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Co-creating sustainable solutions for enhancing WEFE nexus governance through stakeholder engagement

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A B S T R A C T

Governance of the Water–Energy–Food–Ecosystems (WEFE) nexus requires approaches that integrate stakeholder knowledge and support structured decision-making. However, existing participatory processes often struggle to translate stakeholder inputs into structured evaluations of alternative solutions. This study develops a structured co-creation framework and applies it to the Segura River Basin (Spain), combining interviews, multi-actor dialogues, Group Model Building, and Fuzzy Cognitive Mapping (FCM), a semi-quantitative tool for representing feedback structures and integrating qualitative inputs. The process engages stakeholders from the water, energy, food, and ecosystems sectors to jointly identify a set of solutions and evaluate them against twelve system challenges. The results reveal clear differences in the scope and distribution of impacts across the nexus. Solutions focused on renewable energy planning and those promoting alternative water resources generate the most significant cross-sectoral effects, whereas measures related to water governance produce more sector-specific outcomes. A combined efficiency and feasibility assessment identifies interventions based on alternative water resources and renewable energy planning as the most strategically balanced. Beyond the case-specific findings, the proposed framework provides a transparent and transferable approach for linking participatory processes with solution prioritisation in complex socio-ecological contexts.

1. Introduction

Governance of complex socio-ecological systems requires approaches that can effectively address interdependencies across sectors such as water, energy, food, and ecosystems (Al-Saidi and Elagib, 2017). The Water–Energy–Food–Ecosystems (WEFE) nexus provides a systemic perspective to understand these interactions, highlighting feedbacks, and synergies that are often overlooked in sectoral decision-making (Liu et al., 2018). Achieving sustainability within this nexus requires not only technical optimisation but also the integration of diverse stakeholder perspectives, values, and knowledge systems (Reed et al., 2018).

Participatory approaches have gained prominence for enhancing the legitimacy, inclusiveness, and robustness of decision-making. They facilitate cross-sectoral collaboration (Liu et al., 2018) and support transition governance through reflexive learning (Avelino and Wittmayer, 2016).

These also improve knowledge integration and decision quality, particularly in complex management contexts (Baratella et al.,

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2023; Gerlak et al., 2023). In this context, co-creation is understood as a collaborative and open process through which multiple actors jointly construct knowledge, based on interaction, trust, and the integration of diverse perspectives. It goes beyond consultation by actively involving stakeholders in the co-production of shared understandings and solutions, and is closely linked to principles of open science and innovation (Ramírez and García-Peñalvo, 2018).

However, participatory processes face persistent limitations, including difficulties in conveying system complexity, divergent knowledge, and translating qualitative inputs into structured outputs (Tiller et al., 2021; Kenny and Castilla-Rho, 2022; Deutsch et al., 2024).

These challenges are evident in the Spanish context. Despite progress under the Water Framework Directive (WFD), stakeholder participation remains uneven, with overrepresentation of some sectors and marginalisation of others (De la Peña Varona and Mondragón Ruiz de Lezana, 2024; Hernández-Mora et al., 2014). Participation typically occurs late in the decision-making process, rarely in early phases such as system diagnosis or solution design (del Moral Ituarte, 2022). Additionally, water, energy, food, and ecosystem governance remain fragmented, limiting integrated responses. These dynamics mirror stabilising forces typical of entrenched sociotechnical regimes, which hinder innovation and cross-sectoral coordination (Geels, 2002).

To address these limitations, analytical tools have been increasingly used to better capture system interactions and support decision-making under uncertainty. These include digital twin technologies, which enable the representation of system processes and the exploration of cross-sectoral tensions in WEFE systems (Shehadeh et al., 2024), as well as Fuzzy Cognitive Mapping (FCM). FCM has been widely used to capture causal relationships, feedback loops, and stakeholder perceptions in socio-ecological systems (Kosko, 1986; Eden, 2004; Santoro et al., 2019). Digital twin approaches often rely are data-intensive requiring intense observation and detailed quantitative inputs. By contrast, FCM provides a flexible means of integrating qualitative knowledge and facilitating stakeholder engagement within participatory contexts. Its ability to combine qualitative and semi-quantitative information makes it particularly suitable for participatory modelling (Hassenforder and Barreteau, 2021). Decision-support tools for exploring alternative pathways are increasingly recognised as essential for nexus governance (Penny et al., 2022). However, existing applications often focus on system representation or scenario analysis, with limited integration of structured participatory processes for the system conceptualization, solution co-creation and prioritisation.

Despite these advances, a gap persists between participatory approaches, which emphasise stakeholder engagement and deliberation, and analytical methods, which provide structured insights into system relationships. This gap limits the transition from shared problem understanding to systematic solution evaluation.

Recent initiatives in the Segura River Basin, such as the AG-WaMED project, (AG-WaMED, 2025), have made substantial progress in co-creating solutions through participatory and Living Lab approaches. These efforts have contributed to the joint identification of challenges and the development of context-specific management strategies. However, they rely primarily on deliberative and planning processes, with more limited integration of semiquantitative analysis to systematically assess cross-sectoral impacts or support the prioritisation of alternative solutions. This underscores the need to further integrate co-creation processes with analytical approaches in order to enhance the evaluation and comparison of proposed interventions.

This study addresses this gap by developing and applying an integrated methodological framework that combines participatory processes with Fuzzy Cognitive Mapping (FCM) for analysing the feasibility and acceptability of solutions for the nexus. The framework structures stakeholder engagement across multiple stages, including system diagnosis, Group Model Building (GMB), solution co-creation, and the evaluation of alternative interventions. It translates stakeholder knowledge into a semi-quantitative system representation, enabling the examination of feedbacks, and cross-sectoral effects associated with different solutions. This approach builds on the assumption that integrating participatory processes with semi-quantitative modelling can improve the systematic evaluation and prioritisation of solutions in complex WEFE systems.

The framework is applied to the Segura River Basin (Spain), a highly stressed socio-ecological system characterised by water scarcity, governance fragmentation, and increasing pressures from agricultural and energy demands (Hernández-Mora et al., 2014; del Moral Ituarte, 2022; Pellicer-Martínez and Martínez-Paz, 2018). These challenges reflect broader structural constraints that may hinder integrated and transformative responses (Geels, 2002).

The main objective is to develop a participatory modelling framework for identifying, evaluating, and prioritising solutions within the WEFE nexus. Specifically, the study aims to:

(i) integrate diverse stakeholder perspectives into a shared system representation;
(ii) analyse the systemic effects of different solutions using FCM, incorporating stakeholder inputs; and
(iii) combine efficiency and feasibility criteria to support an initial stage of decision-making.

This study contributes to the literature in three main ways. First, it links participatory processes with system-based evaluation of solutions. Second, it demonstrates how Fuzzy Cognitive Mapping (FCM) can be operationalised within a co-creation process to support the comparison and prioritisation of interventions. Third, it offers empirical insights into the dynamics and trade-offs of the WEFE nexus in the Segura River Basin, with implications for governance in similar socio-ecological contexts.

Developed and tested within the GoNEXUS project (H2020, GA 101003722), the proposed approach provides a practical basis for informing policy-relevant deliberation and supporting transformative pathways in complex systems. More broadly, it helps bridge the persistent gap between nexus thinking and its practical implementation in environmental management and development planning (Howarth and Monasterolo, 2017).

2. Method

This section outlines the methodology and key research steps. The flowchart presented in Fig. 1 summarizes the approach, illustrating the three main components: participatory processes, fuzzy cognitive mapping, and solution analysis.

Each component is described in the sections below.

2.1. Compilation of relevant information and stakeholders selection

As in any research project, the compilation of relevant information is the first step before beginning the methodology. In this particular case, this gathering also includes selecting key actors in the system.

2.1.1. Stakeholder selection

A stakeholder is defined as any actor affected by, influencing, or holding relevant knowledge about the issue (Habitat, 2002). In the context of participatory processes, conducting a thorough stakeholder analysis is crucial, as the success of the process largely depends on the participants involved (Kusters et al., 2018).

Stakeholder analysis identifies, categorises, and selects key actors to ensure diverse and representative participation within the system. By understanding who the stakeholders are and how they interact, we can gain insights into the system's potential dynamics and challenges (Baratella et al., 2023). This analysis is particularly important for collaborative knowledge production, where it is necessary to consider power disparities, conflicts, and differences in technical capacity, resources, and levels of trust. Engaging a diverse range of stakeholders incorporates multiple perspectives and supports more context-sensitive and relevant outcomes.

For this project, stakeholder selection follows the guidelines of Roorda et al. (2014). The process is divided into three key steps:

- Actor Identification: An extensive list of potential stakeholders is first compiled, consisting of individuals or groups impacted by the issue, those possessing relevant expertise, knowledge, or resources, and others who have the potential to contribute or play a significant role in the process. The initial list of stakeholders was developed through a combination of document review, expert consultation, and snowball sampling, allowing the identification of actors with recognised roles, expertise, or stakes in the system.
- Actor Categorization and Mapping: Once the list is complete, stakeholders are grouped into categories based on their backgrounds, skills, interests, and the type of influence or authority they hold. Additionally, their role in the nexus components is also considered.
- Actor Selection: Following this analysis, stakeholders were selected based on three explicit criteria: (i) representation of all WEFE nexus components (water, energy, food, and ecosystems), (ii) diversity of actor types (e.g. public administration, private sector, academia, civil society), and (iii) relevance to the system in terms of both influence and affectedness.

To reduce subjectivity in the selection process, these criteria were applied systematically across the initial stakeholder list, ensuring that no single sector or actor group was overrepresented.

While complete representativeness cannot be fully guaranteed, the use of explicit criteria and a structured selection process enhances transparency and reduces potential biases in stakeholder inclusion (Reed, 2025).

2.2. Participatory processes

2.2.1. Interviews

Semi-structured interviews are conducted as an initial step in the participatory process. An interview guide is used to ensure consistency across participants while still allowing for open-ended discussion.

The interviews pursue three main objectives: (i) to engage stakeholders and introduce the overall process; (ii) to capture their individual understanding of the system, including key components and interrelations; and (iii) to identify the main challenges and

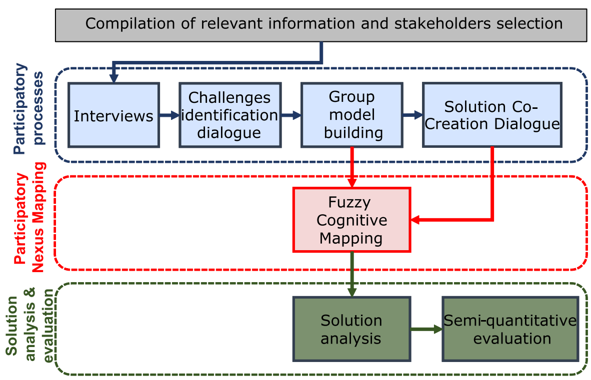

Fig. 1. Solutions analysis and evaluation methodology.

pressures perceived from their sectoral perspective.

This phase initiates stakeholder involvement, supporting both data collection and participants' familiarisation with the subsequent co-creation and modelling activities.

2.2.2. Challenges identification dialogue

The challenges dialogue combines plenary discussions with small-group work, supported by specific participatory techniques. Participants are organised into heterogeneous subgroups to promote diversity of perspectives and reduce sectoral biases. Stakeholders were grouped according to their role, interest, and influence to ensure broad representation and effective exchange (Baratella et al., 2023).

In this context, the use of participatory tools and techniques is essential to facilitate an equitable exchange of perspectives, shifting the focus from solely generating scientific knowledge towards facilitating knowledge sharing among stakeholders (Castelli et al., 2025).

Participatory techniques support the identification and structuring of challenges. A visual and reflective exercise inspired by the "Points of You" technique (Points of You, 2025) is used to elicit and revisit perceptions previously identified in individual interviews, followed by the application of the Pentagonal Problem framework (GoNEXUS Project, 2022). This tool organizes challenges across WEFE nexus components and facilitates the identification of interdependencies and long-term drivers. Challenges are then validated, refined, and prioritised through subgroup discussions and plenary sessions, supporting the co-construction of a shared understanding that integrates individual and collective perspectives.

2.2.3. Group model building

Causal Loop Diagrams (CLDs) are widely used in system dynamics to represent the structure of complex systems by capturing the relationships among variables and the feedback loops that shape system structure. A CLD consists of variables connected by causal links with defined polarity (positive or negative), and organised into reinforcing and balancing feedback loops that explain system patterns (Mirchi et al., 2012; Giordano et al., 2025). This approach is particularly suitable for participatory modelling, as it enables the integration of stakeholder knowledge and supports the exploration of interdependencies within socio-ecological systems, providing the conceptual basis for the group modelling phase implemented in this study.

The group modelling phase identifies the key components and variables that shape the Water–Energy–Food–Ecosystems (WEFE) nexus and clarifies how they interact across processes. This step helps establish a shared understanding of system complexity and guides subsequent governance-oriented analysis.

Through co-creation, stakeholders map the variables they consider essential and link them to the main system components of the WEFE nexus, revealing relationships between water, energy, food, and environmental factors. During this process, participants also define the polarity and relative strength of causal relations using a predefined qualitative scale (weak, moderate, strong), supported by colour coding to ensure a common interpretation.

Cognitive mapping and diagramming techniques are employed to develop a visual representation of causality, where arrows indicate influence and polarity (+/−). The discussion of causal strength from the co-creation phase naturally informs this mapping exercise, supporting effective communication, consensus-building, and the development of a shared systemic perspective.

This approach is aligned with Shared Vision Planning, which emphasizes collaborative modelling, structured engagement and transparency to build trust and shared ownership (Palmer et al., 2013). Recent applications of participatory systems mapping show its value in revealing systemic dynamics and reinforcing local ownership of sustainability transitions (Figueiredo et al., 2022).

The causal loop diagram (CLD) produced in this phase represents the feedback structure driving system behaviour in the Segura River Basin and serves as the basis for constructing the Fuzzy Cognitive Map (FCM) used for subsequent analysis and simulation, ensuring a direct and traceable transition from qualitative system conceptualization to semi-quantitative modelling.

2.2.4. Solution Co-creation dialogue

Building on the outcomes of the first dialogue, where the main challenges within the WEFE nexus were identified, the second dialogue shifts focus to presenting and discussing potential solutions. The goal is to collectively agree on a set of measures to be modelled in future scenarios and to define indicators for monitoring their success.

During this phase, stakeholders explore various development scenarios and solutions to address the earlier challenges, considering how external factors—such as climate change, population growth, and resource availability—may alter the system. With a deeper understanding of the system's challenges and their interconnections within the WEFE nexus, this phase is designed to support stakeholders in co-creating future-oriented solutions. This strategic shift towards co-creation emphasizes generative governance, an approach that facilitates collaborative problem-solving by bringing together diverse public and private actors (Ansell and Torfing, 2021).

To help guide the discussion, a matrix is introduced that organizes the main challenges according to the different components of the WEFE nexus. This tool helps focus the conversation on finding specific solutions for each challenge and nexus component. The proposed solutions are then discussed collectively, with particular attention to identifying potential barriers to their implementation.

This process supports the development of solutions that are practical, context-sensitive, and informed by stakeholder perspectives, providing a basis for further exploration and potential implementation.

2.3. Fuzzy cognitive mapping

Fuzzy Cognitive Mapping (FCM) is a tool that facilitates the understanding and modelling of interrelationships within complex systems by representing them as networks of nodes (variables or concepts) connected by weighted arrows. Each node represents a concept or factor relevant to the system, and the arrows illustrate cause-and-effect relationships—positive or negative—where the weight reflects the strength of influence (Kosko, 1986). FCM provides a structured framework for analysing multidimensional problems (Eden, 2004), making it particularly effective for integrating stakeholder input and comparing perceptions across groups (Santoro et al., 2019). This approach is especially relevant when aligned with iterative phases of participatory and transition-oriented governance (Hassenforder and Barreteau, 2021).

Unlike traditional cognitive maps, FCMs incorporate fuzzy logic to quantify relationships between variables, translating qualitative degrees of influence ("low", "medium", "high") into semi-quantitative values, allowing the explicit representation of perceived causal links while accommodating uncertainty common in socio-ecological systems.

To construct the FCM, the causal structure obtained during the GMB session was used as the basis for model formalisation. The qualitative assessments of influence strength agreed during the GMB were directly mapped to a numerical fuzzy scale (± 0.3 for weak, ± 0.6 for moderate, and ± 1 for strong), preserving the sign of each relationship. This step translated the participatory CLD into a weighted network without reinterpreting stakeholder inputs, ensuring full traceability between stages. Redundant or unused links were removed to maintain model parsimony.

The resulting FCM was implemented in Mental Modeler, a software tool designed for semi-quantitative conceptual modelling (Eriksson et al., 2023; Gray et al., 2015). The simulations use a hyperbolic tangent (tanh) activation function with automatic normalisation, and iterative calculations continue until convergence. Each solution identified by stakeholders was tested through an individual simulation scenario by activating only the corresponding solution node.

System challenges identified in the participatory process were treated as outcome nodes. After each simulation, the equilibrium activation values of these challenge nodes were normalised using a min–max procedure. An overall efficiency score for each solution was then calculated as the average of the normalised activation levels across all challenge nodes.

Although no explicit sensitivity analysis was performed, the transparency of the CLD-to-FCM transformation, the agreed rules for weight assignment, and the criteria for link inclusion support reproducibility and provide a robust basis for solution prioritisation, while acknowledging the methodological boundaries inherent to qualitative-to-quantitative translation.

2.4. Solution analysis and evaluation

Once the main challenges of the system have been identified—along with the key variables, their interrelations, and the perspectives of system users and stakeholders—the proposed solutions are analysed and evaluated based on their efficiency and feasibility.

2.4.1. Solution analysis

The analysis of the solutions is divided into two different but complementary analyses:

- Efficiency Analysis: efficiency refers to the magnitude and direction of the expected systemic impact that each solution exerts on the set of challenges identified by stakeholders. Efficiency is assessed using a semi-quantitative approach based on the Fuzzy Cognitive Map (FCM) simulations generated in Mental Modeler, where one simulation scenario is executed for each solution. In each scenario, only the node representing the selected solution is activated, allowing the model to reflect its effects across the system.

The final activation values of the challenge variables at model equilibrium are extracted for every scenario. These values are then normalised to enable comparability across variables, and the overall efficiency score for each solution is computed as the aggregated mean of these normalised activation levels. Higher efficiency scores indicate a more substantial positive influence across nexus challenges, whereas lower scores reflect reduced or predominantly neutral impacts.

- Feasibility Analysis: feasibility refers to the perceived ease or difficulty of implementing each solution, based on the barriers identified by stakeholders during interviews and dialogue sessions. These perceptions were coded and categorised into four types of barriers: governance, financial, technical, and cultural. The feasibility of each solution is thus expressed as the number of barriers associated with its implementation, where a greater number of barriers corresponds to lower feasibility.

This qualitative assessment synthesises stakeholder insights into a structured indicator that captures the main constraints that could hinder or delay implementation. Although feasibility is based on perceptions rather than quantitative metrics, it provides critical information about the institutional, socio-economic and operational conditions surrounding each proposed measure.

2.4.2. Semi-quantitative evaluation

The semi-quantitative evaluation combines the efficiency and feasibility results to support solution prioritisation. By contrasting the systemic impact derived from the FCM simulations with the stakeholder-identified implementation barriers, this step allows for a comparative assessment of trade-offs and complementarities among solutions. This integrated perspective helps identify measures with high systemic relevance, those with strong implementability, and those requiring enabling conditions or phased implementation strategies.

3. Case study

The Segura River Basin (SRB), located in the southeast of the Iberian Peninsula, covers four autonomous regions, with Murcia holding the largest share of its territory (Fig. 2). The basin operates as a single exploitation system, encompassing surface and groundwater resources, along with hydraulic infrastructure and regulatory frameworks to balance water supply and demand (Hidrográfica and Segura). However, managing these resources is complex due to the diversity of water sources—surface water, inter-basin transfers, groundwater, treated wastewater, and desalinated water—and the persistent imbalance between water supply and demand, with an estimated annual deficit ranging from 400 to 700 hm^3 (Pellicer-Martínez and Martínez-Paz, 2018).

The basin faces extreme climatic variability, including droughts, heatwaves, and floods, increasing desertification risk (Miró et al., 2023).

These environmental constraints are closely linked to the socio-economic structure of the basin. Agriculture dominates water use in the basin, accounting for approximately 80–85% of demand, supported by highly efficient irrigation systems (CHS, 2022). However, the efficiency of these irrigation technologies comes at a high energy cost, further intensifying the region's challenges. Water and energy are closely linked in the SRB, with substantial energy consumption required for water distribution, groundwater extraction, and desalination, particularly for agricultural use. Desalination alone represents 44% of the cost of water due to its energy intensity, even though reverse osmosis is the most energy-efficient technology available (Soto-García et al., 2013). Additionally, the basin heavily relies on recycled water for irrigation, using around 144 hm^3 annually, though the energy demands of recycling vary based on treatment processes (Hernández-Sancho et al., 2010). Recent assessments further highlight that the energy requirements and associated CO_2 emissions vary significantly across water sources, with desalinated water presenting the highest energy intensity (around 4.3 kWh/m^3) and carbon footprint compared to alternatives such as surface or groundwater resources, thereby reinforcing the strong interdependencies within the water–energy nexus (Odriozola et al., 2025).

A key governance and infrastructural element shaping water management in the basin is the Tagus-Segura Water Transfer (Fig. 2), operational since 1979, which supplies vital water resources from the Tagus River to the Segura Basin (García-López et al., 2023).

This interbasin transfer is essential to sustaining the region's intensive agriculture and securing water for economic activity and urban consumption. It currently contributes between 200 and 600 hm^3 annually, depending on hydrological availability (CHS, 2022). Its strategic importance lies in the volume of water supplied and its relatively low energy cost compared to desalination. However, the Tagus-Segura transfer has long been a source of political and territorial conflict, generating tensions between the donor (Tagus) and recipient (Segura) basins, especially during drought.

Climate change is expected to significantly reduce water availability in the donor basin, threatening the long-term viability of the transfer and increasing regional vulnerability (Estrela et al., 2012). Future projections also indicate a likely increase in the frequency and intensity of drought events, leading to greater reliance on non-conventional and energy-intensive water sources, which may further exacerbate both economic and environmental pressures in the basin (Paredes-Beltran et al., 2024).

In response, the current basin plan foresees a substantial increase in desalination capacity to compensate for projected reductions in transfer volumes and rainfall due to climate change (Ministerio para la Transición Ecológica y el Reto Demográfico, 2023). However, this strategy also implies a sharp rise in energy consumption, posing new environmental and economic challenges.

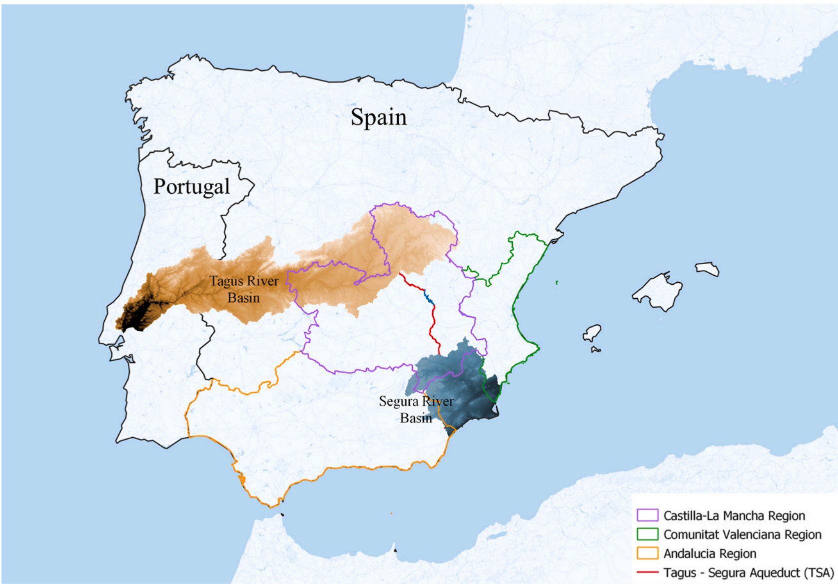

Fig. 2. The Segura River Basin case study area.

This infrastructure has been essential for the agricultural expansion observed in the basin over the past few decades (CHS, 2022), doubling the agricultural area in approximately 10 years (Zuluaga-Guerra et al., 2023). However, this expansion has also intensified socio-ecological tensions between the donor and recipient basins due to the redistribution of water resources. Combined with high agricultural pressure, this results in a severe socio-ecological crisis characterised by the loss of semi-natural areas (Zuluaga-;Guerra et al., 2023) and the overexploitation and contamination of aquifers (Pellicer-Martínez and Martínez-Paz, 2016).

In summary, the Segura River Basin exemplifies a highly stressed socio-ecological system where agricultural water demand, interbasin transfers, energy consumption, and environmental degradation are deeply intertwined. The basin's reliance on diverse water sources—including the Tagus-Segura water transfer, desalination, and water recycling—illustrates ongoing efforts to manage resources sustainably. However, significant challenges remain in balancing supply with the increasing demands of agriculture, urbanization, and ecosystems, especially under the growing pressures of climate change. In this context, the Segura River Basin provides a relevant case study for applying participatory and system-based approaches aimed at understanding and addressing complex WEFE nexus interactions.

4. Results

This section presents the results of applying the methodology previously described to address the basin's resource management challenges within the WEFE nexus.

4.1. Stakeholder selection

Given the interconnected nature of the WEFE components, engaging a wide range of stakeholders was essential, ensuring comprehensive representation from all nexus areas.

- *Actor identification*

In the Segura Basin, key stakeholders include irrigation managers, public administrators, farmers, and researchers involved in water governance coordinated by the Confederación Hidrográfica del Segura (CHS) (Alcon et al., 2014). Agricultural stakeholders are prominent due to the importance of irrigation. Energy use in water and irrigation systems is linked to renewable solutions. Environmental actors are involved in relation to aquifer overexploitation and agricultural pollution, supporting compliance with ecological standards.

- *Actor categorization and mapping*

Stakeholders were categorised by networks, sectors, and WEFE nexus components. Agricultural actors were the most represented, reflecting the dominance of agriculture in the region. Fewer actors were identified in the energy component, where the role of energy is mainly related to consumption rather than production.

Fig. 3 presents the categorization and mapping of actors in the basin, with parentheses indicating the actors' count for each category.

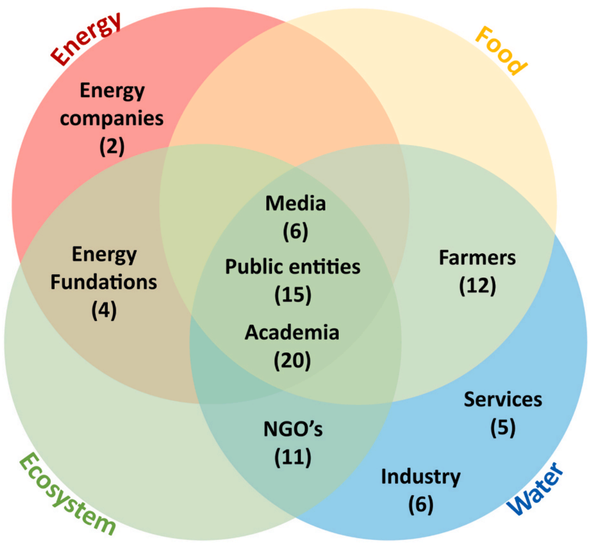

Fig. 3. Mapping of the number of actors identified and categorised by nexus component.

• *Actor selection*

Once the main actors of the system, their roles, and perspectives, as well as their influence within the nexus, are identified, a selection of stakeholders is made to ensure equitable participation across the four components of the nexus. Additionally, representatives from each social category (public entities, academia, services, farmers, etc.) are included. The selected stakeholders are presented below.

● Water:

Future Water: Industry.
Taibilla Channels Association: Government (Local)

● Energy:

Sustainable Development Foundation: Energy foundations.

● Food:

Letur Irrigation Community: Farmers.
Irrigation Community of Campo de Cartagena: Farmers.

● Environment:

Service for Environmental Promotion and Climate Change: Government (Regional)
Plataforma Pacto por el Mar Menor: Civil Society (NGO)

● Transversal:

Segura River Basin Authority: Government (River Basin)
Murcia University: Academia.

4.2. Participatory processes

4.2.1. Actor interviews

In this phase, interviews were conducted with key stakeholders from each component of the WEFE nexus—Water, Energy, Food, and Ecosystems. Additionally, public entities, media outlets, and academic institutions involved in these sectors were interviewed to gather diverse perspectives. The interviews focused on understanding stakeholders' roles, their perceptions of governance, and the main challenges within the system. These insights are fundamental for developing a comprehensive view of the system's complexities and informing the broader analysis of resource management and sustainability.

4.2.2. Challenges identification dialogue

The first dialogue aimed to identify and prioritise the main challenges in the Segura Basin. Key representatives from various sectors—including agriculture, industry, public management, environmental organizations, academia, and government agencies—participated, ensuring a comprehensive exchange of perspectives. As a result, four major challenges were defined: water

Table 1
Challenges and sub-challenges identified in the first stakeholder dialogue, with sub-challenge prioritisation.

Challenges	Subchallenges	Prioritisation
Water scarcity	Efficiency and assurance in water use	4
	Climate change and water deficit	3
	Irrigation management	3
	Aquifer overexploitation	2
	Alternative resources (Desalination, brine removal, denitrification)	5
Energy transition	Sustainable implementation of renewable energies	7
	New energy consumption model	3
Environmental sustainability	Environmental protection	6
	Environmental balance and integration of activities	4
	Enforcement of the Mar Menor Law	2
Agri-food sustainability	Food security (demographic challenge)	5
	Sustainable agriculture	4
	Compliance with the law (illegal irrigation)	3
	Food sovereignty	2

scarcity, energy transition, environmental sustainability and agrifood sustainability.

Table 1 illustrates these challenges along with their corresponding sub-challenges, ranked by priority according to stakeholder feedback during the dialogue sessions. Each sub-challenge highlights critical issues such as aquifer overexploitation, sustainable energy integration, and environmental protection, reflecting the diverse concerns within the nexus. The prioritisation indicates the frequency and perceived importance of each topic as expressed by participants.

4.2.3. *Group model building*

In this stage, stakeholders identified the variables they considered most influential in the behaviour of the Segura River Basin system. Key elements included resource availability, energy use linked to water and economic activities, agricultural production, and ecosystem sustainability, as shown in Fig. 4.

The variables identified by stakeholders mirror the challenges raised in the first dialogue and provide a comprehensive view of the dynamics shaping the Segura River Basin. The resulting causal loop diagram reveals several key feedback mechanisms that structure system behaviour. For example, Loop R1 captures how agricultural production reinforces tourism and broader economic activity, increasing overall demand. In contrast, loops B1 and B2 highlight regulatory processes linked to groundwater extraction and recharge that help stabilise resource deficits. These feedbacks illuminate critical leverage points and areas where proposed measures may either amplify or mitigate existing dynamics.

4.2.4. *Solution Co-creation dialogue*

The primary goal of the second dialogue is to identify sustainable solutions and measures to address the various challenges facing the Segura River Basin. These solutions must be framed within a holistic context that accounts for the system's complexity and the interrelationships between its variables.

Drawing on the system's behaviour mapped in the group model building process and the challenges identified in the first dialogue, a matrix was presented to the stakeholders. This matrix clearly outlines each nexus component and its main challenges, guiding the conversation toward sustainable and context-appropriate solutions.

The identified solutions are:

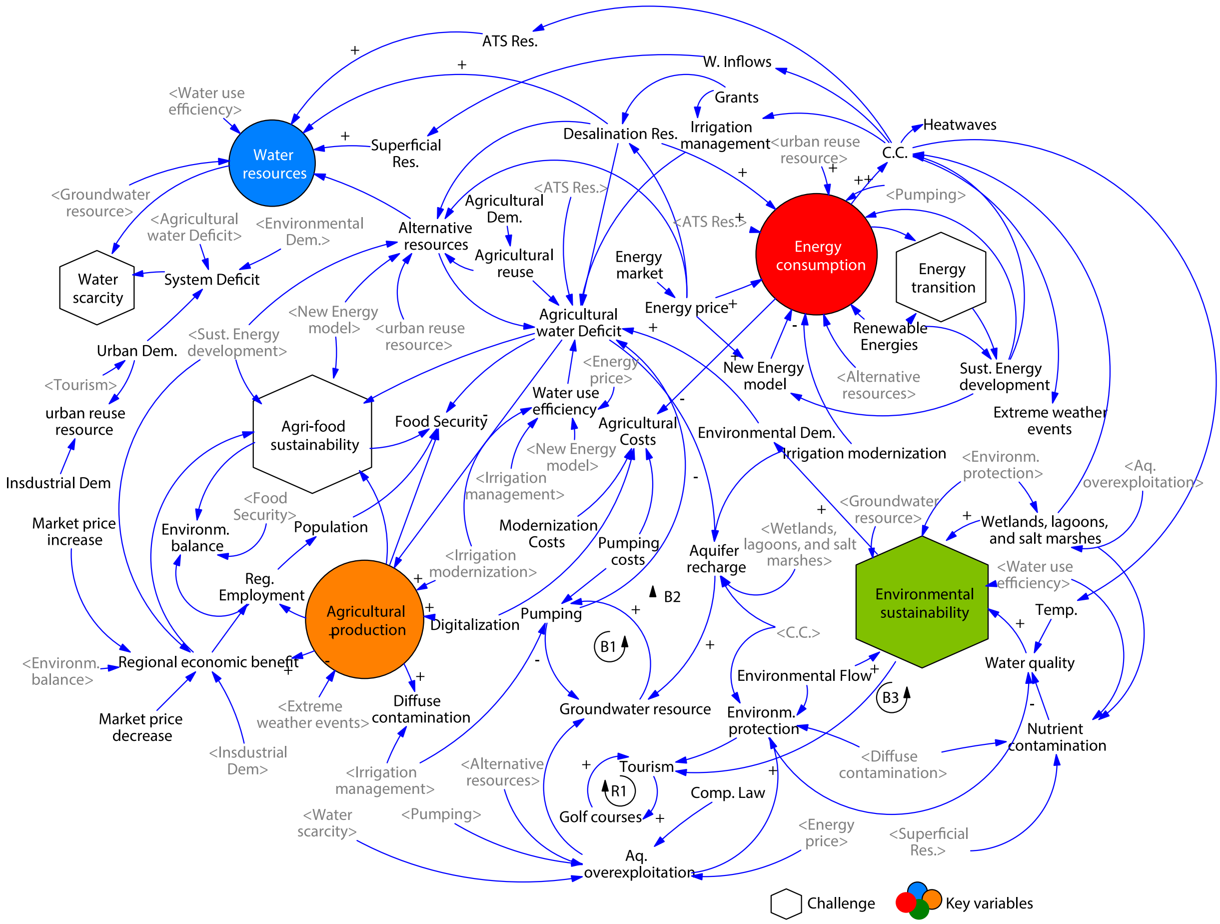

Fig. 4. Causal Loop Diagram of the system.

- **Solution 1**: Groundwater extraction control
- **Solution 2**: Increase the use of alternative resources
- **Solution 3**: Groundwater usage levy
- **Solution 4**: Improve access to the grid to promote the use of renewable energies and self-consumption
- **Solution 5**: Planning and management of renewable energy deployment
- **Solution 6**: Implement agile and equitable procedures
- **Solution 7**: Enhanced advisory services for agricultural producers
- **Solution 8**: Promote organic farming

4.3. Fuzzy cognitive mapping (FCM)

The Fuzzy Cognitive Map developed for the Segura River Basin synthesises the system structure perceived by stakeholders, capturing the main variables of the WEFE nexus and the causal interactions shaping resource governance. Fig. 5 provides a visualisation of the resulting map as constructed in Mental Modeler, illustrating the overall configuration of nodes and causal links identified during the process. The final map includes 62 variables connected through 170 causal links, reflecting the complexity of interdependencies identified during the participatory process. Eight of these nodes correspond to the proposed solutions discussed in the second dialogue, while at least four represent the systemic challenges prioritised earlier.

Embedding both challenges and solutions in the same cognitive structure enables a comprehensive visualisation of how proposed measures are expected to influence the system. The configuration of the map highlights the centrality of variables related to water availability, groundwater dependence, agricultural production, and environmental pressures, which form densely connected clusters. These structural patterns, visible in Fig. 5, help clarify the pathways through which pressures propagate across the nexus. Their position and the directionality of surrounding links reveal how pressures propagate and where responses may create reinforcing or balancing effects.

Integrating the solutions as active nodes within the map allows examination of their potential system-wide implications. This includes identifying possible synergies with existing governance processes, as well as unintended consequences or trade-offs that may arise from shifting pressures across components of the nexus. In this way, the FCM provides a structured basis for interpreting how interventions may reshape dynamics in the Segura River Basin, offering a systemic lens through which to anticipate their broader impacts.

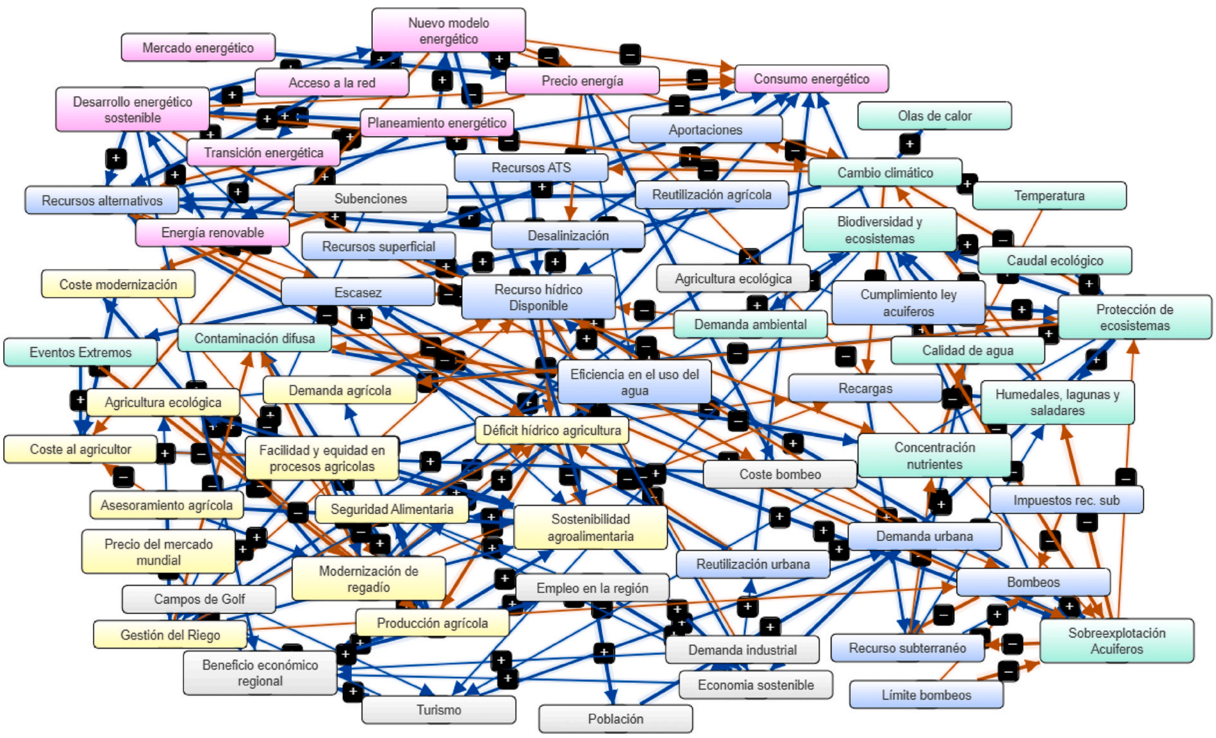

Fig. 5. Fuzzy cognitive map in mental modeler.

4.4. *Solution analysis and evaluation*

4.4.1. *Solution analysis*

This section presents the key findings from the evaluation of the eight stakeholder-proposed solutions.

- Efficiency Analysis

The efficiency analysis reveals clear differences in how the proposed solutions influence the challenges prioritised by stakeholders. Table 2 presents the results obtained from the stakeholder-built Fuzzy Cognitive Map (FCM), showing the intensity of each solution–challenge relationship. Darker colours indicate stronger positive impacts, while lighter tones reflect weaker or more negative influences. The complete numerical outputs for all solution-specific scenarios can be consulted in the Supplementary Material.

The efficiency patterns derived from the FCM simulations reveal that the proposed solutions differ substantially in the breadth and direction of their impacts across the WEFE nexus. In general, solutions with a strong regulatory or supply-oriented focus tend to concentrate their influence within the water domain, whereas measures linked to energy planning and agricultural transformation display more cross-sectoral effects. This distribution underscores the multi-dimensional nature of the nexus and highlights relevant synergies and potential tensions among interventions.

Solutions 1 and 3—both centred on groundwater governance—show strong, positive, and relatively concentrated effects on water-related challenges, with limited influence on energy, food, or environmental issues. Their targeted profile suggests that strengthening water governance may improve resource reliability and legal compliance but generates few indirect benefits for the remaining sectors.

In contrast, Solution 2 (Increase the use of alternative resources) exhibits a broader systemic reach. By influencing both water availability and the environmental implications of resource use, it acts across multiple nexus components, offering potential synergies between water security and environmental improvement. However, this solution may also suggest a potential trade-off: while its positive effects on water scarcity are clear, its reliance on energy-intensive processes suggests possible tensions with long-term energy transition objectives, reflected in the relatively lower values associated with energy-related challenges.

Solution 5 (Planning and management of renewable energy deployment) stands out as the intervention with the strongest multi-sectoral impact. Its positive influence on both energy challenges and environmental protection positions it as a key lever for enabling cross-nexus benefits. By contrast, Solution 4 (Improved access to the grid) shows more modest effects, suggesting that enabling infrastructures alone may be insufficient without comprehensive planning strategies such as those represented by Solution 5.

Within the food sector, the solutions promoting procedural improvements and shifts in production practices (Solutions 6 and 8) show targeted but positive effects, particularly on food security and sustainable agriculture. Their influence is mainly intra-sectoral, though they also present potential indirect benefits for water management by encouraging more sustainable farming practices. Solution 7 (Advisory services) displays very limited cross-sectoral effects, indicating that information-based measures may require complementary structural interventions to generate broader systemic influence.

Overall, the results reveal that no single solution addresses all components of the WEFE nexus. Instead, solutions vary in the extent

Table 2
Heatmap of challenges and solutions.

CHALLENGES	SOLUTIONS							
	1	2	3	4	5	6	7	8
Efficiency and reliability in water use								
Climate change and water deficit								
Irrigation management								
Aquifer overexploitation								
Alternative resources (desalination, denitrification, etc.)								
Sustainable deployment of renewable energies								
New energy consumption model								
Environmental protection								
Environmental balance and integration of activities								
Food security (demographic challenge)								
Sustainable agriculture								
Compliance with the law (illegal irrigation)								

Impact	
	+
	-
	+
	-
	+
	-
	+
	-

to which their effects cascade across sectors. Among them, Solutions 2 and 5 emerge as those with the strongest cross-nexus influence, each with distinct synergy–trade-off profiles: Solution 2 enhances water security but raises energy implications, while Solution 5 strengthens both energy and environmental outcomes with limited direct benefits for water or food challenges. These patterns underscore the need for combined solution packages that maximise synergies and mitigate trade-offs across the nexus.

- Feasibility Analysis

The feasibility analysis complements the efficiency assessment by examining the main barriers that may affect the implementation of each proposed solution. Stakeholder insights point to four key types of constraints: governance, economic, technical, and cultural. Table 3 summarizes these barriers, reflecting the issues identified by participants.

Overall, the feasibility of the solutions varies considerably. Solutions such as groundwater extraction control (S1) and implementation of agile and equitable procedures (S6) show relatively high feasibility due to their clear operational focus and alignment with existing governance frameworks, although both face resource limitations (e.g., staff availability or data quality constraints).

Conversely, solutions involving extensive infrastructure or regulatory changes, such as increasing the use of alternative resources (S2) or implementing groundwater levies (S3), are associated with higher economic or institutional barriers. For instance, high costs and complex administrative processes may delay their execution despite their substantial systemic impact. Similar systemic barriers have been identified in climate-oriented agricultural transitions, where farmers face technical, financial, and socio-cultural constraints that hinder engagement (Andersson and Wamsler, 2021).

Solutions 4 and 5, related to the energy transition, highlight technical challenges, including grid stability and the need for strategic spatial planning. Institutional reforms proposed in Solutions 7 and 8 are promising in terms of long-term impact but face challenges due to limited personnel and economic incentives.

This feasibility assessment underscores the need to complement systemic relevance with practical considerations, ensuring that the most impactful solutions are also viable in the short to medium term.

4.4.2. Semi-quantitative evaluation

Fig. 6 shows clear contrasts between the systemic efficiency of the proposed solutions and the number of barriers associated with each one.

Solutions 2, 5, and 7 exhibit the highest efficiency values, with S7 (Advisory services for producers) slightly surpassing S2 and S5. These three measures demonstrate the strongest potential to generate system-wide impacts, although they differ in feasibility: while S2 and S5 present relatively lower barrier counts (two each), S7 is associated with three barriers, suggesting a more complex implementation landscape despite its elevated efficiency.

Solutions 3 (Groundwater usage levy) and 4 (Improved access to the grid) show intermediate efficiency levels. Their positions reflect interventions with the capacity to deliver meaningful benefits, but with feasibility profiles that differ: S3 presents fewer barriers (two), whereas S4 shows a higher constraint level (three barriers), indicating potential delays or operational challenges.

Solutions 6 (Agile and equitable procedures) displays a similar efficiency range to S3 and S4 but, like S4 and S7, is associated with three barriers. This combination suggests that while the measure can contribute to incremental improvements across nexus challenges, its implementation may require adjustments to administrative or governance structures.

Solutions 1 (Groundwater extraction control) and 8 (Promotion of organic farming) fall at the lower end of the efficiency distribution, with markedly reduced system-wide influence. Both are linked to three barriers, positioning them as low-impact, low-

Table 3
Barriers identified.

Solution	Governance	Economic	Technical	Cultural Resistance	Number of barriers
S1	Lack of inclusion of water quality monitoring in governance systems		Need for implementation of telemetry		2
S2		High implementation costs	Construction of new desalination infrastructure		2
S3	Need for centralised and organised groundwater monitoring and control systems			Potential resistance to water being treated as a public domain resource	2
S4			Grid instability/long distances for connection/limited access to main grids		3
S5	Lack of regulatory planning	High implementation costs	Technical and operational complexity		3
S6	Insufficient staff to cover all farmers/complex procedures			Low awareness and interest from farmers	3
S7	Lack of personnel/bureaucratic overload	High implementation costs			3
S8	Need for policies supporting organic production	Lower profitability than conventional farming		Farmers' preference for conventional practices	3

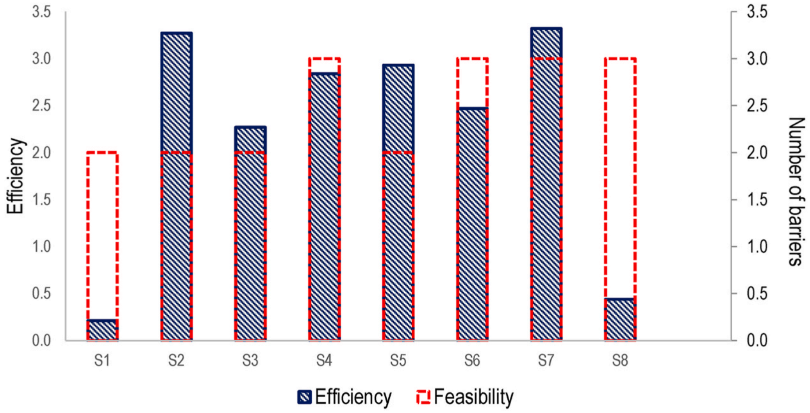

Fig. 6. Results for the cross-analysis of efficiency and feasibility of the proposed solutions.

feasibility options within the current governance and resource context.

Taken together, these results highlight clear strategic contrasts. Solutions 2, 5, and 7 emerge as the most systemically influential, with S2 and S5 showing the most balanced profiles due to their comparatively lower number of barriers. By contrast, low-efficiency, high-barrier measures such as S1 and S8 appear less suited for prioritisation under current conditions. These patterns reinforce the need to identify solution portfolios that combine high-impact interventions with those offering more straightforward implementation pathways.

5. Discussion

The integrated framework proved effective in identifying context-specific and context-relevant solutions in a complex WEFE setting. Its main contribution lies in linking participatory processes with FCM to enhance the transparency and practical relevance of governance-oriented decision-making (Hassenforder and Barreteau, 2021).

These findings are consistent with previous research conducted in the Segura River Basin, particularly expert-based assessments of nature-based solutions (NBS), which highlight a persistent trade-off between technical effectiveness and implementation feasibility. Solutions targeting river and floodplain restoration are often identified as highly effective but face substantial socio-economic and political barriers, including high costs, land-use conflicts, and limited stakeholder acceptance (Luján Soto et al., 2025). Similarly, the participatory process in this study revealed that the most systemically efficient solutions are not necessarily those that are easiest to implement. This reinforces the importance of explicitly incorporating feasibility considerations alongside systemic performance.

The results also align with broader regional analyses that emphasise the structural dependence of the basin on external water transfers and the central role of irrigated agriculture in the regional economy. A reduction in water availability can have significant economic and social impacts, including decreases in regional output, gross value added, and employment (Azorín et al., 2025). In this context, the prioritisation of solutions addressing water–energy interactions reflects not only environmental concerns but also systemic vulnerabilities embedded in the basin's socio-economic structure.

From a water planning perspective, the findings are also consistent with studies highlighting the chronic imbalance between water demand and availability in the Segura Basin, where total demand exceeds renewable water resources (Aldaya et al., 2019). While these studies stress the need for more integrated approaches to water management, they often lack operational tools to systematically explore cross-sectoral feedbacks. In contrast, the FCM-based approach applied here provides a structured means to explicitly represent and analyse these interdependencies, thereby supporting a more holistic understanding of system behaviour.

These findings are also consistent with policy-oriented assessments of non-conventional water resources in Spain, which identify similar barriers to implementation, including institutional fragmentation, high energy-related costs, regulatory constraints, and socio-cultural resistance to water reuse (Efthimiou et al., 2025). The convergence between these structural barriers and those identified through the participatory process reinforces the robustness of the results and highlights the need to explicitly address feasibility constraints in nexus-oriented governance strategies.

A relevant comparison can also be made with participatory approaches implemented in the same basin to co-develop river basin management strategies. These approaches emphasise stakeholder engagement and co-creation as key elements for addressing water scarcity and nexus challenges. In these cases, prioritised measures often focus on feasible and incremental interventions, such as improving irrigation efficiency, promoting water reuse, and strengthening institutional coordination.

Similarly, the present study identifies solutions that address systemic vulnerabilities, particularly those related to water–energy interactions. However, the FCM-based approach extends beyond deliberative processes by enabling the explicit representation of system relationships. This allows for a more structured consideration of potential trade-offs between systemic performance and implementation feasibility. In this sense, while AG-WaMED demonstrates the value of participatory co-creation for building consensus and policy relevance, the framework proposed in this study complements such approaches by providing an analytical layer that supports the evaluation of alternative interventions and their potential system-wide impacts.

This contribution is therefore not only empirical but also methodological. While participatory decision-support methods such as multi-criteria analysis or hierarchical ranking are widely used to prioritise policy options, they often provide limited insight into system feedbacks and interactions across sectors (Papadopoulou et al., 2025). By integrating these elements into a coherent methodological sequence, the proposed framework advances participatory modelling practice. It offers a practical, end-to-end process for supporting governance decisions in complex nexus contexts.

The identification of Solutions 2 and 5 as the most systemically efficient reflects the basin's long-standing vulnerabilities—particularly the dependence on external transfers and increasing water–energy pressures. Similar insights have been reported in previous FCM-based studies in Spain (Martinez et al., 2018), where collaborative modelling helped illuminate system feedback and strengthen the contextual relevance of proposed measures.

From a governance perspective, combining stakeholder dialogues, conceptual system mapping, and FCM supported capacities such as reflexivity, anticipation, and cross-sectoral coordination. Embedding proposed solutions directly within the system representation and examining their effects through simulations enabled participants to question assumptions, compare alternative intervention pathways and consider feasibility alongside technical performance. This is particularly relevant in Spanish water governance, where participation has often been limited to consultative roles and late decision-making stages (De la Peña Varona and Mondragón Ruiz de Lezana, 2024; Kochskämper et al., 2016). The process also aligns with co-production perspectives that emphasise inclusive knowledge integration and attention to power relations (Turnhout et al., 2020).

The methodological sequence—from problem identification to system mapping, and solution evaluation—offered more than a set of participatory activities. It provided a clear structure that helped stakeholders move from individual viewpoints toward a shared understanding of system behaviour that can inform concrete governance choices. This is particularly valuable in fragmented governance settings such as the Segura Basin, where coordination across sectors and administrative levels remains limited. The results are consistent with previous participatory modelling applications in socio-ecological systems (e.g. Djenontin et al., 2025; Martinez et al., 2018), while extending them by explicitly linking systemic performance with feasibility considerations relevant to policy implementation.

Despite these strengths, some limitations should be acknowledged. First, the approach relies on qualitative stakeholder inputs, which may introduce subjectivity and depend on the representativeness of participants. Second, while FCM enables the exploration of system dynamics, it does not provide predictive accuracy comparable to fully quantitative models. Third, the application is based on a single case study, which limits the generalisability of the findings. These limitations are consistent with those identified in other participatory modelling approaches and suggest the need for future research combining qualitative and quantitative methods, as well as testing the framework across multiple case studies.

Overall, combining participatory processes with FCM addresses key challenges in nexus governance, including fragmented information and the integration of diverse perspectives. By supporting reflexivity, cross-sectoral dialogue and shared analytical understanding, the framework contributes to participatory and transition-oriented governance practices. More broadly, it illustrates how analytical modelling and deliberative processes can be combined to support adaptive, forward-looking and policy-relevant strategies, which are increasingly important for sustainability transitions in complex socio-ecological systems.

6. Conclusions

This study presents a structured and participatory framework that integrates stakeholder engagement with Fuzzy Cognitive Mapping (FCM) to support systemic decision-making within the Water–Energy–Food–Ecosystems (WEFE) nexus. Its main contribution is to demonstrate how a sequenced combination of stakeholder dialogues, system mapping, and semi-quantitative modelling can consolidate diverse forms of knowledge into a shared analytical structure, enabling a clearer understanding of cross-sectoral interactions and the systemic implications of proposed measures.

The approach offers a transferable methodology for other socio-ecological contexts, particularly those characterised by institutional fragmentation or complex nexus pressures. Its transparency, replicability, and emphasis on consensus-building make it suitable for supporting integrated planning processes and strengthening coordination across governance levels and sectors. The method's capacity to foster systemic literacy and structure collective exploration of trade-offs provides a practical pathway for improving engagement quality and supporting more coherent decision-making beyond the Segura River Basin.

More broadly, the framework contributes to sustainability transitions research by operationalising key elements of transformative governance—such as reflexivity, anticipatory thinking, co-creation, and cross-sectoral collaboration. By linking participatory processes with semi-quantitative modelling, it demonstrates how deliberative spaces can be coupled with analytical tools to support forward-looking and adaptive strategies. Such integration offers actionable insights for advancing transition-oriented governance practices in other complex and contested socio-ecological systems.

Thus, while this study provides a structured approach to addressing WEFE nexus challenges and identifying context-relevant solutions, further work is needed to strengthen the link between system analysis and practical implementation. Future efforts should focus on incorporating more quantitative, scenario-based tools to support policy evaluation under uncertainty. This would help bridge the gap between participatory system analysis and effective nexus governance.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors utilised ChatGPT and Grammarly to enhance the clarity of writing and assist with English language revision. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Valentina Mónico González: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Amparo Martínez-Domingo:** Conceptualization, Data curation, Methodology, Validation. **Eulalia Gómez Martín:** Conceptualization, Methodology, Supervision, Writing – original draft. **Adrià Rubio Martín:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Manuel Pulido-Velazquez:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Manuel Pulido Velazquez reports financial support was provided by European Union Horizon Programme. If there are other authors, they 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.envdev.2026.101515.

Data availability

Data will be made available on request.

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