I-CISK

HUMAN CENTRED CLIMATE SERVICES

Deliverable D4.5

Bidirectional feedbacks between adaptation actions and climate service information

28-08-2025

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I-CISK

Innovating Climate services through Integrating Scientific and local Knowledge

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Executive Summary

This Deliverable presents the outcomes of WP4 of the I-CISK project, which focused on developing a suite of models of varying complexity to explore the dynamic, bidirectional feedbacks between climate adaptation actions and climate service (CS) information. These models have been tested and validated across a range of living labs, each reflecting diverse temporal and spatial contexts.

A key finding is that climate services are not inherently "no-regret" solutions. While intended to support effective adaptation, their design and implementation can sometimes result in unintended consequences, including maladaptive outcomes. To address these challenges, this report introduces a set of models and tools that enable stakeholders to anticipate potential risks and trade-offs, enhancing the capacity for informed, adaptive decision-making.

The models presented here captures the complex interactions between human behavior, drought management, and the influence of CS on socio-ecological system dynamics. Human responses to water governance frameworks shape consumption patterns, resource allocation, and ecological pressures within intricate hydro-systems. While adaptive measures are implemented to reduce vulnerability, they can sometimes produce maladaptive outcomes, where interventions inadvertently exacerbate or redistribute risks, compromising long-term system sustainability.

CSs are pivotal in guiding decision-making within these coupled socio-ecological systems. However, human-climate interactions and feedbacks are often non-linear, producing unexpected adaptation outcomes that challenge conventional management strategies. Understanding these dynamics is essential for developing resilient and sustainable approaches to drought management and resource governance.

This research also highlights the significant role of power asymmetries among stakeholders in shaping the development, accessibility, and overall impact of climate services. For instance, in the Crete living lab, the prioritization of tourism—driven by its economic influence—has the potential to increase the vulnerability of other key sectors, particularly those already marginalized in policy and resource allocation.

To support sustainable and equitable adaptation, climate services must be developed through inclusive, participatory governance processes. Addressing systemic power imbalances is crucial to prevent CS initiatives from reinforcing existing inequalities. Superficial stakeholder engagement is insufficient; meaningful inclusion of underrepresented and “non-targeted” sectors is essential throughout co-design, co-production, and co-delivery processes.

Importantly, the effective identification and engagement of stakeholders require more than participatory frameworks. Systems thinking methodologies, such as system dynamics modelling, are necessary to navigate complex interdependencies and uncover hidden power dynamics within socio-ecological systems.

In conclusion, embedding climate service development within frameworks that explicitly recognize and address power differentials is essential. Only then can climate services fulfill their promise as tools for enhancing resilience and enabling just, inclusive climate adaptation outcomes.

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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

1 Introduction

Effective climate adaptation hinges on equitable access to climate information and the ability of stakeholders to meaningfully participate in decision-making processes (Hewitt et al., 2020; Lemos et al., 2012; Vaughan & Dessai, 2014). Climate Services (CS), designed to provide timely and tailored climate information, are increasingly recognized as tools to enhance adaptation and resilience to climate-related risks. However, as shown in this research (as a part of Work Package 4 of the I-CISK project), bidirectional feedbacks between adaptation actions and climate service information can potentially generate unintended consequences, including the emergence of undesired risks or maladaptive dynamics as described in Biella et al. (2024).

Prior work in the I-CISK project has shown that the management of climate hazards, such as drought, is not solely a technical or ecological challenge but is deeply shaped by human behaviour. Adaptive responses to water governance frameworks influence patterns of consumption, resource allocation, and ecological pressures within complex hydro-systems. However, strategies intended to enhance resilience do not always achieve their desired outcomes. In some cases, adaptation measures result in maladaptive dynamics, where efforts to reduce vulnerability inadvertently redistribute or intensify risks, threatening the long-term sustainability of socio-ecological systems.

Moreover, the development, access, and application of CS products are often shaped by stakeholder power dynamics, leading to inequities in adaptation outcomes (Brouwer et al., 2013; Howarth et al., 2022; Nost, 2019; Vaughan & Dessai, 2014). As the I-CISK project emphasizes human-centred CS development that integrates scientific and local knowledge, understanding how power influences the uptake and outcomes of CS is vital to ensuring that these tools foster inclusive and effective adaptation strategies.

Power asymmetries result from the unequal distribution of influence, resources, and decision-making authority among stakeholders engaged in the co-production process (Gerlak et al., 2023; Vallet et al., 2019). These asymmetries can manifest through preferential targeting of certain sectors, uneven resource allocation, or exclusion of marginalized groups, potentially leading to maladaptation and exacerbated vulnerabilities (Garcia et al., 2024; Holland, 2017; Thomas & Twyman, 2005). Despite the growing emphasis on participatory approaches such as co-creation, co-design, and co-production (Co-Co-Co), sectoral prioritization often reinforces existing inequalities by favouring dominant stakeholders (Cantone et al., 2023; Reed et al., 2019).

In this report, we expand on the work done in WP4 (Biella et al., 2024; Rastogi et al., 2025) and present a set of models built by the I-CISK Work Package 4 team to capture bidirectional feedbacks between adaptation actions and climate service information across different living labs (LLs) characterized by a range of temporal and spatial scales. These models also cover different levels of complexity, ranging from conceptual and generic models of drought management and human behaviour (Section 2) to more complex, mathematical tools capturing power asymmetries in a specific LL (Section 5).

2 Human behaviour and drought management

Drought management and human behaviour are closely linked in a two-way feedback loop. Whenever governments or water managers introduce drought mitigation measures, such as volumetric rationing, priority allocation, dynamic tariff structures, or the temporal closure of hydraulic infrastructure, society will need to adapt. Because of this, households will change water consumption, farmers reschedule irrigation, and industries change their production practices. These adaptation dynamics reshape spatio-temporal demand, social inequalities, water availability patterns, influence return flows, and alter the salinity and ecological stress in receiving water bodies. A concrete example of these dynamics emerge in drought management practices in the Rijnland Living Lab, one of the seven Living Labs (LL) in the I-CISK project. The management of shipping lock movements is the principal strategy for counteracting salt intrusion under drought conditions. Rijnland is one of the Netherlands' oldest regional water authorities and manages an intricate polder-and-canal system that discharges excess water to the North Sea via the Grote Sluis at Spaarndam. During dry periods, freshwater is withdrawn from the River Lek (a branch of the River Rhine) at the sluice at Gouda. This freshwater is in part used to control salinity levels in the management area of the Rijnland water authority, though during droughts and consequent low flows in the Rhine River, freshwater availability may be reduced. Besides managing water quality and quantity, the authority must keep the waterways navigable for commercial and recreational shipping.

The water authority uses ensemble-based drought and salinity forecasts, together with the nationally defined hierarchy for water-use prioritisation (Verdringingsreeks), to determine its water management strategies. Recreational boating is classified as low priority, and hence, during droughts measures for recreationists are common. To inform recreationists of the drought measures outlook, they use a climate service in the form of a colour-coded message system. Each code indicates the (expected) enacted measure(s) taken by the water-authority, and hence the available routes and opening times of locks. Changes in the available routes and lock opening timings influence waterway traffic, and hence lock water use and salt intrusion, and public acceptance of subsequent restrictions.

Based on these considerations, we developed a conceptual model representing the dynamics between climate services, water availability, gate regulations, and boat owners, based on discussions and workshops with stakeholders in the LL. We developed two models based on either short-term (Figure 2.1) or long-term (Figure 2.2) adaptation and consequent impacts. In particular, we considered that boat recreationist owners can react to the weather forecast and colour code regulation provided by Rijnland by i) waiting at the lock gates; ii) taking an alternative route; or iii) not going out with their boat at all. Each of these decisions will lead to different feedbacks and implications. However, while many dynamics were theoretically identified, we could not find strong evidence that changes in boat recreationists' behaviour would affect the environment and thus Rijnland water management (red dashed lines in Figures 2.1 and 2.2). Below are some explanations regarding the dynamics between boat recreationists, CS, Rijnland, and the environment in the short-term.

Waiting at the lock gate, typically for one to three hours during code yellow restrictions, has negligible hydrological or ecological repercussions. The water authority's discharge-reduction targets remain unchanged because the lock water volume released per cycle is fixed. For the ecosystems, we did not find academic literature or anecdotal evidence which indicated that extended queue times measurably alter turbidity, bank erosion, or disturbance to riparian fauna. Socially, recreational sailing culture in the Netherlands has long normalised waiting as an inherent component, especially among wind-powered craft that are accustomed to weather-induced delays. Recent growth in motorboat tourism is attenuating this tolerance, but systematic complaints or non-compliance remain rare and confined to peak holiday weekends.

Taking an alternative route can be a complex adaptation decision. In some cases, no viable route exists and boats may be unable to leave the harbour. However, where substitute routes do exist, it can be that temporary traffic increase, leading to dangerous crowding. No statistically significant increase in environmentally deleterious events (e.g., bank collapse, bird-nest disturbance) can be attributed to crowding. Likewise, salinity intrusion remains unaffected because the alternative locks discharge to the same receiving waters and operate under equivalent salinity-trigger protocols.

Finally, while not going out with boats will lead to short-term revenue losses for local businesses (e.g. mooring fees, fuel, and hospitality services), this will, however, not have a significant effect on the water authority. The Rijnland water authority is aware of these impacts but is bound by the national hierarchy for water-use prioritisation (Verdringingsreeks), which ranks recreational boating below public water supply and ecosystem protection. Consequently, economic considerations, while noted, do not modulate the water authority Rijnland lock-closure decisions.

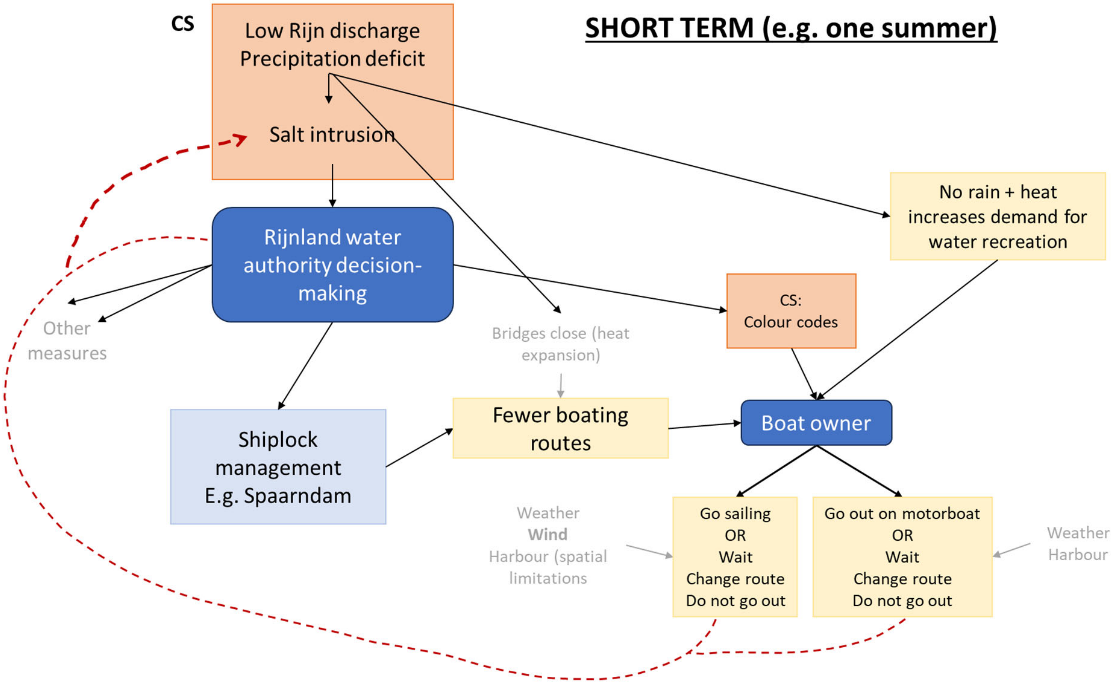

Figure 2.1. Short-term relations between water management, climate service, and boat recreationists in Rijnland. The orange boxes represent the climate service (CS) and water authority Rijnland decision, yellow boxes are the boat recreationists' options, rounded boxes are actor decision points, dotted red lines are the hypothetical feedback.

Long-term behavioural adaptation of recreational boating under recurrent drought restrictions can lead to prolonged or frequent lock closures and trigger changes in user behaviour far beyond seasonal itinerary adjustments. Conversation with the Rijnland water authority representative suggested two principal adaptation pathways for recreational boat owners. (i) Vessel substitution: Owners of wind-powered boats face disproportionately high impediments to recreation when shiplock closures coincide with bridges malfunctioning due to heat (the height of masts requires bridges to be opened, especially for boats where masts cannot easily be lowered), and calm wind conditions that prevent sailing. This could lead some owners to shift toward motor-powered boats, which exhibit greater route flexibility and lower sensitivity to intermittent lock service and bridge heat malfunctions. However, motorised boating is, based on discussions in the LL, a different recreational activity and many recreationists would not find a motorised boat a substitute for a wind-powered sailboat. (ii) Spatial relocation: an alternative response is to move to a different harbour. However, while this could happen, many owners seem to have a strong preference for remaining at their current harbour because of social capital (peer networks, club memberships), proximity to home, and the scarcity of vacant berths. Consequently, even under repeated access constraints, a majority of boaters exhibit a bias towards the status-quo, opting to remain rather than move to a different harbour.

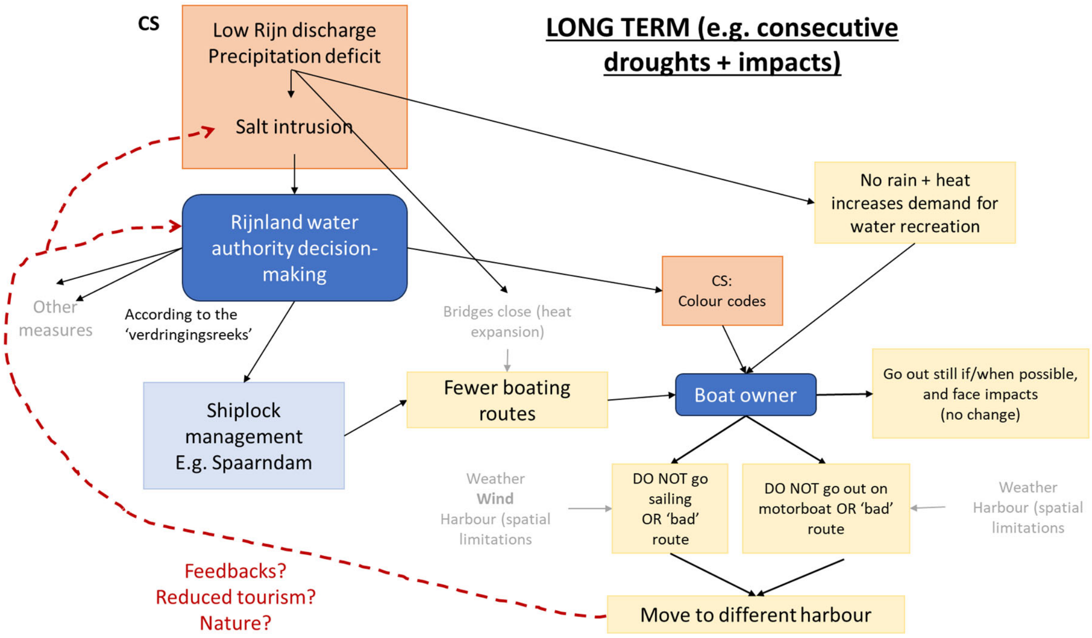

Figure 2.2. Long-term relations between water management, climate service, and boat recreationists in Rijnland. The orange boxes represent the climate service (CS) and decision taken by the Rijnland water authority, yellow boxes are the boat recreationists' options, rounded boxes are actor decision points, dotted red lines are the hypothetical feedback.

3 Maladaptive dynamics across living labs

Maladaptation refers to adaptation actions that, while intended to reduce climate vulnerability, end up increasing it for the same or other systems, sectors, or social groups (Barnett & O'Neill, 2010; Juhola et al., 2016; Eriksen et al., 2011; Magnan et al., 2016). According to Barnett and O'Neill (2010), it can be defined as "action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups." This concept is further refined by Juhola et al. (2016), who offer three typologies of maladaptation: i) rebounding vulnerability, ii) shifting vulnerability, and iii) eroding the conditions for sustainable development.

In the context of Climate Services (CS), maladaptation may occur when short-term benefits provided by CSs lead to long-term negative outcomes, either by reinforcing existing vulnerabilities or by creating new ones (Biella et al., 2024). Adaptation measures inherently carry a risk of maladaptation, especially in complex socio-ecological systems (SES) where feedback loops and unintended consequences are common (Biella et al., 2024). Traditionally, CS development and implementation relies on assumed benefits of CSs, with little attention paid to long-term or systemic effects. Biella et al. (2024) challenge this "no-regret" assumption, highlighting the need to consider the potential for unintended consequences, particularly in systems characterized by rapid hydro-climatic and socio-economic change.

Complex socio-ecological systems are defined by interdependent components and feedback loops. These systems have been increasingly studied through complex systems modelling and system dynamics approaches (Elsawah et al., 2017; Nabavi et al., 2017; Naylor et al., 2020; Verburg et al., 2016). These systems do not behave linearly, and adaptation interventions often yield unexpected outcomes. System archetypes, drawn from system dynamics theory, help illustrate how these feedbacks play out in adaptation scenarios supported by CSs. They provide simplified, reusable representations of recurring system behaviours (Wolstenholme, 2003; Mirchi et al., 2012; Moallemi et al., 2022).

To support the assessment of maladaptive risk, the research carried out by Biella et al. (2024) for the I-CISK project integrated system archetypes models with a maladaptation framework based on Magnan et al. (2016). System archetypes are simple conceptual models used to simplify complex feedback dynamics (Wolstenholme, 2003; Mirchi et al., 2012; Elsawah et al., 2017; Moallemi et al., 2022). In the case of CSs, archetypes help to reveal the complex and dynamic pathways through which CSs may contribute to maladaptive outcomes. The research ultimately aims to provide tools and methodologies for adaptation managers and CS developers to anticipate and mitigate maladaptation risks.

Four archetypes of maladaptation were identified across the I-CISK Living Labs (LLs). These were based on the in-depth characterization of LLs developed within the I-CISK project (Masih, 2022). These archetype models were identified through a mixed-methods approach involving desk research, stakeholder surveys, and in-depth interviews with Living Lab leaders. The data collected was used to identify recurring systemic patterns, which were then interpreted using system dynamics theory. This approach allowed researchers to conceptualize how different configurations of CSs, user behaviour, and adaptation goals could result in distinct maladaptive dynamics. The archetypes serve as heuristic tools to reveal and anticipate such risks across diverse socio-ecological contexts. Deliverable 4.2 and Biella et al. (2024) describe four archetypes across the I-CISK Living Labs (LLs):

i. **Fixes that Fail** (Fig. 3.1a): Short-term solutions that address symptoms but ignore root causes, leading to worsened conditions over time. For instance, in Spain and Georgia, CSs support water-intensive agriculture, mitigating immediate drought impacts but fostering groundwater over extraction and ecological degradation (Biella et al., 2024).
ii. **Band-Aid Solutions** (Fig. 3.1b): These reflect tensions between short-term relief and long-term sustainability. In Italy and the Netherlands, short-term CSs aid irrigation but delay transitions to more sustainable water practices (Biella et al., 2024).
iii. **Success to the Successful** (Fig. 3.1c): When certain groups disproportionately benefit from CSs due to better access or capacity, exacerbating existing inequalities. In Greece, CSs favoured the tourism sector over agriculture, deepening socio-economic divides (Biella et al., 2024).
iv. **Eroding Goals** (Fig. 3.1d): the eroding goals archetype (also known as "drifting goals") refers to situations where long-term objectives are progressively adjusted downward due to persistent system pressures or failures to meet desired outcomes. Instead of identifying and addressing underlying problems, actors lower their expectations or targets, which can institutionalize suboptimal outcomes over time. While this archetype was not directly linked to maladaptation, it provides valuable insights into the process of how CSs can end up under-delivering on their usability goals (I-CISK Deliverable 4.2).

The dynamics illustrated in these archetypes demonstrate how maladaptive outcomes emerge not from poor intentions but from structural and systemic blind spots in CS design and implementation.

Across the I-CISK Living Labs, these archetypes revealed context-specific maladaptive processes. In the Spanish LL, the "Fixes that Fail" archetype manifested through the use of CSs to support dairy farming under increasing drought conditions. While seasonal drought forecasts enabled short-term water management, they inadvertently encouraged over-extraction of groundwater, deepening long-term vulnerability. In Georgia, similar dynamics occurred in the wine-producing Alazani river basin. Seasonal streamflow forecasts, while supporting economic growth through irrigation, contributed to unsustainable water use in a semi-arid region already threatened by desertification.

The Italian LL demonstrated the "Band-Aid Solutions" archetype. Farmers used short-term CSs to manage irrigation during dry periods, but this reliance reduced incentives to adopt more transformative practices, such as shifting to less water-dependent crops or improving irrigation infrastructure. This short-termism risks locking the region into unsustainable agricultural pathways. In the Dutch LL, a comparable dynamic was observed in response to saltwater intrusion. Here, short-term CSs allowed farmers to adjust practices without addressing the underlying problem, delaying more robust long-term adaptation like changing crop types or altering land use.

The Greek LL provided a clear example of the "Success to the Successful" archetype. Climate services were more accessible and useful to the tourism sector than to agriculture, contributing to a widening gap in resilience between these two economic groups. This inequity raises concerns about the erosion of adaptive capacity in sectors less scientifically literate or eager to collaborate with European projects.

Finally, in the Lesotho LL, while the primary user of the climate services (CSs) is the Disaster Management Authority (DMA), the intended beneficiaries are the farmers. The DMA's main limitation in using CSs lies in poor inter-agency communication, whereas farmers struggle with low adaptive capacity, even when relevant information is available. However, farmers are underrepresented in the process, which risks tailoring CSs only to the DMA's needs, leaving otherwise important usability aspects excluded—such as the inclusion of local knowledge. Similarly, in the Georgia and Italy LLs, the pressure to deliver a functional CS may also overshadow the importance of customization, local knowledge, and co-creation, ultimately leading to less usable services.

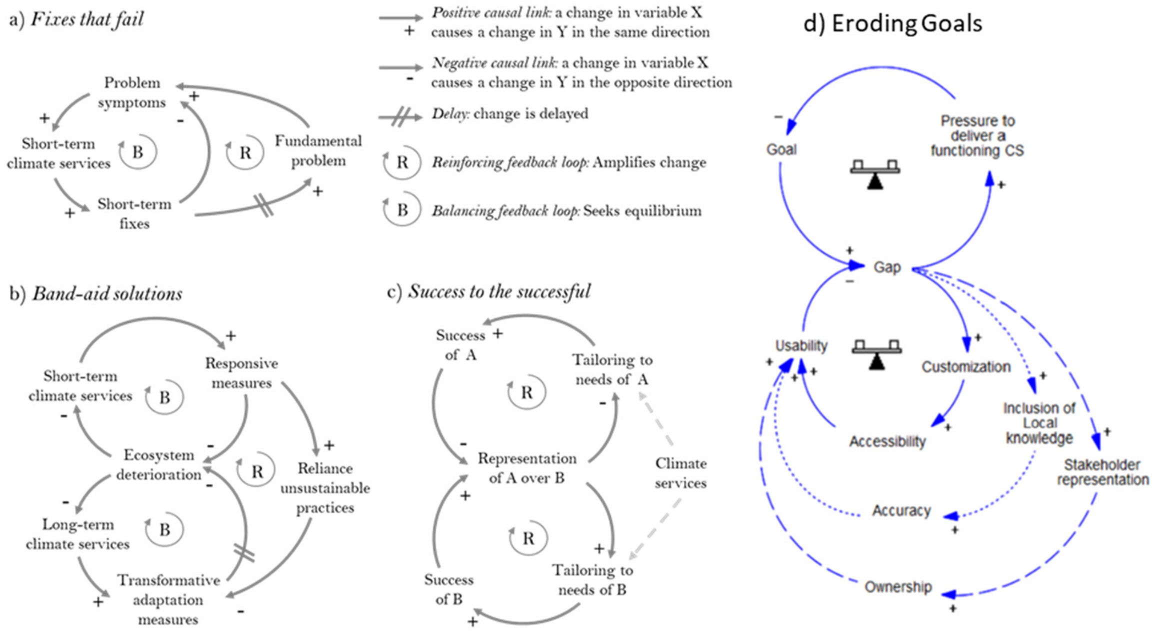

Figure 1.1. The four archetypes of the interaction between climate services and adaptation identified in Biella et al. (2024).

Work by Biella et al. (2024), undertaken as part of the I-CISK project, not only presents a comprehensive investigation into the potential for maladaptation resulting from the use of CSs, but also presents a novel framework grounded in system archetypes which can be used for the ex-ante assessment of maladaptive risk. The framework combines the use of archetype models with the Pathways to Maladaptation framework (Magnan et al., 2016). This integration enables the identification of potential maladaptive effects prior to the deployment of CSs, offering practical guidance for adaptation managers and CS developers. The assessment framework includes key indicators such as the risk of increased resource exploitation, burden shifting to vulnerable groups, and loss of long-term adaptive capacity.

Overall, Biella et al. (2024) call for a rethinking of CS development and evaluation. They urge that CSs be seen not as inherently positive tools, but as interventions that must be systematically assessed for unintended consequences. By combining theory with grounded empirical research, the paper contributes significantly to our understanding of how to design CSs that support sustainable and equitable adaptation. The research underscores that maladaptation is not only possible but always present; and even likely when CSs are often narrowly designed, overly focused on short-term gains, or developed without equitable stakeholder engagement. The integration of maladaptation risk assessment into CS development is essential for ensuring that these tools contribute to sustainable and equitable adaptation. Over-reliance on short-term services can entrench unsustainable practices, delay transformative change, and deepen existing inequities. Biella et al. (2024) shows how a systemic approach to CS development requires:

- Attention to feedbacks and cross-scale interactions.
- Inclusion of diverse stakeholder perspectives to mitigate inequality.
- Balance between short-term utility and long-term resilience.

Failure to assess maladaptive risks may result in climate services that, while successful in immediate uptake, ultimately undermine the adaptive capacity they aim to support. Therefore, maladaptation risk assessment should be a foundational component of CS design and evaluation processes across all LLs of the I-CISK project and beyond.

The Italian Living Lab (LL) is located in the Emilia-Romagna region, one of Italy’s most agriculturally productive areas and a hub of agri-food exports (Masih, 2022). The region has a high density of small- to medium-sized farms, many of which depend on intensive irrigation and are vulnerable to climate change, particularly recurrent summer droughts (Masih, 2022). Water resources are increasingly contested among agriculture, ecosystems, and tourism, raising concerns about long-term sustainability.

Stakeholders identified a reliance on short-term reactive measures to cope with drought, such as emergency irrigation support and infrastructural expansion, often guided by seasonal climate forecasts. These responses have helped buffer immediate impacts but may reinforce overdependence on increasingly scarce water supplies (Biella et al., 2024). This behaviour corresponds to the "Band-Aid Solutions" archetype—where repeated short-term fixes address symptoms without tackling root causes—leading to potential path dependency and vulnerability lock-in (Biella et al., 2024). The Italian LL therefore provided an appropriate context for developing a synthetic model that captures this maladaptive dynamic and explores alternative adaptation pathways.

The synthetic model developed for the Italian LL builds directly upon the methodology, data collection, and analysis carried out by Biella et al. (2024). In their work, Biella et al. combined qualitative data from five I-CISK LLs with system dynamics principles to identify recurring patterns of maladaptation, including the Band-Aid Solutions archetype. We translate the conceptual system archetypes into a synthetic quantitative socio-hydrological model (Fig. 3.2). This extends the conceptual models in Biella et al. (2024) by introducing formalized state variables, decision rules, and climate service indicators, allowing for dynamic simulations of how decision-makers respond to evolving climate signals, resource conditions, and economic incentives. The objective of the model is to formalise the archetype in order to create a platform for testing hypotheses, assessing policy alternatives, and exploring tipping points in maladaptive processes.

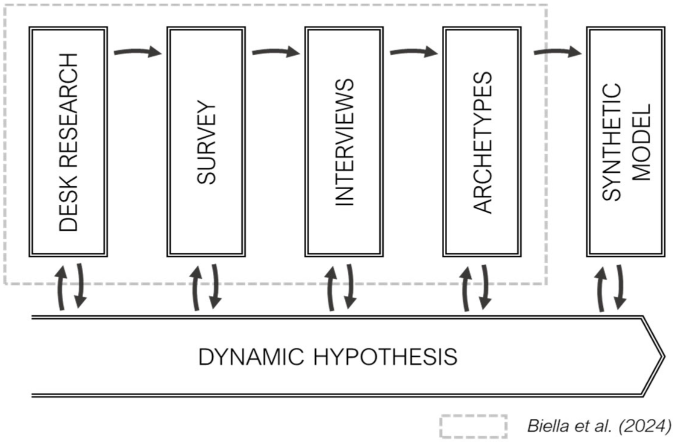

Figure 3.2. Methodology used for the development of the synthetic model for the Italian LL. Note how it is built upon the methodology used for the paper Thinking systemically about climate services: Using archetypes to reveal maladaptation by Biella et al. (2024).

The model is a stylized representation of a managed agricultural catchment with limited water resources and competing land uses. It comprises a range of dynamic variables:

- **Water Volume (V)**: Represents the stored water available for irrigation, influenced by annual recharge and extractions.
- **Reservoir Capacity (Vmax)**: The physical limit to how much water can be stored, this variable can only increase and is expandable through short-term response measures.
- **Agricultural Land Share (UP)**: The fraction of land dedicated to intensive, irrigated agriculture.
- **Ecological Restoration Share (EcoRest)**: The remaining land dedicated to non-agricultural use, such as restored ecosystems that require less water.
- **Wealth (W)**: A synthetic indicator of economic output from both agricultural production and ecosystem services, net of reservoir maintenance costs.
- **Bias Short and Long Term (BiasS and BiasL)**: Two parameters governing whether decisions prioritize short-term or long-term climate information.
- **Replenishment (R)**: The water input from precipitation, generated stochastically to simulate seasonal variability and long-term trends.

A unique feature of the model is its integration of synthetic CSs. The FSCS (Focus on Short-term Climate Services) index is computed annually based on a comparison between the current year's recharge and a moving average of recharge in recent past years. A significant drop in recharge increases FSCS, simulating the urgency conveyed by seasonal forecasts during dry spells. The FLCS (Focus on Long-term Climate Services) index is calculated by comparing the projected average recharge for the coming decades against a historical baseline, representing the emergence of a long-term drying trend. While FSCS reacts sharply to short-term fluctuations, FLCS evolves gradually over time. These synthetic indices translate climate signals into decision-relevant metrics that inform whether the model agent should prioritize immediate infrastructural responses or transformative adaptation strategies.

- **FSCS (Focus on Short-term Climate Services)**: Reflects reliance on seasonal climate forecasts by comparing the recharge for the upcoming year with the historical average. It increases during dry years and triggers short-term infrastructural responses, such as expanding the reservoir.
- **FLCS (Focus on Long-term Climate Services)**: Encodes attention to long-term climate change signals by comparing the predicted average recharge for the upcoming 50 years with the historical average. Through its outlook on climate change, it influences transformative adaptation strategies, such as shifting land from agriculture to restoration.

FSCS is highly variable and responds to recent seasonal deviations in rainfall, simulating the volatility of short-term forecasts. FLCS evolves more smoothly, capturing decadal-scale climate signals. Together, these metrics operationalize how different types of climate information shape decisions.

By explicitly linking climate information to adaptation choices, the model enables exploration of feedbacks, thresholds, and maladaptive lock-ins under varying decision-making paradigms. Its simplicity supports transparency and experimentation while retaining the core dynamics observed in the context of the Italian LL.

While simplified, the synthetic case is calibrated to reflect dynamics observed in the Italian LL and is largely similar to the Italian LL in size and recharge. Key characteristics include:

- A water-limited agricultural system dependent on seasonal irrigation.
- The presence of a reservoir with finite capacity and maintenance costs.
- Competing land uses, where restoring land reduces immediate revenue but increases long-term sustainability.
- A decision-making agent (representing collectives or authorities) who chooses between expanding infrastructure or shifting land use based on climate information.
- Physical dimensions, climate, and projected climate change similar to those of the Italian LL.

The model replicates the Italian context by assigning higher economic returns to irrigated agriculture than to ecological restoration, reflecting real-world incentives. Seasonal rainfall variability is introduced through a stochastic recharge function, with long-term drying trends to simulate climate change. CSs influence adaptation choices via the FSCS and FLCS indicators, whose parameters are tuned to reflect available information sources in the region (e.g., seasonal forecasts vs. regional climate scenarios).

This setup enables us to abstract core dynamics without replicating all real-world complexities, thereby preserving analytical clarity while maintaining relevance to the Italian LL. It serves as a “learning laboratory” for testing how different CS framings influence decisions and long-term outcomes.

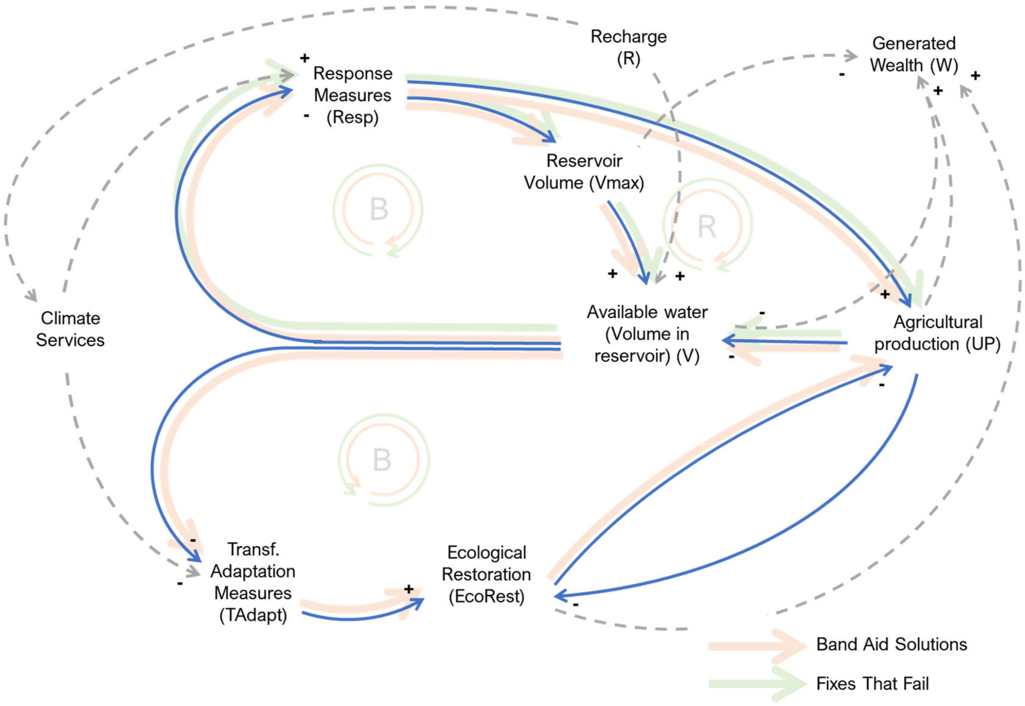

Figure 3.3. Causal Loop Diagram showing the functional representation of the model.

The synthetic model provides a versatile tool for examining the implications of maladaptive decision-making in agricultural water systems. Key experiments and applications include:

- **Policy Scenario Exploration**: The model can simulate the impact of interventions, such as subsidies for restoration, penalties for over extraction, or enhanced long-term forecasting, helping to evaluate their influence on system trajectories. These scenarios can be an application of the as ex-ante assessment of maladaptation risk discussed in the previous section. By simulating future pathways under different decision rules and climate inputs, the model enables foresight into potential maladaptive outcomes.
- **Sensitivity Analyses**: Parameters such as irrigation efficiency, recharge variability, or maintenance costs can be varied to assess tipping points or nonlinear effects. This can identify thresholds beyond which the system flips into undesirable regimes.
- **Learning and Education**: The simplicity and transparency of the model make it ideal for stakeholder workshops, allowing users to explore consequences of decision-making in a safe, controlled environment.

These tests are valuable not only for researchers but also for practitioners and decision-makers seeking to understand how institutional preferences, climate information, and resource constraints interact to shape long-term sustainability.

Preliminary simulations using the synthetic model suggest that strongly short-term oriented adaptation strategies—characterized by a high reliance on seasonal forecasts—can lead to rapid economic gains in the initial years but result in long-term instability (Fig. 3.4a and Fig. 3.4b). These trajectories often exhibit cyclical crises, reservoir depletion, and ultimately, system collapse due to over-expansion of irrigated land and mounting infrastructure costs. By contrast, scenarios guided by long-term climate services favour slower economic growth but yield more stable and resilient outcomes (Fig. 4c). These include sustained reservoir levels, fewer drought-induced shocks, and higher shares of restored land.

The most maladaptive outcomes occur when institutional preferences are heavily biased toward immediate action and short-term rewards. Under such conditions, repeated short-term responses create reinforcing feedbacks that amplify vulnerability and degrade long-term adaptive capacity. The model also illustrates potential regime shifts: after prolonged collapse, systems may transition into more sustainable but less productive configurations dominated by ecological restoration (Fig. 3.4a).

Taken together, these findings highlight the crucial role of information framing and decision-making horizons in shaping adaptation outcomes. They demonstrate that maladaptation can emerge not only from poor design but also from excessive reliance on short-term information, even when that information is accurate and timely. This underscores the need for CSs that align with long-term resilience goals.

Maladaptation is inherently difficult to study because it unfolds over long timescales and often emerges from well-intentioned actions. Traditional monitoring tools may miss slow-building risks, and ex post evaluations are limited by path dependency. Models like the one presented here fill this gap by offering foresight into how today's decisions affect tomorrow’s vulnerabilities.

By combining system dynamics with insights from climate service studies, the model captures essential features of socio-ecological feedbacks. It formalizes intuitive archetypes like Band-Aid Solutions and makes them testable. Moreover, it highlights the importance of information framing: the same physical system can evolve differently depending on which signals are emphasized and how decision-makers interpret them.

In summary, this modelling approach offers a flexible, robust framework for investigating long-term maladaptation. It helps bridge theory and practice, supports ex-ante risk assessment, and informs the design of climate services that foster—not hinder—transformative adaptation. As climate variability increases and adaptation becomes more urgent, such tools are indispensable for exploring the potential for climate adaptation actions leading to unintended consequences.

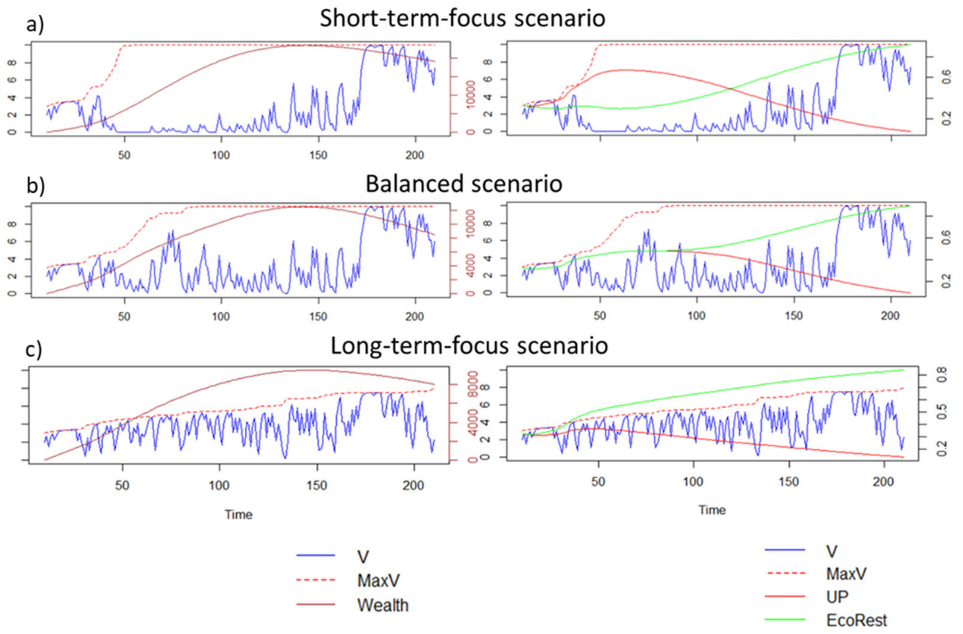

Figure 3.4. Outcome of the three scenarios based on the type of climate services used, namely: mostly long term, mixed (50% of each type); and mostly short term. Each scenario displays the main systemic variables of: reservoir volume (V); maximum reservoir volume (MaxV); Wealth (W); fraction of the catchment under agricultural production (UP); and fraction of the catchment under ecological restoration (EcoRest).

4 Climate Services based expectations and groundwater dynamics

System Dynamics (SD) methods enable us to understand feedbacks between socioeconomic and physical systems and the effects that external factors can have on those systems. Causal loop diagrams (CLDs) are commonly used diagramming tools in SD and are often employed to develop a preliminary dynamic hypothesis (Elsawah et al., 2017). In the Los Pedroches LL in Andalusia, Spain, we developed two CLDs to explore the effect of CS information on livestock production decisions and their effect on the physical system. The design of the CLDs was based on extensive interactions with local stakeholders throughout the project duration.

Los Pedroches-Andalusia LL

The Los Pedroches-Andalucia LL covers a rural region in the Northern part of Córdoba (Spain) (Figure 4.1). It is home to around 52,000 residents. One of the main landscapes in the area is the *dehesa*, which is a landscape defined by gently rolling hills and shallow soils that lie atop granite bedrock. In this area, water sources for both livestock and wildlife primarily come from groundwater-fed seasonal streams, traditional wells and, more recently, deep boreholes. The granite-based terrain underlying the *dehesa* contains a shallow, fractured, and varied aquifer system, which is replenished by rainfall.

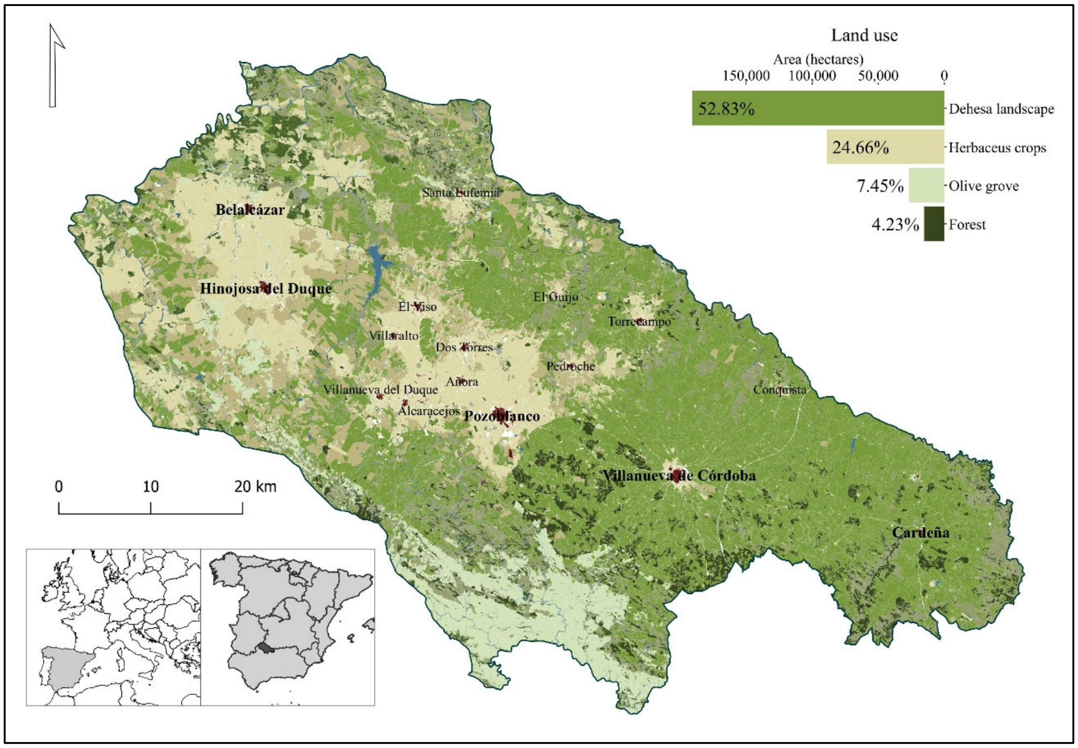

Figure 4.1. Case study location and main land uses (modified from Ropero Szymañska et al., 2025).

To assess bi-directional feedbacks between adaptation actions and climate service information, we focused on how local livestock sector interacts with the local groundwater system and how the provision of (reliable) seasonal (6-month lead time) forecast for temperature and rainfall can impact farmers' decisions. The goal of the assessment is to explore how water table levels respond to changes in farmer decisions resulting from decreased uncertainty about temperature and precipitation in the following months because of improved CS.

Livestock-farming Production Systems

The Los Pedroches region represents the largest livestock farming area in Andalusia (Broekman et al., 2022), where most farms are family-owned (ADROCHES, 2021). Livestock use is related to two main sectors, milk and Iberian pig meat production. As a primarily rainfed production system, its sustainability is particularly vulnerable to droughts and heat waves, and is threatened by the increasing intensity and duration of these climatic hazards.

Iberian pigs are reared based on a combination of acorns and pasture or other complementary feeds. The percentage of acorns in the pigs' diet is closely linked to the final market value of their meat, with products from Iberian pigs that are mainly acorn-fed being especially prized. The season when acorns fall from the oaks and are consumed by the pigs—usually October and November—is referred to as the *montanera*. The number of piglets bred or acquired by the farmers every year in the fall depends on the expectations of acorn production and water availability in the following year. This, in turn, depends mainly on spring rainfall and temperatures.

Milk production, by contrast, is more controlled, as dairy cows primarily eat fodder and can breed any time of the year. Milk cows consume 100-150 litres of water per day, with total volume varying in response to the reproductive cycle, external temperatures and type of feed. The aim of farmers is to have stable milk production throughout the year, managing heat waves or prolonged high temperatures that negatively affect milk production. On a standard dairy-only farm, farmers' decision-making focuses on how to balance food provision from local winter cereal production and purchase of corn-based fodder from external sources and ensure sufficient water supply (Iglesias et al., 2016).

Rainfall is the main water resource for livestock farming and is harvested directly through livestock ponds, or indirectly through shallow wells or boreholes. In an average hydrological year, the rainy season matches the period of the lowest water demand, summer being the highest water demand period. As intermittent rivers common to the region dry up naturally during summer and rainfall is reduced, groundwater becomes the main water source during the dry season. During drought periods, groundwater-dependence increases, extending into spring and autumn, sometimes becoming the only water source throughout the year in severe drought years. In extremes cases, famers must buy water that is brought in by water tanker from external sources to complement local water resources (Ropero Szymañska et al., 2025).

Decision making context

The CLDs developed for Los Pedroches LL builds directly upon the data collected through two workshops, two focus groups and seventeen in-depth interviews with livestock farmers (see Ropero Szymañska et al., 2025), held between October 2022 and November 2023. To reflect the sequencing of livestock farmers' decisions, their production activities were summarised along two decision timelines, one for Iberian pigs and one for dairy cows (for more details, see van den Homberg et al., 2023).

Livestock farmers are constantly making management decisions on their farms but there are times of the year when decisions are particularly critical. For both types of livestock, early autumn (October) is a key moment for planning the production for the following year based on the farmer's expectations of the forthcoming months in terms of precipitation and temperature, among other considerations.

In absence of CS, farmers will make decisions based on experience and their own intuition about the climatic conditions in the forthcoming months. With sufficiently reliable CS information, decisions will be made for a less uncertain future. In this context, we modelled two possible scenarios for CS predictions provided in October of a given year:

- **Scenario A**: Average/wet conditions in the forthcoming 6 months (winter-spring).

- **Scenario B**: Dry conditions in the forthcoming 6 months (winter-spring).

Under these two scenarios, we modelled the potential impact of the farmers' actions in response to the information provided by the CS on the physical system, more specifically on the local water table levels and their recovery time at the end of the summer season each year. The model comprises three types of dynamic variables:

- **Climate related expectations** (grey in Fig. 4.2 and 4.3), i.e. how farmers expect the incoming 6 months to be in terms of accumulated precipitation and evolution of temperatures.
- **Production-related decisions** (orange), these refer to:
  a) number of hectares to be seeded with winter cereals to be used as fodder for milk cows;
  b) number of tons of maize-based fodder to be purchased to complement winter cereals (milk cows)
  c) number of Iberian piglets that farmers plan to have in the following *montanera* (acorn grazing for pig fattening);
  d) number of cows that will be inseminated, as a function of milk production needs (cows have the peak of milk production approximately two months after giving birth).
- **Physical variables** (blue), these refer to:
  a) Total water demand
  b) Duration of groundwater abstraction
  c) Duration of surface water supply
  d) Volume of abstracted groundwater
  e) Water table decrease
  f) Long-term health of oak trees

Causal Loops Diagram for Scenario A (normal/wet conditions)

In Scenario A (Figure 4.2), the model hypothesis that in October of a given year, farmers have the following **climate-related expectations**, based on their observations and confirmed by CS information for the following 6 months:

a) All the rainfed arable land that will be seeded with winter cereals in autumn will yield a good harvest in spring/early summer of the subsequent year. Acorn production for the *montanera* will be good in the following autumn, as acorn production is positively impacted by a wet spring.
b) With sufficient winter and spring rainfall to recharge the aquifer and the groundwater-dependent streams, surface water supply for livestock farming will be sufficient to last until the end of spring. Groundwater pumping is expected to be necessary only during the summer, when streams and ponds dry up.

The **production-related decisions** associated to those expectations will be:

a) Farmers will plant the maximum available arable land with (rainfed) winter cereals for animal feeding, to be harvested in spring/summer. This option is preferable to farmers to using maize based fodder.
b) Farmers will minimize the purchase of maize-based complementary fodder as they count on an abundant cereal harvest for the incoming year.
c) Farmers will not store groundwater in tanks in winter and spring as they expect to have sufficient surface water for the supply until end of spring.
d) Farmers will maximize the number of livestock animals in anticipation of abundant cereal harvest (milk cows) and acorn (Iberian pigs), limited or no heatwaves (milk cows) and a favourable hydrological year.

The **physical variables** will respond as follows to those decisions:

a) Total water demand will increase because of the maximization of livestock load.
b) As a result of a), surface water supply may last less than usual.
c) As a consequence of a) and b), groundwater pumping will be more intense in time, causing sharper decreases in the water table.
d) As a result of c), in the groundwater levels will take longer to recover in autumn, and even more so in case of a dry winter/spring in the following hydrological year. This, in turn, will negatively affect the surface water supply, as local streams are rain- and groundwater-dependent.

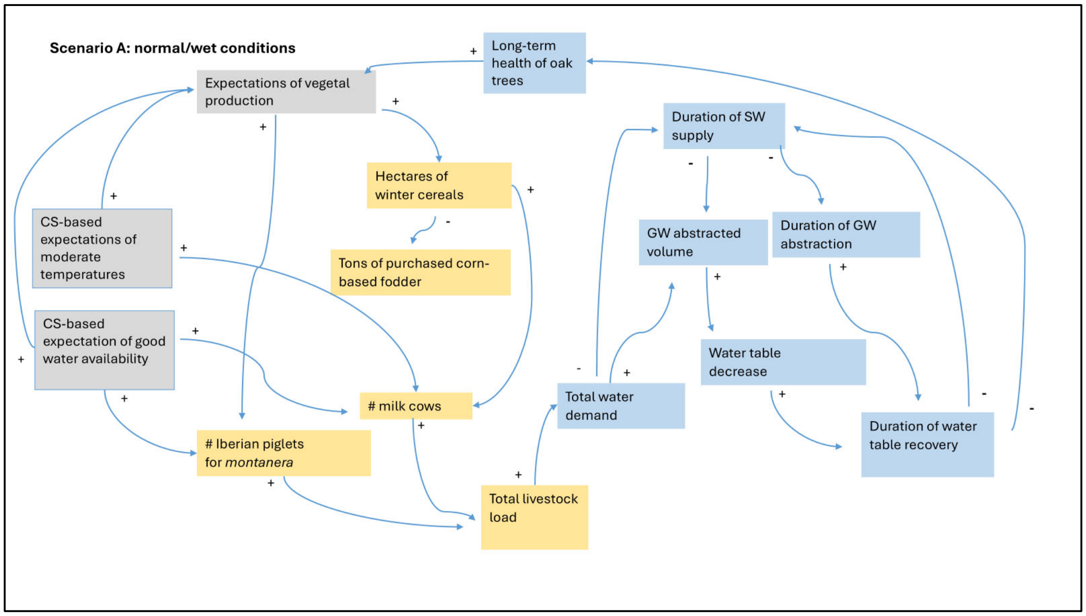

Figure 4.2. CLD of Scenario B (normal/wet conditions).

Scenario B (dry conditions)

Under this Scenario (Figure 4.3), the model hypothesizes that in October of a given year, farmers have the following **climate-related expectations**, based on their observations and confirmed by CS information for the following 6 months:

a) Rainfed production of winter cereals will fail due to insufficient rains during the following winter and spring; and acorn production for *montanera* in the following autumn will be scarce due to insufficient spring rains.
b) Rainfall recharge of the aquifer and streams will be limited, thus reducing surface water availability for livestock farming in winter/spring and limiting the recovery of water table levels during the winter.

The **production-related decisions** associated to those expectations will be:

a) Farmers will plant little or no (rainfed) winter cereals for animal feed. Instead, they will place orders to purchase maize-based fodder produced outside the region. This will increase their operational costs.
b) Farmers will need to rely on groundwater for their operations since early spring (or when streams run dry) and will implement measures to ensure on-farm water access during the summer, e.g. by increasing groundwater abstraction points, by pumping water all year round and storing it in local tanks and ponds. This will increase their operational costs due to construction of wells/boreholes

and increased energy costs. Moreover, they may need to buy water brough in by water trucks at the end of the dry season

c) Farmers will maintain or reduce the number of livestock heads in order to maximize meat and milk production while limiting extra costs due to unfavourable weather conditions (low rainfall and high temperatures).

The **physical variables** will respond as follows:

a) Total water demand will decrease because of the reduction in livestock load.
b) Because of the dry conditions surface water supply will last less than usual.
c) As a result of b), groundwater pumping will be more intense and distributed in time, causing sharper decreases in the water table levels.
d) As a result of c), groundwater levels will recover slowly and even more so in case of a dry winter/spring in the following hydrological year. This, in turn, will negatively affect the surface water supply, as local streams are rain- and groundwater-dependent.

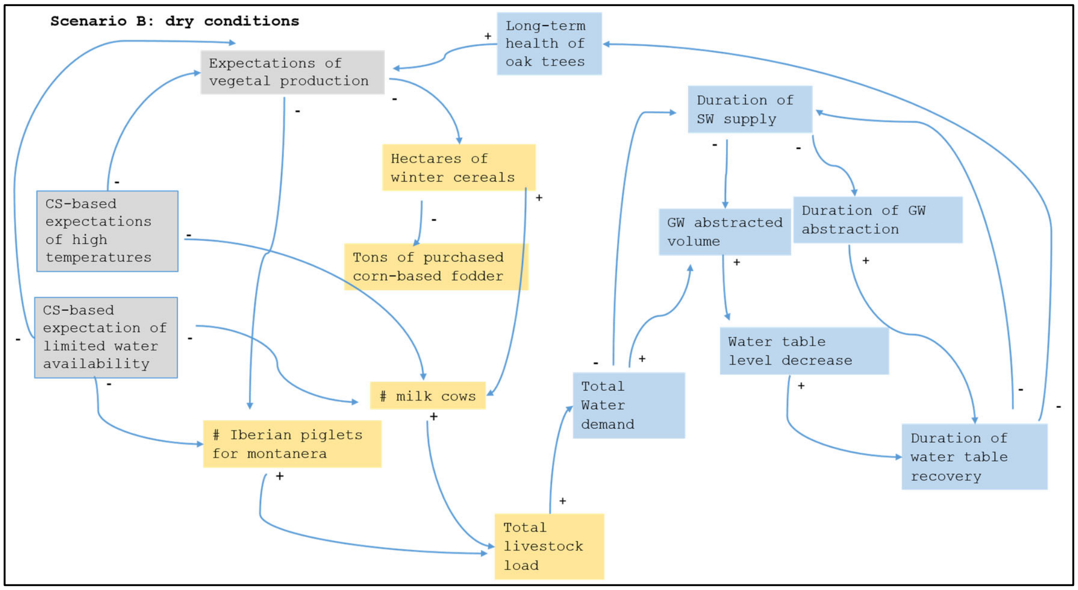

Figure 4.3. CLD of Scenario B (dry conditions).

Impact of CS-informed decisions on groundwater dynamics

Figure 4.4. and 4.5 depict a synthetic evolution of water table levels under Scenarios A and B during two consecutive years, to illustrate the effects of decisions in a context of potential multiannual droughts, which is typical of the LL climate. The evolution of the water table is shown for a context with (dotted lines) and without (solid lines) enhanced CS to inform farmer's decisions.

In Scenario A (wet period), we observe that higher certainty about water availability for the forthcoming months due to reliable CS information is likely to initially produce a positive effect on the aquifer because farmers will avoid unnecessary and expensive groundwater pumping and storage in winter. However, the knowledge of favourable climate conditions is also likely to generate an increase in total water demand associated with the breeding of a higher number of livestock animals. As a result, groundwater levels will start to decline in late spring – earlier than without improved CS, when no additional livestock would be added to the system – and the decline will be more pronounced due to higher total water demand. This may locally generate risk of wells temporarily drying up and the need for some farmers to purchase (expensive) water trucks to ensuring the viability of their famers' operations. If the aquifer recharge generated by the autumn rains of the following year is also average or high (line c), the water table recovery will be slower than without CS (line a) but will enable the system to recover by mid-winter. Nevertheless, if the subsequent year is dry (line d), this could cause the system to start a dry period with unfavourable conditions, generating negative consequences, as there will be less water availability for farming operations, and because abnormally long periods of low groundwater levels negatively affect the long-term health of holm oaks and the associated acorn production.

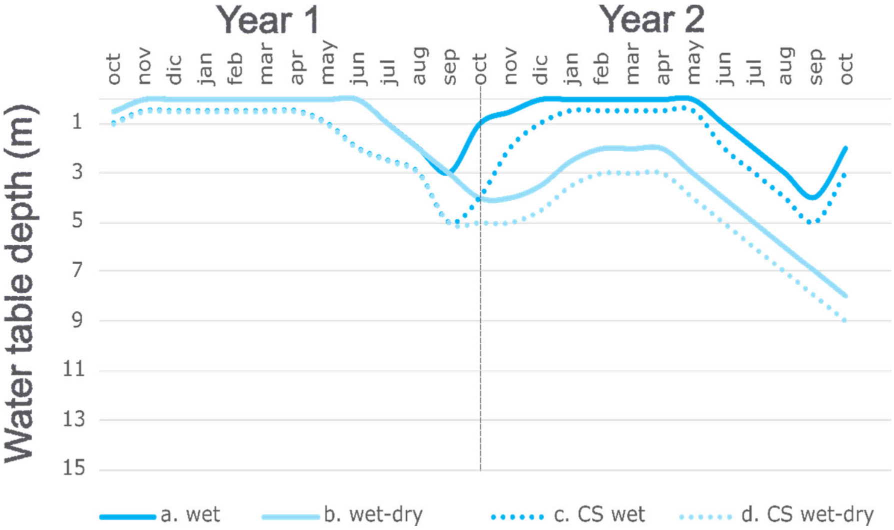

Figure 4.4. Effects on the groundwater system during a wet period (Scenario A).

In Scenario B (a in Figure 4.5), farmers will prepare for a dry and hot year by reducing the livestock load and by pumping groundwater. While the first decision will have a positive effect on the water table levels because it implies decreasing the total water demand, the increased pumping and longer pumping periods will result in lower water table levels for a longer period of time and in a larger portion of the aquifer. This will reduce even more the time surface water will be available in groundwater–dependent streams and will increase the time needed for the aquifer to recover at the end of the summer.

The effects of the dry year will be felt in the aquifer both in the case of a wet/average year (line b) or a second dry year (line a), and water table levels may not be able to recover sufficiently as to feed temporary streams in late winter and early spring. This, in turn may trigger a new cycle of groundwater pumping sustained in time even if hydrological conditions are more favourable than during the previous year, with the subsequent negative consequences for the natural system and the viability of livestock farms due to increased operations costs.

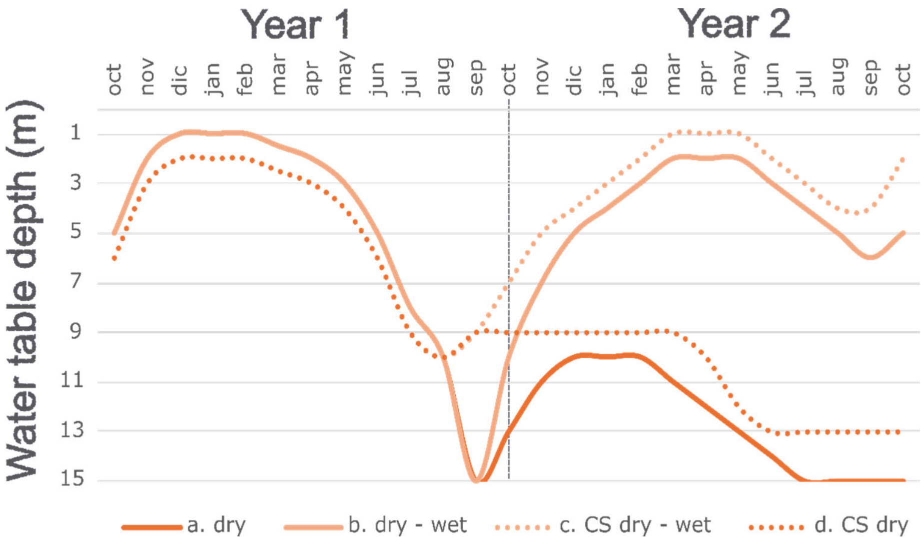

Figure 4.5. Effects on the groundwater system during a dry period (Scenario B).

Short-term impacts from the use of climate services depend on the weather conditions in the subsequent years. In this sense, climate services can potentially increase future vulnerability when they predict a favourable (wet) conditions, as this could trigger actions such as increased livestock stocking, which increases total water demand. Predictions of dry conditions can help groundwater systems to recover more quickly as it triggers contention of groundwater use in absolute terms.

5 Power asymmetries

The Greek Living Lab (LL4) of the I-CISK project is situated on Crete, the largest Greek island and a critical economic hub, particularly for tourism (Masih et al., 2022). The region is highly vulnerable to climate change, with projections indicating significant increases in temperature (up to 4.4°C under RCP8.5 by 2100) and decreases in precipitation (up to 27.1%) (Georgoulias et al., 2022). These changes will intensify risks such as droughts, water scarcity, floods, and coastal erosion (AQUAMAN project, 2017).

Tourism, the primary sector in the area, significantly contributes to Crete's economy but is intricately linked to other vulnerable sectors including water management, energy, and transportation infrastructure. Water scarcity, in particular, poses a critical threat to tourism by affecting guest experiences, energy production, and food security (Masih et al., 2022).

Despite the cross-sectoral nature of climate risks, existing governance structures, resource allocations, and CS development processes often favour tourism at the expense of secondary sectors such as agriculture or marginalized communities (CCISC, 2011; Masih et al., 2022). This entrenched sectoral prioritization may amplify vulnerabilities and constrain adaptive capacity, particularly in resource-dependent sectors like agriculture. Figure 5.1 demonstrates the historical and projected water exploitation indices at basin level.

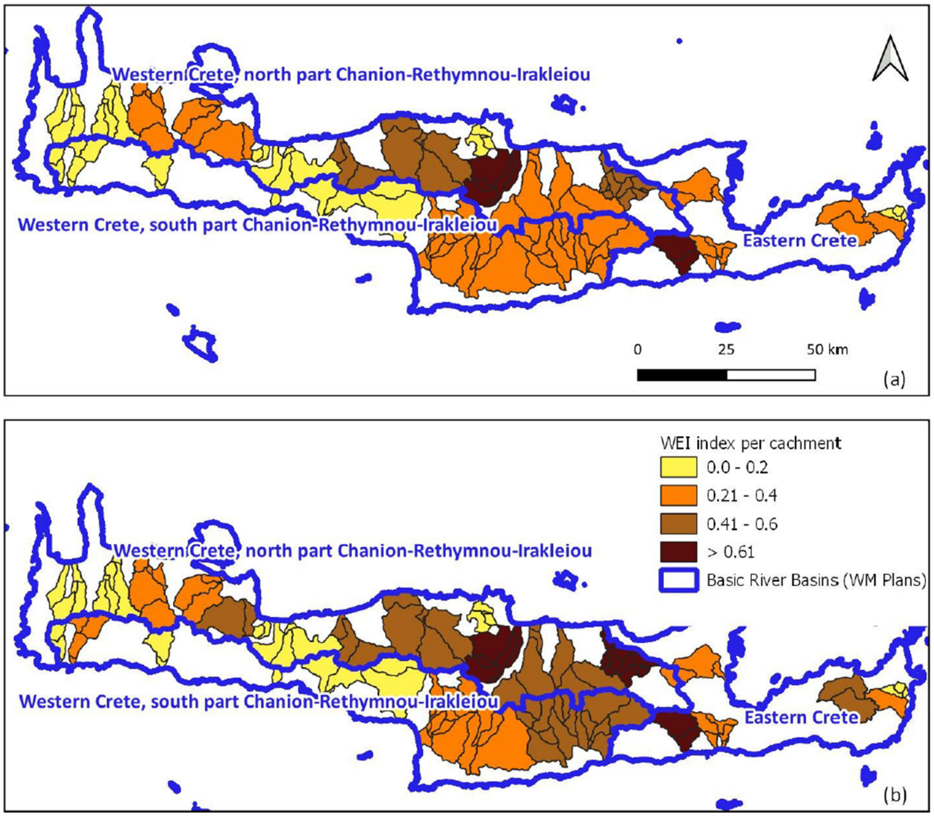

Figure 5.1. Water exploitation index at basin level in Crete: (a) Reference period 1983-2009, and (b) projected period (2040-2059) – adopted from (Ziogas & Tzimas, 2022).

Recognizing these interdependencies, the Island of Crete seeks to advance next-generation CS products that account for multi-sectoral needs, reduce systemic vulnerabilities, and promote equitable adaptation.

A system dynamic modelling approach was developed to investigate how stakeholder power imbalances influence the development, accessibility, and effectiveness of CS, using Crete as a case study (Wamucii et al., 2025). The model conceptualized the human-environmental system as comprising five interconnected sectors: tourism, water, energy, transport, and agriculture. The model integrated climatic inputs, sectoral adaptation capacities, resource demands, and feedback loops to simulate sector-specific outcomes and overall system sustainability (Fig 2).

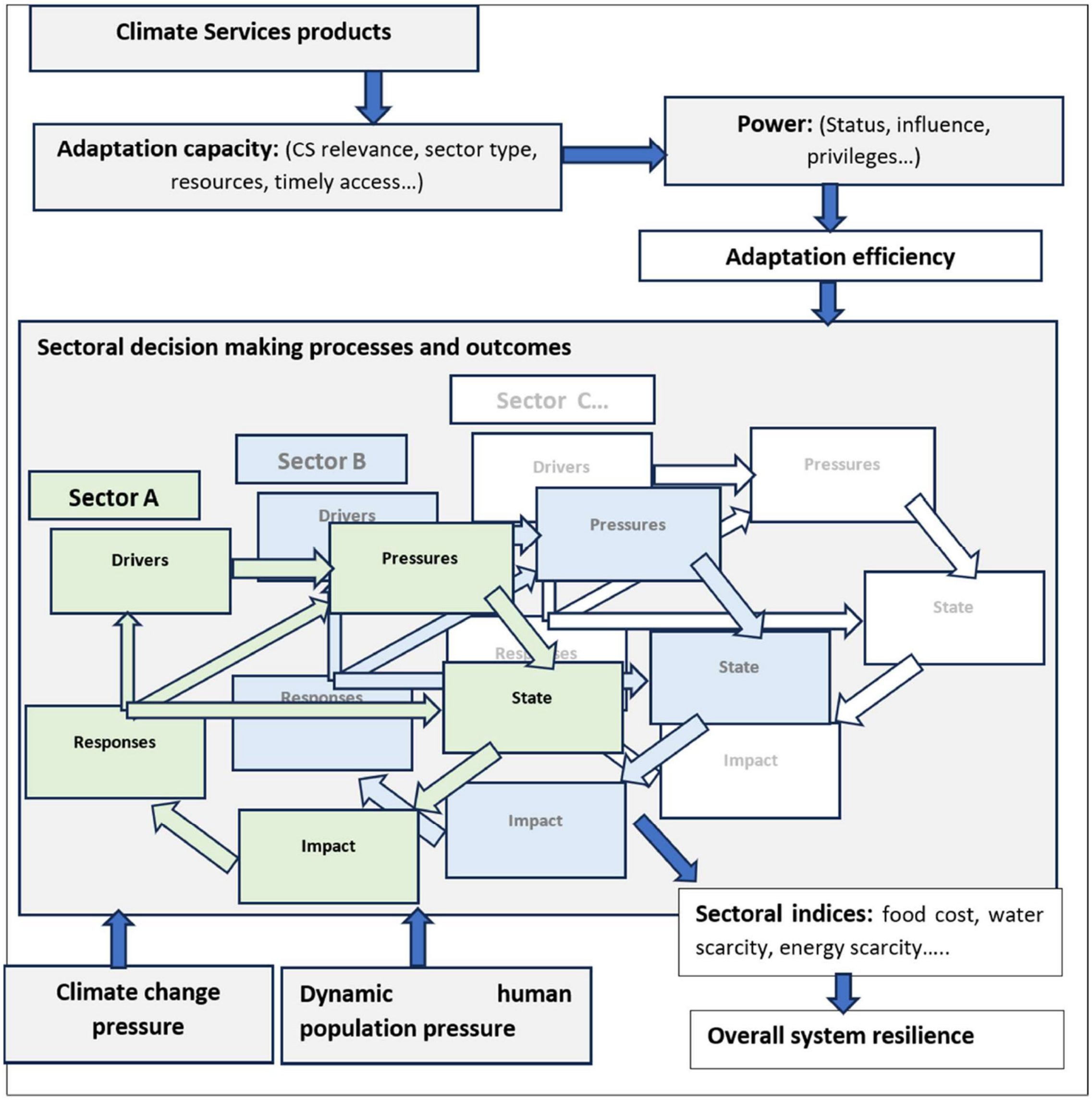

Figure 5.2. The conceptual framework – adopted from (Biella et al., 2024). The different colours represent the concept of multi-sectors i.e. sector A, B, C etc.

Crucially, the model incorporated power asymmetries by quantifying sectoral adaptive capacities based on: sector type (primary, secondary, non-targeted), relevance of CS, timely access to CS, proximity to CS providers, resource availability for adaptation, legacy climate information (existing climate knowledge). Power imbalances are formalized as weighted adaptive capacities influencing access to resources, prioritization in decision-making, and sectoral benefits from CS. The model explores three scenarios:

1. **Mono-sector**: CS targets only one sector, in this case tourism as the primary sector.
2. **Multi-sector**: CS follows hierarchical sector prioritization (tourism as primary, water/energy/transport as secondary, agriculture as non-targeted).
3. **Equi-sector**: All sectors have equal priority and access to CS.

More details on the model description, and assumptions are provided in (Biella et al., 2024). Data sources included I-CISK reports, regional climate projections, stakeholder inputs, and literature. Vensim software was used for model execution, with participatory validation involving living lab scientists and sector stakeholders (Wamucii et al., 2025).

The analysis of the three scenarios revealed significant power asymmetries among various stakeholders. In the mono-sector scenario, in which the tourism sector was identified as the exclusive primary sector and all other sectors were categorized as non-targeted, the simulated power influence of the tourism sector was markedly high (Fig. 3). In contrast, the multi-sector scenario showed a decrease in the power influence of the tourism sector, accompanied by a slight increase in the power influence of both the transport and water sectors, while the power influence of the energy sector exhibited a marginal decline. Conversely, the non-targeted agricultural sector experienced further suppression of its power. In the equi-sector scenario, which posited that all sectors were considered primary, a more equitable distribution of power among the sectors was observed, indicating that no individual sector exhibited disproportionate power within this theoretical framework.

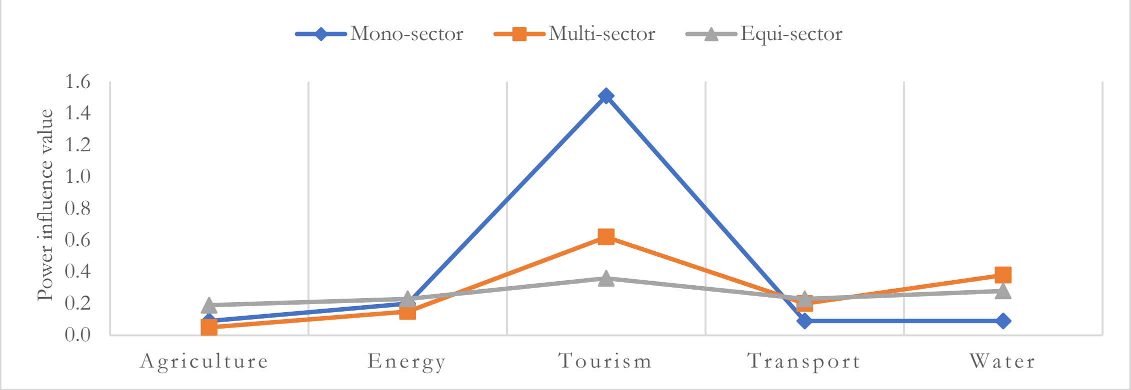

Figure 5.3. Simulated sectoral power influence.

To evaluate the impact of the power influence changes across the three scenarios, the sectoral resources were used as proxy indicators. In the mono-sector scenario, the tourism sector was simulated to have the higher numbers of tourists compared to multi-sector and equi-sector scenarios. With high numbers of tourists, the energy availability, food availability, and water storage capacity were simulated to have minimal values (Fig 4). According to Wamucii et al., (2025), the food production is simulated to be low, as the 'non-targeted' sector such as agricultural sector has minimal power influence in regard to water resources distribution, reducing food production capacity

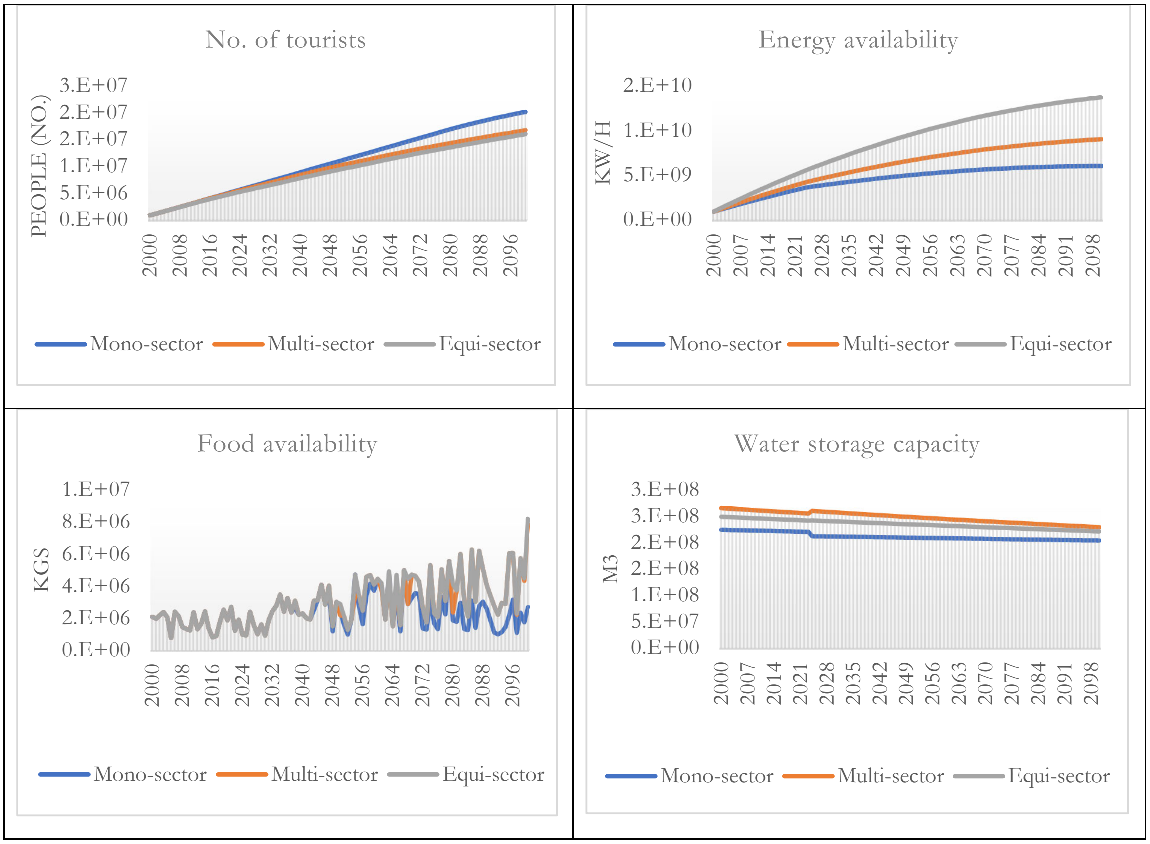

Figure 5.4. Simulated sectoral resources.

In the mono-sector scenario, the prioritization of a single sector, such as tourism, serves to amplify sector-specific advantages (for instance, an increase in tourist numbers). However, this approach concurrently intensifies vulnerabilities within the water, energy, and agriculture sectors, thereby heightening systemic risk. Consequently, the overall vulnerability of the system is exacerbated, increasing the likelihood of cascading failures across interconnected sectors. Conversely, the multi-sector scenario aligns with the dynamics observed in the current Crete living lab, where secondary sectors derive benefits from climate services (CS) yet continue to encounter constraints in adaptation. Agriculture, categorized as a non-targeted sector within this framework, faces significant resource scarcity and exhibits limited capacity for adaptation. In the equi-sector scenario, an equilibrium of power and equitable access to climate services across all sectors yields the most favourable outcomes, fostering enhanced resilience and sustainability within the human-environmental system. This scenario notably results in reduced systemic vulnerabilities, improved security regarding water and energy resources, stabilized agricultural production, bolstered resilience of transportation infrastructure, and sustainable growth of the tourism sector (Wamucii et al., 2025). Furthermore, the model elucidates feedback loops whereby sectoral prioritization may engender self-reinforcing inequalities, often referred to as "Success to the Successful" dynamics, and can lead to unintended consequences such as resource scarcities within prioritized sectors.

The findings highlight the potential risks associated with reinforcing sectoral power asymmetries in the development of CS products, particularly in regions such as Crete, where tourism exerts significant influence over economic and policy priorities. If these imbalances remain unaddressed, they may compromise adaptation efforts, exacerbate resource competition, and diminish prospects for long-term sustainability. The development of CS products within narrowly defined, sector-specific frameworks can inadvertently intensify existing power disparities, increasing the likelihood of maladaptation and inequitable outcomes. Water scarcity, a persistent challenge in Crete, exemplifies how resource scarcity driven by entrenched power imbalances can constrain the adaptive capacity of marginalized sectors.

To mitigate these risks within the Crete Living Lab, it is essential to extend the Co-Co-Co (co-design, co-development, co-delivery) approach beyond its current tourism-centric focus, ensuring systematic inclusion of underrepresented sectors such as agriculture. Furthermore, integrating multi-sectoral systems thinking (such as system dynamics modelling) into CS co-design processes is critical for identifying trade-offs and anticipating cascading socio-environmental impacts. Equally important is enhancing the accessibility, relevance, and equitable distribution of CS products, particularly for stakeholders engaged in water and food production sectors. Revisiting and potentially restructuring CS governance mechanisms may also be necessary to reduce sectoral hierarchies and strengthen cross-sectoral climate adaptation.

Beyond the Crete living lab, these findings demonstrate that equitable CS development, grounded in participatory governance and inclusive knowledge co-production, can support the emergence of sustainable adaptation pathways. The approach developed here provides a transferable framework with applicability to other regions characterized by complex socio-environmental dynamics.

6 Conclusions

This Deliverable presents a suite of models of varying complexity developed by the I-CISK WP4 team to capture the bidirectional feedbacks between adaptation actions and climate service (CS) information. These models have been applied across diverse living labs, each characterized by different temporal and spatial scales.

The work conducted in WP4 reveals that climate services do not always yield "no-regret" solutions in the context of climate adaptation. On the contrary, their development and application can sometimes produce unintended consequences, including maladaptive outcomes. However, this report presents models and tools specifically designed to help anticipate and mitigate such risks, supporting more informed and adaptive decision-making processes.

This report also highlights the critical role of human behaviour in shaping the management of climate related risks, including drought. Adaptive responses to governance frameworks influence consumption, allocation, and ecological pressures across hydro-systems, yet they may also produce unintended, maladaptive consequences. Such outcomes underscore the need to carefully evaluate how risk is redistributed and to ensure that short-term coping strategies do not undermine long-term socio-ecological resilience.

Our findings underscore the critical influence of stakeholder power asymmetries in shaping the design, accessibility, and effectiveness of climate service products. In the Crete living lab, for example, the prioritization of the tourism sector—driven by its economic dominance—risks exacerbating vulnerabilities in other essential sectors, particularly those already marginalized in policymaking and resource distribution.

Achieving sustainable, system-wide climate adaptation requires the intentional integration of equitable approaches to CS development, grounded in inclusive and participatory governance. Addressing underlying power imbalances is essential to prevent climate service initiatives from reinforcing existing social and economic inequalities.

Stakeholder engagement must go beyond superficial consultation to ensure the meaningful inclusion of marginalized groups and "non-targeted" sectors in decision-making and co-production processes. However, the effective identification and involvement of relevant stakeholders cannot be achieved through the Co-Co-Co (Co-design, Co-production, Co-delivery) approach alone. This must be complemented by systems thinking methodologies, such as system dynamics modelling, which provide the analytical tools necessary to map and address complex interdependencies and power structures.

Ultimately, embedding climate service development within frameworks that explicitly recognise and address power differentials is vital for realizing their full potential as instruments of resilience-building and for promoting equitable adaptation outcomes.

References

AQUAMAN project. (2017). Integrated drought management study for the Region of Crete, Innovative Water Resources Management Methodologies regarding the Governance and Adaptation to Climate Change of the Region of Crete, Oct. 2016 (in Greek). AQUAMAN Project . https://aquaman.tuc.gr/images/users/sotiria/%CE%A0%CE%B1%CF%81%CE%B1%CE%B4%CE%BF%CF%84%CE%AD%CE%BF_1.pdf

ADROCHES. (2021). *Estrategia de desarrollo local de la comarca de Los Pedroches*. https://adroches.org/

Broekman, A., Comas, N., De Stefano, L., Hernandez-Mora, N., Pesquer, L., & Prat, E. (2022). *Characterization of the I-CISK Living Labs: Andalusia living lab, Spain*. I-CISK Project.

Barnett, J., & O'Neill, S. (2010). Maladaptation. Global Environmental Change, 20(2), 211–213. https://doi.org/10.1016/J.GLOENVCHA.2009.11.004

Biella, R., Wamucii, C. N., Mazzoleni, M., Baldassarre, G. Di, De Stefano, L., Henrndez, N., & Zapata, M. (2024). Bidirectional feedbacks between adaptation actions and climate service information, I-CISK Deliverable 4.5 ICISK, Human Centred Climate Services. https://icisk.eu/resources/

Biella, R. et al. (2024) Thinking systemically about climate services: Using archetypes to reveal maladaptation, Climate Services, 34, p. 100490. Available at: https://doi.org/10.1016/j.cliser.2024.100490.

CCISC. (2011). *The environmental, economic and social impacts of climate change in Greece. Climate Change Impacts Study Committee of the Bank of Greece*. Study Committee of the Bank of Greece. https://www.bankofgreece.gr/publications/ClimateChange_FullReport_bm.pdf

Elsawah, S., Pierce, S.A., Hamilton, S.H., Van Delden, H., Haase, D., Elmahdi, A. and Jakeman, A.J. (2017), "An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies", Environmental Modelling and Software, Vol. 93, pp. 127–145, doi: 10.1016/j.envsoft.2017.03.001.

Eriksen, S., Aldunce, P., Bahinipati, C. S., Martins, R. D. A., Molefe, J. I., Nhemachena, C., O'Brien, K., Olorunfemi, F., Park, J., Sygna, L., & Ulsrud, K. (2011). When not every response to climate change is a good one: Identifying principles for sustainable adaptation. In Climate and Development (Vol. 3, Issue 1, pp. 7–20). https://doi.org/10.3763/cdev.2010.0060

Iglesias, E., Báez, K., & Diaz-Ambrona, C. H. (2016). Assessing drought risk in Mediterranean Dehesa grazing lands. Agricultural Systems, 149, 65-74. https://doi.org/10.1016/j.agsy.2016.07.017

Juhola, S., Glaas, E., Linnér, B. O., & Neset, T. S. (2016). Redefining maladaptation. Environmental Science & Policy, 55, 135–140. https://doi.org/10.1016/J.ENVSCI.2015.09.014

Georgoulias, A. K., Akritidis, D., Kalisoras, A., Kapsomenakis, J., Melas, D., Zerefos, C. S., & Zanis, P. (2022). Climate change projections for Greece in the 21st century from high-resolution EURO-CORDEX RCM simulations. *Atmospheric Research*, *271*, 106049. https://doi.org/10.1016/j.atmosres.2022.106049

Magnan, A. K., Schipper, E. L. F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaar, J., & Ziervogel, G. (2016). Addressing the risk of maladaptation to climate change. WIREs Clim Change, 7, 646–665. https://doi.org/10.1002/wcc.409

Masih, I. (2022). Characterization of the I-CISK Living Labs. www.icisk.eu/resources

Masih, I., van Cauwenbergh, N., Ziogas, A., Broekman, A., Tzimas, A., Mihalik, B., Prat, E., Moschini, F., Renzi, F., Bela, G., Pesquer, L., De Stefano, L., van den Homberg, M., Schaafsma, M., Gamtkitsulashvili, M., Apakidze, M., Tevzadze, N., Comas, N., Hernández-Mora, N., … Werner, M. (2022). Characterization of the I-CISK Living Labs, I-CISK Deliverable 1.1. ICISK, Human Centred Climate Services. https://icisk.eu/resources/

Mirchi, A., Madani, K., Watkins, D., & Ahmad, S. (2012). Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems. Water Resources Management, 26(9), 2421–2442. https://doi.org/10.1007/s11269-012-0024-2

Moallemi, E. A., Hosseini, S. H., Eker, S., Gao, L., Bertone, E., Szetey, K., & Bryan, B. A. (2022). Eight Archetypes of Sustainable Development Goal (SDG) Synergies and Trade-Offs. Earth's Future, 10(9). https://doi.org/10.1029/2022ef002873

Nabavi, E., Daniell, K. A., & Najafi, H. (2017). Boundary matters: the potential of system dynamics to support sustainability? Journal of Cleaner Production, 140, 312–323. https://doi.org/10.1016/J.JCLEPRO.2016.03.032

Naylor, A., Ford, J., Pearce, T., & Van Alstine, J. (2020). Conceptualizing Climate Vulnerability in Complex Adaptive Systems. One Earth, 2(5), 444–454. https://doi.org/10.1016/J.ONEEAR.2020.04.011

Rastogi, S., Van Cauwenbergh, N., et al. (2025): Participatory modelling for allowing citizens, stakeholders and decision-makers to become active players in climate action, I-CISK Deliverable D4.4, Available online at www. Icisk.eu/resources

Ropero Szymañska, N., Hernández-Mora, N., & De Stefano, L. (2025). Characterizing adaptation responses to drought risk of livestock farmers in the Spanish dehesa agroforestry system. *Frontiers in Environmental* Science, 13. https://doi.org/10.3389/fenvs.2025.1540818

Van den Homberg, I., Rastogi, S., & Hernandez-Mora, N. (2023). Concepts and methods to characterise and integrate local and scientific knowledge (I-CISK Deliverable 2.2). http://www.icisk.eu/resources

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. van der, Seitzinger, S., Steffen, W., & Syvitski, J. (2016). Methods and approaches to modelling the Anthropocene. Global Environmental Change, 39, 328–340. https://doi.org/10.1016/j.gloenvcha.2015.08.007

Wamucii, C., Ziogas, A., Pechlivanidis, I., Di Baldassarre, G., Van Loon, A., & Mazzoleni, M. (2025). Modelling the interplay between stakeholders' power asymmetries and the use of climate services. *Manuscript in Preparation*.

Wolstenholme, E. F. (2003). Towards the definition and use of a core set of archetypal structures in system dynamics. System Dynamics Review, 19(1), 7–26. https://doi.org/10.1002/sdr.259

Ziogas, A., & Tzimas, A. (2022). Living Lab Report: Crete, Greece. *EMVIS SA*.

I-CISK

HUMAN CENTRED CLIMATE SERVICES

Colophon:

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