

Modelling the interplay between sectoral power asymmetries and the use of climate services

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ABSTRACT

Effective climate adaptation requires the integration of equitable and evidence-based decision-making tools and data, such as climate services (CS) products. However, the development and use of CS products are often shaped by stakeholder power asymmetries, which can influence who benefits the most and who remains vulnerable. This study uses a system dynamic modelling approach to evaluate how these power imbalances affect sectoral outcomes and the overall sustainability of the human–environmental system. Using the island of Crete, Greece, as a case, we simulated three scenarios reflecting different configurations of CS prioritization across five key sectors: tourism, water, energy, transport, and agriculture. Results show that prioritizing a single dominant sector amplifies adaptation benefits for that sector but increases systemic vulnerabilities elsewhere. Equitable prioritization across sectors fosters more balanced power distributions and improved sustainability outcomes. The findings highlight the need to rethink stakeholder engagement frameworks, such as the Co-create, Co-design, and Co-produce approach, by embedding systems thinking and stakeholder inclusivity from the outset of CS development. This study underscores the critical role of transdisciplinary modelling in informing just and sustainable climate adaptation strategies.

Practical Implications: This study demonstrates that the effectiveness and fairness of climate services (CS) depend not only on technical quality but on who participates in their design and how power is distributed among sectors. The Crete case study shows that when CS co-creation is dominated by a single powerful sector, such as tourism, adaptation benefits become concentrated to that sector, while vulnerabilities increase in less influential sectors, particularly water management and agriculture. For practitioners, this highlights that power asymmetries are a practical design risk that must be addressed explicitly. The key lesson from Crete, therefore, is that climate services that prioritize dominant sectors can improve short-term efficiency but undermine system-wide resilience. Practitioners should therefore treat equitable participation as a core operational requirement, not an aspirational goal.

Key recommendations for practitioners:

- i. *Map sectoral power at the outset of CS development:* Model results show that unexamined power hierarchies shape adaptation outcomes. Practitioners should systematically identify which sectors control resources, data, and decision-making authority, and use this mapping to adjust participation rules during co-creation.
- ii. *Ensure balanced, cross-sectoral participation:* In Crete, only the equi-sector scenario, where all sectors had equal participatory weight, produced system-wide resilience gains. CS processes should therefore assign structured roles to less powerful but system-critical actors (e.g., smallholder farmers), rather than relying on voluntary or informal inclusion.
- iii. *Use systems-based tools to reveal trade-offs before implementation:* The Crete case shows how sectoral prioritization (e.g., tourism water use) can cascade into higher energy demand and food stress. System

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dynamics models and scenario simulations should be integrated into CS workflows to test alternative allocation strategies and identify unintended consequences early.

- iv. *Design CS outputs for collective, not sector-specific, use:* Practitioners should move beyond tailored products for individual sectors and instead develop shared indicators and dashboards that make cross-sector impacts visible (e.g., water–energy–food–tourism linkages). This supports informed negotiation rather than competition among sectors.
- v. *Institutionalize iterative feedback and learning:* The Crete living lab showed that stakeholder engagement improves relevance but requires sustained facilitation. CS should be embedded in adaptive governance cycles where user feedback, changing climate risks, and shifting sectoral roles are regularly reassessed.

Broader relevance: For other tourism-dependent islands and Mediterranean regions, the Crete case underscores that resilience emerges from balancing sectoral interests within environmental limits. Practitioners who embed equity, systems thinking, and transparency into CS design can reduce maladaptation risks and ensure that climate services function as shared public goods rather than selective advantages.

1. Introduction

Climate variability and change pose significant challenges to human-environmental systems by impacting various interconnected sectors simultaneously. The ways in which these sectors respond and adapt to climate influence the sustainability of the human-environmental systems, affecting sectoral development and human wellbeing (Bell et al., 2018; Kumar, 2021; Naumann et al., 2021). Climate services (CS) are designed to deliver customized, timely, and pertinent climate products that extend beyond providing weather or climate change information, such as forecasts or projections. The CS are tailor-made indicators and indices used in decision making as well as early warning systems. These services are instrumental in supporting decision-making processes within specific sectors, thereby facilitating effective adaptation to climate change and variability (Lemos et al., 2012; Pappenberger et al., 2015; Pechlivanidis et al., 2025; Vaughan and Dessai, 2014). The CS products aim to transform the human-environmental system to adapt to the anticipated changes in climatic variability through informed adaptation-decisions. Different socio-economic sectors are systemically interlinked, which means the risk adaptation decisions in one sector could potentially have cascading (positive or negative) effects on other sectors, both directly through sectoral interactions and indirectly through environmental impacts (Berkhout et al., 2006; Clements et al., 2013; Hsiang et al., 2017; Mechler et al., 2010). Hence, adaptation effects associated with CS products may vary significantly within complex human-environmental systems.

Various studies have recently highlighted the benefits of CS products in improving resilience and reducing vulnerability to climate impacts (Hewitt et al., 2020). However, the development and deployment of CS is shaped by a variety of factors, including disciplinary lens (mono-, inter, and trans-disciplinarity), funding sources, power and politics of stakeholders involved (Crochemore et al., 2024; Harvey et al., 2019; Lugen, 2020; Nobert and Wen, 2022; Nost, 2019; Vaughan and Dessai, 2014; Webber and Donner, 2017; Ziogas et al., 2021). These factors influence the conceptualization, development, and application of climate services, thereby impacting their effectiveness in enhancing stakeholders' adaptive capacities for addressing climate variability and change. The local dynamics of power and privilege are reported to influence the climate adaptation efficacy (Brouwer et al., 2013; Howarth et al., 2022; Mkonda, 2022). The powerful stakeholders have the political supremacy and status to influence adaptation decisions, resources allocation, implementation of policies, flow of information, benefit from short term gains etc. (Amiraslani and Caiserman, 2018; Holland, 2017; Thomas and Twyman, 2005). Asymmetry in power dynamics can lead to inequity in climate adaptation where the CS-based decisions may favour certain privileged sections of society while less privileged continue to face adaptation difficulties (Brouwer et al., 2013; Garcia et al., 2024; Holland, 2017; Swanson, 2021).

The Co-Co-Co approach (i.e., Co-create, Co-design, Co-produce) in climate services follows a sectoral thinking framework, emphasizing the prioritization of individual sector needs (Cantone et al., 2023; Reed

et al., 2019). The user-oriented approach systematically categorizes stakeholders into primary, secondary, and/or non-targeted groups based on their levels of priority and engagement, and project objectives. This classification is crucial for effectively tailoring climate services to specific stakeholder needs (André et al., 2023). However, the sectoral thinking approach has been identified as a cause of maladaptation in other studies (Atteridge and Remling, 2018; Biella et al., 2024; Biella and Di Baldassarre, 2023; Hellin et al., 2022; Osbahr et al., 2010). The tendency for co-produced CS products to focus on specific sectors (in isolation of others) can result in atomistic responses. Consequently, this approach may inadvertently increase the vulnerability of particular societal groups within complex human-environment systems. The decisions made within the different sectors can lead to 'system epitomes' such as "Tragedy of Commons", a situation where self-interested decisions lead to ultimate harm of all (Dutta and Sundaram, 1993; Ostrom, 2009), "Fixes that Fail" where decisions mainly address the symptoms but fail to consider unintended outcomes (Biella et al., 2024; Flood, 1999), "Limits to Growth" where decisions are limited by availability of resources (Gardner, 2004), "Success to the Successful" where the primary stakeholders progressively benefit at the expense of others (Biella et al., 2024; Kunsch et al., 2007). Confronting the complexity of human-environmental systems requires a transdisciplinary approach to analyse multisectoral dynamics and the interactions between human and earth systems (Reed et al., 2022).

System dynamic modelling can be used to explore the risk of maladaptation to climate variability and change by revealing complex human-environment interactions and anticipating the potential for unintended consequences of adaptation strategies (Beckensteiner et al., 2023; Biella et al., 2024; Di Baldassarre et al., 2013; Gohari et al., 2013; Li and Simonovic, 2002; Madani and Mariño, 2009; Turner et al., 2016). The existing literature indicates that the handling of climate adaptation politics is characterized by a lack of rigor, thereby rendering maladaptation an unavoidable outcome (Atteridge and Remling, 2018; Morrison et al., 2017; Tschakert et al., 2013). To the best of our knowledge, there are limited studies that have examined CS products and their integrated benefits and risks across multiple sectors. (de Brito et al., 2024) reported that very few methods support the analysis of cross-scale dynamics. According to (Perrels, 2020), there are no universal methodologies for evaluating the benefits and risks of CS products. Traditional approaches often fail to capture the complex interdependencies between societal and climatic changes (Zscheischler et al., 2018).

Using a system dynamic modelling approach, this study examined the effectiveness of the CS products by accounting for asymmetry in power dynamics among stakeholders across different sectors categorised as primary, secondary, and 'non-targeted' in the CS development and dissemination. We developed a general system dynamic model representing the dynamics between climate, risks (such as droughts, heat-waves, and floods), adaptation strategies, and five key sectors (i.e. tourism, water, energy, transport, and agricultural sectors). We then applied this model on one case study under the human-centred climate

services (I-CISK) project (I-CISK, 2022). The overall research question is: *How do power asymmetries across different sectors influence sector-specific outcomes and the overall sustainability of the human-environmental system?*

2. Methodology

2.1. The model conceptualization

This study employs a system dynamic modelling approach to understand the interactions between climatic events, multisectoral adaptation responses, and the effect of CS products. A key assumption in the model conceptualization is that the climatic events define the status of the hydrological conditions and therefore multiple sectors will inevitably be affected by the dynamics of too much or too little water (Bloetscher, 2012; Sadoff and Muller, 2009). Thus, the water system serves as a crucial medium for analysing inter-sectoral dynamics in response to climate variability.

The conceptual framework (Fig. 1) illustrates the interconnections among five key sectors: tourism (cyan blue), water (blue), energy (yellow), transport (purple), and agriculture (orange). Each sector is structured hierarchically in two parts. Part A describes the sectoral adaptive capacities and power imbalances. This hierarchical progression extends downward to part B, culminating in sector-specific outcomes (represented in grey), referred to in this study as sectoral indices. These indices collectively influence the overall status of the human-environmental system. External pressures exerted on the human-environmental system (primarily driven by climate variability and change, as well as dynamic human population trends) are indicated in red arrows. Climate Services (CS) products (depicted in pink) are designed to provide

tailored information that enhances sectoral adaptation efficiency. However, the extent of sectoral involvement in the co-creation, co-design, and co-production (Co-Co-Co) of CS products varies. Consequently, the relevance of CS products varies depending on the sector type (i.e. primary, secondary, or non-targeted). In addition, other factors influencing adaptive capacities include resource availability, timely access to CS products, and proximity to CS providers, leading to disparities in sectoral power dynamics, status, and privileges. As a result, CS-driven decision-making leads to sectoral variations in adaptation efficiency, which in turn produces distinct sectoral indices. Ultimately, these variations shape the overall sustainability and resilience of the human-environmental system.

2.2. The power imbalances

To define the power imbalances, we first defined the adaptive capacities of each sector. Based on a review of climate services and adaptive capacity literature, we identified six (non-exclusive) parameters that define adaptive capacity of stakeholders to respond to climate variability. The selection was guided by established adaptive capacity frameworks (Engle, 2011; Gupta et al., 2010; Smit and Wandel, 2006) and recent empirical studies on climate services utilization (McLeod et al., 2016; Swart et al., 2021; Torabi et al., 2024; Williams et al., 2020). We selected parameters that: (1) appeared consistently across multiple conceptual frameworks, (2) were empirically validated in climate services contexts, and (3) were measurable within our study design. These parameters included: (i) the types of sectors, (ii) the relevance of the CS products to each sector, (iii) the timely access to the CS, (iv) distance to the CS provider, (v) the availability of CS products,

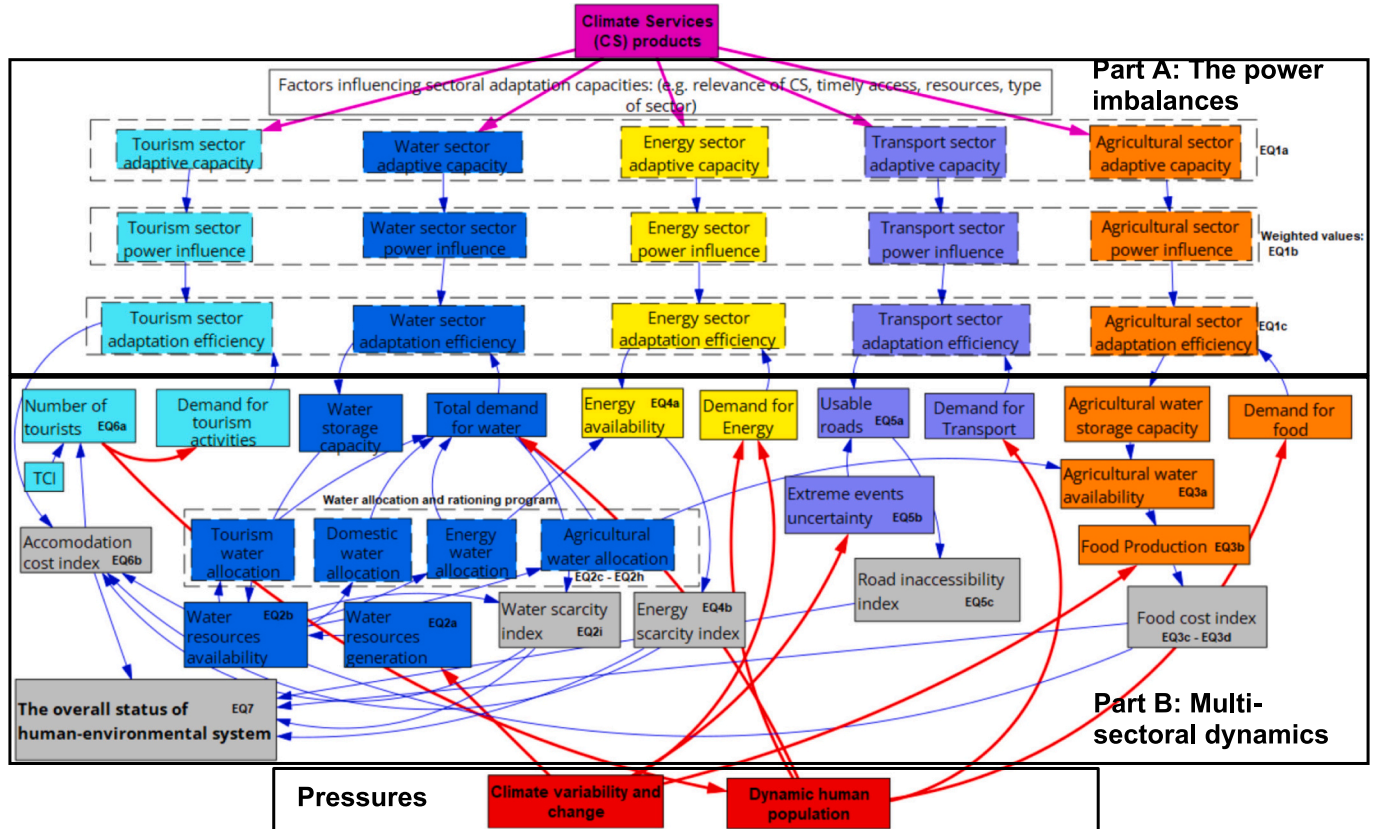


Fig. 1. The conceptual framework. Different sectors are shown in a different colour. The red arrows represent the pressure into the system mainly from the climate variability and change and dynamic human population. The pink arrows represent the input of CS products to enhance sectoral climate adaptation. The blue arrows represent the interlinkages between the sectors. TCI stands for Tourism Climate Index. EQ stands for the numbers of the different equations included in this paper. Detailed description of model parameters is provided in supplement 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and (vi) resources to support responding to climate variability and change. Together, these parameters capture both supply-side (availability, accessibility) and demand-side (relevance, resources) dimensions of adaptive capacity. The parameters are given values ranging between 0 and 1. For instance, when specifying the scores for type of sector, a primary sector will have a value closer to 1 and a non-targeted sector a value closer to zero. The sectoral adaptive capacity was formulated as follows:

$$S_{ADC} = (S_{is} + S_{sp} + S_d + S_{rr}) * (CCI + (S_{cs} * S_r)) \quad (1a)$$

where S_{ADC} is the sectoral adaptive capacity, S_{is} is the type of a sector, S_{sp} is timely access, S_d is the distance to the CS provider, S_{rr} is the sectoral resources, S_{cs} is the availability of the CS product, and S_r is the relevance of the CS. CCI is the value of conventional climate information that were available prior to the development of specialized Climate Services (CS) products, such as forecasts and early warning systems. As opined in (Mayers, 2005)(Mayers, 2005), the power and privileges of stakeholders can be quantified based on the weighted adaptive capacities. This was formulated as indicated in Eq. 1b:

$$S_{pp} = \left(\frac{S_i}{\sum S_{ADC}} \right) \quad (1b)$$

where S_{pp} is the sectoral power and privileges, which is defined as a ratio of the adaptive capacity of a specified sector S_i and a summation of adaptive capacities of all sectors $\sum S_{ADC}$. Based on literature, despite climate information improving adaptation efficiency, other pressures such as demand for resources due to human population growth can affect optimal efficiency (Henderson et al., 2024; Maja and Ayano, 2021; Walsh et al., 2016)(Henderson et al., 2024; Maja and Ayano, 2021; Walsh et al., 2016). To mimic this viewpoint, the power and privileges were formulated to influence sectoral adaptation efficiency as follows:

$$S_{ADE} = S_{pp} \left(1 - \left(\frac{D_i}{D_{max}} \right) \right) \quad (1c)$$

where S_{ADE} is the sectoral adaptation efficiency, defined as the capacity of a sector to fulfil the overall demand for resources, taking into account the sector's inherent power dynamics and privileges, D_i is the actual annual demand of resources in a sector, D_{max} is the estimated maximum possible demand of resources in a sector within the simulation period. The resources considered for each sector include demand for food, usable roads, energy, water, and tourism accommodation. Eq. (1c) assumes that sectoral adaptation efficiency declines progressively as resource demand approaches the maximum resource capacity available within the simulation period. Here, adaptation efficiency is conceptualized as a normalized indicator of the capacity of a sector to satisfy its resource requirements, rather than as an ideal measure of operational efficiency. Consequently, when $D_i = D_{max}$, the adaptation efficiency approaches zero, representing a theoretical boundary condition in which no additional adaptive capacity remains to meet increasing demand. This boundary condition is intended to represent adaptation limits arising from finite environmental, institutional, and economic resources rather than implying that adaptation activities cease entirely. Such resource-constrained adaptation limits are consistent with resilience and climate adaptation theory, which recognizes that adaptive capacity progressively diminishes as systems approach resource saturation and critical thresholds (Adger, 2006; Dasgupta and Mäler, 2003; Dow et al., 2013; IPCC, 2022). A linear formulation was adopted to provide a transparent representation of this relationship while avoiding additional unconstrained parameters associated with more complex nonlinear functions.

2.3. The multi-sectoral dynamics

2.3.1. Water sector

Assuming a steady state which is achieved when the total input (i.e. precipitation) equals the total output (i.e. evapotranspiration and water yield) (Han et al., 2020)(Han et al., 2020), a simplified annual water balance of a landscape can be expressed as follows:

$$T = ET + W^G \quad (2a)$$

where T is the total rainfall, ET is the actual evapotranspiration and W^G is the water yield generated. The water yield is assumed to constitute the summation of the infiltration and the runoff (Koutroulis et al., 2013), hence estimated based on runoff and infiltration coefficients. In this study, runoff and infiltration are defined as independent fractional components of total precipitation, rather than sequential fluxes, such that infiltration represents groundwater recharge and does not subsequently reappear as baseflow within the annual water balance framework. The annual total water available component was formulated as a function of water resources generated, water storage and the water allocation as follows:

$$\frac{dT W_A}{dt} = W_t^G + W_{t-1}^S - W_t^D \quad (2b)$$

where dTW_A is the changing annual total water available over time (dt). W_t^G is the total water generated per year (summation of infiltration and runoff). W_{t-1}^S is the estimated total water harvested and stored from previous year. W_t^D is the estimated annual total water allocation to all the sectors. The variable dTW_A quantifies the annual potential volume of water accessible to stakeholders across various sectors (i.e. from rivers, dams, or groundwater).

The total volume of water harvested and stored was established as a function of the sectoral adaptation efficiency within the water sector, as articulated below:

$$W_{t-1}^S = (1 + S_{ADE_W}) * W_{CV}^S \quad (2c)$$

where S_{ADE_W} is the water sector adaptation efficiency, and W_{CV}^S is the estimated conventional water storage volume.

The annual water allocation was formulated as follows:

$$W_t^D = DR_a + AG_a + EN_a \quad (2d)$$

where W_t^D is the total water allocated, DR_a is the drinking water allocation (including domestic water supplies and water allocated to hotels), AG_a is the irrigation water allocation, and EN_a is the water allocation to the energy sector.

Studies have reported that power imbalances among stakeholders affect the fairness in the sharing of water resources (Arai et al., 2021; Nunes Carvalho et al., 2024)(Arai et al., 2021; Nunes Carvalho et al., 2024)(Arai et al., 2021; Nunes Carvalho et al., 2024). To formalize this concept, two conditions were identified: (i) water rationing will be implemented if the total available water falls below a specified threshold, and (ii) stakeholders with power exceeding a predefined threshold will benefit directly from the water rationing program, receiving reallocated water from other sectors and domestic water supplies. The two conditions are integrated in the following equations:

$$IF [(SPI < X) \text{ and } WS_{idx} > Y], \text{ THEN } \{R = 1\}, \text{ ELSE } \{R = 0\} \quad (2e)$$

where SPI is the standardized precipitation index calculated based on the long-term precipitation data. WS_{idx} is the water scarcity index calculated based on total water demand and total water available. The water scarcity index increases as the gap between total water demand and total available water widens, such that scarcity is low when available water meets or exceeds demand and high when demand exceeds supply. This normalized formulation allows water stress to be evaluated

consistently across time steps and serves as a trigger for activating rationing under conditions of combined hydro-climatic stress and demand pressure. The variable X and Y represents the predefined critical value for the SPI and water scarcity index of a study area. $\{R = 1 \text{ or } 0\}$ means there will be a water rationing program at a particular time step or not.

WHEN $\{R = 0\}$, the conventional water allocation program specified in Eq. 2d remains (business as usual).

WHEN $\{R = 1\}$, a water rationing program will be implemented, resulting in the modification of Eq. 2d as follows:

$$W_t^{Dr} = \left[(DR_a + \sum W_R^i) + (AG_a + \sum W_R^i) + (EN_a + \sum W_R^i) \right] \quad (2f)$$

where W_t^{Dr} is the total water allocation under a rationing program. $\sum W_R^i$ is the summation of the water re-allocated from less influential sectors.

The reallocation of water from less influential sectors was defined within a range constrained by a minimum and maximum proportion of the initial allocation, as specified below:

- i. If energy sector is less powerful: $EN_{rr} = (RND((min\% - max\%)EN_a))$ (2g)
- ii. If agricultural sector is less powerful: $AG_{rr} = (RND((min\% - max\%)AG_a))$

The drinking water allocation if less powerful: $DR_{rr} = (RND((min\% - max\%)DR_a))$. Drinking water allocation accounts for both hotels and domestic water allocation. The assumption is that hotels and individual households are mainly served by a common water pipeline network, and mostly under a local water resources authority. where, EN_{rr} , AG_{rr} , and DR_{rr} represent potential water re-allocated from energy sector, agricultural sector, and domestic water supply respectively. RND denotes the process of randomization within a defined range, representing the minimum and maximum proportion of water that can be reallocated from a conventional allocation. Randomization is incorporated into the model to account for uncertainties associated with water reallocation in the context of water resources management and governance (He et al., 2023; Zhao et al., 2024)(He et al., 2023; Zhao et al., 2024)(He et al., 2023; Zhao et al., 2024).

Hence, the summation of the water re-allocated from less powerful sectors was calculated as follows:

$$\sum W_R^i = DR_{rr} + EN_{rr} + AG_{rr} \quad (2h)$$

In the occurrence of a rationing program $\{R = 1\}$, which is implemented in response to both declining rainfall (i.e. $SPI < X$) and the water scarcity index (i.e. $WS_{idx} > Y$) – representing the status for water demand versus actual water availability), the probability of the most influential stakeholder benefiting from the re-allocation program was expressed as follows:

$$IF \{(\{S_{pp} > Z\}), THEN \{B = 1\}, ELSE \{B = 0\}\} \quad (2i)$$

The variable S_{pp} represents the power status of the individual sectors (based on the Eq. 1b). The parameter Z denotes the threshold value which, if achieved by a stakeholder, establishes them as the most powerful stakeholder within the human-environmental system.

WHEN $\{B = 0\}$, the water reallocation program is assumed to confer no direct benefits to any sector. Instead, the reallocated water is incorporated into the conventional water storage volume component as represented in Eq. 2c, while Eq. 2d remains unchanged.

WHEN $\{B = 1\}$, the most powerful stakeholder directly benefits by getting all reallocated water defined in Eq. 2h.

The water scarcity index in the different sectors was formulated as follows:

$$TW_{idx} = \left(\frac{(TW_{dmd} - TW_{avb})}{TW_{dmd}} \right) \quad (2j)$$

where TW_{idx} is the water scarcity index, TW_{dmd} is the total amount of water demanded, TW_{avb} is the actual amount of water available (i.e. allocated based on Eq. 2d or 2f).

2.3.2. Agricultural sector

Increasing water storage, a key climate change adaptation strategy within the agricultural sector, complements other common approaches such as water-saving techniques, drought-tolerant crops, and diversification to effectively address the challenges of water scarcity (Diandra et al., 2024; Peña-Arancibia et al., 2023)(Diandra et al., 2024; Peña-Arancibia et al., 2023)(Diandra et al., 2024; Peña-Arancibia et al., 2023). Supplemental irrigation has been reported to increase conventional agricultural production by over 25% (Dahri et al., 2024; Ozdogan, 2011; Wang et al., 2021). For optimal agricultural activities during dry seasons, the agricultural adaptation efficiency (based on Eq. 1c) was assumed to increase the agricultural water availability as follows:

$$AG_{WS} = (AG_a + \sum W_R^i) + ((1 + AG_{ADE}) * AGW_{Cv}) \quad (3a)$$

where AG_{WS} is the water availability in the agricultural sector, which is determined by the water conventional water allocation (AG_a), the direct benefits ($\sum W_R^i$) if the agricultural sector is a powerful influential stakeholder in the water re-allocation program, and the agricultural adaptation efficiency (AG_{ADE}). AGW_{Cv} is the conventional water storage capacity in the agricultural sector (based on estimated farm level rain-water harvesting and storage). Eq. (3a) assumes that the conventional water allocation can be doubled with optimal adaptation efficiency.

Increasing agricultural water availability (AG_{WS}) is assumed to enhance agricultural production, including expanding irrigation areas to meet the food demands of a growing population. The impact of (AG_{WS}) on food production was represented as follows:

$$FD_{avb} = \left(\frac{(TW_{AGD} - AG_{WS})}{TW_{AGD}} \right) * ((P_a * A_{ag}) + (P_{ir} * AI_{ag})) \quad (3b)$$

where FD_{avb} is the food availability (tons), TW_{AGD} is the agricultural water demand, (P_a) is the conventional production per unit area of the selected major crops under no irrigation, A_{ag} is the agricultural area under no irrigation. P_{ir} is the production per unit area under irrigation, and AI_{ag} is the estimated irrigated area. The food production would impact the amount of food imported and food prices as formulated below:

$$FD_{Imp} = \left(\frac{(FD_{dmd} - FD_{avb})}{FD_{dmd}} \right) * 100 \quad (3c)$$

where FD_{Imp} is the rate of food imported, FD_{dmd} is the total amount of food demanded, FD_{avb} is the actual amount of food available. The food cost index was formulated as shown below. This formulation assumes an increase or decrease in the rate of food imported would result in similar fraction on food cost prices:

$$FC_{idx} = \left(\frac{FD_{Imp}}{100} \right) \quad (3d)$$

where FC_{idx} is the food cost index and assumed to contribute greatly to the overall status of the human-environmental system.

2.3.3. Energy sector

The interaction between the energy sector and water systems is crucial for electricity generation in most regions, particularly through hydropower and coal production (Koh et al., 2022; Mongird et al., 2023; Wu et al., 2023). Energy availability was formulated as follows:

$$EN_{Avb} = \eta(1 - (1 - EN_{ADE})) + \mu(EN_a) \quad (4a)$$

where EN_{Avb} is the energy availability, η is the conventional energy

availability, EN_{ADE} is the energy sector adaptation efficiency, μ is amount of power generated (kwh) per cubic meter of water supplied. Based on the maximum water consumption for electricity generation reported in IPCC report as $4.2 \text{ m}^3/\text{MWh}$ for coal and $209 \text{ m}^3/\text{MWh}$ for hydropower (Edenhofer et al., 2011), the μ values are equivalent to 238 kwh/m^3 in coal-based production, and 5 kwh/m^3 in hydropower-based production. The EN_a is the amount of water allocated to the energy sector (based on Eq. 2d and 2f). The energy scarcity index was then formulated as follows:

$$EN_{idx} = \left(\frac{(EN_{dmd} - EN_{avb})}{EN_{dmd}} \right) \quad (4b)$$

where EN_{idx} is the energy scarcity index, EN_{dmd} is the total amount of energy demanded in the study area, EN_{avb} is the actual amount of energy available. The energy scarcity index is expected to affect the overall status of the human-environmental system.

2.3.4. Transport sector

This sector is considered unique among the five sectors as it lacks a direct connection to the sharing of water resources. Instead, it functions as a supporting sector, playing a critical role in enabling the other sectors to achieve their optimal outcomes as opined in (Vandycke et al., 2022). The assumption posits that enhanced adaptation efficiency within the transport sector would improve the availability of usable roads, facilitated through timely maintenance and the construction of new roads (de Abreu et al., 2022; Singla, 2024). However, heightened uncertainty arising from extreme precipitation events, such as floods, could adversely impact road usability (Beitelmal et al., 2024). This may occur due to delayed responses in repairing damaged roads or inadequate planning for constructing new roads to meet anticipated demand. The availability of usable roads was therefore formulated as a ratio of the uncertainty of climatic events and the adaptation efficiency as follows:

$$TR_{Avb} = IF(SPI > X_i), THEN(Q^*(1 - (TR_d - TR_{ADE}))), ELSE(Q^*\omega) \quad (5a)$$

where TR_{Avb} is the availability of usable roads, X_i is the identified SPI threshold when landslides are likely to happen (i.e. threshold used as a proxy for wet-anomaly-driven hydro-climatic stress), Q is the conventional usable roads, TR_{ADE} is the transport sector adaptation efficiency. TR_d represents the estimated proportion of road infrastructure damaged during extreme rainfall events (i.e., when the Standardized Precipitation Index (SPI) exceeds a predefined threshold value). However, this proportion is expected to decrease over time due to improvements in sectoral adaptation efficiency. The ω is the rate of new roads constructed per year. The road inaccessibility index was formulated as follows:

$$TR_{idx} = \left(\frac{(TR_{dmd} - TR_{avb})}{TR_{dmd}} \right) \quad (5b)$$

where TR_{idx} is the road inaccessibility index, TR_{dmd} is the estimated demand of roads in kilometres, TR_{avb} is the actual kilometres of usable roads available. The road inaccessibility index is expected to affect the overall status of the human-environmental system.

2.3.5. Tourism sector

The relationship between climate variability and tourism activities has been analysed using the Tourism Climate Index (TCI). The TCI index is a single numerical metric of key climatic variables pertinent to tourism such as maximum and mean daily temperature, minimum relative humidity, daily sunshine hours, daily precipitation, and wind speed (Roshan et al., 2016). The TCI index assesses the destination's climatic suitability for tourism activities (Mieczkowski, 1985; Scott et al., 2016; Sultana and Paul, 2023). In this study, the TCI indices were sourced from the European Commission database (Garcia Leon et al., 2023).

A key assumption in the literature is that higher Tourism Climate Index (TCI) values correspond to an increased number of tourists at a destination. While this may hold true, particularly in the context of global warming leading to warmer conditions during traditionally colder months, other factors can also significantly influence tourist numbers. These factors include water scarcity affecting hotel operations, rising accommodation costs (e.g., daily rates, food prices), and additional expenses incurred by hotels. For instance, energy costs may escalate due to increased cooling demands during extreme hot days, while food importation and investments in alternative water sources, such as borehole drilling, can further drive-up operational costs, potentially impacting tourism business. The number of tourists was therefore formulated as follows:

$$T_t^n = N_{t-1} (TCI^* ((1 + TG_{yr}) - AC_c)) \quad (6a)$$

where T_t^n is the number of tourists at a particular time step, and N_{t-1} is the number of tourists from the previous time step. TCI is the Tourism Climate Index, TG_{yr} represents the estimated annual growth rate of tourist numbers, which is directly influenced by accommodation cost index (AC_c).

The accommodation cost index was formulated as an average of different variables as follows

$$AC_c = \left(\frac{(TW_{idx}^T + FC_{idx} + EN_{idx})}{3} \right) - TR_e \quad (6b)$$

where TW_{idx}^T is the tourism water scarcity, FC_{idx} is the food cost index, EN_{idx} is the energy scarcity index. The variable TR_e is the tourism adaptation efficiency.

2.3.6. The overall status of human-environmental system

Developing sectoral indices to understand the environmental impacts of various sectors as they adapt to climate change is indeed an established approach in climate research (Harrison et al., 2015, 2016; Ludeña and Yoon, 2015). This study developed a proxy indicator to estimate the overall status of the human-environmental system by integrating sectoral indices, thereby consolidating the impact from each sector into a single metric as follows:

$$HE_s = 1 - (TW_{idx} + FC_{idx} + EN_{idx} + TR_{idx} + AC_{idx}) \quad (7)$$

where HE_s is the overall human-environmental status, TW_{idx} is the overall water scarcity index, FC_{idx} is the food cost index, EN_{idx} is the energy scarcity index, TR_{idx} is the roads inaccessibility index, and AC_{idx} is the tourism accommodation cost index.

3. Case study and data

3.1. Case study – The island of Crete, Greece

This study provides a case analysis within the framework of the I-CISK project, which is focused on the development of next-generation climate services utilizing a human-centred approach informed by social and behavioural science (I-CISK, 2022). The project seeks to enhance sectoral adaptive capacities, resilience, and climate-smart decision-making by integrating local knowledge with scientific climate data, thereby addressing pertinent challenges across diverse temporal and spatial scales.

The island of Crete (Greece), one of the living labs for the I-CISK project, was selected as case study due to its high vulnerability to climate change, particularly in the tourism, transportation, energy, and water resources sectors (CCISC, 2011; Masih et al., 2022; Region of Crete, 2022). It is the largest island in Greece and the 5th largest in Mediterranean, concentrating a significant and variable economic activity and playing an important economic role for the country. Covering a total area of 8265 km^2 , Crete experiences a Mediterranean climate, with

annual precipitation distributed as 53% in winter, 23% in autumn, 20% in spring, and minimal rainfall during summer (Koutroulis and Tsanis, 2010). More information on sectoral responses to climate change and variability in the island of Crete is provided in supplement 1.

The Co-Co-Co approach (i.e., Co-create, Co-design, Co-produce) was adopted in Crete in the development of CS products. The CS products aimed to address climatic challenges impacting the tourism sector beyond the typical approach of touristic services sector. A multi-sectoral approach was adopted comprising a diverse assembly of stakeholders who encapsulate the needs and challenges across interconnected sectors, including tourism, water management, transportation infrastructure (such as roads and ports), and the energy sector. This collaborative framework was designed to ensure that potential synergies and trade-offs were accounted for during the co-production of CS products (Masih et al., 2022).

In the context of this study, the tourism sector was designated as the primary sector. Concurrently, the sectors of water, energy, and transportation were classified as secondary sectors. Although the agricultural sector was not included among the targeted sectors in the living lab, it was incorporated into this study as a 'non-targeted' sector for comprehensive analysis.

3.2. Data collection and analysis

The data and key model parameters for the selected case study were obtained from multiple sources, including global datasets, observations, I-CISK project reports, peer-reviewed publications, and key informant interviews with the living lab experts and sector representatives. A comprehensive description of the case study area, along with the specific data utilized and their respective sources, is provided in supplement 1. The study employed Vensim PLE Plus software (Ventana Systems, 2025), for the conceptualization and execution of the system dynamics model.

3.2.1. Stakeholder engagement

The information obtained from multiple sources was further enriched through stakeholder engagement, which was essential for gaining insights into sectoral decision-making processes, experiences, and challenges associated with climate information.

In the preliminary phases of model conceptualization, the primary emphasis was on utilizing the comprehensive information supplied by the living lab experts to effectively contextualize the pertinent social-environmental issues. After the development of the initial iteration of the model, the initial model outcomes were presented to both the living lab experts and sector representatives. A critical aspect of this engagement was understanding the conventional sectoral use of climate information, such as weather forecasting, early warning systems, and the perceived added value of tailored climate service products. Stakeholder involvement also facilitated the identification of power imbalances, key challenges related to the uncertainty of climatic events, and sectoral decision-making frameworks while validating the modelling assumptions.

3.2.2. Model validation

Besides involving stakeholders in conceptualizing the model and its components, stakeholder engagement was considered a fundamental step in co-developing model components and co-evaluating model scenarios, hence checking and contextualizing the model. This participatory validation approach, commonly referred to as expert judgment validation, is widely recognized as an essential method for assessing model structure, causal logic, and underlying assumptions in system dynamics modelling (Eker et al., 2018; Krueger et al., 2012; Wamucii et al., 2023; Zarei et al., 2024).

The expert judgment validation process involved systematic presentation and deliberation of model components, parameters, causal relationships, and underlying assumptions during field visits with living

lab experts and stakeholders from various sectors (agriculture, tourism, energy, and infrastructure). These structured interactions served multiple validation purposes: (i) verification of causal loop structures and feedback mechanisms against stakeholder mental models and empirical knowledge, (ii) assessment of parameter ranges and functional forms for plausibility and consistency with local context, (iii) evaluation of model behavior under different scenarios for face validity and policy relevance, and (iv) identification of model limitations and boundary adequacy (Luna-Reyes et al., 2006; Mirchi, 2013).

To complement expert judgment validation and assess model robustness, we conducted systematic sensitivity analysis using the built-in sensitivity analysis tools in Vensim software. Sensitivity analysis is a critical validation technique that quantifies how uncertainty in model parameters affects model outputs and identifies the parameters that most significantly influence model behavior (Ford, 2010; Sterman, 2000). The sensitivity analysis procedure employed in this study adhered to established protocols (Suprun et al., 2022) and involved several key steps. Firstly, we identified critical uncertain parameters across various model sectors, including agricultural productivity, tourism growth, energy efficiency, and infrastructure development, and specified their plausible ranges based on literature, stakeholder input, and available empirical data. Subsequently, we utilized Vensim's Monte Carlo simulation capabilities to conduct 1000 simulation runs, sampling parameters from their designated distributions, thereby generating a spectrum of model behaviors that captures parameter uncertainty. We then computed sensitivity indices for key output variables, such as agricultural production, tourist numbers, energy availability, and road infrastructure, to quantify the relative impact of each parameter on output variance, utilizing in-built multivariate sensitivity analysis tool. Additionally, we ranked parameters by their influence, which guided targeted data collection and the refinement of parameter estimates through stakeholder consultation. More details on sensitivity analysis are provided in the supplementary material.

In addition to expert validation and sensitivity analysis, other tests included: (a) extreme condition tests, where model behavior was examined under extreme but plausible parameter values (e.g., zero and maximum parameter values) to verify that responses remained logically consistent with real-world expectations; (b) verifying whether the model boundary appropriately captures the key variables and relationships necessary to address the research questions while excluding extraneous detail; and (c) all model equations were verified for dimensional.

3.2.3. Scenario analysis

To evaluate how the multisectoral power asymmetries influence sector-specific outcomes and the overall sustainability of the human-environmental system, three distinct scenarios were formulated:

Scenario 1: Sectoral-thinking approach ('Mono-sector').

This scenario represents the conventional sectoral approach in the development of climate services, wherein CS products are designed to target a single sector, while all other sectors are designated as non-targeted (Reed et al., 2019). The tourism sector was selected as the primary sector, with no secondary or supporting sectors considered in this scenario.

Scenario 2: Hierarchical multi-sectoral approach ('Multi-sector').

This scenario assumes a collaborative approach incorporating primary, secondary, and non-targeted sectors based on prioritized needs, reflecting real-world power asymmetries. This scenario reflects the Co-Co-Co (Co-create, Co-design, Co-produce) approach to CS product development, as implemented in the island of Crete (Masih et al., 2022). A multi-sectoral, multi-hazard approach was adopted to assign the sectors to different hierarchical categories based on their identified priorities and needs. The tourism sector was designated as the primary sector, while water, energy, and transport sectors were classified as secondary sectors. The agricultural sector was included as a non-targeted sector to analyse the effects of power asymmetries among primary, secondary, and non-targeted sectors.

Scenario 3: Equitable multi-sectoral approach ('Equi-sector').

This scenario assumes an idealized configuration where all sectors hold equal primary status, enabling the assessment of fully balanced participatory dynamics. This configuration enables an examination of the effects of an equitable distribution of power and influence across all sectors.

The scenarios were simulated using the bias-adjusted Euro-CORDEX climate projections under the Representative Concentration Pathways (RCP) 8.5 emission scenario for the period 2000–2100 (Jacob et al., 2014). RCP 4.5 was however employed as a comparative benchmark in the analysis of the overall status of the human-environmental system, facilitating evaluation of any deviations between the three scenarios. The period from 2000 to 2023 is simulated on the assumption that the multiple sectors had conventional access to climate change information from sources such as national meteorological agencies, media outlets, and historical data. Consequently, it is posited that a foundational level of conventional climate information existed prior to the introduction of customized climate services products. Model outputs from 2000 to 2023 were evaluated for reliability by comparing model outputs with available observed data.

4. Results

4.1. Comparison of model outputs (2000–2023) with observational data

A critical aspect of enhancing confidence in a system dynamics model lies in evaluating its capacity to replicate observed historical behavior patterns (Sterman, 2000). This assessment serves as a structural confidence check, distinct from traditional model calibration and validation processes. The objective was to confirm that the model's causal structure and feedback mechanisms, which were parameterized through empirical data, literature, and expert judgment, produced behaviors that align with historical observations. Initial analyses indicated that while the model generally overestimates observations, the simulations conducted for the period from 2000 to 2023 demonstrated considerable alignment with the observed data, as illustrated in Fig. 2.

This bolsters confidence in the model's structural integrity. Notably, the significant decline in tourist numbers in 2020, presented in Fig. 2B, is attributable to the COVID-19 pandemic's impact, which is not represented in the model's framework. High Kling-Gupta Efficiency (KGE) values indicate the model's competency in capturing long-term trends but should be interpreted as a conventional validation rather than evidence of predictive accuracy. Model validation fundamentally depends on structural tests, sensitivity analyses, and expert judgment (Section 3.2.2).

The sensitivity analysis indicates that uncertainty in the primary governing inputs primarily affects the Part A components of the model (Fig. 1), those governing sectoral power and privileges, where the widest confidence bounds were observed across the 1000 Monte Carlo simulations. These variations also influenced sectoral adaptation efficiencies, although to a lesser degree. In contrast, the downstream multisectoral dynamics (Part B of the model) showed markedly lower sensitivity to perturbations in the governing inputs. Key sectoral indices, including the water scarcity index and food cost index, exhibited minimal variation across confidence bounds. Several system variables, such as total water availability, drinking-water allocation, irrigation-water demand, food availability, and usable road infrastructure, remained relatively stable. These results demonstrate that while the governing input parameters shape the distribution of sectoral power influence, the model's broader behavioural patterns and emergent cross-sector interactions are largely driven by the endogenous system structure and feedback mechanisms. More details on sensitivity analysis are provided in the supplementary material.

4.2. Sectoral power dynamics and adaptation efficiency across scenarios

We next present sectoral power relations and adaptation efficiency, with particular attention to the dominant role of the powerful sector and the contrasting trajectories of secondary sectors.

The analysis of the three scenarios elucidated the power asymmetries among various stakeholders. In the mono-sector scenario, where the tourism sector was designated as the sole primary sector and all other

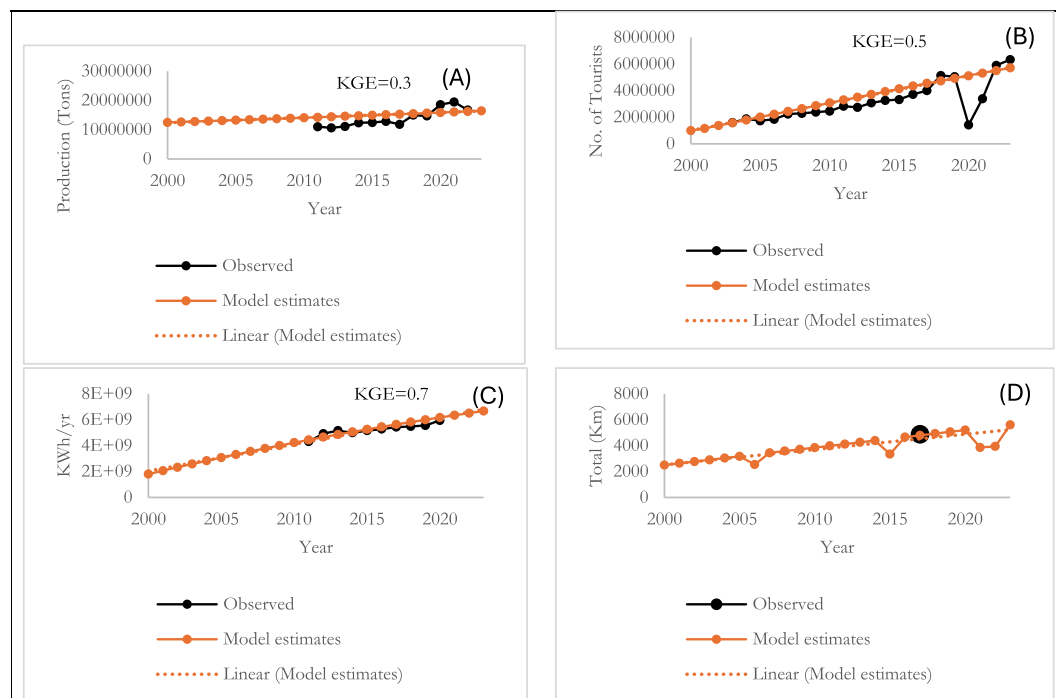


Fig. 2. Comparison between model simulations under the baseline scenario and available observed data from 2000 to 2023 for the following variables: Agricultural production in tons (A), number of tourists (B), energy availability in KWh/yr (C), and extent of usable roads in Km (D). More information on available observed data is provided in supplement 3.

sectors were classified as non-targeted, both the adaptive capacity and the power influence of the tourism sector were simulated to be relatively high (Fig. 3). In the multi-sector scenario, the adaptive capacity of the tourism sector remained stable; however, noticeable increases in adaptive capacity were observed in the secondary sectors (Fig. 3A). This shift resulted in a reduction of the power influence of the tourism sector, coupled with a slight enhancement of the power influence of the transport and water sectors, while the power of the energy sector experienced a marginal decline (Fig. 3B). Conversely, the power of the non-targeted agricultural sector faced further suppression (Fig. 3B). In the equi-sector scenario, which postulated that all sectors were considered primary, a more equitable distribution of power among the sectors was evident, as indicated by an increase in sectoral adaptive capacities; notably, no individual sector demonstrated disproportionate power in this theoretical construct.

The sectoral adaptation efficiency, conceptualized as a function of endogenous pressures including the increasing demand for sectoral resources, exhibited varying outcomes across the three scenarios. The immediate impact of the introduction of CS products on sectoral adaptation efficiency was assessed by comparing the baseline efficiency in 2023 with the efficiency following the introduction of CS products in 2024, as illustrated in Fig. 4A. In the mono-sector scenario, the primary tourism sector demonstrated a significant increase in adaptation efficiency; however, multi-sector and equi-sector scenarios resulted in decreased efficiency within the same sector (Fig. 4A). Long-term simulations indicated that only the tourism sector experienced an increase in adaptation efficiency following the introduction of CS products under the mono-sector scenario (Fig. 4B). Conversely, the non-targeted agricultural sector exhibited the lowest adaptation efficiency, which further declined in the multi-sector scenario when all other sectors were treated as primary and secondary (Fig. 4C).

Variations in adaptation efficiency for secondary sectors were observed across the three scenarios. Specifically, the energy sector experienced a reduction in adaptation efficiency from the mono-sector scenario to the multi-sector scenario (Fig. 4D), while both the transport sector (Fig. 4E) and the water sector (Fig. 4F) demonstrated an increase in adaptation efficiency. Although a relative increase in sectoral adaptation efficiency was noted for the agriculture, energy, and transport sectors in the equi-sector scenario, the tourism and water sectors did not exhibit similar patterns. In fact, in the equi-sector scenario, the tourism sector had the lowest adaptation efficiency when compared to mono-sector and multi-sector scenarios (Fig. 4B). The water sector also displayed a decrease in adaptation efficiency in equi-sector scenario relative to multi-sector scenario (Fig. 4F).

Based on results presented in Fig. 4, it is evident that the primary tourism sector exhibited disproportionately high adaptation efficiency values, particularly in the mono-sector and multi-sectoral scenarios. Conversely, in the idealized equi-sector scenario, a convergence of

adaptation efficiency values across sectors was observed. This outcome suggests that no specific sector displayed significantly superior relative efficiency within equi-sector scenario. Nevertheless, it is important to underscore that the tourism sector consistently sustained higher adaptation efficiency values relative to the other sectors throughout the entire simulation period.

4.3. Impacts of sectoral adaptation efficiencies on water resource availability and allocation

We next investigate how variations in sectoral adaptation efficiencies across the three scenarios influenced both the overall availability of water resources and their allocation between drinking and irrigation uses.

Variations in sectoral adaptation efficiencies across different scenarios correspondingly affect the availability of water resources. In the mono-sector scenario, the water sector was simulated to exhibit the lowest availability of water resources (Fig. 5A). The water resources availability increased by approximately 17% in the multi-sector scenario, followed by a decrease of about 5% in the equi-sector scenario. The agricultural sector's water storage capacity experienced a decline of approximately 2% between the mono-sector scenario and the multi-sector scenario, subsequently increasing by about 8% in the equi-sector scenario (Fig. 5B). These differences appear to reflect the alterations in sectoral adaptation efficiencies, as depicted in Fig. 4, where an increase in sectoral adaptation efficiencies seems to coincide with enhanced water resources availability.

Regarding drinking water allocation, the mono-sector scenario exhibited significantly elevated allocations relative to multi-sector and equi-sector scenarios (Fig. 5C). This shift appears to elevate the average water allocation to markedly higher levels compared to the allocation trends observed during the conventional period from 2000 to 2023. Conversely, the multi-sector and equi-sector scenarios demonstrate allocation patterns that oscillate around an average that closely aligns with those of the conventional period.

In terms of irrigation water allocation, a notable reduction in allocations was recorded in mono-sector and multi-sector scenarios, with values falling below the average of the conventional period (Fig. 5D). Nonetheless, in the equi-sector scenario there were no significant fluctuations in irrigation water allocations; rather, the allocations remained stable throughout the duration of the model simulations.

4.4. Sectoral indices under alternative scenarios

Here we present the simulation outcomes for sectoral indices, which serve as proxies for sectoral performance under climate and anthropogenic pressures.

Sectoral indices serve as critical proxy indicators for assessing the

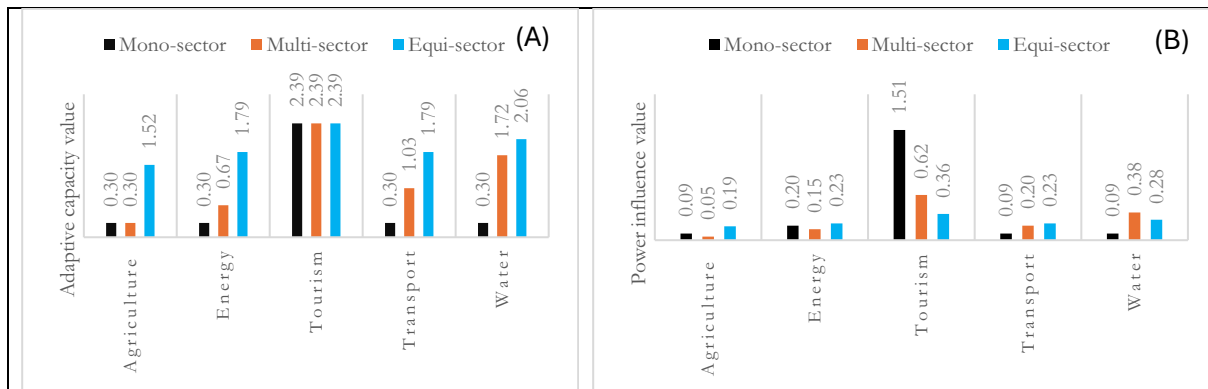


Fig. 3. Power asymmetries: sectoral adaptive capacities (A) and power influences (B).

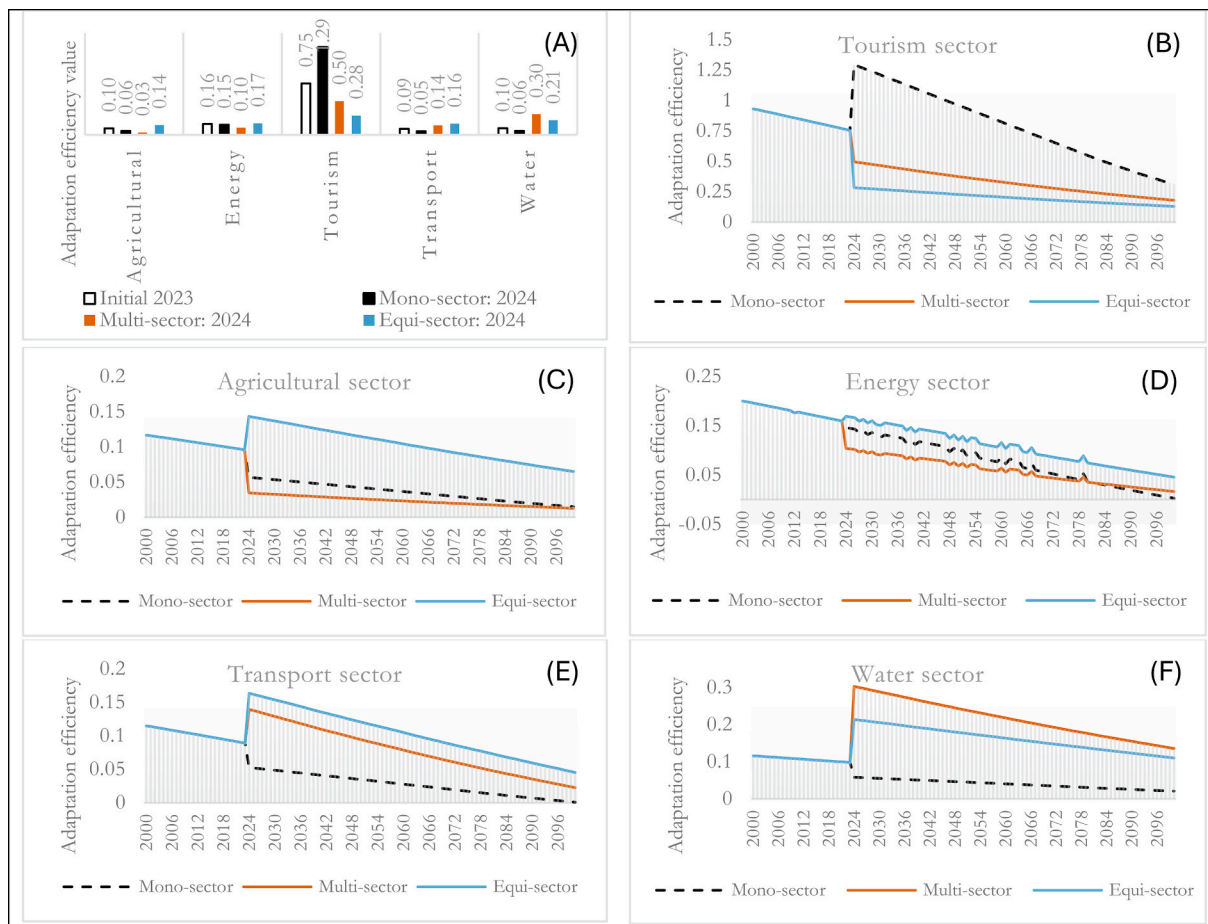


Fig. 4. Sectoral adaptation efficiency across various domains: A comparison of conventional sectoral efficiency and after the introduction of the CS products (A). Sectoral adaptation efficiencies (B–F). The period 2000–2023 represents the baseline scenario prior to the introduction of CS products.

performance and the status of various sectors in response to climate change and anthropogenic pressures. Simulation results indicated that the accommodation cost index was comparatively lower in the mono-sector scenario relative to the multi-sector and equi-sector scenarios (Fig. 6A). Conversely, both the energy scarcity index and the roads inaccessibility index exhibited opposing trends to the accommodation cost index, with higher scarcity values simulated in the mono-sector scenario and the lowest values observed in the equi-sector scenario (Fig. 6B and D). Notably, a pronounced increase in the road's inaccessibility index was predicted for the year 2035, which correlates with a concurrent spike in hydrological conditions (i.e. the year 2035 with an SPI of 1.9) as depicted in (Fig. 7B) and described in Eq. 5a. The food scarcity index demonstrated distinct behavior, with an increase in the multi-sector scenario above the values recorded in the mono-sector scenario, whereas the equi-sector scenario exhibited comparatively lower food scarcity values (Fig. 6C). This finding suggests that food scarcity was exacerbated in the multi-sector scenario. The water scarcity index was projected to be markedly elevated in the mono-sector scenario, while the multi-sector and equi-sector scenarios showed no substantial differences in this index (Fig. 6E).

4.5. The overall status of the human-environmental system

The simulated sectoral indices exert significant influence on the overall status of the human-environmental system, as depicted in Fig. 7A. The mono-sector scenario resulted in lower overall system status values for both RCP 8.5 and RCP 4.5. This configuration corresponded with elevated scarcity values across most sectors (Fig. 6). In contrast, the equi-sector scenario demonstrated relatively higher overall system

status and reduced sectoral scarcities.

Systemic pressures, illustrated in Fig. 7B, further elucidate these dynamics. The human population is projected to increase markedly under mono-sector scenario, where the primary sector tourism increases the influx of tourists. Furthermore, the anticipated increase in tourist influx under a mono-sector development scenario is likely to intensify pressure on a hydrological system that is already projected to be fragile in future especially under RCP 8.5 (Fig. 7B). This elevated human population pressure may account for the higher sectoral scarcity indices observed in Fig. 6. Notably, despite low accommodation cost index values within the primary sector under the mono-sector scenario, increasing human pressure appears to drive accommodation costs upward (Fig. 6A), a trend attributable to also deteriorating hydrological conditions anticipated in the future (Fig. 7B).

5. Discussion

5.1. Climate services, power asymmetries, and sectoral inequities

While climate services are designed to enhance sectoral resilience, our results underscore how sectoral prioritization can reinforce existing inequalities. In particular, scenarios where one sector (e.g., tourism) was treated as a primary target consistently showed heightened power influence for that sector but at the cost of suppressing power influence in others, notably the non-targeted sector. By operationalizing power as a relative, system-level attribute influencing access to resources and decision leverage, the model aligns with relational and institutional perspectives on power in governance systems (Avelino and Rotmans, 2009; Clement, 2010). This quantitative representation does not predict

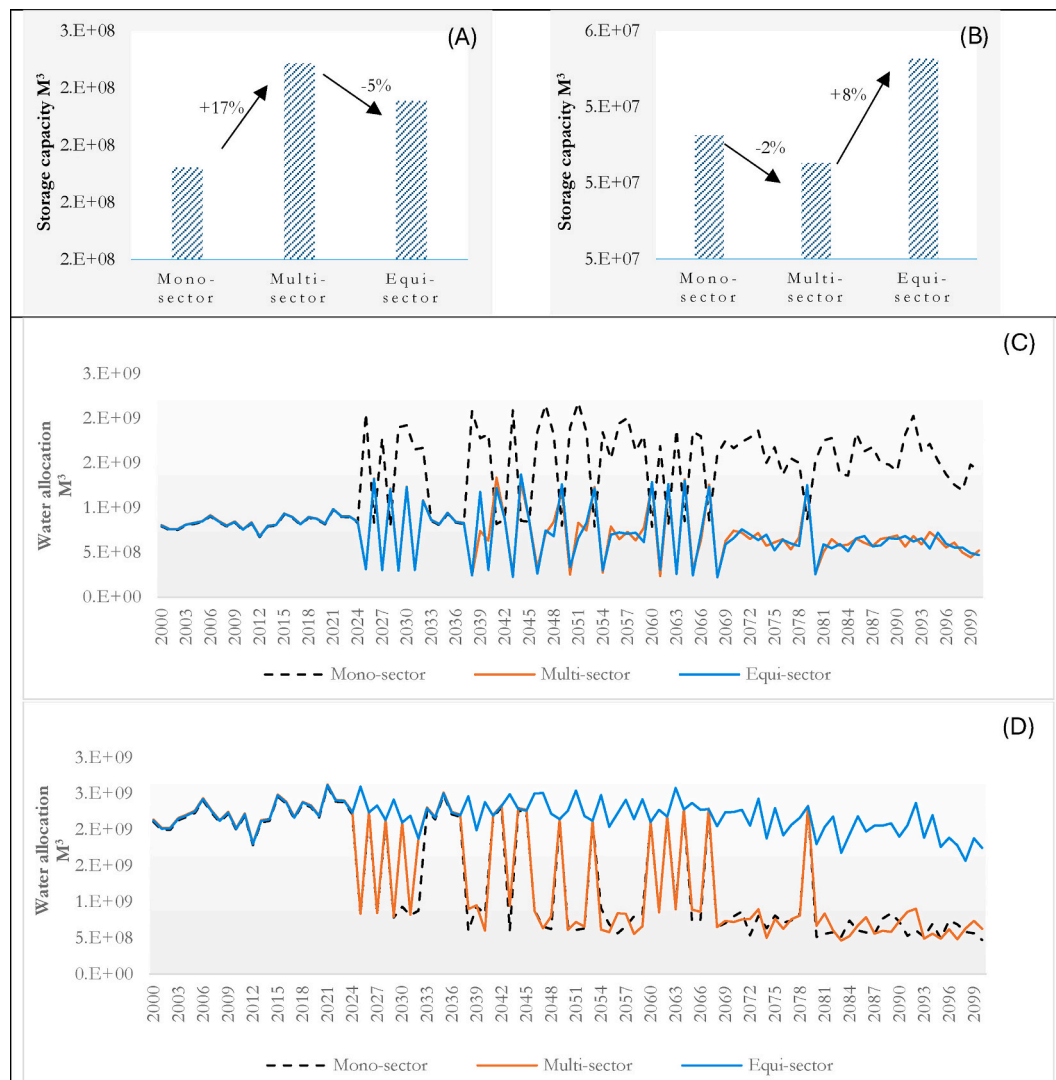


Fig. 5. The simulated changes in water resource availability; long-term average storage capacity within the water sector (A), long-term average storage capacity within agricultural sector (B), allocation of drinking water (C), and allocation for irrigation purposes (D).

political outcomes but allows systematic exploration of how power asymmetries shape adaptation pathways.

In the mono-sector scenario, where Climate Services (CS) development was modelled to exclusively target a single primary sector, the outcomes were markedly asymmetric, resulting in increased systemic vulnerability within non-prioritized sectors. The targeted primary sector appeared to have high conventional adaptation efficiency. This condition reflects the symptoms of “Success to the Successful” archetype, where dominant stakeholders who are already advantaged are more likely to benefit (Biella et al., 2024; Kunsch et al., 2007). In contrast, the equi-sector scenario, characterized by equal prioritization of CS products across all sectors, produced the most balanced power distribution and exhibited consistent adaptation efficiency. These findings indicate that a balanced multi-sectoral engagement strategy may facilitate a more equitable and sustainable pathway.

These results support prior critiques of sectoral thinking approach and atomistic adaptation decisions and their contribution to maladaptation (Cantone et al., 2023; Defries and Nagendra, 2017; Eriksen et al., 2021; Magnan et al., 2016; Reed et al., 2019). In this context, tourism-focused adaptation improves short-term economic performance while exacerbating long-term water and food system stress, a pattern characteristic of maladaptive dynamics. The results underscore the need for early-stage system-based assessments to guide vulnerability-targeted CS

design, rather than relying solely on sectoral hierarchies or economic considerations. For example, as illustrated in Fig. 3, the agriculture and energy sectors exhibited the lowest conventional adaptive capacities. Looking critically at the vulnerability assessments that led to the identification of the tourism sector as the primary sector (CCISC, 2011; Region of Crete, 2022), it is evident that generic methodologies were employed, including climate projection through different models and general equilibrium modelling (GEM-E3) to evaluate overall economic impacts on sectoral vulnerabilities. Additionally, previous studies have also identified tourism sector as the dominant sector in Island of Crete (Briassoulis, 2003; Lampropoulos et al., 2021; Vourdoubas, 2020, 2024). However, the findings of this study suggest that the implementation of system dynamics-based assessments, characterized by a comprehensive delineation of sectoral interlinkages and power imbalances, would likely have prioritized the agriculture and energy sectors as primary sectors, instead of the tourism sector (a traditionally powerful sector).

The model also uncovered the cascading effects across sectors. When powerful sectors, like tourism, gain privileged access to resources during stress events, as simulated under water rationing conditions, other sectors incur elevated systemic costs. This pattern affirms that decisions made within a sector are not isolated; benefits accrued in one sector may indirectly elevate systemic costs elsewhere, echoing the “Fixes that Fail”

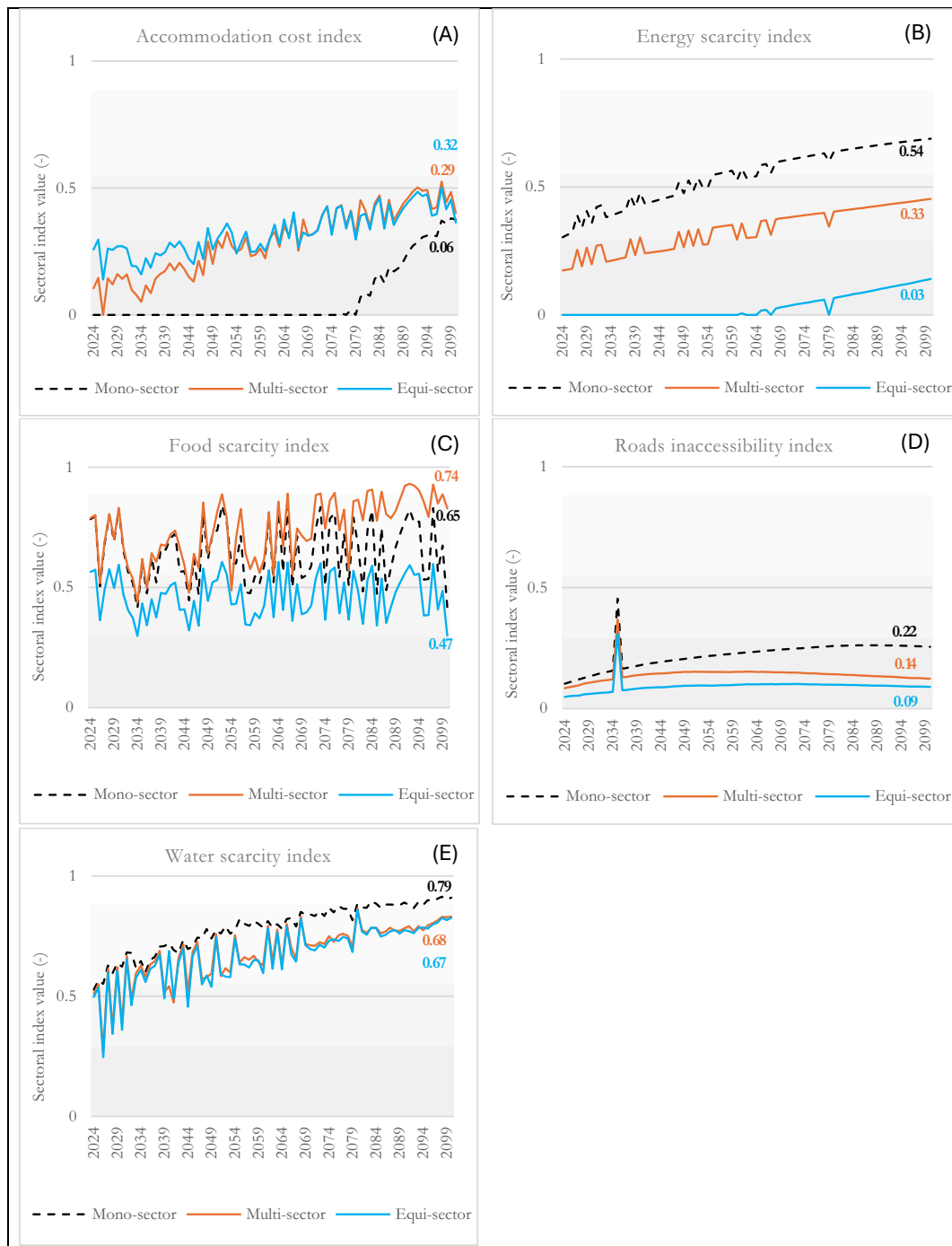


Fig. 6. Simulated sectoral indices representing (A-E). The numbers represent the long-term mean values of the sectoral indices.

systems archetype (Benninger et al., 2021; Biella et al., 2024; Hallett and Hobbs, 2020). The capacity of dominant sectors to exert influence over the reallocation of water resources toward less powerful sectors underscores significant justice-related issues within the management and governance of water resources (Rezaee et al., 2021; Turley, 2023; Valipour et al., 2024).

5.2. Rethinking the Co-Co-Co stakeholder engagement approach

Past studies have reported that end-users often find CS products irrelevant to their specific needs because climate scientists typically produce supply-driven services, rather than demand-driven ones, creating a 'usability gap' (Brasseur and Gallardo, 2016; Brooks, 2013;

McNie, 2007; Porter and Dessai, 2017; Raaphorst et al., 2020; Rigby and Preist, 2023). The I-CISK project similarly acknowledged persistent challenges, including the failure to adequately incorporate social and behavioural factors as well as local knowledge and customs of CS users (I-CISK, 2022). Hence, to make CS products sectorally relevant, specialized sectoral focus is essential. As emphasized in the literature, a sectoral thinking approach can enhance the usability of CS by tailoring services to specific decision-making contexts and supporting societal adaptation to climate change (Cantone et al., 2023; Reed et al., 2019). However, our findings indicate that sectoral thinking alone is insufficient. This study highlights the necessity of complementing sectoral approaches with multisectoral engagement strategies and early-stage system-based assessments to guide vulnerability-targeted CS design. A

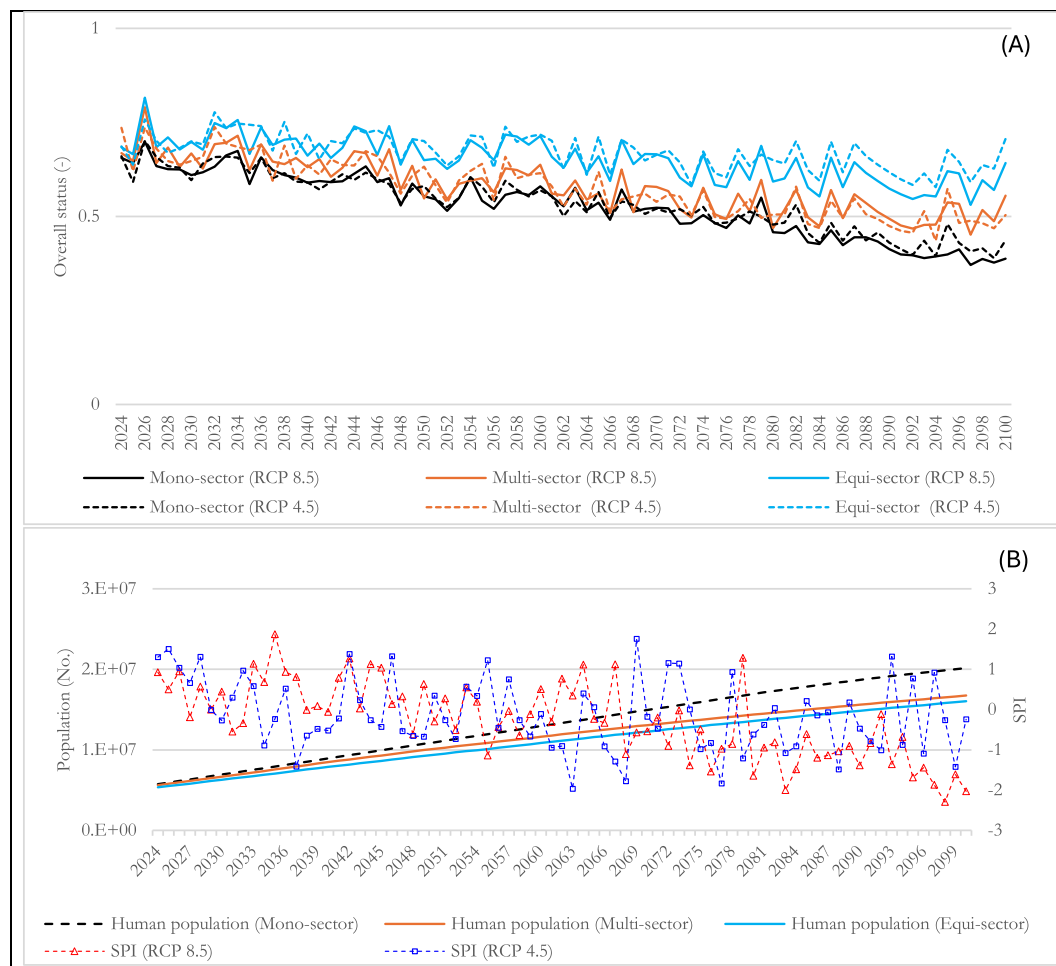


Fig. 7. Overall status of the human-environmental system (A) and associated pressures exerted on the system (B).

combination of sectoral and cross-sectoral approaches appears better suited to addressing end-user requirements, facilitating adoption, and supporting a power balanced and equitable adaptation effort.

The findings of this study further indicate that the conventional sectoral-thinking approach may inadvertently impede adaptive resilience. This becomes especially evident when non-targeted sectors experience intensifying pressures from climate change and human demands, without corresponding improvements in their adaptive capacities. The Crete living lab under the I-CISK project demonstrated the utility of the Co-Co-Co approach, which integrated the primary tourism sector with secondary sectors, such as water, transport, and energy. In the multi-sector scenario tested, this approach yielded partial improvements in sectoral efficiencies relative to the mono-sector scenario. However, the broader literature reveals limited comprehensive guidance on the Co-Co-Co approach, and considerable variability in co-production processes across different contexts (Baulenas et al., 2023; Bojovic et al., 2021; Vincent et al., 2018).

Our findings challenge the traditional classification of stakeholders into primary, secondary, and non-targeted categories. While such categorization represents a step forward from mono-sectoral thinking, it does not adequately capture the complexity of vulnerability profiles, power asymmetries, and the dynamic interconnections across sectors. CS products developed on the basis of ranked sectoral priorities risk addressing narrow sector-specific requirements while overlooking cross-sectoral needs. By contrast, a Co-Co-Co approach that discards rigid sectoral classifications and promotes a balanced distribution of power may be more effective in fostering adaptive resilience (Tudose et al., 2023). Furthermore, sustainable adaptation pathways are unlikely to

remain static and may require ongoing recalibration in response to evolving climate regimes and socio-economic dynamics.

The 2023 Intergovernmental Panel on Climate Change (IPCC) report underscores that systemic barriers continue to inhibit the effective implementation of adaptation strategies within vulnerable sectors (Calvin et al., 2023). Integrating systems thinking into the early stages of the Co-Co-Co approach can help overcome knowledge gaps and realign adaptation pathways (Goldschmeding et al., 2025; Mkandawire et al., 2021; Moallemi et al., 2022). Evidence further suggests that trans-disciplinary methodologies can identify leverage points capable of disrupting systemic inequities and enhancing adaptive capacity across diverse sectors (Hellin et al., 2022; Magliocca, 2023; Mkandawire et al., 2021). In line with this, (Máñez Costa et al., 2022) recommended the adoption of varied engagement strategies to identify and involve stakeholders more effectively, coupled with routine assessments of co-production processes to evaluate performance and impact. These recommendations also emphasize addressing power imbalances by implementing inclusive practices that acknowledge both facilitators and obstacles, thereby fostering equitable collaboration across stakeholders.

Taken together, our findings indicate the need to move beyond static sectoral categorizations and toward inclusive, iterative, and adaptive CS development processes. Such processes must acknowledge dynamic vulnerabilities, systemic interdependencies, and shifting socio-ecological pressures. A recalibrated Co-Co-Co approach, one that integrates co-implementation and co-evaluation, alongside co-design and co-production, offers a more promising pathway for sustained adaptive resilience in the face of climate change.

5.3. Limitations and future research

While the model was validated against observed data (2000–2023) and stakeholder input, some model assumptions may introduce uncertainties. The assumptions of sectoral resource demands, thresholds for privilege-induced reallocation, and climate variables (e.g., SPI) may not fully capture on-the-ground complexities. Moreover, while the model predominantly generates projections based on the RCP 8.5 scenario, with RCP 4.5 employed as a reference, it is imperative to analyse all alternative emissions scenarios. Such analysis is essential for evaluating the robustness of adaptation strategies across a range of potential future conditions, including the specific projections generated by individual models. This type of analysis would be particularly pertinent for informing comprehensive guidance on the Co-Co-Co approach and addressing the significant variability observed in co-production processes across distinct contexts.

The development of sectoral indices provides valuable insights; however, it is critical to acknowledge that an exclusive focus on sectoral impacts may neglect overarching systemic factors. These include socio-economic variables and non-climatic pressures, which can substantially affect the sectoral outcomes of climate adaptation strategies. Future work should prioritize co-developing regionally tailored CS with vulnerable and historically underrepresented sectors. Additionally, expanding the modelling framework to include socio-political shocks (e.g., pandemics, geopolitical conflict) and their interaction with climate stressors may provide a more holistic understanding of adaptation dynamics.

This study models the island of Crete as a single aggregated socio-environmental unit. While this abstraction is appropriate for exploring system-level feedbacks between sectoral power asymmetries and climate service use, it necessarily masks substantial intra-island heterogeneity. In reality, water availability, exposure to climate hazards, and institutional power relations vary considerably across sub-regions of Crete, reflecting differences in hydro-climatic conditions, infrastructure, economic specialization, and governance arrangements. Consequently, the simulated sectoral outcomes should be interpreted as island-wide tendencies rather than localized impacts, and the magnitude of power asymmetries at specific locations may differ from those represented here. Future work could extend the present framework by incorporating spatially explicit sub-regional units to better capture localized pressures and differentiated power dynamics. The Equi-sector scenario is not intended to represent a readily achievable governance arrangement in Crete's tourism-dependent political economy. Rather, it serves as a normative benchmark that illustrates how reduced sectoral power asymmetries could alter system behavior and adaptation outcomes, highlighting the structural consequences of current prioritization patterns rather than predicting near-term political feasibility.

The quantification of stakeholder power asymmetries relied on expert judgment and participatory stakeholder engagement to translate qualitative governance characteristics into model parameters. Although this participatory approach improves contextual relevance and reflects the institutional realities of the ICISK Living Lab, it inevitably introduces a degree of subjectivity into the numerical representation of sectoral adaptive capacities and power relations. The assigned values should therefore be interpreted as plausible representations of the case-study governance context rather than universally applicable estimates. Furthermore, while this study evaluates three contrasting governance configurations (Mono-sector, Multi-sector, and Equi-sector), these scenarios do not encompass the full spectrum of possible stakeholder power distributions. Future research should investigate additional and more extreme sectoral power configurations, including alternative stakeholder rankings and data-driven methods for quantifying stakeholder influence, to further assess the structural robustness and transferability of the model. Combining participatory approaches with empirical social network analysis, institutional indicators, or other quantitative measures of stakeholder influence could further strengthen future model

parameterization while preserving contextual realism.

In addition, several governance processes within the model, such as the threshold-based water reallocation mechanism, were intentionally represented using simplified decision rules. These structural assumptions were designed to capture the dominant institutional mechanisms through which stakeholder power influences resource allocation, rather than to reproduce the full complexity of real-world governance processes. Consequently, the simulated responses should be interpreted as exploratory representations of plausible system behavior under alternative governance configurations, rather than deterministic predictions of stakeholder actions. Future studies could evaluate alternative decision rules, including continuous or probabilistic allocation functions and adaptive governance mechanisms, to assess the sensitivity of model behavior to different institutional representations.

6. Conclusions

This study applied a system dynamic modelling framework to examine how power asymmetries shape the equity and effectiveness of climate services across interdependent sectors, using the island of Crete (Greece) as a case example. The results demonstrate that climate services designed primarily for dominant sectors, can generate adaptation benefits for those sectors but simultaneously exacerbate vulnerabilities and systemic risks in less influential sectors. Such outcomes illustrate the risks of sectoral prioritization and the potential for maladaptive pathways when power dynamics and cross-sectoral interdependencies are overlooked.

To counteract this, equitable engagement of all sectors in the co-production of climate services, grounded in systems thinking and informed by diverse stakeholder perspectives, can help redistribute power more fairly. The findings reinforce the need to move beyond narrow sectoral thinking and static classifications of stakeholders, and instead adopt adaptive, iterative frameworks that recognize dynamic vulnerabilities, systemic interconnections, and justice-related considerations. Such an approach can enhance adaptation outcomes and promote the long-term resilience of coupled human-environment systems.

A recalibrated Co-Co-Co approach, extending co-design and co-production to include co-implementation and co-evaluation, offers a promising pathway for fostering inclusive, demand-driven, and resilience-oriented climate services. Embedding systems thinking and transdisciplinary methods within these processes can help address entrenched power imbalances, identify leverage points, and promote equitable adaptation strategies. Ultimately, advancing climate services that are both effective and just requires sustained commitment to inclusive stakeholder engagement, system-based assessments, and the recognition of socio-ecological complexity.

CRedit authorship contribution statement

Charles Nduhiu Wamucii: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandros Ziogas:** Writing – review & editing, Visualization. **Ilias G. Pechlivanidis:** Writing – review & editing. **Giuliano Di Baldassarre:** Writing – review & editing. **Anne Van Loon:** Writing – review & editing, Visualization, Supervision. **Maurizio Mazzeni:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cliser.2026.100694>.

Data availability

Data will be made available on request.

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