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A Participatory Dynamic Modelling Framework to Support WEFE Nexus Management: Evidence from the Segura River Basin

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1 Abstract

This study presents an integrated methodological framework that links participatory processes with quantitative modelling to support sustainable and adaptive management of the Water–Energy–Food–Ecosystem (WEFE) nexus under increasing resource scarcity and climate change. Conceptual models co-created with stakeholders are translated into a dynamic, empirically validated model capable of reproducing observed system performance.

The approach is applied to the Segura River Basin (south-eastern Spain), one of Europe's most water-stressed regions and highly dependent on the Tagus–Segura inter-basin transfer. The model captures feedback across WEFE components and enables the evaluation of climate change scenarios and stakeholder-defined policy pathways, including potential transfer reductions.

Results indicate a progressive deterioration in nexus performance under increasing climatic pressure, particularly under the more extreme SSP5–RCP8.5 scenario. The analysis reveals significant trade-offs between water supply reliability, which is estimated to decline by around 40%, and energy use, which may increase by up to approximately 6.5% as desalination and groundwater abstraction expand. Agricultural production also shows a decreasing trend, with reductions of up to about 17%, reflecting the system's sensitivity to water availability constraints.

Overall, the results show how climatic pressures and water supply limitations reshape cross-sectoral trade-offs over time, affecting water security, agricultural productivity, energy consumption, and environmental sustainability. The study highlights the value of participatory modelling framework as a decision-support tool for supporting informed management of water-scarce WEFE systems.

Keywords: WEFE nexus; participatory System Dynamics; cross-sectoral trade-offs, Climate Change scenarios, adaptive management

2 Introduction

Ensuring sustainable development in a context of increasing resource scarcity and climate change requires management frameworks that integrate multiple interdependencies across sectors (Liu et al., 2018). In particular, the Water–Energy–Food subsystems—and therefore ecosystems—are expected to be among the most affected (Afshar et al., 2022). The Water–Energy–Food–Ecosystem (WEFE) nexus has consequently emerged as an analytical framework to address these linkages, highlighting how actions in one sector inevitably affect others (González-Rosell et al., 2023; Pérez, 2023).

In parallel, global sustainability discourse has increasingly shifted towards systemic and resilience-oriented thinking, recognising the need to address interconnected socio-ecological challenges in line with the Sustainable Development Goals (SDGs) (Herrera-Franco et al., 2023). This transition reflects growing awareness that fragmented sectoral policies are insufficient to ensure long-term resource security and system resilience.

However, in practice, WEFE management remains largely sectoral and fragmented (Richelle et al., 2025), characterised by persistent governance silos and limited cross-sectoral coordination (Bwire et al., 2023), and is in most cases implemented through top-down approaches (Al-Zu'bi et al., 2025). Such practices often overlook dynamic feedback, cross-sectoral trade-offs, and stakeholder interactions that critically shape system behaviour and policy outcomes (Mooren et al., 2025). These shortcomings have been identified in several European river basins, where WEFE interactions, temporal variability, and cumulative pressures are insufficiently integrated into planning processes (Aldaya et al., 2019).

Beyond these governance limitations, methodological constraints also persist within nexus research. In particular, a growing body of studies has focused on qualitative or semi-quantitative assessments of WEFE (or WEF) interactions. These approaches have improved conceptual clarity and enabled indicator-based benchmarking of cross-sectoral linkages (Molefe & Inglesi-Lotz, 2023) However, they typically do not incorporate structured participatory stages and often lack the dynamic representation and empirical validation required to simulate long-term system behaviour and policy feedbacks under changing climatic and socio-economic conditions.

Addressing both institutional fragmentation and methodological limitations therefore requires stronger integration of stakeholder perspectives within analytical frameworks. Within the WEFE nexus paradigm, cooperation among key actors is not merely desirable but foundational, as the identification of synergies, trade-offs, and interdependencies across sectors depends on shared understanding and knowledge exchange (Papadopoulou et al., 2025). In this regard, participatory approaches are increasingly recognised as essential for strengthening the legitimacy, acceptance, and contextual relevance of WEFE models (Giest & Mukherjee, 2022). Co-production processes help uncover diverse system perceptions and co-design solutions that reflect local priorities (Djenontin et al., 2025). Nevertheless, participation often remains confined to early conceptual stages and rarely advances to meaningful stakeholder integration in decision-making processes.

Recent research emphasises the need for integrated methodologies that combine participatory processes with quantitative models that capture temporal dynamics and cross-sectoral interrelations. According to the recent review (Dan Turtureanu et al., 2025), practical nexus assessments increasingly rely on hybrid approaches that combine qualitative system characterisation, quantitative simulation, and stakeholder engagement. Such approaches address persistent limitations in water and resource planning, including the limited incorporation of participatory and transparent processes that strengthen legitimacy and ownership in decision-making (Aldaya et al., 2019), as well as the insufficient integration of subsystems.

This study addresses this gap by proposing a combined methodological framework that integrates participatory processes, quantitative modelling, and WEFE nexus analysis to support adaptive and cross-sectoral decision-making. The framework is particularly relevant under climate change scenarios, but also applicable to policy evaluation. Linking these components enables the identification of effective measures that enhance the sustainability of the entire system.

In this context, System Dynamics (SD) offers a flexible, integrative methodology that meets these requirements. SD enables the explicit representation of feedback loops, non-linear relationships, delays, and cross-sectoral dependencies, while maintaining the transparency necessary to facilitate stakeholder participation and model co-design (Mirchi et al., 2012; Sušnik & Staddon, 2022). Importantly, SD supports dynamic modelling over extended time horizons, responding to calls for methodologies that move beyond static scenario approaches and better capture the co-evolution of water, energy, agricultural, and environmental indicators.

Several studies have applied System Dynamics to explore nexus interactions and policy alternatives. In the Andalusia region, a participatory system dynamics model was developed that integrates stakeholder perspectives and qualitative system mapping to assess policy impacts (González-Rosell et al., 2020). However, its broad spatial scale, annual time steps, and semi-quantitative nature limit its capacity to reproduce measurable System Dynamics through empirical validation. Other studies, such as those conducted in Iran, China and Spain (Keyhanpour et al., 2021; Rubio-Martin et al., 2020; Wen et al., 2022; Zeng et al., 2022), adopt top-down, scenario-based approaches without stakeholder participation, resulting in technically robust models that remain disconnected from local knowledge, values, and priorities. More recently, European initiatives (Giordano et al., 2025; Pagano et al., 2025) have developed participatory SD frameworks for Mediterranean basins; however, these remain largely conceptual or semi-quantitative and rarely achieve full validation against observed data.

To test the validity of the proposed methodological framework, it is applied to the Segura River basin, one of the most water-stressed regions in Europe (CHS, 2022; Miró et al., 2023). A System Dynamics model is developed from conceptual models co-created with regional stakeholders. The study translates qualitative representations into an empirically validated structure capable of reproducing observed system behaviour and exploring temporal trajectories and trade-offs under multiple policy and climate scenarios.

The main contribution of this research lies in the full integration of participatory co-creation, quantitative validation, and multi-scenario climate analysis within a unified, transparent, and transferable WEFE framework. By systematically linking stakeholder knowledge, dynamic simulation, and empirical validation, the proposed approach moves beyond conceptual nexus assessments and provides an operational tool for adaptive management. Although demonstrated in the Segura River basin, the framework is designed to be replicable in other water-stressed regions facing complex cross-sectoral challenges, thereby supporting more coherent, inclusive, and evidence-based sustainability transitions.

3 Materials and Methods

The proposed methodology is designed as a practical decision-support tool to foster the sustainable management of complex resource systems. It integrates qualitative and quantitative analyses derived from the knowledge of key system stakeholders and validated against empirical data. The approach operates across multiple temporal scales and explicitly considers the synergies and trade-offs arising from WEFE nexus interdependencies.

3.1 General framework

The framework is organised into two sequential and interrelated phases (Figure 1): (i) participatory co-creation of the conceptual

system representation, and (ii) development and application of a dynamics model for simulation and analysis.

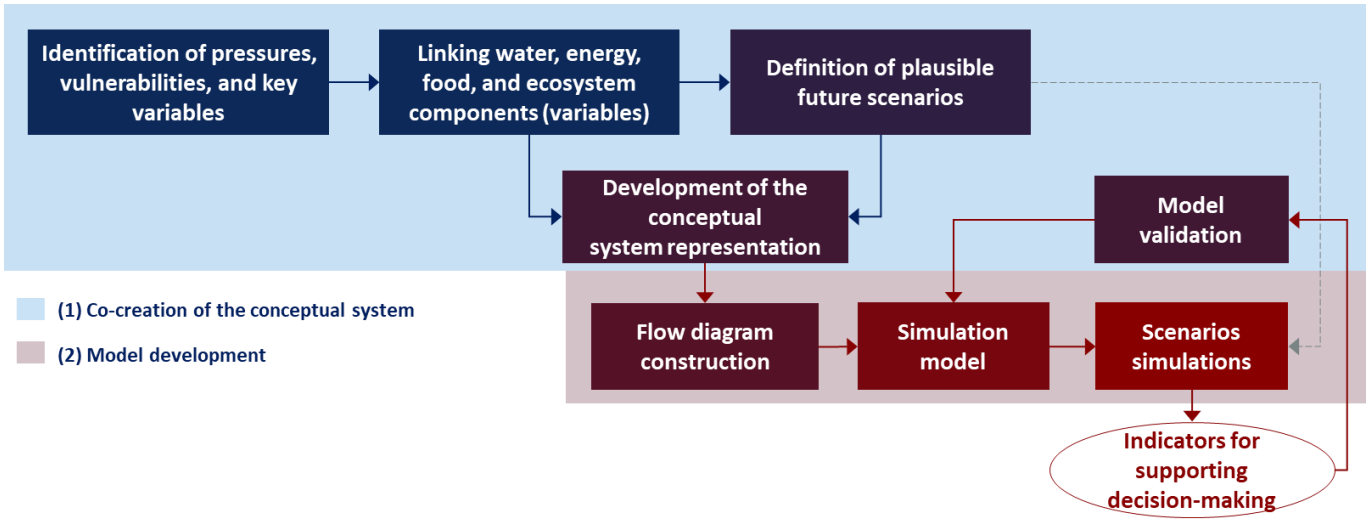


Figure 1. Workflow of the integrated participatory–quantitative framework

The first phase focuses on constructing a shared qualitative understanding of the system through a structured participatory process. Stakeholder workshops and expert consultations are used to identify key system pressures, vulnerabilities, and relevant variables across the WEFE dimensions. Particular attention is given to capturing cross-sectoral interactions and feedback mechanisms, which are often overlooked in sector-based planning approaches (Aldaya et al., 2019).

In parallel, a set of plausible future scenarios is defined that reflects stakeholder perceptions of relevant hydro-climatic, socio-economic, and policy trajectories. The information elicited during this process is used to develop the conceptual system representation. It is synthesised into causal loop diagrams (CLDs), which capture the key feedback structures and interdependencies among WEFE components. CLDs provide a transparent and accessible means of formalising stakeholder knowledge and are widely used in participatory nexus assessments to support shared understanding and collective learning (Mirchi et al., 2012). Beyond their analytical function, they also facilitate reflexive dialogue and collective sense-making, thereby strengthening legitimacy and ownership in decision-support processes (Hurtado et al., 2024).

The outcome of this phase is a co-created, stakeholder-agreed-upon qualitative System Dynamics (SD) structure that serves as the conceptual foundation for quantitative modelling. A detailed description of the stakeholder engagement process, co-creation methodology, and resulting conceptual models is provided in a companion study (Mónico et al., 2026). In the present work, the resulting conceptual structure is used as the basis for the model formalisation.

The second phase translates this qualitative representation into an operational simulation framework. The conceptual model is formalised through the construction of a flow diagram that adopts a stock–flow architecture consistent with SD principles. This structure is implemented as a simulation model, enabling the representation of non-linear interactions, feedback loops, and allocation rules across nexus components over time. The model is subsequently validated against historical data to ensure it can reproduce observed system behaviour. Once validated, it is used to perform scenario simulations that explore system responses under the previously defined future conditions. Simulation outputs are synthesised into a set of indicators for supporting decision-making, enabling the evaluation of system performance across water, agriculture, energy, and environmental dimensions. The resulting simulations and indicators are subsequently presented and discussed with stakeholders, allowing model behaviour and scenario responses to be qualitatively validated against stakeholder knowledge and sectoral experience, while also supporting iterative model refinement.

3.2 Case study description

The Segura River Basin, located in south-eastern Spain (Fig. 5), is one of the most structurally water-scarce regions in Europe and a recognised hotspot of hydro-climatic vulnerability. Its semi-arid Mediterranean climate, with mean annual precipitation of roughly 350–375 mm and high evapotranspiration rates combined with intensive irrigation practices, creates a persistent imbalance between renewable water availability and authorised demands (CHS, 2022). This chronic deficit, intensified by climate change and increasing hydrological variability, makes the basin a critical setting for WEFE analysis, where water scarcity constrains agricultural productivity, increases energy requirements for water supply, and places pressure on ecosystems, thereby challenging long-term sustainability and resource security. At the same time, the basin sustains one of Europe's most intensive and export-oriented

horticultural systems, supplying fresh produce to European markets and linking regional water management to continental food supply chains.

Water availability depends on a diverse but constrained portfolio. Surface resources are limited and highly variable, while groundwater—historically a drought buffer—now shows signs of overexploitation and declining storage (CHS, 2022). The Tagus–Segura Aqueduct (ATS), the largest inter-basin water transfer scheme in Europe, remains central for irrigation, urban, and environmental demands. However, its reliability has decreased due to regulatory changes and climate-induced reductions in inflows. Non-conventional resources, particularly desalinated seawater and reclaimed wastewater, have expanded significantly and now form a strategic component of supply (Gómez-Ramos et al., 2024). Desalination provides a climate-resilient alternative, while reclaimed water supports a substantial share of irrigation.

This diversified supply system entails markedly different energy requirements depending on the water source. While conventional resources such as surface water involve relatively low energy inputs, non-conventional and external sources—particularly desalinated water, inter-basin transfers and groundwater abstraction—require substantially higher energy consumption. Among these, desalination represents one of the most energy-demanding options, illustrating a structural shift towards increasingly energy-dependent water supply strategies. As a consequence, water provision in the basin is closely linked to CO_2 emissions generated throughout the supply chain, from extraction and treatment to distribution, highlighting the embedded energy–carbon dimension of water management (Odriozola et al., 2025).

Irrigated agriculture accounts for more than 80 % of total consumptive use (Calatrava & Martínez-Granados, 2018) and underpins a highly productive, export-driven agro-economy. However, this productivity depends on a fragile combination of groundwater abstraction, inter-basin transfers, and non-conventional sources, which makes the system highly sensitive to hydrological variability and regulatory shifts (Martínez-Alvarez et al., 2023). In this context, groundwater plays a critical but increasingly unsustainable role, as abstraction in several aquifers exceeds natural recharge rates, contributing to long-term resource depletion and reinforcing structural water deficits (Pellicer-Martínez & Martínez-Paz, 2016).

These structural characteristics highlight the basin's suitability for WEFE nexus analysis. Water scarcity limits food production, while the growing reliance on energy-intensive water supply options reinforces strong interdependencies between water availability, energy consumption, and environmental sustainability (Raya-Tapia et al., 2023).

The resulting feedbacks — such as trade-offs between reducing agricultural deficits and increasing energy consumption — underscores the need for dynamic, multisectoral modelling tools capable of capturing long-term system co-evolution.

The combination of chronic scarcity, export-oriented agriculture, energy-intensive supply, inter-basin transfer dependence, and evolving environmental obligations makes the Segura Basin a particularly relevant context for testing an integrated and participatory WEFE modelling framework. Its institutional complexity and the availability of long-term hydrological and operational datasets (CHS, 2022) provide a strong empirical basis for demonstrating the applicability and transferability of an adaptive WEFE decision-support framework.

3.3 Model development

Building upon the qualitative structure and the specific hydrological and institutional characteristics of the Segura River Basin, the quantitative model was developed to operationalise the identified WEFE interactions under the basin's conditions. The configuration of the model, therefore, reflects both the co-created system representation and the water management framework governing allocation and supply within the study area.

System Dynamics was adopted to translate the qualitative system representation into an operational quantitative framework. This approach organises the WEFE nexus into interacting subsystems (water, agriculture, energy, and environment) within a single dynamic structure. Its capacity to represent feedback loops, allocation constraints, and non-linear interactions has been identified as particularly suitable for nexus applications in European and Mediterranean basins characterised by structural water scarcity (Pagano et al., 2025; Sušnik & Staddon, 2022)

The model was implemented using VENSIM PRO (Eberlein & Peterson, 1992) and structured according to a stock–flow architecture. Accumulative elements are represented as stocks, changes over time as flows, and auxiliary variables formalise technical processes, management rules, and behavioural responses. This structure provides a transparent link between the qualitative conceptualisation and its mathematical implementation.

The model operates at a monthly time step, consistent with the temporal resolution of available hydrological and demand datasets. This resolution allows representation of seasonal variability while maintaining computational tractability for long-term simulations.

The simulation horizon extends from 1980 to 2100. The historical period (October 1980–2018) is used for hydrological validation, while the extended horizon enables the exploration of future climate and management scenarios. The structural configuration of the model remains unchanged across validation and scenario analyses; only input variables and boundary conditions are modified to reflect alternative assumptions.

The quantitative model is organised into four interconnected subsystems corresponding to the core dimensions of the WEFE nexus. Each subsystem operationalises the qualitative relationships identified during the participatory phase, while remaining structurally integrated within the overall stock–flow framework.

A complete description of the variables, parameters, units, and model components used in the System Dynamics framework is provided in Supplementary Material S1.

3.3.1 Water subsystem

The water subsystem constitutes the structural backbone of the model, as water availability conditions the performance of the remaining nexus components.

In the qualitative system mapping, water resources were identified as the central element of the basin system. In the quantitative model, this concept is operationalised through six stock variables representing regulated water availability across three basin zones (upper, middle, and lower), as shown in the Figure 2.

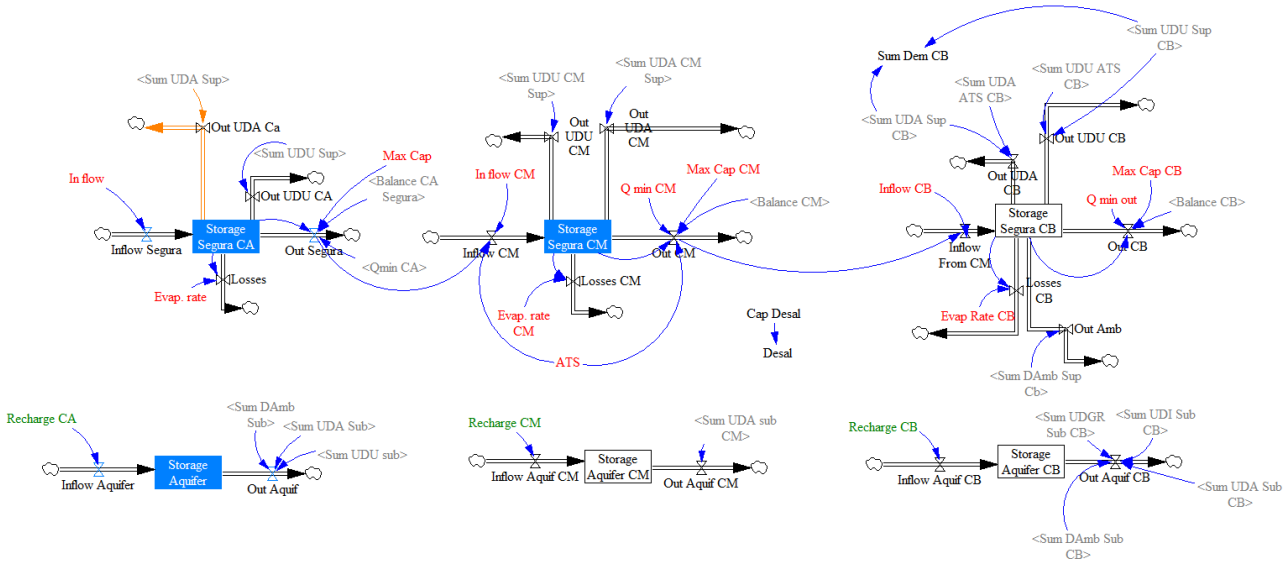


Figure 2. Stock–flow representation of the water subsystem in the System Dynamics model

Three stocks represent surface water availability in each basin zone. These do not reproduce individual reservoir volumes, as storage capacity is spatially distributed across the basin, but instead represent the regulated water available for allocation under current operational conditions. The upper basin aggregates the main regulating reservoirs of the system (Camarillas, Cenajo, Fuensanta, Taibilla, and Talave), while the three zones collectively represent the distribution of water to sectoral demands, including supplies associated with the Tagus–Segura post-transfer system.

Water stock dynamics follow a mass balance formulation:

$$Sz(t) = Sz(t - \Delta t) + (Iz(t) - Oz(t) - Lz(t)) \qquad (1)$$

Where:

- Sz(t) [Mm³]: water storage in zone z at time t
- z: basin zone (upper, middle, lower)
- Iz(t) [Mm³/month]: inflows
- Oz(t) [Mm³/month]: outflows
- Lz(t) [Mm³/month]: system losses
- Δt: simulation time step

Inflows include river runoff and interbasin transfers. Outflows include sectoral withdrawals, environmental releases, and system losses.

Three additional stocks represent effective groundwater availability in each zone. These incorporate recharge processes and regulatory abstraction limits, thereby representing accessible groundwater capacity rather than total aquifer storage.

Desalination is included as a supply variable constrained by installed capacity. All water sources are integrated within a dedicated allocation module that distributes supply to sectoral demands according to predefined prioritisation rules and withdrawal limits. This formalisation translates stakeholder-identified allocation hierarchies into explicit mathematical relationships.

The water subsystem is directly linked to:

- The agricultural subsystem through irrigation supply flows.
- The environmental subsystem through regulated environmental releases.
- The energy subsystem through abstraction, desalination, and transfer volumes.

3.3.2 Agricultural subsystem

In the qualitative representation, agricultural production was identified as strongly dependent on water availability and a key component of the nexus. In the quantitative model, production is represented as a function of cultivated area and irrigation water supply.

Crop groups are defined according to available statistical data. The yield–water relationship follows the FAO 33 approach (Doorenbos & Kassam, 1979), using the yield response factor Ky:

$$1 - \frac{Y_a}{Y_m} = K_y \left(1 - \frac{ET_a}{ET_m}\right) \qquad (2)$$

Where:

- Y_a [Ton/ha]= actual yield
- Y_m [Ton/ha]= maximum yield
- Et_a [mm]= actual evapotranspiration
- ET_m [mm]= maximum evapotranspiration
- K_y = yield response factor

Total agricultural production is computed as the aggregate output across crop groups (Forage, vegetables, cereals, fruit, vineyard, etc.). This structure embeds the qualitative linkage between water scarcity and food production into a measurable dynamic relationship within the model (Figure 3).

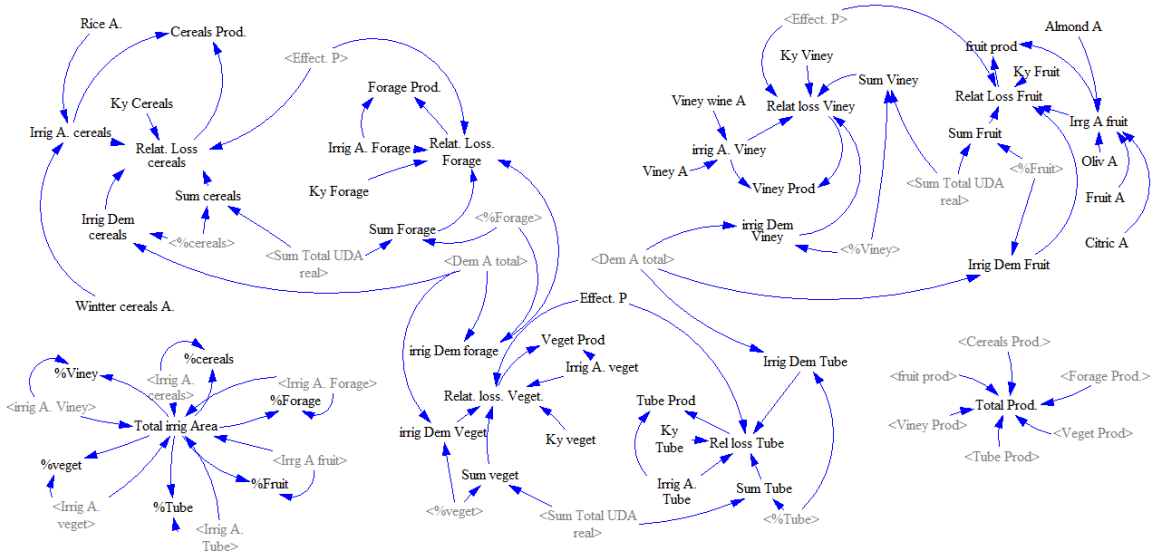


Figure 3. Stock–flow representation of the agricultural subsystem in the System Dynamics model

The agricultural subsystem connects to:

- The water subsystem through irrigation allocation.
- The energy subsystem through irrigation-related energy requirements.

3.3.3 Energy subsystem

The energy subsystem (Figure 4) captures the resource implications of water supply decisions, formalising the link between water sourcing strategies and energy consumption.

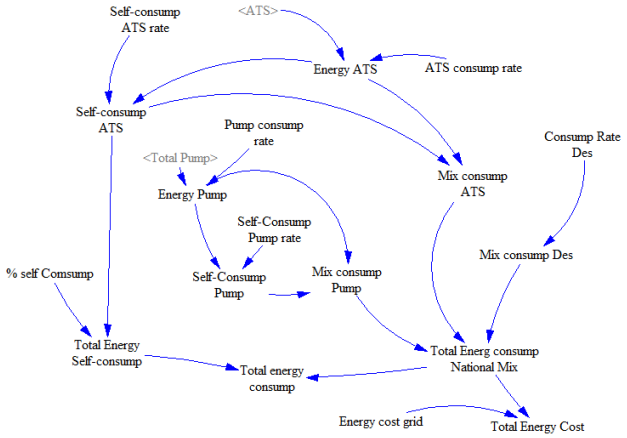


Figure 4. Stock–flow representation of the energy subsystem in the System Dynamics model

In the qualitative mapping, energy was identified as both an enabling input and a constraint linked to water supply decisions. In the quantitative model, energy consumption is calculated as a function of water volumes abstracted, desalinated, conveyed, or treated. The subsystem represents the main energy-demanding water supply and irrigation processes operating across the basin, including groundwater abstraction, desalination, water transfers, and irrigation pumping.

$$Energy_{total} = \sum_i (Volume_i * EI_i) \qquad (3)$$

Where:

- E [kWh]: total energy consumption
- i: water source or process
- $Volume_i$ [Mm³/month]: water supplied from source i
- EI_i [kWh/m³]: energy intensity coefficient of source

This formulation ensures that changes in supply composition are reflected in corresponding variations in energy consumption. Where applicable, renewable self-consumption systems may be incorporated to offset net energy use.

3.3.4 Environmental subsystem

Environmental sustainability was identified in the qualitative mapping as the ecological core of the WEFE nexus. In the quantitative model, environmental requirements are operationalised as regulated water demands embedded within the allocation structure.

Environmental water needs include required minimum ecological streamflow and the hydrological requirements of sensitive ecosystems such as wetlands, lagoons, and salt flats. These requirements are defined according to the River Basin Management Plan (RBMP), which establishes regulatory thresholds to ensure ecosystem functioning and compliance with environmental objectives. Environmental deficits are defined as:

$$Def_{env} = D_{env} - S_{env} \qquad (4)$$

Where:

- Def_{env} [Mm³]: environmental deficit
- D_{env} [Mm³]: environmental water demand
- S_{env} [Mm³]: environmental water deliveries

By embedding environmental requirements within the allocation hierarchy, the model translates sustainability objectives into explicit quantitative constraints affecting sectoral water distribution. The environmental subsystem interacts dynamically with the water subsystem through regulated releases and indirectly with agriculture and energy through shared allocation pressures.

3.3.5 WEFE Nexus Indicators

To evaluate nexus interactions in a structured and policy-relevant manner, a coherent set of performance indicators was defined. The selection of indicators constitutes a critical methodological step, as it determines how synergies and trade-offs across water, agriculture, energy, and environment are interpreted.

Consistent with the participatory modelling framework adopted in this study, indicators were discussed and validated during stakeholder engagement processes. This ensured that the selected metrics reflected management priorities, institutional thresholds, and sectoral concerns specific to the Segura River Basin. The objective was not only to measure system performance, but to capture dimensions considered decision-relevant by basin actors.

For the Segura case study, five core indicators were selected to represent the key nexus dimensions.

- Reliability of Environmental Supply

Environmental performance is assessed through the reliability of environmental water allocation. Reliability is defined as the proportion of time in which environmental demand requirements are fully satisfied (Hashimoto et al., 1982) and is calculated as:

$$Rel_{env} = 1 - \frac{N_f}{N} \qquad (5)$$

Where:

- Rel_{env}: environmental supply reliability
- N: total number of time steps
- N_f: number of months in failure

This formulation captures the frequency of ecological deficits over the simulation horizon. Higher values indicate improved environmental protection and greater compliance with sustainability objectives.

- Agricultural Production (Normalised)

To enable comparison across scenarios and time horizons, production [Ton] is normalised using observed minimum and maximum values within the simulation period:

$$Ag_Pr = \frac{P(t) - P_{min}}{P_{max} - P_{min}} \qquad (6)$$

Where:

- Ag_Pr: normalised agricultural production
- P(t): agricultural production
- P_{min}: minimum production in reference/simulation period
- P_{max}: maximum production in reference/simulation period

An increase in this indicator indicates improved food production.

- Storage Reliability

Water system robustness is represented through an availability indicator linked to storage conditions in the upper basin. In line with the operational thresholds established by the basin authority (CHS), a failure is recorded when regulated storage falls below the alert threshold defined in the drought management plan.

Storage reliability is computed as:

$$Rel_{st} = 1 - \frac{N_{fst}}{N} \qquad (7)$$

Where:

- Rel_{ST}: storage reliability
- N: total number of time steps
- N_{fst}: number of months below threshold

This indicator reflects the structural condition of basin storage and serves as a proxy for system-wide water security.

- Reliability of Agricultural Supply

Agricultural water security is evaluated through supply reliability. A failure occurs when the irrigation deficit exceeds an acceptable or expected threshold defined in consultation with the stakeholders.

Reliability is calculated analogously to the environmental indicator:

$$Rel_{agr} = 1 - \frac{N_{agr}}{N} \qquad (8)$$

Where:

- Rel_{agr}: agricultural supply reliability
- N: total number of time steps
- N_{agr}: number of months in failure (unacceptable deficit)

- Energy Consumption (Normalised)

Energy performance is measured as total energy consumption associated with water abstraction, desalination, water transfer conveyance, and irrigation pumping and pressuring.

To ensure comparability across scenarios, energy use is normalised using simulated minimum and maximum values:

$$En_Co = \frac{E_{max} - E(t)}{E_{max} - E_{min}} \qquad (9)$$

Where:

- En_Co: normalised energy consumption
- E(t): total energy consumption
- Emax: simulated maximum energy consumption
- Emin: simulated minimum energy consumption

In contrast to agricultural production, lower values represent improved performance, as reduced energy consumption implies greater system efficiency and lower resource intensity.

Together, these five indicators enable a multidimensional evaluation of nexus performance. The reliability-based indicators capture temporal robustness, while the normalised production and energy indicators reflect resource productivity and efficiency. By combining frequency-based reliability metrics with magnitude-based performance measures, the framework allows identification of:

- Synergies (e.g., simultaneous improvements in reliability of environmental supply and agricultural production),
- Trade-offs (e.g., increased energy consumption associated with improved water supply reliability),
- Structural vulnerabilities under alternative climate or management scenarios.

This indicator set therefore operationalises the participatory WEFE framework into a measurable, decision-support structure suitable for long-term scenario analysis.

4 Results

This section presents the results from applying the participatory modelling framework to the Segura River Basin. Building upon the model development described in the methodology, the co-created system representation was translated into a dynamic simulation tool capable of capturing cross-sectoral interactions and temporal evolution within the WEFE nexus.

The results are organised in two stages. First, the model is evaluated against historical data to assess its ability to reproduce observed system behaviour. Second, the validated structure is employed to explore system responses under alternative future conditions, analysing temporal trajectories and interactions across water, energy, food, and environmental components.

4.1 Model Validation

To validate the quantitative model and its suitability for scenario analysis, simulated outputs were compared with observed hydrological data from the CEDEX (2022). Figure 5-a shows the basin configuration, including the main reservoirs, river network, the Tagus–Segura Aqueduct (TSA), and the selected validation points.

The first validation point (Figure 5-b) corresponds to total regulated water storage in the upper basin. This location is particularly relevant, as upper-basin reservoirs account for more than 80% of the basin's principal storage capacity and largely condition interannual water availability. The second control point (Figure 5-c) is located at the transition between the middle and lower basins. Modelled inflow to the lower basin was compared with observed discharge downstream of Ojos gauging station (CEDEX, 2022).

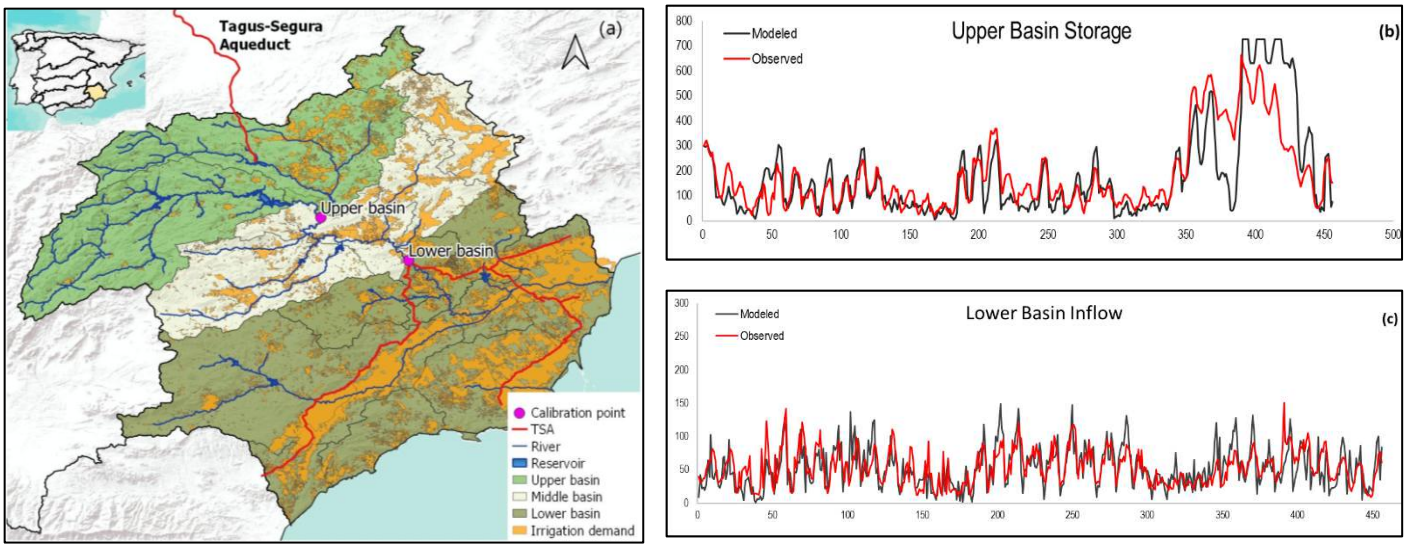


Figure 5. Schematic of the Segura River Basin and model validation results. ***(a)*** *Spatial representation of the basin, including the river network, main reservoirs, the Tagus–Segura Aqueduct (TSA), and selected validation points.* ***(b)*** *Comparison between simulated and observed upper basin storage.* ***(c)*** *Comparison between simulated and observed inflow to the lower basin.*

The model reproduces the main seasonal and interannual storage patterns over the validation period. Simulated storage follows observed low-storage phases (1991–1995; 2005–2008) and high-accumulation periods (1996–1998; 2010–2015). The Pearson correlation coefficient between observed and simulated storage is 0.81, indicating strong agreement in behaviour at the monthly scale.

The simulated series captures the dominant temporal patterns, including drought sequences and peak inflow events. Although simulated peaks are occasionally sharper than observed values, overall correspondence remains consistent. The correlation coefficient of 0.75 indicates satisfactory agreement in representing downstream hydrological variability.

Together, these results indicate that the aggregated model structure reproduces the principal hydrological signals governing basin-scale water availability and allocation dynamics.

In addition, simulated agricultural production levels were compared with the statistics reported for the basin (Table 1). Observed values were obtained from the Region of Murcia Statistics Centre (CREM, 2023) and represent the average production recorded for the period with available data. Modelled values correspond to the average production simulated by the model for the same years.

Table 1. Comparison of observed and simulated agricultural production by crop group

	Forage	**Vegetables**	**Cereals**	**Fruit**	**Vineyard**
Observed	57,174	1,729,007	52,234	1,390,393	236,979
Simulated	59,436	1,804,426	45,354	1,925,702	196,873

All values expressed in tons per year.

Overall, the simulated values reproduce the general magnitude of the observed agricultural production across the main crop groups. A close correspondence is observed for forage and vegetables, while cereals and vineyards show moderate deviations. The largest difference appears in fruit production, where the model tends to overestimate the reported values. Nevertheless, the results indicate

that the model captures the relative importance of the different crop groups within the basin's agricultural system.

4.2 Scenario simulations

4.2.1 Climate change scenarios

The climate change scenarios analysed were obtained from the Coupled Model Intercomparison Project (CMIP6), the most established source for climate change projections in response to IPCC-developed scenarios. Projections encompass five CMIP6 models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) for both historical and future scenarios within the ISIMIP framework. The dataset included downscaled and bias-corrected monthly temperature and precipitation projections for the three Representative Concentration Pathways considered in the study (2.5, 7.0 and 8.5), spatially matched to the hydrological units of the Segura basin. Hydrological time series for climate change were generated using the TETIS model (Francés et al., 2007), a fully distributed eco-hydrological model that provides a calibrated and physically consistent representation of the basin's processes.

Although simulations were conducted using five climate models under three SSP pathways, results are presented here in aggregated form to facilitate comparison across scenarios. For each SSP pathway, outputs from the five climate models were averaged in order to highlight consistent scenario-driven patterns while reducing variability associated with individual projections.

Figure 6 summarises the simulated evolution of the main WEFE variables for the reference period and for the short-, medium- and long-term horizons. Results are presented as box plots in order to illustrate both central tendencies and dispersion across simulations.

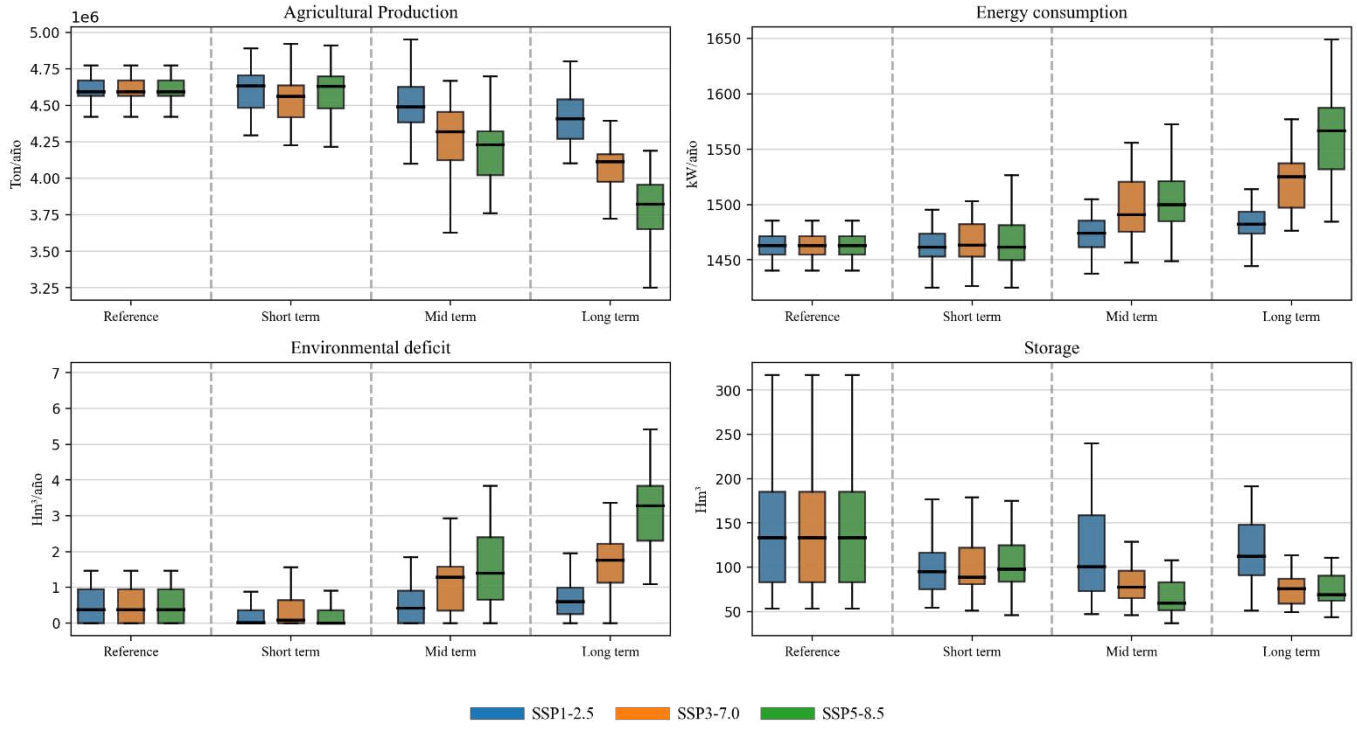


Figure 6. Evolution of WEFE nexus indicators across climate scenarios and time horizons

Overall, the simulations indicate a progressive deterioration of water-related variables over time, particularly under SSP3–RCP7.0 and SSP5–RCP8.5. Water availability and agricultural production show declining median values towards the long-term horizon, while environmental deficits and energy consumption increase across the scenarios. By the long-term horizon, agricultural production decreases by approximately 4.1% under SSP1-RCP2.6 and 16.9% under SSP5-RCP8.5 relative to the reference period, while energy consumption increases by around 1.1 – 6.5%, reflecting the growing reliance on energy-intensive water supply sources.

While the previous analysis presents the simulated evolution of the main system variables under the different climate scenarios, it does not directly reflect how these changes translate into the performance of the WEFE nexus as defined in the participatory process. To address this, the results are further synthesised using the set of nexus indicators identified and prioritised by

stakeholders during the model development phase.

Figure 7 illustrates the evolution of the selected WEFE indicators across scenarios and time horizons using radar diagrams. The indicators correspond to the key dimensions of the nexus previously defined in the methodology.

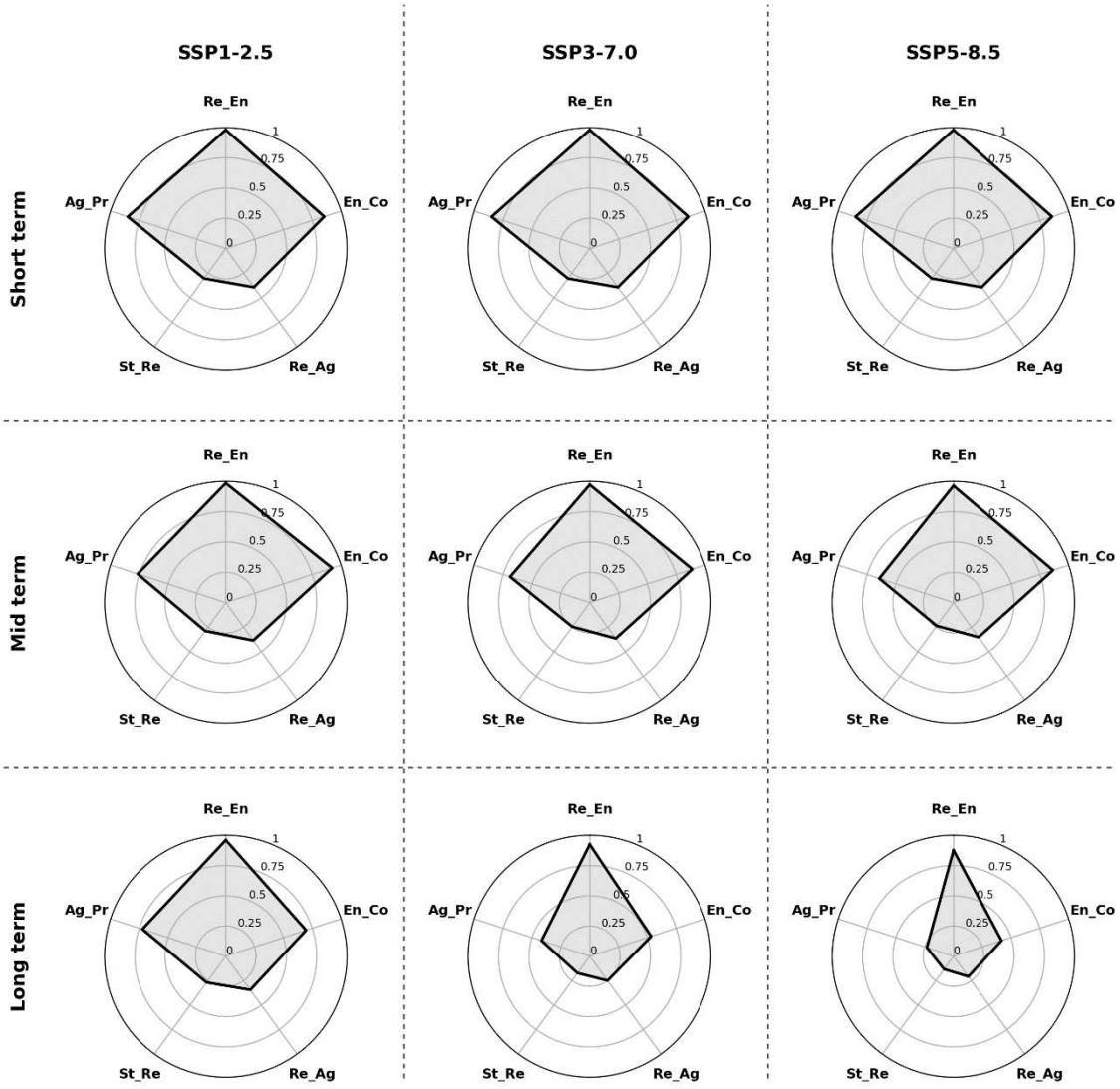


Figure 7. Evolution of WEFE nexus indicators across climate scenarios and time horizons. Radar plots show values for the selected indicators: ***Re_En*** *(reliability of environmental supply),* ***En_Co*** *(energy consumption),* ***Re_Ag*** *(reliability of agricultural supply),* ***St_Re*** *(Storage Reliability), and* ***Ag_Pr*** *(agricultural production).*

The radar diagrams reveal a progressive contraction of nexus performance over time, particularly under the more severe climate scenarios. In the short-term horizon, the overall structure of the system remains relatively similar across the three SSP pathways, with high values for reliability of environmental supply and agricultural production and comparatively lower values for water supply and reliability. In the medium-term, reductions become more visible, particularly in agricultural production and water supply under SSP3–RCP7.0 and SSP5–RCP8.5. By the long-term horizon, the contraction of the radar shapes becomes markedly stronger, indicating simultaneous declines in several nexus dimensions. The most pronounced reductions are observed in water supply and agricultural production. Agricultural production declines by roughly 55% between the short- and long-term horizons under SSP5–RCP8.5, while water supply decreases 40%**,** indicating the strong sensitivity of the basin's productive system to increasing climatic pressure.

In contrast, the environmental indicator shows comparatively smaller variations, decreasing 22% between the short- and long-term horizons, which reflects the priority assigned to environmental flows within the basin's allocation rules.

4.2.2 Sensitivity Analysis of Tagus–Segura Transfer Reductions

In combination with the climate change projections, a policy-driven scenario was analysed, focusing on potential reductions in water transfers through the Tagus–Segura Aqueduct (TSA). Transfers through the TSA are governed by operating rules based on the aggregated storage available in the upper Tagus basin. These rules regulate the volumes of water that can be transferred under different hydrological conditions, making them highly sensitive to both climatic variability and policy decisions. In particular, ongoing and expected developments—such as reductions in storage associated with climate change and the potential increase in environmental flow requirements under the Tagus River Basin Plan—are likely to significantly affect the volume of water available for transfer in the future.

As no definitive projections of future transfer volumes are currently available, this analysis was designed as a structured sensitivity assessment rather than a forecast. Reductions in TSA inflows were simulated in incremental steps of 10%, ranging from 10% to 90% relative to baseline conditions. This approach allows exploration of system responses across a wide range of possible transfer constraints. Results are presented for each climate scenario and for the three time horizons considered in the study.

Figure 8 summarises the response of the WEFE indicators using radar diagrams. Each coloured line represents a reduction level in TSA transfers, illustrating how the performance of the nexus evolves as inter-basin water availability decreases.

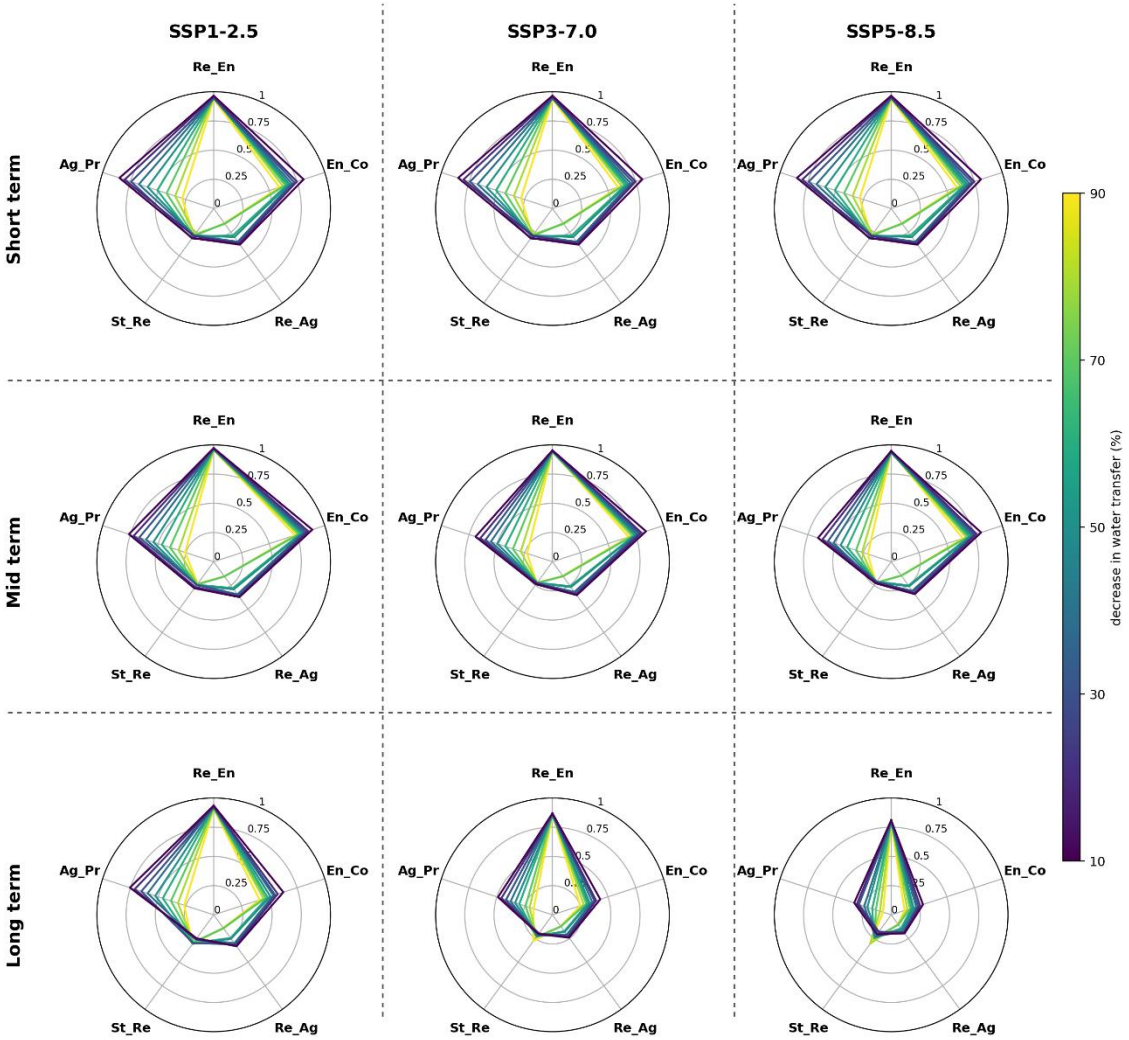


*Figure 8. Sensitivity of WEFE nexus indicators to reductions in Tagus–Segura water transfers across climate scenarios and time horizons. Radar plots show values for the selected indicators: **Re_En** (reliability of environmental supply), **En_Co** (energy consumption), **Re_Ag** (reliability of agricultural supply), **St_Re** (Storage Reliability), and **Ag_Pr** (agricultural production)*

The radar diagrams reveal clear differences in the sensitivity of the WEFE indicators to reductions in Tagus–Segura transfers. Agricultural production and water supply show the strongest response, declining steadily as transfer reductions increase across all scenarios and time horizons. Under the most severe reductions (90%), agricultural production declines 55% compared to the 10%

reduction case, while water supply decreases 65%, highlighting the strong dependence of irrigated agriculture on transferred water resources.

In contrast, the reliability of the environmental supply indicator remains largely unchanged across the different reduction levels. The indicator varies by less than 10% across the full range of transfer reductions reflecting the priority given to environmental flow requirements within the basin's water allocation rules, which limits the variability of this indicator even under reduced transfer conditions.

System reliability presents an intermediate response, with moderate declines as transfer reductions intensify. The sensitivity of the indicators also becomes more pronounced in the medium- and long-term horizons, where reductions in transferred water increasingly affect agricultural production and overall system reliability. For example, agricultural production under SSP3–RCP7.0 declines from 0.75 to 0.55 in the short-term horizon, but from around 0.45 to below 0.20 (0.25% variation) in the long-term horizon, illustrating the increasing vulnerability of the system over time.

5 Discussion

The results obtained for the Segura River Basin highlight the strong dependence of the basin's agricultural system on both water availability and external water resources. Under climate change scenarios, reductions in water availability are consistently associated with declining agricultural production and reduced reliability of irrigation supply, particularly under the more severe climate trajectories. These patterns suggest that increasing hydro-climatic variability may reinforce existing structural imbalances between water availability and irrigation demand, with implications for the long-term stability of water-dependent systems.

The sensitivity analysis of reductions in the Tagus–Segura transfer further reinforces this structural dependence. Agricultural production and water supply indicators show the strongest response to reductions in transferred water across all scenarios and time horizons, declining progressively as transfer reductions intensify. This reflects the role of the transfer infrastructure in sustaining irrigated agriculture in the basin. Previous studies have similarly highlighted the importance of the Tagus–Segura Aqueduct in supporting one of Europe's most productive export-oriented horticultural systems (Calatrava & Martínez-Granados, 2018; Gómez-Ramos et al., 2024). Although desalinated water and reclaimed wastewater have expanded in recent decades, their capacity to offset substantial reductions in transferred water appears insufficient to fully compensate for such reductions, particularly when energy requirements and infrastructure constraints are considered (Martínez-Alvarez et al., 2023).

The simulations also reveal clear cross-sectoral trade-offs within the basin, particularly between water supply strategies and energy consumption. As water availability declines, the system increasingly relies on alternative sources such as groundwater abstraction and desalinated seawater. While these contribute to supply diversification, they are associated with substantially higher energy requirements. Consequently, reductions in water supply reliability are partially offset by increased energy consumption, illustrating a water–energy trade-off that becomes more pronounced under conditions of scarcity. Similar dynamics have been identified in recent assessments of resource security in Spain (Martínez-Alvarez et al., 2023; Raya-Tapia et al., 2023).

Interestingly, the environmental indicator shows comparatively limited variation across the transfer-reduction scenarios. This behaviour does not necessarily indicate improved ecological conditions but rather reflects the allocation rules embedded in the basin's water management framework, which prioritise environmental flow requirements. This contributes to the relative stability of the environmental supply indicator even under increasing scarcity and illustrates how institutional priorities influence the distribution of water deficits among sectors (Giest & Mukherjee, 2022; Mooren et al., 2025). However, it should be noted that the environmental indicator is defined in an aggregated manner and does not explicitly represent groundwater dynamics, which may be particularly relevant in the basin. As such, some localised environmental pressures may not be fully captured by the current modelling framework.

From a management perspective, these findings underscore the importance of integrated planning approaches that explicitly account for cross-sectoral interactions within the WEFE nexus. In water-scarce basins such as the Segura, strategies aimed at enhancing water security may alleviate agricultural deficits but simultaneously increase energy consumption and environmental pressures. This suggests that sectoral approaches may overlook important system feedbacks, while integrated approaches can provide a more systemic perspective for balancing water security, agricultural productivity, energy consumption, and environmental protection.

Beyond the specific case of the Segura basin, the results are consistent with broader findings in water-scarce regions, where reduced water availability constrains agricultural production, increases energy requirements, and affects ecological conditions. Similar interactions have been highlighted in nexus research, which emphasises the need to analyse the dynamics of water, energy, food, and ecosystems as interconnected components of socio-ecological systems (Afshar et al., 2022; Liu et al., 2018; Sušnik & Staddon, 2022).

The research also contributes to the development of integrated nexus modelling approaches. By combining participatory system

conceptualisation with a System Dynamics model calibrated against observed hydrological behaviour, the framework illustrates how qualitative system representations can be translated into a quantitative structure capable of exploring cross-sectoral interactions over time. The dynamic structure enables the representation of feedbacks and delayed responses, supporting the analysis of how climate and policy pressures influence nexus interactions over time.

6 Conclusions

This study contributes to the growing body of research on integrated resource management by proposing a participatory and dynamic framework for analysing interactions within the Water–Energy–Food–Ecosystem (WEFE) nexus. The main contribution lies in integrating participatory co-creation, empirical validation, and dynamic scenario analysis within a unified modelling framework. By linking stakeholder-driven system conceptualisation with a System Dynamics model capable of reproducing observed hydrological behaviour, the approach demonstrates how qualitative system understanding and quantitative simulation can be combined into a transparent and operational tool for analysing complex resource interactions. In doing so, the framework responds to increasing calls for methodologies that move beyond conceptual nexus assessments and provide practical support for integrated decision-making. Because the model integrates and reconciles perspectives across different sectors and stakeholders, it provides a shared, co-produced evidence base that strengthens legitimacy and collective buy-in. This aligns with previous participatory WEFE and System Dynamics studies (González-Rosell et al., 2020; Pagano et al., 2025; Papadopoulou et al., 2025), suggesting that stakeholder involvement can improve the transparency and policy relevance of nexus-oriented assessments.

The application of this framework to the Segura River Basin illustrates its capacity to capture the dynamic interactions that characterise highly water-stressed systems. The simulations show that increasing hydro-climatic pressures may progressively affect several nexus dimensions simultaneously. Climate change scenarios indicate declining water availability and agricultural production, accompanied by reduced reliability of agricultural supply and increased energy consumption for water supply. These results highlight how pressures affecting water resources propagate across interconnected subsystems, reinforcing the systemic nature of WEFE interactions in semi-arid regions.

The analysis of potential reductions in the Tagus–Segura transfer further reveals the basins irrigated agriculture's structural dependence on inter-basin water resources. Although non-conventional sources such as desalinated and reclaimed water contribute to supply diversification, the results suggest that they may not fully compensate for substantial reductions in transferred water without generating additional trade-offs, particularly through increased energy consumption. This finding underscores the importance of evaluating water management strategies within an integrated nexus perspective that explicitly considers interactions between water availability, food production, energy use, and environmental sustainability.

At the same time, the results should be interpreted within the scope and assumptions of the modelling framework. The analysis was conducted at an aggregated spatial scale and simplifies certain hydrological processes, agricultural adaptation dynamics, and management decisions. In addition, uncertainties associated with climate projections remain significant, while groundwater dynamics were not explicitly represented within the environmental indicator, despite being a particularly critical component of the Segura River Basin. Consequently, the simulations should be understood as indicative trajectories that support the exploration of system behaviour under alternative scenarios rather than as precise forecasts.

Overall, the results emphasise the importance of analytical frameworks capable of capturing feedbacks, trade-offs, and long-term System Dynamics across interconnected resource systems. In water-scarce regions facing increasing climatic and institutional uncertainty, such as the Segura River and many other Mediterranean basins, participatory and dynamic modelling approaches can support more informed, transparent, and adaptive resource governance. By enabling the systemic exploration of alternative scenarios and cross-sectoral trade-offs, the proposed framework provides a transferable methodological basis for advancing integrated and consensus-oriented WEFE nexus management in other water-stressed basins.

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8 Use of AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT/OpenAI for language editing and clarity improvement. The

authors reviewed and edited the content and take full responsibility for the final version of the manuscript.

9 Data Availability Statement

The data supporting the findings of this study are derived from publicly available sources. Hydrological observations were obtained from the Spanish Centre for Public Works Studies and Experimentation (CEDEX), agricultural production statistics from the Statistics Centre of the Region of Murcia (CREM), and water management information from the Segura River Basin Authority (CHS) River Basin Management Plan. Climate change scenarios were derived from bias-adjusted CMIP6 projections developed within the ISIMIP framework and processed through the TETIS hydrological model.

The datasets generated and analysed during the current study, including model inputs and simulation outputs, are available from the corresponding author upon reasonable request.

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