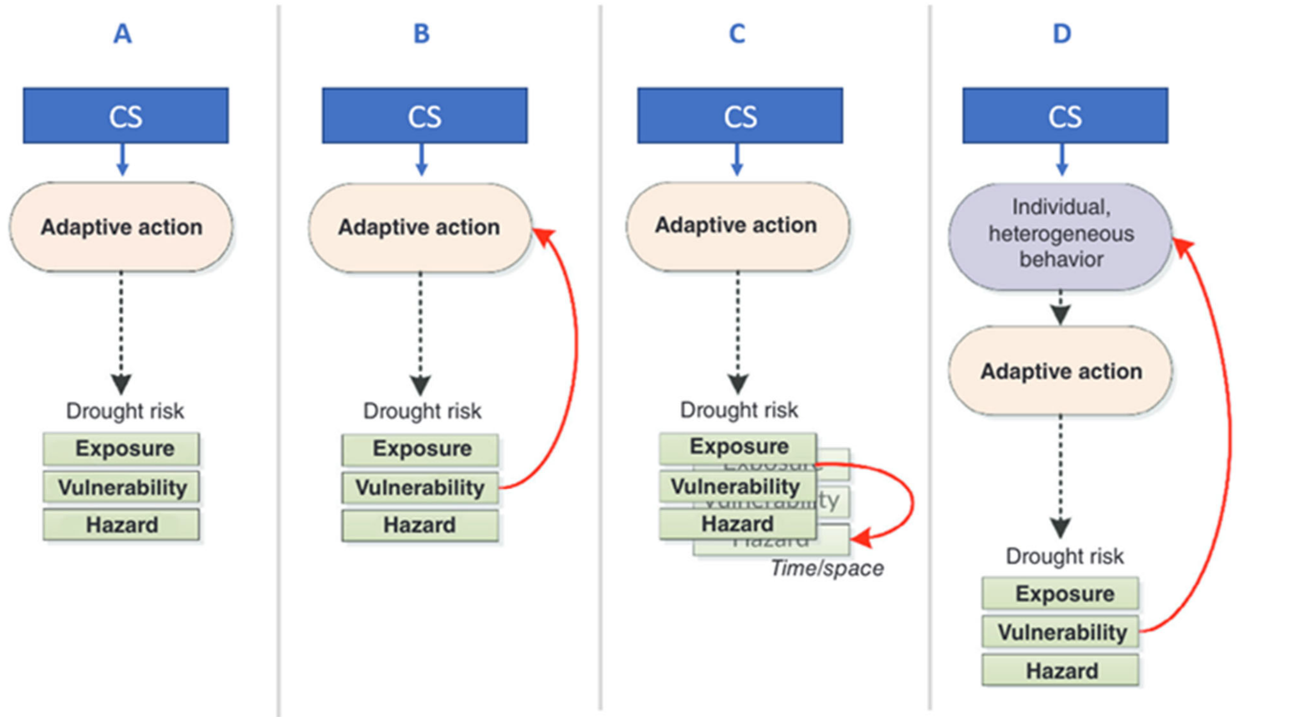

Figure 2: Plausible feedbacks between climate services (CS), adaptation and drought risk. This figure has been adapted from Wens et al. (2019) to include climate services.

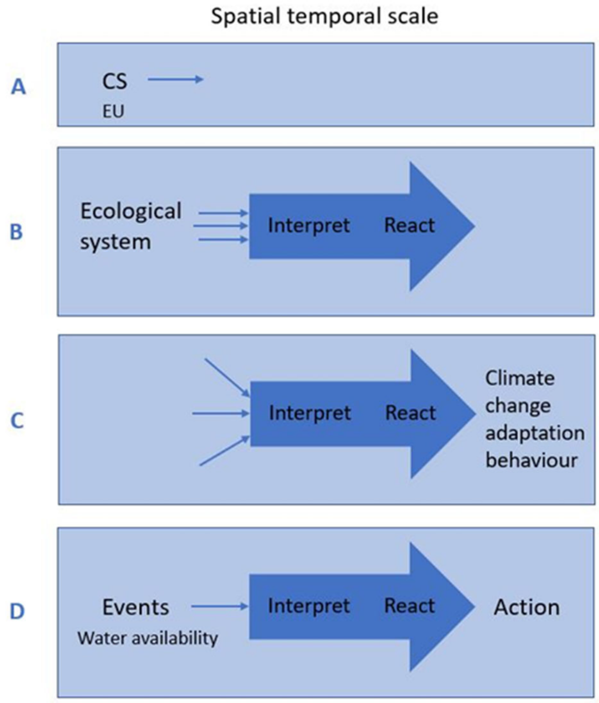

Figure 3: Stylised summary of existing literature. Box A refers to the work by Cortekar et al. (2020), Box B of Schlüter et al. (2017), Box C of van Valkengoed and Steg (2019), Box D of Meijer et al. (2021).

However, to date no review exists of how users of climate services respond to climate services. Existing literature is scattered, and unconnected; this is illustrated by the preliminary findings shown in Figure 3. The arrow represents the translation of input information/events to actions (similar to Figure 2D where climate services affect individual heterogeneous behaviour, which in turn affects adaptive action). For instance, Cortekar et al. (2020) claimed that 'to develop a market for climate services, information on the current landscape of climate service providers and their portfolios is needed' and hence conducted a systematic analysis of EU based climate service providers. This analysis is not connected to whether these climate services were demanded by users or caused a behavioural response in users, see Figure 3A. Schlüter et al. (2017) have created a framework for mapping and comparing behavioural theories in models of social-ecological systems. This framework considers social-ecological system prompts (e.g. potentially climate services) and how people process information, however, it does not connect to resulting behavioural actions, see Figure 3B . Schlüter et al. (2017) also is not tailored to climate services and adaptation/mitigation behaviour. Van Valkengoed and Steg (2019) report a meta-analysis of factors motivating climate change adaptation behaviour. They do not connect this to climate services and how people respond to this, see Figure 3C. Lastly, Figure 3D represents work by Meijer et al. (2021), where they conduct a literature review to assess what methods, theories or concepts authors have used to quantify human responses to changes in water availability. This is not tailored to climate services/information provision, but to an event, and with a focus on how behaviour is quantified, which does not always align with actual behavioural responses. There is currently limited literature that directly addresses the behavioural responses to climate services, and additionally literature may be difficult to find given that the term climate services may not be used. These preliminary findings would benefit from being connected through, for instance, a systematic literature review.

Despite this, there are a multitude of general behavioural theories from psychology and economics, which could be include in the modelling of feedback mechanisms. These theories differ widely in how they assume individuals perceive risk, consequently, make decisions based on risks and the complexity thereof. An example of a rational behavioural theory is *expected utility theory*, where an agent chooses between risky options by comparing expected utility values. Boundedly rational theories include relaxing assumptions from rational behavioural theories, for instance, by allowing the likelihoods used to calculate expected utility to be subjective (*subjective expected utility theory*). Yet this type of behavioural theory remains very restrictive; In many cases people have, for example, cognitive biases as shown by *prospect theory* (Tversky and Kahneman, 1992). Prospect theory incorporates that people value losses differently to gains.

Alternative theories focusing on how individuals behave under stressful situations have originated from psychology and other social sciences. For example, the *Theory of Planned Behaviour*, where behavioural decisions are influenced by the agent's attitude, subjective social norms and perceived control over the situation (Ajzen, 2011). Another frequently cited theory is *Protection Motivation Theory* (Rogers, 1975). In this theory, agents' intentions to adapt depend on threats and coping appraisals.

Behavioural theories also vary in scope, for example, the *Consumat approach* incorporates various aspects of boundedly rational theories, while influenced by social network (Jager et al., 2000). Schlüter et al. (2017) developed a framework for mapping and comparing behavioural theories in models of social-ecological systems. This not only demonstrates the varying focus and scope of behavioural theories, but that these theories can be combined.

Despite the variety in focus, scope and combinations of behavioural theories, behaviour is often not included in water risk models. According to Palmer and Smith (2014), omitting human behaviour from Earth system models is the equivalent to 'designing a bridge without accounting for traffic'. Human activity and behavioural responses are having profound influence on the global environment, in particular, human interactions with the water cycle (Blair and Buytaert, 2016; IPCC, 2021). Hence, modelling without understanding and accounting for human behavioural responses could lead to poor prediction, and consequent mismanagement of water systems (Srinivasan et al., 2012; Van Loon et al., 2016). For instance, considering the different responses linked to the social collective trust in early warning system can lead to different adaptation actions and consequent impacts of extreme events (Sawada et al. 2022). Additionally, poorly informed water and climate-related policies can lead to counter intuitive consequences that result from unexpected behavioural responses (Di Baldassarre et al., 2019). The field of socio-hydrology aims to estimate water risk more realistically by modelling social systems together with physical systems. However, if human behaviour is included in the socio-hydrologic approach, it is remains unrealistic; human behaviour is represented by rational behaviour (e.g. expected utility theory) performed by a representative agent, ignoring heterogeneity in behaviour (Di Baldassarre et al., 2015; Wens et al., 2019; Schrieks et al., 2021; Meijer et al. 2021).

I-CISK could make use of the richness of existing behavioural theories to better represent feedback mechanisms than is currently the case. However, how these theories are integrated also depends on modelling methods. Meijer et al. (2021) find that although there are differences in representation of behaviour in human-water models depending on modelling methods used, but that in general only a limited number of studies base their inclusion of human behaviour on existing behavioural theories. According to Wens et al. 2019, feedback mechanisms such as in Figure 2D are better suited to agent-based modelling as these support heterogeneous individuals, in contrast to System dynamics. This will be discussed in greater detail in the following section.

3 Methods used to represent CS-human interplays

3.1 Modelling complex systems

Modelling the interactions between society and the environment is a difficult task, riddled with uncertainties, complexity, and unexpected dynamics. Even what one might at first glance consider a simple system can often be almost impossible to understand, let alone act upon without giving rise to unintended consequences. In a brilliant display of lateral thinking, Newell and Wasson (2002) argue how designing policies for the flood management of a small Australian town could be considered a harder task than planning the trajectory of the Voyager 2 Grand Tour of the solar system. Their argument does not try to discredit rocket science, rather to highlight the complexities and uncertainties involved in the science of human-environment interactions, and how arduous it can be to act on a Socio-Environmental System (SES) (Newell and Wasson, 2002).

The SES is a term developed in the sustainable development field around the need to manage complex interactions and operationalize the concept of sustainability (Musters et al., 1998). SESs are open systems, characterized by multiple relations with other systems, as well being embedded in complex hierarchies of systems (Musters et al., 1998). Complexity is a feature of the SES that arises from its internal processes and relations between its elements. Combinatorial complexity depends on the sheer number of elements in the system and the number of links between these elements (Sterman, 2001). Yet, a system can be complex despite having only a few elements when the system is dominated by elements that are tightly coupled, non-linearly dependent, self-organizing, adaptive, and governed by feedbacks, this is called dynamic complexity (Sterman, 2001). Consequently, these systems can often behave in counter-intuitive ways, and it is therefore important to be able to understand their properties if we want to effectively act on them.

Over the years many approaches have been developed in order to model the complexity of the SES. Some of these approaches inductively try to generate a conceptual model starting from the observations of the state of the system, such as in the case of participatory system dynamic modelling. Others, like system archetypes, try to deductively infer specific system behaviours onto specific system models (Elsawah et al., 2017). In recent years, new approaches such as agent-based modelling have instead tried to abductively model the system (Schlüter et al., 2017). This is done by mixing generalized theories of human-behaviour and bottom up modelling (Schlüter et al., 2017). In the following sections the aforementioned approaches; system dynamics and agent-based modelling, are discussed in relation to their use in the I-CISK project.

3.2 System dynamics

Among the tools designed to deal with the complexity of the SES, System Dynamics (SD) is one of the most commonly applied due to its flexibility. Developed for industrial process control in the 1950s by Jay Forrester at the Massachusetts Institute of Technology, it was soon adopted to model socio-economic interaction (Forrester, 1970; Forrester, 1997). In 1972, the think tank "Club of Rome" used this methodology to prove how short-term policies can lead to overshoot and societal collapse in the long-term in the influential book "*Limits to Growth*" (Meadows et al., 1972). Despite criticisms to the book, it constituted a milestone in the science complex socio-ecological interactions modelling, demonstrating how control theory and system thinking can help us design a sustainable future.

In SD, a problem is represented by quantitatively tracking the changes in state of a network of elements causally interacting with each other (Sterman, 2014). State variables are referred to as "stocks" and rate of change in said stocks called "flows". Feedbacks loops in particular are one of the central aspects of SD, as they allow to conceptualize complex behaviours in the system (Richardson, 2011; Sterman, 2014). In system dynamics, feedback loops can be of two types, reinforcing and balancing, and have two polarities, positive and negative. Reinforcing feedback loops are self-reinforcing and can explain why the effects of an action might spiral out of control in the long-term (Sterman, 2014). Balancing feedback loops are instead self-dampening and can be the reason why another action fails to effectively bring change to the state of the system (Sterman, 2014). The combination of several feedback loops is what causes the emergence of complex system behaviours. Hence, SD is generally not used to model a steady state, rather to simulate dynamic behaviours through time (Richardson, 2011; Elsawah et al., 2017). SD allows the user to depict and model complex interactions, non-linearities, and feedbacks among various elements of a system with a simple causal network. Thus, making it possible to explore the effects of management measures on the system as a whole or on specific performance indicators (Elsawah et al., 2017). As a consequence, SD has been successfully employed in many scientific fields dealing with SES modelling. For example: socio-hydrology (Di Baldassarre et al., 2018; Di Baldassarre et al., 2019, Mazzoleni et al., 2021); urban water management (Qi and Chang, 2011; Zhang et al., 2017); climate vulnerability assessment (Sahin and Mohamed, 2014); water-energy-food nexus (Akhtar et al., 2013); as well as many others.

Thanks to its flexible and intuitive nature, SD is an ideal tool to model complex systems. Elsawah et al. (2017) identify three ways to approach the construction of a model. First, SD can be used as a holistic exploratory framework describing a system through the depiction of linkages and feedbacks. Hence, investigating unintended consequences, long-term effects, emerging behaviours, and other complex system interactions. Second, due to its simple and intuitive graphical representation, SD can be used to engage stakeholders in participatory co-creation of a system model. Finally, SD can be used as a predictive tool to quantitatively simulate the processes of a system, these being biological, physical, social, or socio-economical. However, the three approaches do not exclude one another. Instead a study can employ all three at different stages and even iterate between them as the model gets refined.

SD is nevertheless limited by the complexity of the SES and the need for simplification as in any type of modelling. Firstly, collecting data from all relevant sources is an arduous and task that needs to combine various methodologies capable of synthesizing both quantitative and qualitative data. The data collected needs to fit the methodological design, yet remain practical enough for the researcher to collect. Second, identifying the right level of aggregation can be difficult, as the model should find a balance between the number of processes that it tries to reproduce, and its usability. Third, many processes might have a spatial component to them, which most SD model are not equipped to deal with effectively. While some software allows working with spatially distributed datasets, this comes with limitations in the ease of modelling and communicability of the model (Elsawah et al., 2017). Finally, the modelling of a SES tends to be time and resource consuming, especially in systems where the social components are more relevant.

3.2.1 System archetypes

System archetypes are simple system conceptualizations highlighting a specific emergent behaviour of the system (Wolstenholme, 2003; Mirchi et al., 2012). While not exclusive to SD, they are generally represented by paired feedback loops using SD as a modelling framework, and despite their simplicity they are a common shortcut to gain insights into complex processes (Elsawah et al., 2017). Many of the dynamics that these archetypes aim to reproduce are familiar to the general public. For example, *tragedy of the commons*, *limits to growth*, and *success of the successful*, represent concepts often considered of common-wisdom. An example of SD archetypes used as a tool to highlight challenges arising from complex emerging system behaviours can be found in Moallemi et al. (2022), where the researchers use SD archetype to conceptualize synergies and trade-offs between different Sustainable Development Goals.

In the case of WP4, system archetypes will be used deductively as a preliminary scoping tool. This step will see the researchers matching archetypes with specific challenges and dynamics across temporal or spatial scale highlighted by the LLs. The preliminary models so created are then presented and evaluated with the LLs to parse out those that are considered relevant for the LLs. While archetypes are a useful conceptualization tool in SD, the researcher should be mindful of not trying to force-fit the observed system behaviours over specific structures (Elsawah et al., 2017). Interaction with the LLs is therefore essential in this step of the project, as the ultimate goal of the model is that of representing reality.

An example of a simple system model based on these archetypes was constructed by Biella et al, 2022 and presented at the EGU General Assembly in May 2022. In this example, a generalized model was constructed around the archetype *"success of the successful"* as a way to explore how climate services might benefit one actor at the expenses of another and suggested corrective policy measures to prevent this (*see* Figure 4). In this model two competitors are competing over limited resources while climate change impacts them by shrinking the total resource pool. Both competitors carry out adaptation measures. However, Competitor A, having more resources, can access tailored climate services, hence can develop a more effective adaptation, while competitor B only uses free, less specific services. Over time, A benefits from the adaptation measures and from the reduced competitiveness of B (see panels b and c). By the end of the scenario, competitor B has disappeared from the system while A has managed to get through the scenario unaffected. In the same work, the author also explored a possible solution scenario using system dynamic modelling to model the effects of subsidies to adaptation. This preliminary model was created as a proof of concept and was not related to any LL.

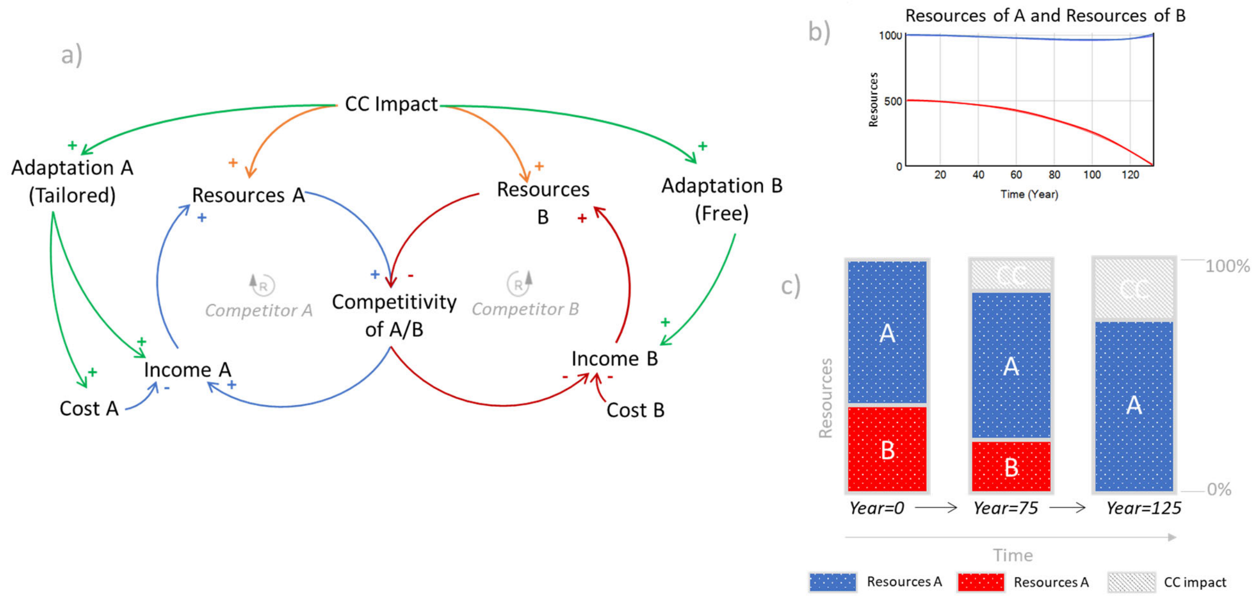

Figure 4: Conceptual model based on the *"success of the successful"* archetype.

3.2.2 Causal Loop Diagrams

Once the dynamics have been discussed and identified by the LLs using the system archetypes, these conceptual models can be used as a guideline to co-create a more detailed SD model in close collaboration with the LLs. To this end, the Causal Loop Diagrams (CLDs) (**Error! Reference source not found.**4) are a common tool to operationalize a SD in close collaboration with stakeholders, as they are generally easy to understand and encourage engagement and reflection (Elsawah et al., 2017). The advantage of CLDs is that they present a very intuitive representation of the model that offers a middle ground between conceptual and operational, and can be co-developed from the bottom-up by involving the stakeholders. In the case of WP4, these will be developed by modifying and combining those created based on the system archetype models with information provided by the LLs during one or more co-creation workshops.

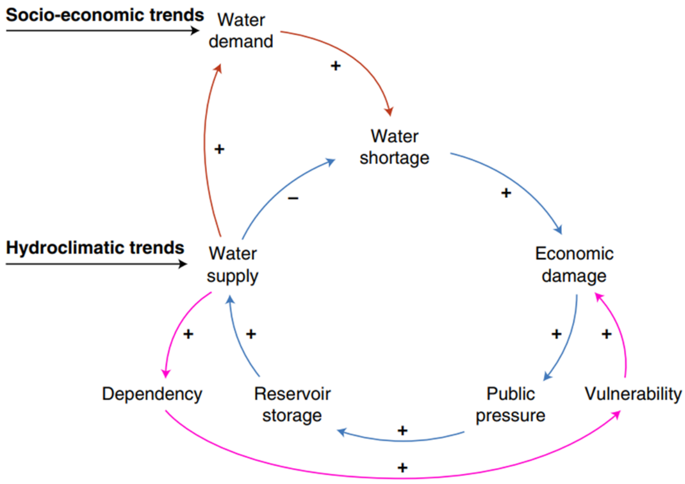

Figure 5. Example of Causal Loop Diagram showing how increasing water supply can increase demand, hence nullifying the effects of the increased supply in the first place. At the same time, vulnerability is increased as the system becomes more and more dependent on the supply of water. Taken from Di Baldassarre et al., 2018

3.2.3 Applications of system dynamics models in water resources

Traditional methods for assessing hydrological risk (e.g., Jongman et al., 2014; Shahid and Behrawan, 2008; Winsemius et al., 2016) do not explicitly account for the feedback mechanisms operating in human-water systems. This may lead to a systematic underestimation or overestimation of changes in hydrological risk. Socio-hydrological models based on a system dynamic framework have been extensively developed in recent years to represent the human-water dynamics and predict the emergence of socio-hydrological phenomena. Different adaptation measures can be adopted to reduce risk and the impact of hydrological extremes (Kreibich et al., 2019; Sterle et al., 2019). However, these measures can have unexpected impacts or unintended consequences in the long term because of the complexity of fully coupled human-water systems. For example, Albertini et al. (2020), Di Baldassarre et al. (2015), Ridolfi et al. (2020), and Viglione et al. (2014) have developed socio-hydrological models for representing the levee effect, which emerges when structural risk reduction measures (such as levees) are built and risk awareness tends to decrease due to the presence of the structure (Mård et al., 2018). Similarly, Garcia et al. (2016), among others, have proposed different models to investigate the supply-demand effect (Gohari et al., 2013) due to the interactions between water supply, demand, and the population's awareness of water shortages under different reservoir operating policies. Gonzales and Ajami (2017) proposed a model to quantitatively represent the rebound effect, occurring when an improvement of the efficiency in the water infrastructure systems ultimately defeats the original intended purpose, inducing higher water consumption and consequent significant water stress and in case of future drought conditions (Alcott, 2005; Dumont et al., 2013). Just recently, Mazzoleni et al. (2021) proposed a system dynamic model to simulate the interplay between floods, droughts, society, and four water management strategies (no actions, fighting floods, water conservation, and water exploitation). The study showed that changes in flood and drought awareness can help contribute to the emergence of multiple phenomena. Moreover, the model outcomes indicated that water-management strategies aimed at specific hydrological extremes can in turn shape the severity of opposite natural hazards. However, all these previous studies do not consider the feedback between climate information and the human system. This is the focus of the I-CISK project.

3.3 Agent based modelling

An ABM is a computerised simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules' (Farmer and Foley, 2009). ABMs allow the user to study emergent phenomena and test whether changing the actions of a specific agent can influence the meso-level and macro-level behaviours of the system (Schlüter et al., 2019). ABMs are considered a form of bottom-up modelling, as they allow the agents to interact with one another on the basis of simple rules applied to them. Emerging system behaviour are a consequence of these interactions. ABMs have become increasingly used to model coupled social-physical models, for example, flood risk assessment (Zhuo and Han, 2020), land use change (Groeneveld et al., 2017) or drought risk assessment (Wens et al., 2019).

Among the benefits of using ABMs are their ability to enable diverse agents to be represented in modelling (Troy et al., 2015) and of exploring emergent behaviours and feedbacks in a system by creating them from the ground-up. However, implementing realistic decision rules for these agents is a key challenge for ABM as these are often based on ad-hoc assumptions of human behaviour (An, 2012; Filatova et al., 2013; Schlüter et al., 2017; Groeneveld et al., 2017). In addition, as the model is bottom-up, results may be difficult to interpret due to potentially high relational and dynamic complexity; as relationships become opaque the model becomes more complex. . Results may not be generalisable, and have limited predictive power (An, 2012; Schlüter et al., 2012; Blair and Buytaert, 2016).

ABM generally implements the following general steps for developing a model, as identified by Blair and Buytaert (2016):

1. Problem definition
2. Determination of relevant system agents
3. Description of the environment in which agents exist
4. Elicitation of agent decision-making process and behaviours
5. Determination of the interactions between agents
6. Determination of the interactions between agents and the environment
7. Development of computational algorithms to represent agents, environment, decision-making processes, behaviours and interactions
8. Model validation and calibration.

As ABM is a time and resource intensive process. As a consequence, it will not be carried out within all the LLs, but only in those in which context and needs are most suitable for this type of study. Close collaboration with the LLs will be necessary for carrying out step 1 to 6 of the steps described by Blair and Buytaert (2016). Step 7 will be carried out by WP4 in collaboration with LLs and mainly with WPs1, 2 and 3, while step 8, the validation of the model, will see the involvement of the LLs to ensure that the model is realistic. However, this process is not linear, rather it is iterative. During the validation of the model, the model and the LL will co-create agent characteristics and processes to better reflect the reality of the LL.

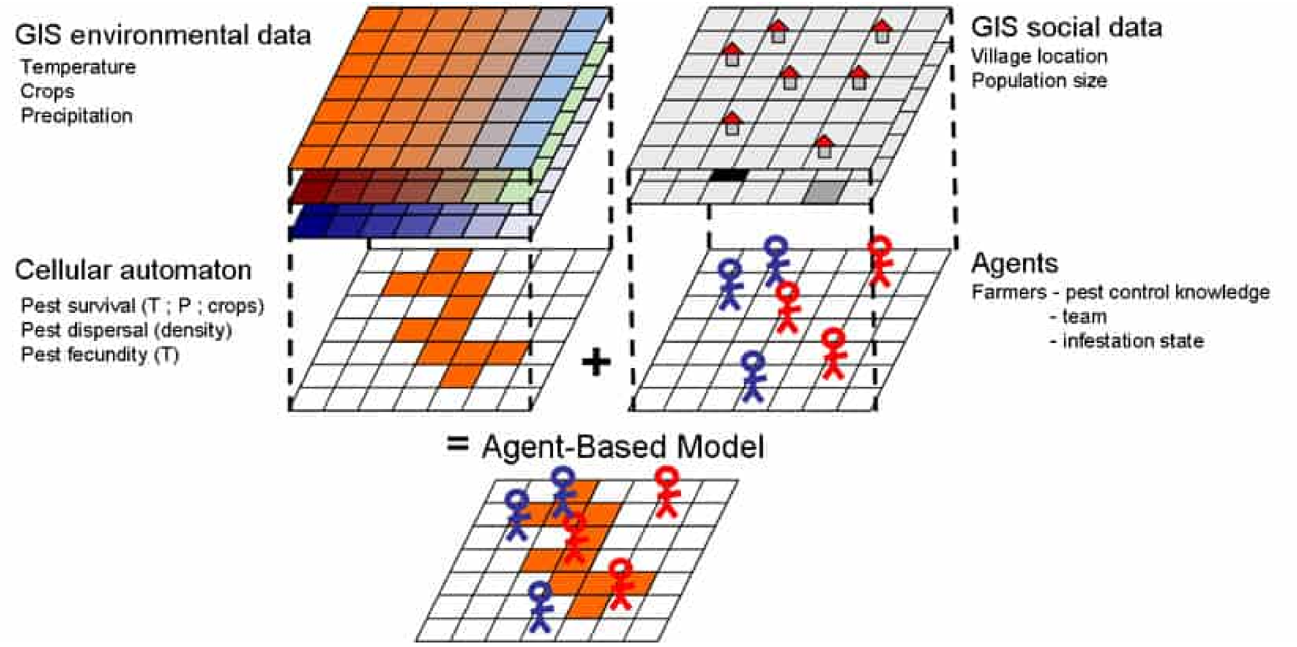

Figure 6: An Example of ABM in Agriculture Pest Control Studies. (Source: University of Surrey)

3.3.1 Applications of ABM models in water resources

In parallel with the development of system dynamics approaches (see previous section), ABM have been extensively used to gain a deeper understanding of human-water management to develop sustainable management strategies (Dubbelboer et al., 2017; Filatova, 2015; Haer et al., 2019; Janssen and Ostrom, 2006; Tonn and Guikema, 2018). However, system dynamics models cannot represent the heterogeneity of individual risk perception due to their lumped structure. For this reason, ABM has been extensively used to gain deeper understanding of complexity about imperfect heterogeneous actors and their individual decisions, activities and interactions (Wens et al., 2020). Thus, an ABM seems suitable to model human decision-making in quantitative flood risk assessment.

ABMs have been recently applied to flood and drought risk assessment, analysing mainly different aspects of human behaviour, the effects of flood insurance, drought adaptation actions, and risk communication on development of time of flood and drought risks (Filatova, 2015; Wens et al., 2019). In particular, Haer et al. (2017) compared three different behavioural frameworks for the decision-making of household agents about investing in loss-reducing measures, namely expected utility theory, prospect theory and prospect theory including adaptation of behaviours through Bayesian updating. Haer et al. (2020) quantified the levee effect in Europe with an ABM and further discussed policy implications. Abebe et al. (2019) developed a new framework for integrating a hydraulic model into an ABM to represent individuals and institutions decision-making during flooding. Just recently, Michaelis et al. (2020) showed that their proposed agent-based model was able to explain flood adaptation and the levee paradox. With respect to drought risk management, Wens et al. (2019) proposed an ABM focused on individual and collective actions to simulate the adaptive behaviours of different stakeholders and examine how emergent actions might influence projected drought risk. Schrieks et al. (2021) proposed provides a schematic framework for drought risk using ABM in the context of agricultural communities in which individual decision-making process of the farmers is driven by behavioural changes.

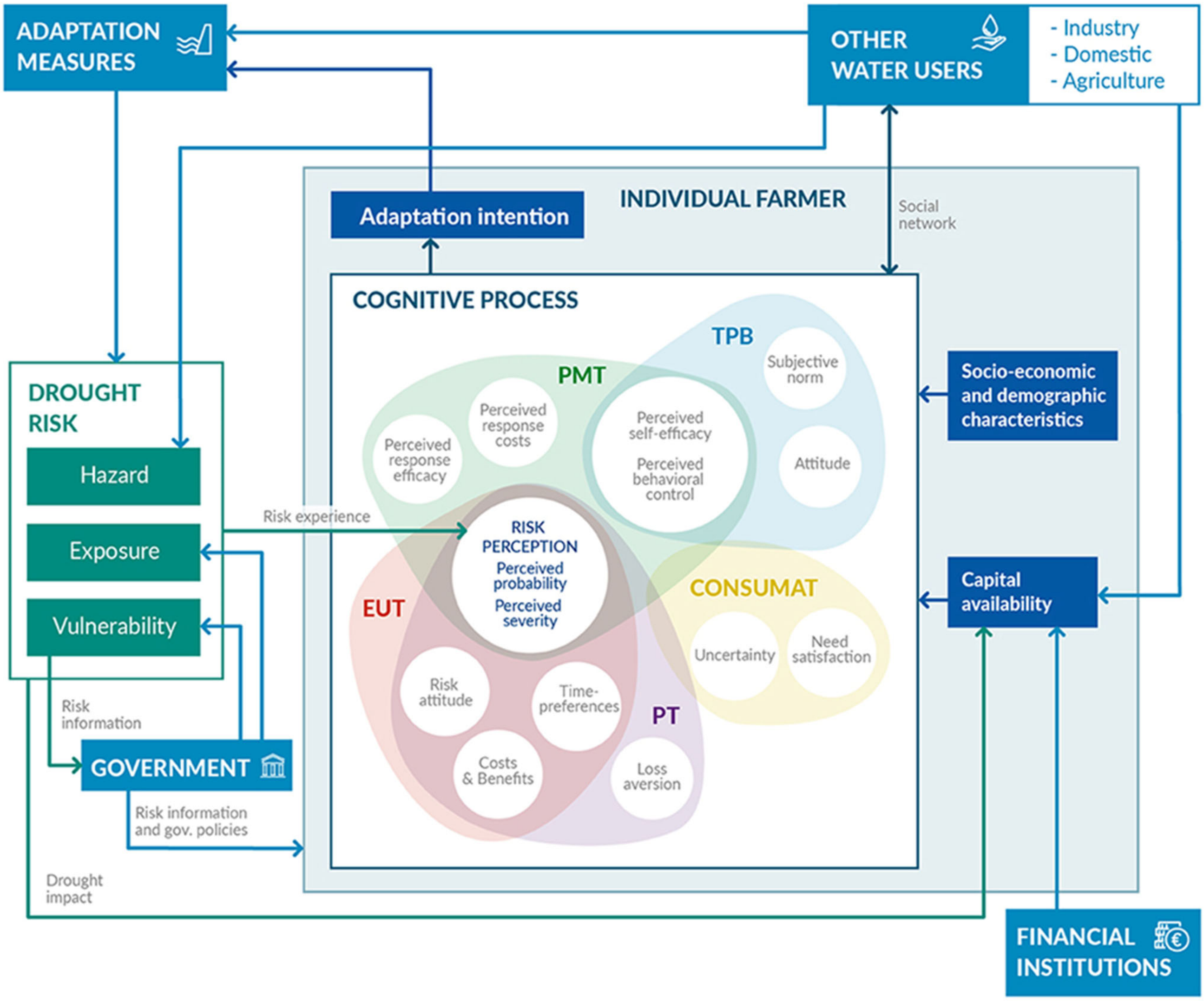

Figure 7: Conceptual framework agricultural drought risk ABM (source: Schrieks et al., 2021)

4 CS-human dynamics in the different living labs

CS are fundamental to reduce risk and avoid future disasters. While the benefits of CS have been widely explored by existing literature, the main feedbacks between CS, adaptation measures and climate-related extreme events are still unclear. In this section, we provide a preliminary overview of such dynamics and their characterization within the different living labs (LLs) of the project.

To this end, we provide a brief description of each LL along with the main objectives and challenges from the WP4 perspective that were identified during I-CISK workshops and meetings held in the first year of the project. The system archetypes described in this section refer to the aforementioned work by Moallemi et al. (2022), which is based on Senge's book (*The fifth discipline*, 1990).

Budapest (Hungary). This LL consists of an urban area challenged by rising temperatures and heatwaves, exacerbated by urban heat islands (UHIs). One of the aims in this LL is raising awareness around UHI and potentially influence policy by e.g. promoting urban greening. In terms of human-climate interactions, this LL shows potential for the analysis of feedbacks between short-term (coping) measures and long-term (adaptive) measures (including unintended consequences) with potential emergence of system archetypes, including Fixes that fail.

Alazani River basin (Georgia). In this LL, droughts and water shortages challenge multiple needs (e.g. agriculture, hydropower) as well as several sectors (e.g. tourism, forestry). In particular, there is interest in expanding the availability of seasonal and sub-seasonal forecast by downscaling global information and integrating it with in-situ observations. CSs are meant to inform the development of hydropower sector as well as public water allocation for multiple purposes (farmers are explicitly considered), while at the same time reducing environmental impacts. There is potential to unravel human-climate interactions by building upon archetypal dynamics, such as the Tragedy of the commons or Band-aid solutions (for competing interests), as well as Success to the successful (for inequality in access).

Senqu Valley (Lesotho). The focus in this LL is food security, drought and humanitarian aid. The project will focus on the implementation of a forecast system to raise preparedness for humanitarian actions. More specifically, the Red Cross delivers anticipatory financing to farmers based on seasonal drought forecasts as a way to increase preparedness. Besides the limitations of seasonal drought forecast in a data-poor area, challenges in this LL include the "last-mile" uptake and different levels of literacy. Management of competing interests gives rise to Tragedy of the commons or Shifting the burden, while inequality in access can be described by the Success to the successful archetype. Sustainability trade-offs include Band-aid solutions and Fixes that fail.

Rijnland basin (The Netherlands). This LL presents trade-offs in water use between agriculture, recreation, shipping and nature conservation. In terms of CS information, the demand is from e.g. farmers and recreationists for measurements and forecasting of salt water intrusion and fresh water level. In this LL; there are rather different needs among stakeholders, not only between farmers and recreationists, but also within (different types of) farmers. There are also different dissemination needs: farmers are more eager to get informed than the recreationists. This can raise inequality in access to information (Success of the successful), as well as competing interests and needs that might lead to overexploitation (Tragedy of the commons).

Guadalquivir basin (Spain). The focus on this LL is on the interplay between agriculture, livestock, forestry and water scarcity. The aim of the project in this LL is to create a platform for the display of various hydrological indexes to meet the needs of farmers and livestock producers. In particular, monitoring the level of the water and sub-seasonal forecast. These are expected be complemented by long-term projections, which are also of interest primarily to inform the public decision-making process, including water allocation planning for different water users. The farmers have also expressed the need of a platform that can be accessed through an app. There is room to explore trade-offs between seasonal planning (based on measurements and forecasts) and long-term adaptation strategies (based on projections), as well between incremental versus transformative adaptation. Various system dynamics archetypes can be at play in this LL: Tragedy of the commons for competing interests, Success to the successful because of uneven access to information/resources.

Emilia Romagna (Italy). This LL deals with agricultural and industrial water use. The aim is to develop a tool to manage water allocation between farmers (represented by a consortium) and a multi-industry consortium. The allocation process is managed by the local public water body. In this project, the focus is on improving seasonal allocation of water resources, especially during drought conditions. One technical aspect consists of implementing a forecast with a temporal resolution of 3-days (compared to the current 7 days). Competing interests between agricultural and industrial water use can give rise to Tragedy of the commons archetypes.

Crete (Greece). Tourism is one focus of this LL in relation with multiple hazards and climate change. The project is dealing with the development of a seasonal forecast at smaller scale for both tourism and water allocation, as well as long term projections of climate change. This CS information is used to support the seasonal and long-term planning of commercial activities. One of the goals is to raise awareness about the risks associated with some tourist activities. There are trade-offs with short- versus long-term planning and concrete risks for unplanned exploitation (Tragedy of the commons).

The Table below summarises the main system dynamics archetypes that characterise human-climate interactions and feedback mechanisms in the different LLs. It shows how the interplay between climate change, CS information, policy, behaviour and extreme events often give raise to Fixes that fail, Success to the successful and Tragedy of the commons.

The preliminary knowledge of the system dynamics archetypes and behavioural theories used in each LL to unravel the human-climate dynamics will be used as input in system dynamics and ABM modelling framework to quantitively assess past and future risk trajectories in order to avoid trade-offs and unintended consequences. Co-creation processes (WP2) will be used to develop these models.

5 Conclusions

Understanding the feedback mechanisms underlying the interplay between climate change and adaptation actions is of pivotal importance to achieving a resilient future. This report aims to provide more insights into the human-climate dynamics by first reviewing previous studies focused on assessing the behavioural responses of people and societies to different availability of CS. We then present the two main modelling frameworks that WP4 has and will adopt: System Dynamics (SD) and Agent Based Modelling (ABM). Firstly, a brief overview of SD is given and benefits and challenges are laid-out. Two approaches related to conceptual modelling in SD are explained thereafter. System archetypes, being a powerful scoping tool in highly complex Socio-Environmental Systems, and Causal Loop Diagrams, will be used to set the preliminary model structure to be discussed and improved during for participatory modelling activities with stakeholders and end-users in the LLs. The second modelling framework explored, ABM, is a powerful tool for both quantitative modelling and qualitative exploration of emergent system behaviours. Contrary to SD, ABM has the advantage of constructing the model from the bottom up, starting from the characteristic of the agents and their interactions. Finally, we highlighted the presence of feedback interaction between CSs and adaptation among the living labs. We conducted a preliminary scoping exercise discussing said interactions utilizing system archetypes and presented the ways in which the other modelling methodologies can be used to further the research ensuring the co-creation principles at the heart of I-CISK.

This preliminary review performed in WP4 shows that individuals change their perception and behavioural options over time, based on CS availability. Together, an individual's perception and behavioural options are influenced by their subjective norms, attitudes, risk preferences and biases. Despite this rich knowledge from various social sciences, when modelling water risk, human behaviour is often omitted, or modelled using unrealistic assumptions (e.g. using homogeneous rational agents). To be able to capture the feedback between climate services, human behaviour and the environment, understanding and modelling of behavioural responses to climate services is essential.

System dynamics and ABM are powerful tools to the human-climate dynamics both qualitatively and quantitatively. As an initial step, the implementation of system archetypes within a system dynamic framework allowed us to conceptually infer complex emergent system behaviours, such as the long-term consequences of unequal access to CSs. This report showed that the feedbacks between human and CS present in the different living labs can be summarized by the existing system archetypes. This step will be followed by more in-depth participatory methodologies and quantitative modelling. These human-climate models will also show possible trade-offs between multiple adaptation goals and CS availability when focusing at different spatial-temporal scales and avoid possible future unintended consequences. This will allow us to investigate the causal dynamics in each living labs and evaluate the bi-directional feedbacks between adaptation actions and CS availability to describe future risk trajectories and show the effect of CS used for short/medium forecast on longer time scales (T4.1).

The results of this preliminary report are expected to pave the way for the implementation of modelling framework within the different living labs (T4.3 and T4.4) in order to formalize human responses to climate change and CS information by also building upon results from WP1 and WP2. As a next research step, we will assess if (as well how and for whom) the adaptation actions adopted by the end-users using the available CS in the different LLs are effective in achieving a resilient future. Participatory modelling approaches and serious games will be also used to increase stakeholders' awareness on the climate change impacts and the interplays with the human-climate system.

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Appendix 1 Glossary

Acronym	Definition
API	Application Programming Interface
C3S	Copernicus Climate Change Service
CDS	Climate Data Store
CEMS	Copernicus Emergency Management Services
CMIP	World Climate Research Programme's Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CS	Climate Services
CSIS	Climate Services Information Systems
DRR	Disaster Risk Reduction
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GUI	Graphical User Interface
IPCC	Intergovernmental Panel on Climate Change
LL	Climate Services Living Labs
NHMS	National Hydro-meteorological Service
MOOC	Massive Open Online Course
OGC	Open Geospatial Consortium
S2S	Sub-seasonal to Seasonal
TRL	Technology Readiness Level
UNCCD	United Nations Convention to Combat Desertification
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme
WFD	Water Framework Directive
WMO	World Meteorological Organization

Colophon:

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