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Causal Loop Diagrams for bridging the gap between Water-Energy-Food-Ecosystem Nexus thinking and Nexus doing: Evidence from two case studies☆

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ABSTRACT

The concept of Nexus management is gaining increasing attention in the scientific community as it emphasizes the mutual interdependencies among different sectors (typically Water, Energy, Food and Ecosystems – WEFE), overcoming the 'silo' approach that usually characterizes the management of natural resources along with a rather water-centered perspective. Supporting a comprehensive understanding of the cross-sectoral interdependencies and influences among sectors is a cutting-edge research issue, specifically as far as the production of 'actionable' knowledge for policy makers is concerned. Despite its success, the actual implementation of the Nexus holistic approach is still hampered by several barriers. Starting from the analysis of those barriers, this work describes a methodological approach based on Qualitative System Dynamic Model (and specifically Causal Loop Diagram – CLD), capable of enabling the transition from Nexus thinking to Nexus doing. The methodological approach maps and describes the dynamic evolution of complex WEFE Nexus systems, and proposes an innovative 'leverage analysis' – based on graph theory measures – for identifying policy interventions capable of impacting system state and potential evolution. The proposed approach is highly participatory as stakeholders engagement is facilitated throughout the modelling process. Besides a description of the methodology, the present work provides also full details on the results of its implementation in two different case studies in Europe.

1. Introduction

The challenges posed by the Anthropocene claim to be addressed accounting for the closely intertwined social and ecological changes (Biggs et al., 2021). Managing complex socio-ecological systems requires the development of methodological frameworks that are sufficiently integrative to guide research to deliver the necessary insights into all the key components of the system, and to analyse the complex and non-linear interactions of multiple, mutually reinforcing social and ecological processes at different spatial and temporal scales (Biggs et al., 2021). Different methods for conceptualizing and analysing the interconnected system of resources have emerged in the last decades (Dargin et al. 2019). A recurrent criticism of the existing "integrated" approaches – i.e. aiming at achieving integration and coordination for efficient, equitable and sustainable management of natural resources, such as the Integrated Water Resources Management (IWRM) – is that they tend to assume a rather water-centred perspective while considering the other sectors – e.g. food, energy and ecosystem – as mere users of the water resources (Bazilian et al., 2011; Smajgl et al., 2016; Di Baldassarre et al., 2019). In the existing literature, the centrality of the

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water sector in the integrated approaches is justified considering its tight interconnection with global challenges such as climate change (Pahl-Wostl, 2019).

However, the adoption of a water-centered perspective may have negative impacts. First, it may help capture the essential dynamics and interdependencies associated with water systems while overlooking or downplaying (both in time and space) the broader complexity of interconnections that exist beyond water (Dargin et al., 2019; Ravar et al., 2020). Many interconnected systems, such as energy and food, are influenced by and impact water resources, but they also have intricate relationships among themselves that need to be considered for a comprehensive understanding (Bloschl et al., 2019). Therefore, these tools support policy and decision-makers in optimizing the use of a specific resource, neglecting the potential trade-offs over the others (Shannak et al., 2018).

Second, the capability of the integrated approaches to enhance policy coherence and cross-sectoral collaboration is rather limited (Stringer et al., 2018). This is mainly due to the difficulty in translating integrated conceptual frameworks into practical policy implementation as well as to the complexity of coordinating multiple sectors and stakeholders with different interests towards achieving consensus (Pahl-Wostl, 2007). As a result, the implementation on the ground of the IWRM is hampered, notwithstanding its broad promotion in national and international policy arenas (Pahl-Wostl, 2019).

Recently, several authors tackled complexity moving from integrated approaches towards holistic approaches, i.e., capable of emphasizing the intertwined nature of the socio-ecological systems and unravelling the complex linkages and feedbacks occurring across different temporal and spatial scales, and between different levels, sectors and groups (de Amorin et al., 2018; Stringer et al., 2018; Schlüter et al., 2019). These approaches recognize that, although complex socio-ecological systems can be influenced, the system cannot be understood, nor can its behaviour be predicted based solely on the analysis of its individual parts (Biggs et al., 2021). Complexity theory, as articulated by Cilliers (2000), plays a crucial role in this paradigm shift. It posits that complex systems, such as socio-ecological systems, cannot be fully understood or predicted based solely on an analysis of their individual parts, as their behaviors emerge from the interactions among components. This challenges the feasibility of "fully describing" such systems, especially in the context of Nexus research, where the objective is to understand interactions among various resources like water, energy, food, and ecosystems (WEFE).

The "Nexus" approach, which is gaining traction (Grady et al., 2023; Teutschbein et al., 2023), seeks to holistically address the mutual interdependencies among key sectors like water, energy, food, and ecosystems (Smajgl et al., 2016). It focuses on these interactions and emphasizes synergies and trade-offs across sectors (Namany et al., 2019; Pahl-Wostl, 2019). Adopting and operationalizing the WEFE Nexus requires, therefore, a paradigm shift from "siloed" institutional and policy setting towards those aligned with the Nexus thinking, which account for the interconnections among politics, resource security, environment, economy and society (Naidoo et al., 2021).

To bridge the gap between Nexus thinking and doing, transdisciplinarity is not merely a methodological choice but a pivotal enabler. By dismantling disciplinary silos, transdisciplinarity fosters a collaborative environment where diverse knowledge systems—scientific, local, and policy-oriented—can converge (Liu et al., 2018; Biggs et al., 2021). This integration is vital for addressing the barriers that impede the practical application of the Nexus approach. However, as highlighted in our analysis, overcoming these silos does not inherently resolve the complexity and uncertainty of Nexus systems, which require dedicated frameworks for capturing their dynamic evolution and interdependencies.

Despite its potential, several barriers impede the operationalization of transdisciplinary Nexus approaches (Weitz et al., 2017; Naidoo et al., 2021; Ramos et al., 2022). The transition from Nexus *thinking* to Nexus *doing* is hampered by several barriers, such as i) the fragmented institutional structures and governance arrangements across sectors (Hoff, 2011; Kharanagh et al., 2020); ii) the presence of disciplinary silos, which limits the understanding of interconnections and trade-offs and hamper the transdisciplinarity based on holding multiple types of knowledge; iii) the challenges in fully describing the complexity and uncertainty of a Nexus system, consisting of interactions and feedback loops among different sectors and dimensions (Wiek et al., 2012); iv) the lack of effective stakeholder engagement and collaboration across sectors, which is paramount for an effective WEFE Nexus management (Nhamo et al., 2018); v) the tendency of the WEFE analytical tools to focus on techno-economic and biophysical analysis, limiting the role of social sciences (Ramos et al., 2022); vi) the static nature of most analytical frameworks, which does not account for the highly dynamic nature of policy implementation processes (Weitz et al., 2017). Transdisciplinarity directly addresses these barriers. For instance, while disciplinary silos constrain our understanding, transdisciplinary processes—by involving stakeholders across sectors—create shared platforms for knowledge exchange. This approach not only fosters collaboration but also enriches our understanding of Nexus challenges and the trade-offs associated with policy interventions. Moreover, as demonstrated in this work, transdisciplinary methods can guide the transition from conceptual system mapping to actionable leverage point identification, thereby linking thinking and doing.

System Dynamics Modelling (SDM) has been recently identified in the scientific literature as an effective modelling approach for supporting Nexus analysis and management (see e.g., Simonovic, 2009; Pahl-Wostl, 2007; Smajigl et al., 2016; Abdelkader et al., 2018; Ravar et al., 2020; Keyhanpour et al., 2021; Wen et al., 2022). As demonstrated by these authors, SDM could contribute to overcoming the above-mentioned barriers to WEFE implementation. SDM enables the adoption of a transdisciplinary perspective which is key in dealing with Socio-Ecological Systems by combining inputs from different disciplinary domains and accounting for the different peoples' perceptions of real world system based especially causal relationships and feedbacks among components within a system (Sterman, 2000; Clifford-Holmes et al., 2018; Biggs et al., 2022), providing a valuable holistic framework for addressing Nexus challenges (Meadows, 2008; Laspidou et al., 2020; Wu et al., 2021). It helps to describe the dynamic patterns, feedback loops, trade-offs and synergies that shape the interactions between the systems, leading to more effective decision-making and coherent policy development (de Vito et al., 2019; Pagano et al., 2019; Coletta et al., 2024b). SDM can thus support the development and analysis of different scenarios, supporting the analysis of the dynamic evolution of the Nexus system under different conditions and policy interventions (Susnik et al., 2021; Murphy, 2022). Stakeholders' engagement is also at the core of several works related to SDM implementation for Nexus management (Yang et al., 2016a; Clifford-Holmes et al., 2018; Purwanto et al., 2019).

Although the application of SDM in nexus management is promising, some gaps still exist in literature. The lack of consistent frameworks for developing SDM for Nexus systems analysis is limiting its practical application (Kaddoura & El Khatib, 2017; Albrecht et al., 2018; Estoque, 2023). In addition, SDM has been criticized because it remains functionalist in nature, failing to account for the innate subjectivity of human beings and, thus, to adequately integrate stakeholders' viewpoints in the SDM and to support participation, ultimately allowing an effective co-creation process for Nexus policies (Clifford-Holmes et al., 2018; Sušnik et al., 2018; Kimmich et al., 2019).This undermines the potential for a successful policy implementation (Gallagher et al., 2020). Lastly, many works related to SDM implementation in Nexus analysis primarily concentrate on the technical aspects of the WEFE Nexus management, often overlooking the critical policy and governance dimensions (Foran, 2015; Sušnik et al., 2021). Bridging these gaps is crucial for enhancing the suitability of SDM in bridging the gaps between Nexus thinking and Nexus doing.

Starting from these premises, this work describes a multi-step methodological framework aiming to develop and analyse a Qualitative System Dynamics Model (QSDM) capable of supporting stakeholders and decision-makers in: i) mapping the complex web of interactions among the different elements affecting the dynamic evolution of the WEFE Nexus system; ii) combining and integrating a wide range of knowledge systems across multiple institutions in a transdisciplinary domain (Cockburn et al., 2018); iii) identifying potential policy interventions capable of changing the system's dynamic evolution; iv) screening the most suitable WEFE Nexus policies, i.e., those capable of enhancing synergies and reducing trade-offs among the different sectors. The framework envisages the involvement of stakeholders throughout the modelling process. The methodological approach has been developed within two EU-funded projects, namely REXUS (H2020, GA 101003632) and LENSES (Prima Programme, GA 2041), and tested in several case studies in Europe and beyond. Two case studies, namely the Jucar River Basin (Spain) and the Koiliaris River Basin (Greece) are detailed in the present work, as they are characterized by different WEFE Nexus challenges and different socio-institutional and technical contexts.

This work is organized as follows. Section 2 describes the different steps of the proposed methodological approach for developing and analysing the CLDs. Section 3 provides an overview of the two case studies where the approach was implemented, and results are described in full detail in Section 4. Section 5 provides a critical discussion of the main advantages and pitfalls of the methodological approach. Concluding remarks are described in Section 6.

2. Materials and methods

The methodological approach has been inspired by the framework and related stages of qualitative system dynamics modelling proposed by Egerer et al. (2021) based on the seminal work by Richardson and Pugh (1981). The whole process was designed to be strongly participatory and thus stakeholders from various sectors have been engaged throughout the modelling process. Efforts were made to enhance the usability of the QSDM in communicating the results of system analysis to the stakeholders. This allowed establishing a common understanding of the problem and incorporating stakeholders' knowledge into the model, ultimately improving the quality of information provided to decision-makers and enabling collective learning processes (Winz et al., 2009; Voinov and Bousquet, 2010; Egerer et al., 2021).

Table 1 summarizes the different steps of the adopted methodology, their objectives, the tools/methods used, and the participatory activities carried out in each phase. This work focuses on the first three phases of the methodological approach, i.e., those based on the QSDM. The fourth phase requires the development of a Quantitative SDM, that will be described in future work.

The methods adopted in each phase and the participatory activities carried out are further described in the dedicated sections.

2.1. System conceptualization

Fig. 1 shows the different activities to be carried out in this phase and the inputs to be used.

The system conceptualization phase has threefold goals. Firstly, it aims at defining the set of stakeholders to be engaged. To this aim, the socio-ecological-technical (SET) network approach was adopted in this work (Pagano et al., 2022). Describing the SET method is out of the scope of this work. Some details are provided in the Supplementary Material. The Ecosystem Services (ESs) that need to be produced for the Nexus sustainable management are at the core of the SET network approach. In this work, we consider the ESs as the services provided by an ecosystem as an intrinsic property of its functionality and the benefits (and occasionally disbenefits) that people obtain from ecosystems. Three main categories of ESs have been defined, i.e. provisioning, regulating and cultural (IPBES, 2021). Adopting an ES-based approach means that actors are not linked exclusively through formal interactions. Informal – and often hidden – interactions happen in the biophysical system, e.g. using the same resources or competing for the ESs. In this work, the SET method was used to identify: i) agents responsible for the management of the ecological resources; ii) agents whose decisions/actions affect the ecological processes; iii) agents benefitting from the ES provision; iv) agents exerting pressure on the ecological resources and hampering ES production; v) agents managing the technical infrastructures needed for the ES provision (e.g., irrigation system management). The analysis of the network of interactions among the different agents allowed us to identify the key – the most central – stakeholders for each Nexus sector to be involved in this phase.

Semi-structured interviews with the identified stakeholders were carried out to help enriching the available information (see the supplementary material for the protocol of the interviews) and developing. The result of 'system conceptualization' is twofold. On the one hand, the specific target (and boundaries) of the SDM can be identified. On the other hand, the preliminary identification of the main challenges and concerns can help better framing the problem, facilitating the stakeholder engagement, and enhancing the effectiveness of the process. The draft CLD was, then, improved/finalized during the system mapping phase.

2.2. System mapping

The second step of the approach is identified as 'System mapping' (Fig. 2). This step is directly oriented to develop the QSDM, whose main

Table 1
Overview of the methodological framework.

Phase	Objective	Method	Participatory activities
System conceptualization	**Background information** collection and retrospective analysis to identify the main **challenges** and potential sources of sectoral and inter-sectoral conflicts	Baseline information on pilot areas: collection of data and information from previous projects and other activities SET network mapping and analysis.	Semi-structured interviews with key stakeholders.
System mapping	Identification of the main **variables** for understanding system structure and **interconnections** among sectors: Nexus mapping.	Definition of a preliminary version of the CLD from the analysts Model revisions and finalization based on the stakeholders' engagement	Participatory mapping exercise Focus groups
System behavioural analysis	Get insights into system state, identifying **central variables**, inter-sectoral dependencies and potential sources of **conflicts**, suggesting **leverage points**	'Descriptive' analysis of the CLD (focusing on feedback loops).'Structural' analysis of the CLD (based on the graph theory metrics) CLD analysis validation.	Stakeholders' workshop for CLD analysis validation.
System simulation	Supporting the transition towards 'Nexus doing': identification and testing of potential **measures**, support to their **evaluation** based on a quantitative model	Simplified scenario analysis using CLDs Transition to a stock and flow model for supporting a comprehensive simulation of system evolution under different scenarios	Participatory intervention scenarios development.

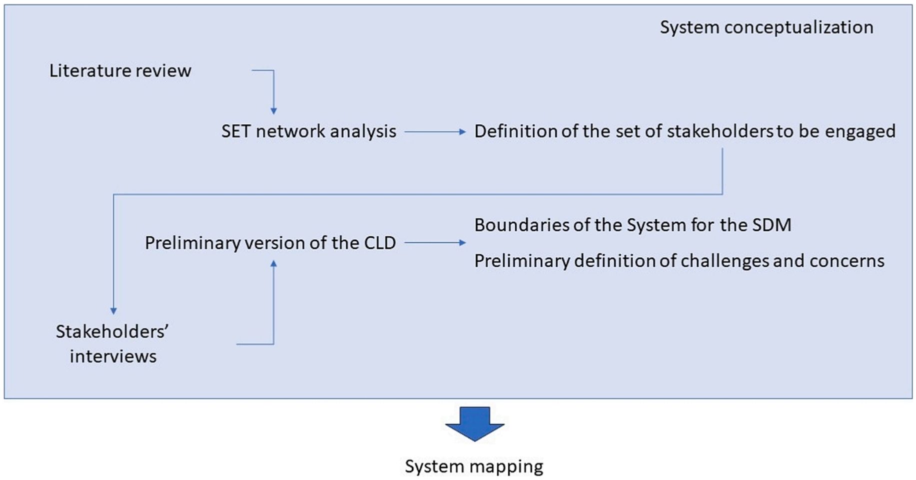

Fig. 1. Activities, inputs and outputs of the system conceptualization phase.

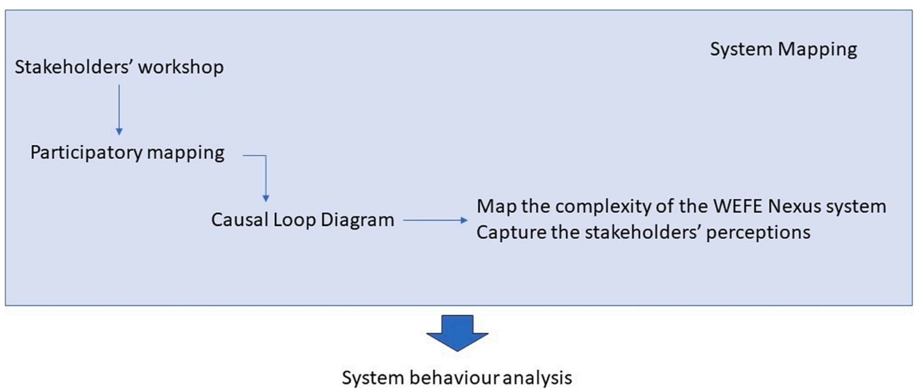

Fig. 2. Activities, inputs and outcomes of the System mapping phase.

scope is to: i) map the complex web of connections among the different elements affecting the dynamic evolution of the WEFE Nexus system; and ii) visualize the complex issues from the stakeholders' perspective, capturing their mental models (Sterman, 2000; Egerer et al., 2021). A Causal Loop Diagram (CLD) was adopted in this work for the purpose, as CLD can effectively capture how elements in the system are interrelated (Mirchi et al., 2012; Sterman, 2000).

The core building (Fig. 3) blocks of CLD are variables and their direct causal relationships, which can be either positive or negative (if they increase in the same direction or in the opposite direction, respectively) (Sterman, 2000). Another key element of CLDs is represented by feedback loops. A feedback loop consists of two or more causal links between elements that are connected in a cyclical form. There are two different types of feedback loops: positive and negative feedback loops. A positive (or reinforcing) feedback loop is self-enhancing and generates exponentially escalating behaviour which could be (extremely) beneficial or (extremely) detrimental. A negative (or balancing) feedback loop generates balancing or goal-seeking behaviour, being sources of stability as well as resistance to change. Complex system behaviours often arise due to shifts in the relative strengths of feedback loops (Coletta et al.,

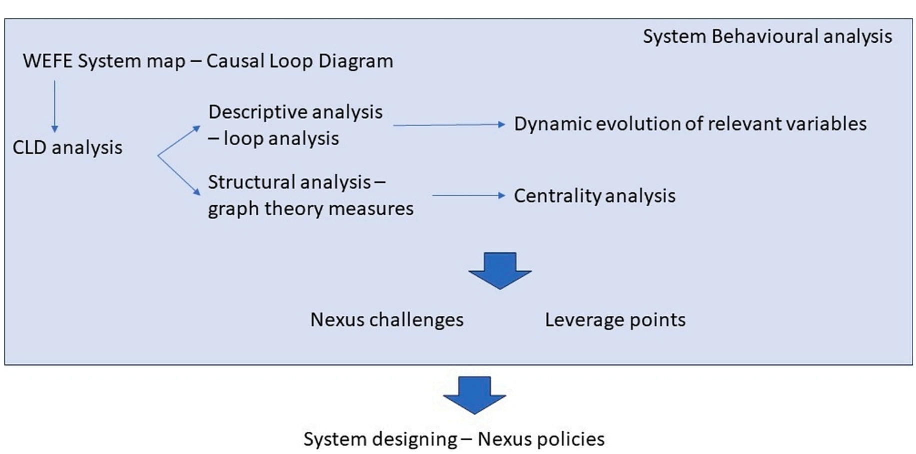

Fig. 3. Activities, inputs and outcomes of the System Behavioural Analysis phase.

2024a).

A weight (typically between 0 and 1) can be also assigned to each link of the CLD, representing the strength of the interconnection between variables. It can be either defined by the analyst (based on the available knowledge) or directly by the stakeholders through specific participatory exercises.

The stakeholders' engagement in the CLD development allowed to (i) exchange and aggregate information, knowledge and even emotions on existing and desired systems, (ii) gradually develop understanding, insight, confidence and commitment, and (iii) address factors excluded from the actual models (Forrester, 1990; Kwakkel and Pruyt, 2013; Giordano et al., 2020). It can also help build social capital – i.e. bonds of trust, reciprocity and social connections – among stakeholders (Stave, 2010; Coletta et al., 2023; Scrieciu et al., 2021). Participatory modelling exercises, and specifically CLD development, could become the "space of mediation", in which stakeholders share their own understanding of the analysed systems, become aware of the others' perspectives and learn how different policy options might affect the interests of the other participants, promoting conflict resolution and collective decision-making (Stave, 2010; Voinov et al., 2018).

The system mapping was carried out involving stakeholders in a participatory mapping workshop. To this aim, the results of the SET network mapping and of the first round of interviews were used to define the group of stakeholders to be involved in this activity (question 11 in the interviews framework – supplementary material). Efforts were carried out to represent all the Nexus sectors in the participatory mapping exercise. The main scope of this exercise was to co-define Nexus interactions and sectoral interdependencies. Concerning the latter, participants were requested to identify key variables (starting from a list proposed by the analysts and based on the results of the step 1 – System Conceptualization) and to draw relevant connections among those, while providing details on their meaning and relevance. Details on the polarity and weight of the connections were also asked during this activity. A draft CLD was drawn during the workshop and, subsequently, formalized by the analysist using the kumu.io platform (https://www.kumu.io). The CLD built during this step needs to be interpreted as a 'living' model, open to revisions and updates as new information is produced throughout the process through the interaction with the stakeholders – e.g. focus groups.

2.3. System behaviour analysis

The main scope of this phase is to understand the dynamic behaviour of the WEFE Nexus system and to support the definition of the Nexus policies. To this aim, the CLD developed in the previous step was analysed. Although CLDs only include qualitative information, their analysis can help deconstruct system interactions and understanding behaviors that might often be unpredictable and counterintuitive (Murphy and Jones, 2021). The step 3 comprises two intertwined activities, related to the 'descriptive' and 'structural' analysis of the CLD. The former relates to the analysis of the main dynamics that affect the state and potential evolution of relevant variables (mainly based on feedback loops). The latter is based on the use of graph theory measures: by measuring network structure (e.g., how densely coupled variables are, or how central a node is) important information about the nature of the network as a whole can be inferred (Murphy and Jones, 2020). The combination of the descriptive and structural analysis allows the identification of "Nexus challenges" (i.e. key intersectoral issues affecting the Nexus sustainability that need to be addressed across sectors in an integrated way), and the selection of leverage points, i.e., points in the system where local intervention could have large impacts at system scale (Meadows, 1997; Abson et al., 2017; Birney et al., 2021; Egerer et al., 2021).

As a CLD can be represented as a directed graph of variables and their connections, centrality measures can help quickly and objectively pinpoint important phenomena regardless of the size or complexity of the map. Table 2 shows the centrality measures adopted in this work and their relevance.

The measures were calculated in weighted form, accounting for the information related to the relative strength of each connection collected during the system mapping exercise. The Kumu (www.kumu.io) Social Network Analysis module was used for the purpose. The combination of the different centrality measures allowed us to identify the Nexus challenges.

Once the Nexus challenges were identified, the second step of this phase consisted in the analysis of feedback loops containing those challenges. As already mentioned, feedback loops represent a key component and organising structure for complex systems. The analysis of the feedback loops allows formulating hypotheses on the potential dynamic evolution of the Nexus challenges due to their position within the system, and identifying the elements that could provoke change. System archetypes were used in this analysis (Vennix, 1996; Egerer et al. 2021).

To support policy design, leverage points were also identified through the analysis of feedback loops and closeness centrality measure. The leverage points are places within a complex system where a small shift in one thing can produce big changes at system scale (Meadows, 1999; Fischer and Riechers (2019), Egerer et al., 2021). Structured analytical methods are needed since they are hard to identify and isolate in a system (Murphy and Jones, 2020). In our analysis, the leverage points are considered as the elements that can strongly affect the dynamic evolution of the Nexus challenges, towards Nexus sustainability. By integrating the loop analysis and the closeness centrality, our approach aims at supporting the identification of the leverage points and

Table 2
Centrality measures in CLDs (Murphy and Jones, 2020).

Centrality measure	Definition in graph theory	Description and relevance
Degree Centrality	It counts the number of connections each element has.	In general, elements with higher degree are the local connectors/hubs. The centrality degree indicates the elements having a high number of intersectoral connections
Betweenness centrality	It measures how often a variable is in the shortest path between other elements	Elements with high betweenness act as key bridges within the network and, specifically, among different sectors in the WEFE system. They can also be potential single points of failure – i.e., bottlenecks hampering the intersectoral cooperation.
Closeness centrality	It indicates the network dependency on a specific element and the potential for spreading information. Closeness measures how distant each element is from all other elements,	Elements with a high closeness can have a large impact on what happens in the system and can influence system changes.
Eigenvector centrality	Eigenvector centrality measures how well connected an element is to other well connected elements. Relative scores are assigned to all nodes in the network based on the concept that connections to high-scoring nodes contribute more to the score of the node in question than equal connections to low-scoring nodes. A high eigenvector score means that a node is connected to many nodes who themselves have high scores.	Elements with high eigenvector centrality are the leaders of the network.

to enhance stakeholders' understanding about the impacts on system behavior due to their changes. The leverage analysis can thus be used for supporting a preliminary identification and screening of Nexus actions/measures.

Stakeholders are engaged in validating the results of the CLD analysis. A second round of stakeholders' workshop is organized. To facilitate the validation phase, the developed CLD is broken down into smaller pieces, representing the key loops that affect the Nexus management. Stakeholders are, then, requested to discuss the connections in each loop and to identify potential points of intervention. At this stage, the validation phase is still ongoing in most case studies.

2.4. System designing

Step 4, lastly, is referred to as 'model simulation'. The main scope of this section is to use the developed model to support the design of WEFE Nexus policies. To this aim, the results of the CLD analysis can be used to identify potential policies interventions and for a preliminary evaluation of the impact those policies might have on the system. Specifically, the detection of the main challenges and leverage points can support the preliminary identification of policy interventions capable of activating the leverage points and addressing the Nexus challenges. Moreover, the CLD analysis could allow the detection of potential trade-offs due to implementation of policy interventions.

Finally, the CLD could be used as a conceptual basis for building quantitative 'stock and flow' models that can be used for a thorough comparison of the impact of actions/measures and for analyzing scenarios (e.g., Egerer et al., 2021).

3. Overview of the case studies

The methodological approach was experimentally implemented in

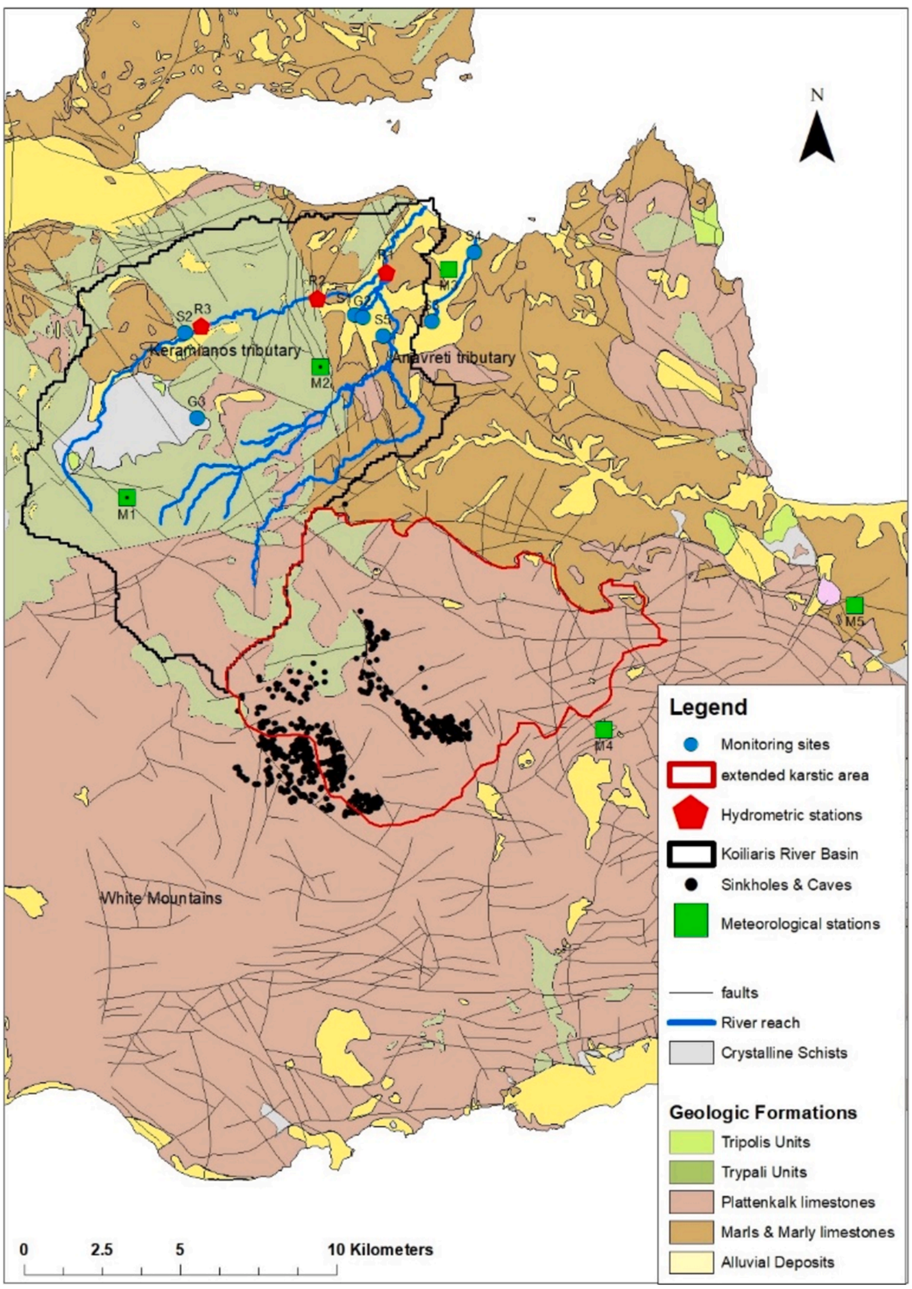

Fig. 4. Map of the Koiliaris River basis (. adapted from Lilli et al., 2020)

two Nexus-related case studies, namely the Koiliaris River Basin and the Jucar River Basin. Although these case studies have some common characteristics – e.g. both areas are characterized by the centrality of agricultural activities and by the need for innovation in view of a more efficient use of water resources and more reduced environmental impacts – they are characterized by different Nexus challenges, different biophysical elements, as well as by different socio-economic and institutional frameworks.

3.1. Koiliaris River Basin (Crete, Greece)

The Koiliaris River watershed is a Critical Zone Observatory (CZO) (https://www.koiliaris-czo.tuc.gr) on the island of Crete and part of the European LTER (Long Term Ecological Research) Network and the LTER-Greece Network (Fig. 4). It is characterized by severely degraded soils due to heavy agricultural impacts, including grazing, for many centuries. It is also affected by the imminent threat of desertification due to climate change. The main activities are related to intensively grazed shrubland and pasture (over 67 % of the area), olive, citrus groves, vines, vegetables (over 32 % of the area) and mixed forest. The drainage network mainly consists of a river and two ephemeral streams providing surface runoff, and a relevant role is played by karstic springs which merge with the rest of the streams to form the main segment of the Koiliaris River. Currently, a limited efficiency of water management over the area is acknowledged. Further details can be found in previous works that have been reviewed by Lilli and coworkers (2020).

The information used for building the CLD for the Koiliaris case study results from the integration of: i) baseline information obtained through the review of background information on the study area; ii) expert knowledge, provided by the pilot leaders (TUC Team) who have an extensive knowledge of the area due to measurements and modelling activities performed in the last two decades; iii) stakeholder knowledge,

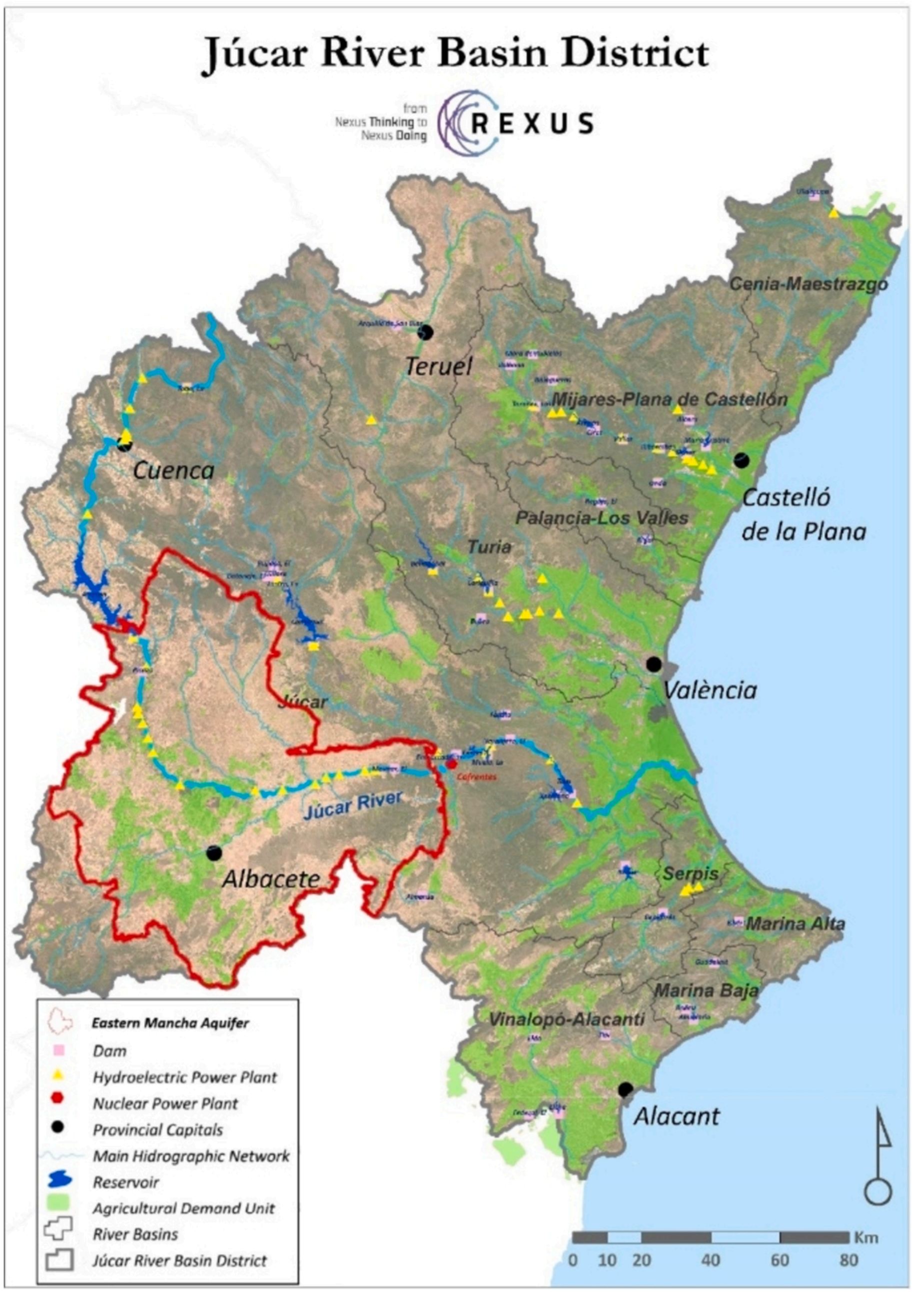

Fig. 5. The Jucar River Basin District.

elicited through a round of semi-structured interviews with key stakeholders, a workshop for the finalization of the CLD, and two focus groups with farmers, oriented to better understand the role of agricultural activities over the area and the potential for innovation. The Koiliaris Critical Zone Observatory is an LTER site which has been operated since 2004. Therefore, stakeholders have been widely engaged in mutual learning and knowledge exchange activities over these years in the premises of several European and national funded projects. The main stakeholders that have been interacting with the observatory are the Region of Crete, the Decentralized Administration of Crete, local municipalities, academic institutions, the local public water companies, the Ministry of Environment, the Development Organization of Crete, the Natural Science Museum of Crete and local farmers and associations. The knowledge collected during the 20 years of continuous interaction with the stakeholders was used to identify the key stakeholders and to map their interactions, both formal and informal, and to draft the preliminary version of the CLD. The model was, then, finalized carrying out a round of semi-structured interviews with the above mentioned key stakeholders. This initial participatory CLD was further verified and finalized with stakeholders' workshops. Finally, two focus group meetings with targeted stakeholders – such as the Avocado Farmers' association and group of farmers from Koiliaris River Basin – were carried out to address specific issues for the CLD finalization The main purpose of the focus groups was twofold: 1) to discuss the effectiveness of the current irrigation practices, and suggest potential strategies to overcome existing barriers to innovation in irrigation practices; 2) to build a *vision* for the Koiliaris valley and Koiliaris River, with the aim to guarantee water security, agricultural development, environmental protection and the well-being of the citizens.

3.2. Jucar River Basin (Spain)

The Jucar River Basin is located in the South-East part of Spain and has a total surface area of 42,735 km^2 (Fig. 5). To fulfil the high irrigation demand and maintain water flows for the natural environment, multiple types of water resources are considered: surface/ground water as well as water transfers from other basins and non-conventional water (desalination and treated wastewater). The basin has good monitoring networks for surface and groundwater linked to an Automatic Hydrological Information System (SAIH), and the Albufera protected wetland has its own control network, that controls also marine intrusion. Agriculture plays a crucial role in sustainable Nexus management, as it is the largest user of water resources and consumes significant amounts of energy, while guaranteeing the well-being of communities and the production of food. The main activity is agriculture, which also is related to the majority of water demand (80 %). Urban and industrial demand are about 16 %, and 4 % respectively. It has a total surface of 374,434 ha corresponding to irrigated crops, distributed on 30 % of herbaceous and vegetables (wheat, maize, rice, summer crops and alfalfa) and 70 % orchards (citric, vineyard, olives, nuts and stone fruits). Total demand of water in the basin for agriculture is 2,400 hm3. An imbalance in the system is increasingly related to climate change and its impacts on water resources. Crucial issues for the river basin are also related to the very limited level of integration of policies (which often show direct or indirect side-effects) and to the limited level of interaction among stakeholders.

The analysis of the previous projects and a literature review allowed us to implement the SET network approach (system conceptualization phase), that showed how the Jucar River Basin Authority (JRBA) should be considered as a key agent, as it oversees WFD implementation and reporting. The system conceptualization also indicated the importance of engaging farmers and communities of irrigators, as users of the ESs and managers of the technical infrastructures needed to provide the ESs. Other key stakeholders were mainly related to land-use and environmental resources management (i.e. the Regional Authority), and protection of environmental resources and ecosystem (i.e. Environmental protection NGOs). Finally, agencies involved in the energy production were engaged in the participatory activities. These key stakeholders were involved since the early phase of the participatory modelling. A round of semi-structured interviews was carried out to this aim involving the JRBA (one representative – water sector), the Regional Authority (two representatives from the water sector and the agricultural section), the communities of irrigators of the upper and lower Jucar River Basin (that provided also the farmers' perspective at this stage) (5 representatives from the food production sector), and a NGO for the environmental protection (two representatives from the ecosystem sector).

The results of the interviews were used to draft the CLD describing the Nexus interactions, and to finalize the identification of the stakeholders to be engaged in the participatory system mapping (second participatory activities). Twenty stakeholders representing the different Nexus sectors attended the participatory system mapping workshop. Besides the key stakeholders, representatives from the Province, SMEs providing consultancy in the agricultural sectors, consultancy agencies in the energy sectors, and the Regional Agencies for the environmental resources protection and sustainable development were invited at the workshop.

4. Results

The present section provides details on the implementation of the proposed methodological approach in the study areas. A critical analysis of the results is provided in the Discussion section.

4.1. Koiliaris River Basin (Crete, Greece)

Fig. 6 presents the final version of the CLD produced for the Koiliaris River Basin. A detailed 'narrative' description of the whole structure of the CLD is out of the scope of the present work, but the Figure immediately suggests that a high level of interconnectedness exists among the different Nexus sectors.

The map includes information on the polarity of the links. Moreover, a numeric value in the interval [0, 1] was assigned by the analysts as weight to each link, based on the information collected during the step #1 and 2 of the analysis. It basically represents a quantitative assessment of the strength of the connection between the two variables.

The CLD has been explored through the analysis of selected graph theory measures. As discussed in Section 2, reference is made firstly to the centrality degree, which is used to locate the local connectors/hubs and can be thus used for the identification of the key challenges. Particular attention has been given to high-degree variables that have also multi-sectoral impacts/dependencies, as they can help identify Nexus challenges.

In this regard, the analysis highlights the central role of agricultural activities in the Koiliaris area, as 'agricultural productivity' (Centrality degree 5.2, Betweenness centrality 0.207, Eigenvector centrality 0.079) along with both 'agricultural sustainability' and 'agricultural profitability' (Centrality degree 3.6, Eigenvector centrality 0.067 and 0.059 respectively) are high-ranked. A relevant driver for the sector is the 'Climate change' (degree 3.2), which increasingly contributes to the availability of natural resources but also directly impacts the quality and quantity of agricultural production. A central element in the agricultural sector is related to the level of 'farmers' training' (degree 2.8), which is currently relatively poor considering the issue of land fragmentation and the rather limited number of professional farmers. This aspect has a significant impact on the level of agricultural productivity, but also on the quality of the agricultural practices adopted, since the land is fragmented into small parcels where you cannot achieve economy of scale and maximize the level of profit of traditional products (such as citrus and olive oil), along with a tendency to use unsustainable agricultural practices that often have a severe impact on the environment.

Interestingly, the analysis shows also that agricultural activities in

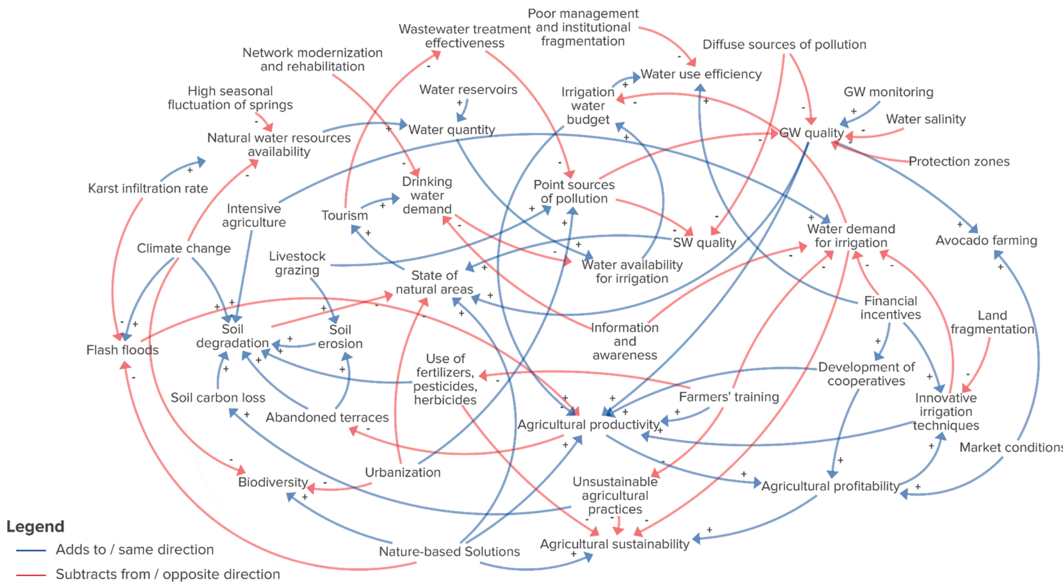

Fig. 6. Causal Loop Diagram developed for the Koiliaris case study.

the area are not limited by water quantity (e.g., 'water availability for irrigation' is relatively low ranked – Centrality degree 1.8), as water is currently relatively abundant. Water is, instead, poorly managed, as for example 'Water demand for irrigation' is central in the analysis (Centrality degree 4) as well as the 'irrigation water budget' (Betweenness centrality 0.151). Furthermore, the model shows that the water sector mainly suffers from competitive water uses between irrigation and drinking, particularly due to the impact of tourism, which can cause insufficient water supply in some areas. This conflict might be exacerbated in the near future due e.g., to climate change impacts. Focusing on the water sector, the main challenge is indeed mainly related to water quality, as 'Groundwater (GW) quality' (Centrality degree 4) is highly ranked. Even though the spring water quality is very good, the groundwater quality has been impacted in some areas by diffuse sources of pollution, and by increasing salinity issues in some coastal areas. It is worth highlighting that the low water quality for irrigation has also increasingly negative impacts on agricultural productivity of certain produce (i.e., chloride concentration on avocado productivity). As far as the environment/ecosystems are concerned, the main challenge is related to 'Soil degradation' (Centrality degree 4.8, Betweenness centrality 0.140) and to the 'State of natural areas' (Centrality degree 4.4, Betweenness centrality 0.175, eigenvector centrality 0.1) which are directly or indirectly impacted by productive activities (intensive agriculture, livestock farming, urbanization, etc.).

A summary of the main Nexus challenges and related centrality measures is provided in the following Table 3.

As detailed in Section 2, the leverage analysis helps identify potential points of intervention in the system, as the use of graph theory measures helps targeting elements where the impacts of a small action could provoke larger impacts on the whole system. Following the proposed methodology, the leverage analysis relies on the analysis of centrality measures which is coupled with the analysis of the feedback loops, particularly focusing on a couple of loops that are highly relevant for the Nexus challenges.

The feedback loop represented in Fig. 7 (a *reinforcing* loop) refers to the 'Irrigated agriculture' dynamics and has a central role in understanding the system state and evolution as it involves three variables characterized by high centrality, namely 'Agricultural productivity','Agricultural profitability' and 'Irrigation water budget' and is directly related an inter-sectoral challenge that involves both 'water' and 'food' sectors. An increase in 'Water demand for irrigation' (due e.g., to the spread of irrigated agriculture) can cause a reduction of the 'Irrigation water budget', which is related to a reduction in 'Agricultural productivity'. In this work, we define "irrigation water budget" as the comparison between the water available for irrigation and the irrigation demand. Therefore, it describes to what extent the irrigation demand is satisfied. This, in turn, affects the agricultural productivity, whose reduction could drive a decrease of 'Agricultural profitability'. As lower profits can hamper the spread of innovation in agriculture, a reduction

Table 3
Nexus challenges for the Koiliaris case study.

Nexus challenges	Centrality measures
Agricultural productivity, profitability and sustainability	High centrality degree; high betweenness centrality, High eigenvector centrality
Soil degradation	High centrality degree; high betweenness centrality
State of natural areas	High centrality degree; High betweenness centrality; High eigenvector centrality
Groundwater (GW) quality	High betweenness centrality; high eigenvector degree
Irrigation water budget	High betweenness centrality

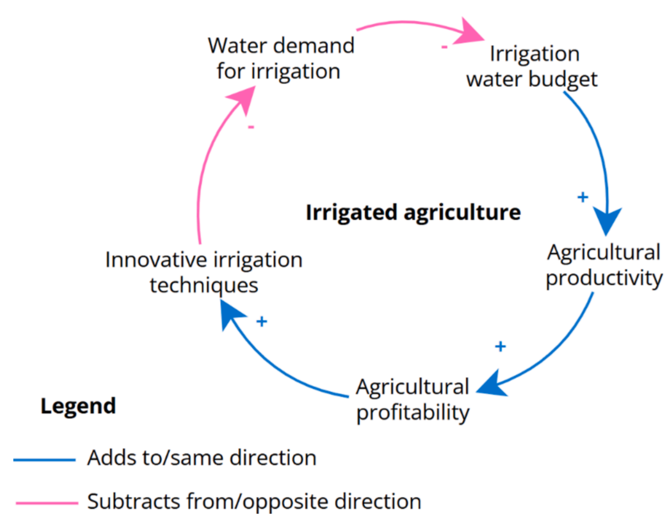

Fig. 7. Focus on 'Irrigated agriculture' feedback loop in the Koiliaris River Basin CLD.

in the adoption of ‘Innovative irrigation techniques’ can occur. This will result in a reduction of ‘Water demand for irrigation’, with a potential cascading reduction of the ‘irrigation water budget’. This could easily drive the system towards unsustainable conditions.

Among the other loops present in the map, a *balancing* one named ‘Agriculture, water and environment’ is shown in Fig. 8, which helps to describe once more the high level of interconnectedness of sectors and sectoral challenges.

The role of ‘Tourism’ is central for the well-being of the area, but a potential reduction in the ‘Wastewater treatment effectiveness’ as a consequence of the heavy increase in the number of tourists (particularly in the summer) has been already experienced. This causes an increase in the ‘Point sources of pollution’, with a cascading impact on the ‘GW quality’ in some areas. The reduction of ‘GW quality’ is directly related to a decrease in ‘Agricultural productivity’, as several products have already shown in the area a high sensitivity to water quality (e.g., the avocado). A significant reduction in the ‘Agricultural productivity’ is then related to the increased risk of ‘Abandoned terraces’, which has already been experienced in the last decades in the Koiliaris area. The abandonment of terraces is responsible for an increased ‘Soil degradation’, which causes a potential reduction of the ‘State of natural areas’. As the quality of the natural environment is reduced, this may cause a reduction in the attractiveness of the places for ‘Tourism’.

The analysis of loops can be coupled with the results of graph theory measures computation, supporting the leverage analysis. In particular, we focused on the closeness centrality, which identifies elements that can easily affect the rest of the network and usually have a high impact on what is happening across the system. The variable characterized by the highest closeness centrality value is the ‘farmers’ training’ (Closeness centrality 0.154), which can directly intervene on the above loops as an increase of ‘farmers’ training’ can positively affect both ‘Agricultural productivity’ and ‘Water demand for irrigation’. This result can be valuable for policy-makers as it clearly highlights that among the multiple actions that can be identified and implemented for supporting the sustainable development of the area, a rather immediate and effective point of intervention is represented by actions oriented to increase the level of technical and scientific knowledge of farmers (e.g., on the quantity of water actually needed for irrigation, on the need to reduce the amount of chemicals and fertilizers and/or to use more sustainable options, etc.). In this regard it should be mentioned that the ‘Intensive agriculture’ and the ‘Unsustainable agricultural practices’ are also highly ranked (the Closeness centrality is 0.118 and 0.098, respectively). Among the high-ranked variables in terms of closeness centrality, the role of ‘Nature-based Solutions’ (Closeness centrality 0.142) is also central, as their implementation is directly related to an increase of ‘Agricultural profitability’ (which can have a favorable influence on the above loops) and potentially also to an increase of water availability that might positively impact the ‘Irrigation water budget’, besides having multiple positive impacts on the state of ecosystems (as they influence either directly or indirectly the level of ‘Soil degradation’ and the ‘State of natural areas’). Lastly, other potential leverage points refer to the socio-economic system as the increase of ‘Financial incentives’ (Closeness centrality 0.087) that can exert a strong influence on the adoption of ‘Innovative irrigation techniques’ and the ‘Development of cooperatives’ (Closeness centrality 0.06) that can directly affect the productivity (and profitability) of agriculture.

A summary of the results of the leverage analysis is provided in

Table 4
Results of the leverage analysis for the Koiliaris case study.

Nexus challenges	Leverage points
Agricultural productivity, profitability and sustainability	Farmers’ training Nature-based Solutions Development of cooperativesAvocado farming
Soil degradation	Nature-based solutions Reduction of unsustainable agricultural practicesFarmers’ training
State of natural areas	Nature-based Solutions Protection zonesReduction of intensive agriculture
GW quality	Reduction of the diffuse sources of pollution Protection zonesGW monitoring
Irrigation water budget	Farmers’ trainingNetwork modernization and rehabilitation

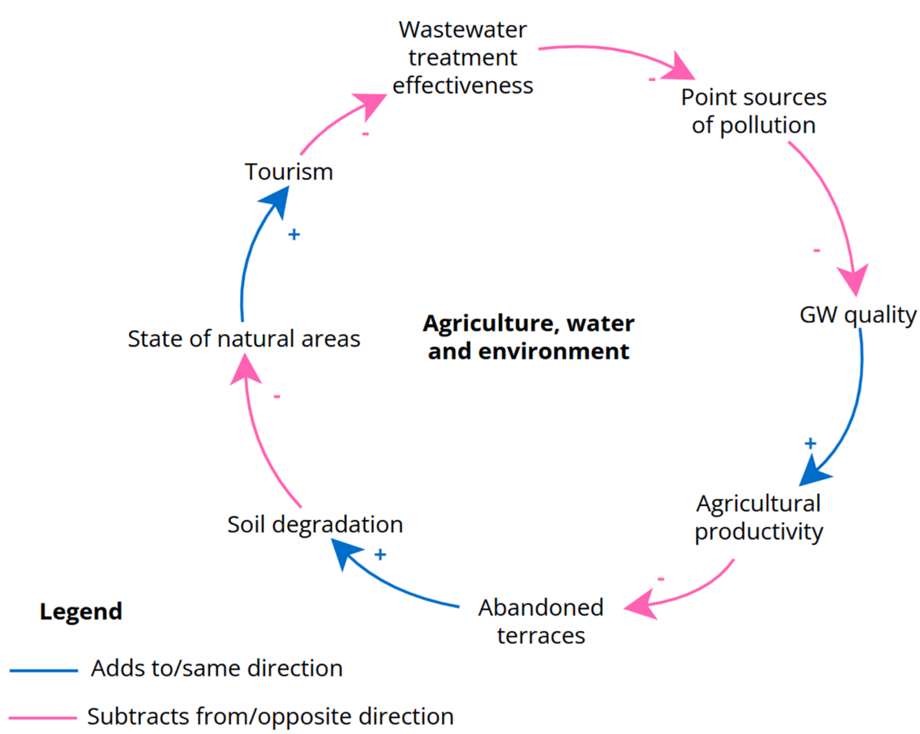

Fig. 8. Focus on ‘Agriculture water and environment’ feedback loop in the Koiliaris River Basin CLD.

Table 4.

4.2. Jucar River Basin

As stated in Section 2, the first step concerns the development of the SET network allowing for the identification of the key stakeholders to be engaged. To this aim, the main ESs needed for the Nexus sustainable management were identified. Fig. 8 shows part of the SET network developed for the Jucar River Basin.

As shown in the previous figure, four agents should be engaged to address the issues related to the above-mentioned ES, namely, the Jucar River Basin Authority, the community of irrigators, farmers and agents of the energy sectors. The SET network approach demonstrates how interactions among agents can be activated either directly or through the other elements of the SET – e.g. the irrigation network, the Jucar River baseflow, etc.

Table 5 shows the results of the SET network analysis that was used to identify the key stakeholders to be engaged in the first phases of the participatory process in the Jucar case study.

The results of this analysis were used to identify the key (most central) stakeholders to be engaged in the system conceptualization phase. Interviews were carried out and a first draft of the CLD was developed. The system mapping was finalized with a participatory exercise during a stakeholders' workshop held in Albacete.

During the workshop, stakeholders were required to identify the key Nexus elements among different cards prepared in advance, referring to the system conceptualization. Participants were allowed to add new cards, if needed. Fig. 9 shows the results of the participatory system mapping exercise.

The stakeholders' system map was, then, coded and translated into a CLD, as shown in Fig. 11.

The variables in the CLD are the elements selected by the stakeholders during the system mapping exercise. As already mentioned, the "+" and "-" in the map represent the links' polarity, as expressed by the stakeholders. Ciano links represent positive connections, whereas red arrows represent negative connections. Moreover, a numeric value in the interval [0, 1] was assigned to each link directly by the stakeholders to provide a weight to the connection. The connections are represented with a different thickness according to their weight.

As expected, the key element in this CLD is the Jucar River baseflow. For the sake of clarity, the stakeholders decided to divide the Jucar River Basin into two main areas, i.e., the Upper Jucar River (UJR) basin, and the Lower Jucar River (LJR) basin. This distinction was mainly based on the kind of irrigation system in the two areas. The irrigation in the UJR was mainly based on the use of groundwater, whereas the irrigation in the LJR relied on the surface (river) water.

To better understand the CLD, the complex graph was broken down into more understandable segments, focusing on the key system variables, feedback loops, drivers that are central to the analysis of the CLD of the WEFE nexus. To this aim, the graph theory measures described in Section 2 were implemented, allowing us to identify the key variables, i.e. the Nexus challenges (Table 6).

It is worth noting that, as shown in Table 6, two key environmental resources, i.e., the Jucar baseflow and the Albufera wetland, are characterized by a high betweenness degree. This means that these elements can either enable or hinder the changes in the system. Moreover, the energy sector is not mentioned among the challenges, but it plays a key role in affecting the irrigation costs for farmers, in defining the costs for nitrates use and, finally, affecting the Jucar baseflow (hydropower). This variable was not very central in the CLD because it was a key concern only for farmers but was not considered important by the other stakeholders. As further discussed in the discussion section, the composition of the stakeholders' group could introduce some biases in CLD development and analysis. To reduce this risk, the intervention of the analysts was key in this case. A specific focus group was organized to gather more information on the impacts of energy production on Nexus sustainable management, as discussed further in the text.

In the methodological approach, the key feedback loops are those affecting the nexus challenges. Therefore, the complex CLD was broken down into more understandable portions of the CLD. Fig. 12 shows the loops affecting the dynamic evolution of the challenge "Unauthorized groundwater abstraction".

This CLD is characterized by two balancing loops and a reinforcing loop. The first balancing loop (B1) seems to lead to a reduction of the unauthorized groundwater abstraction due to the increase of the water available for irrigation and, then, of the irrigation budget. The second balancing loop (B2) seems to lead to a reduction of the irrigated areas and of the irrigation demand in case of low availability of water for irrigation (irrigation budget). However, the equilibrium in the system is negatively influenced by the reinforcing loop (R). This loop involves the UJ irrigated area and the UJ farmers' income. As the UJ irrigated area increases, it leads to an increase in UJ agricultural productivity, which in turn increases the UJ farmers' income. With higher income, farmers are more likely to expand the irrigated area, further reinforcing the cycle.

Unauthorized groundwater abstractions increase the agricultural productivity and farmers' income. If farmers perceive this behaviour as successful, they could tend to increase the irrigated areas, provoking an increase in the irrigation demand, leading to an ever-increasing unauthorized abstraction of groundwater. In Fig. 9, the irrigation budget is defined as the ratio between the water available for irrigation and the

Table 5
SET network analysis.

Ecosystem Service	Resources	Infrastructures	Agents
Provisioning – Water provisioning for irrigation purposes	Jucar River baseflowGroundwater	Irrigation network	Jucar River Basin Authority Irrigation users community FarmersEnergy producer companies
Provisioning – Water provisioning for the ecosystem	Jucar River baseflow GroundwaterAlbufera wetland		Jucar River Basin Authority Farmers Irrigation users community Environmental protection agencies Regional AuthorityEnvironmental protection NGOs
Provisioning – Recreational ecosystem services	Jucar River baseflowAlbufera wetland	Ecotourism facilitiesTransportation network	Ecotourism sector companies Transportation agencies Urban communitiesRegional Authority
Provisioning – water provisioning for energy production	Jucar River baseflow	Hydropower plants	Jucar River Basin Authority Energy production companiesFarmers
Regulating ES – flood protection	Jucar River baseflow	Flood protection infrastructures	Jucar River Basin Authority Urban communitiesRegional Authority
Regulating ES – soil degradation protection	Jucar River baseflow Groundwater Albufera wetlandSoil		Farmers Land-use managers and plannersRegional Authority

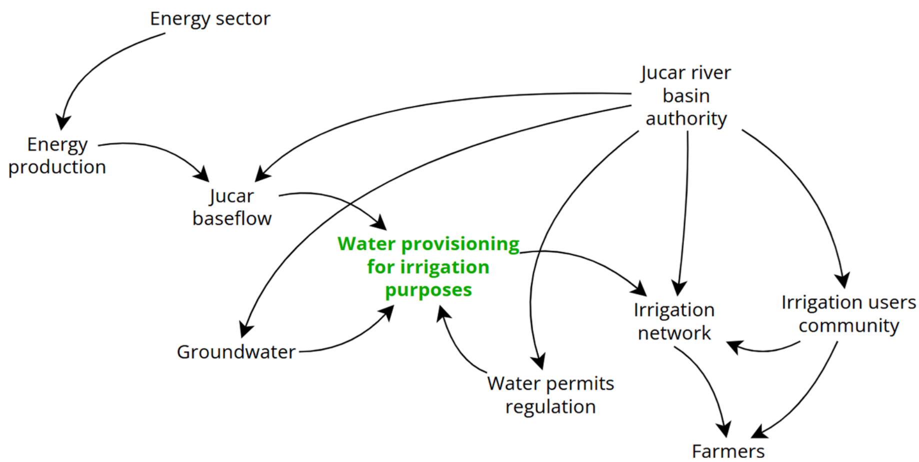

Fig. 9. Part of the SET network of the Jucar River Basin related to ES “Water provisioning for irrigation purposes”.

Fig. 10. Participatory system mapping exercise in the Jucar case study.

irrigation demand. Therefore, the higher the demand and the lower the budget. In this condition, a low irrigation budget will lead to an increase in the unauthorized abstraction. Secondly, the unauthorized groundwater abstraction seems to reduce the irrigation costs because farmers could access water volume for irrigation without paying for water rights. Once again, the success of this strategy – i.e., increase of the farmers' income due to the reduction of irrigation costs – could lead to an ever-increasing irrigation demand and, hence, to the exploitation of unauthorized groundwater volumes for irrigation. Therefore, the irrigation demand plays a key role in the dynamic evolution of this Nexus challenge. Fig. 10 shows the loop affecting the state of the variable “Irrigation budget”.

The loop analysis shows that, to provoke a change in the Nexus challenge “unauthorized groundwater abstraction”, measures are needed to reduce the irrigation demand. The closeness centrality measure was coupled with the loop analysis to identify the leverage points. The three elements connected with the irrigation demand and characterized by the highest closeness degree were: i) “innovative irrigation system”, ii) “farmers' income”, and iii) “farmers' environmental awareness”. This means that the demand of water for irrigation could be reduced by boosting innovative irrigation systems and by finding ways for farmers to reconcile environmental awareness with their financial needs. These could be considered as the leverage points for this nexus challenge.

As already stated, the energy production was not central in the CLD analysis because of the composition of the stakeholders' group attending the workshop. However, given its importance in the WEF Nexus, a further focus group was organized to understand the impacts of the energy production in the Jucar River Basin. The results of this discussion were added to the CLD and further analyzed. Fig. 13 shows the loops affecting the dynamic evolution of energy production.

The energy production by hydropower plants plays an important role in Nexus management. There are 60 hydropower plants in the Jucar River Basin District, capable of producing 2,245 MW. As shown in Fig. 10, on the one hand, an increase in energy production might produce a reduction of the Jucar baseflow and, thus, of water availability for irrigation. This, in turn, will provoke a decrease in the agricultural productivity in the Lower Jucar basin because the irrigation demand, in this area, is primarily satisfied by the distribution of surface water. On the other hand, the need to increase the surface water volume allocated for irrigation purposes could decrease the Jucar baseflow and, thus, the water available for energy production. Therefore, in the Lower Jucar basin, energy production competes directly with agricultural production.

Energy production plays a key role in the upper part of the Jucar River Basin as well. In this area, the irrigation demand is mainly satisfied using groundwater volume. However, energy production could affect the price of the energy, which was one of the main farmers' concerns during the focus group. The reduction of the groundwater level due to the decreasing rainfall, and the contemporary increase of the irrigation demand, is provoking an increase of the energy demand for pumping water for irrigation purposes. A reduction in energy production could provoke an increase in the energy price and, thus, in the irrigation costs. This, in turn, could negatively impact the economic sustainability of the farming activities, as explicitly mentioned by farmers. However, the reduction of irrigation costs (energy) could provoke an increase in groundwater abstraction for irrigation purposes and, thus, it could reduce the groundwater level and its contribution to the Jucar baseflow,

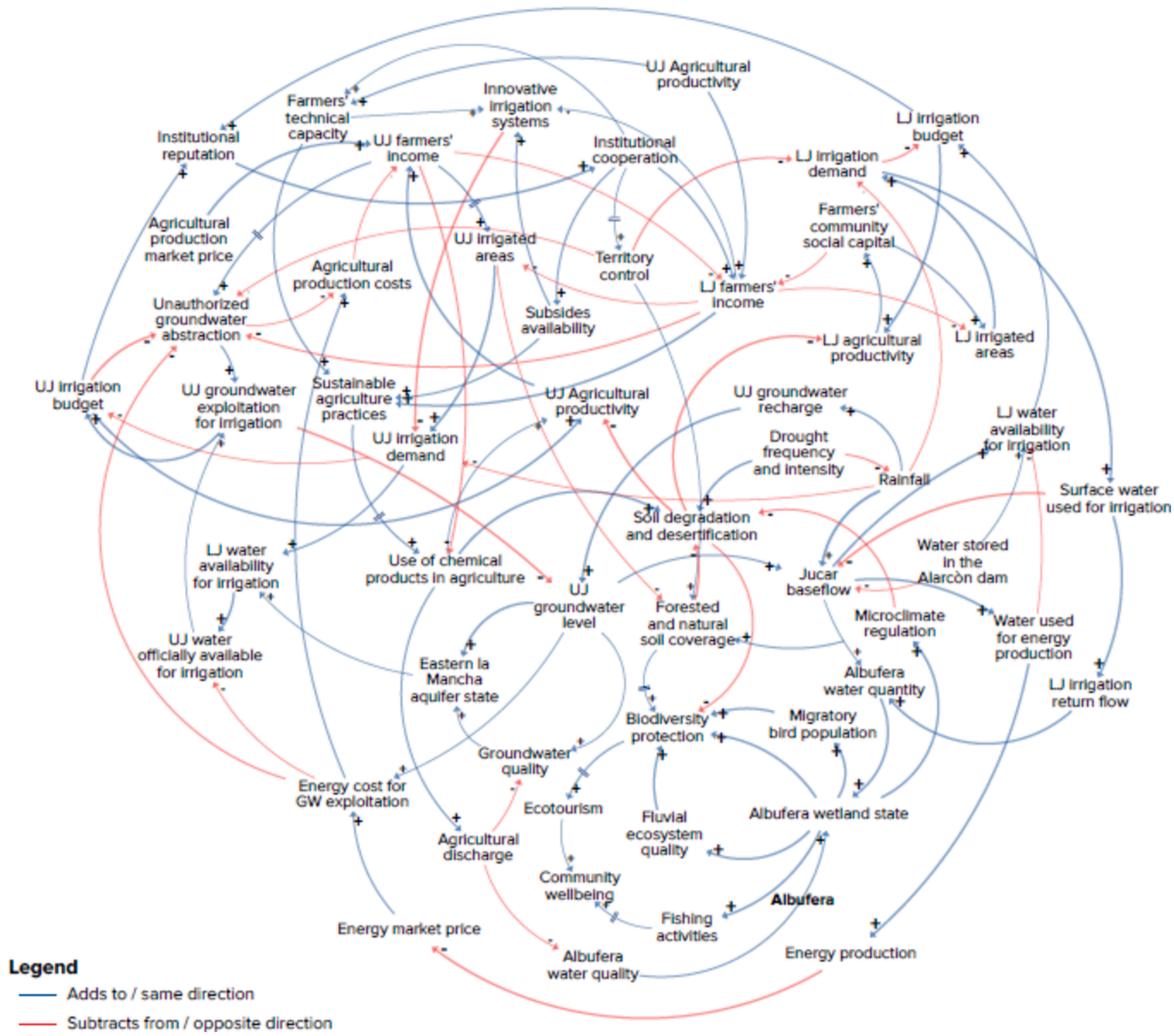

Fig. 11. Causal Loop Diagram developed for the Jucar case study.

Table 6
Nexus challenges for the Jucar case study.

Nexus challenges	Centrality measures
Soil degradation and desertification	High centrality degree
Jucar baseflow	High centrality degree; high betweenness centrality
Albufera wetland state	High centrality degree; High betweenness
Unauthorized groundwater abstraction	High betweenness centrality; high eigenvector degree

which, in turn, affects hydropower (energy) production.

The loops analysis allowed us to identify potential leverage points for addressing the energy production challenge. Interventions are needed to reduce the impact of the energy price on farming activities, and to cope with the conflict between energy production and agricultural production in the Lower Jucar River Basin. Concerning the former, the closeness centrality analysis indicates the "innovative irrigation system" as a potential leverage point. Innovations in the irrigation sector could reduce the water demand and, thus, the energy costs. Concerning the latter, the increase of alternative energy sources could reduce the demand of water for energy production.

Other trade-offs among different policies can be detected by referring to the CLD analysis. The introduction of an innovative irrigation system could enhance the availability of water volume for irrigation, leading to an increased value of the irrigated areas. Avoiding this unintended effect requires the implementation of policies for territory control.

The combination between the loop analysis and the centrality measures allowed to identify the leverage points for activating changes in the other Nexus challenges, as summarized in Table 7.

Referring to Meadows' seminal work, we can define the kinds of Leverage Points we are activating in the WEFE Nexus system. It is worth remembering that Meadows identifies two main categories of Leverage, i.e. deep and shallow leverage points (Meadows, 1999). On the one hand, the shallow leverage points are easier to be activated but could provoke limited change in the system. On the other hand, greater efforts are required to activate the deep leverage points, but they have great potential to bring about transformative changes (Fischer & Riechers, 2018).

Table 8 shows the clustering of the identified Leverage Points into the categories mentioned by Meadows. Moreover, we referred to the three *spheres of transformation* as described in (O'Brien and Sygna, 2013).

As discussed further in the text, the results from this case study show how difficult it was for the stakeholders to go beyond the shallow

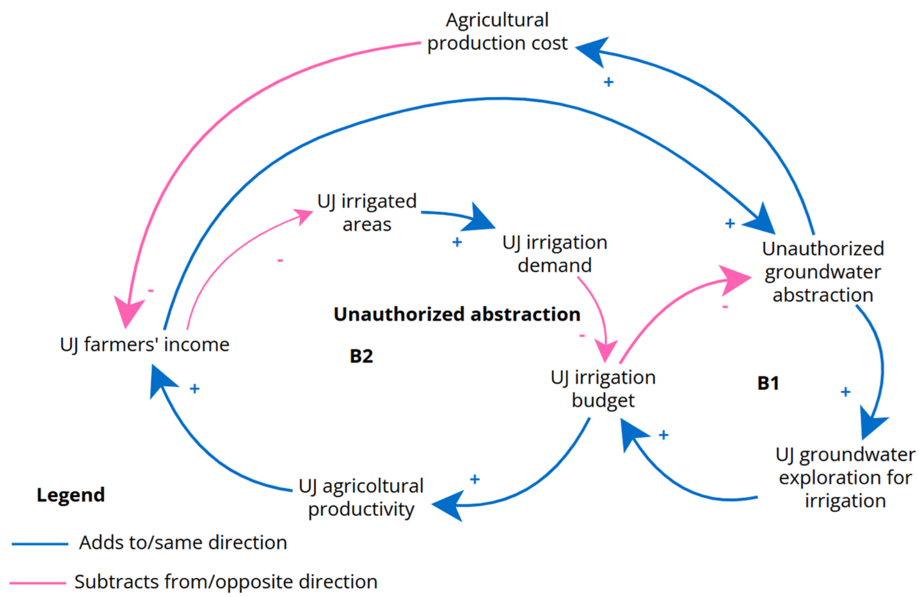

Fig. 12. Loops affecting the challenge “Unauthorized groundwater abstraction”.

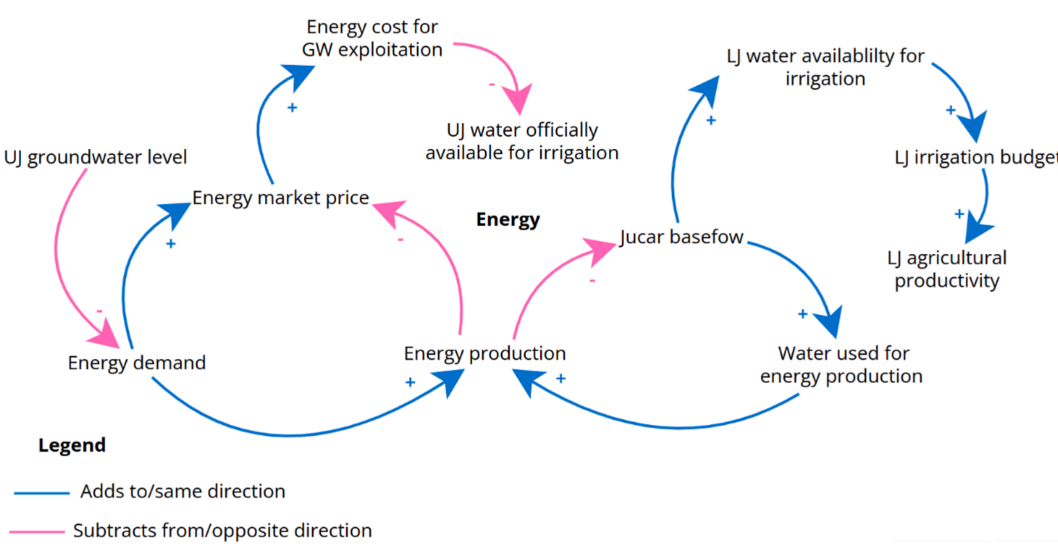

Fig. 13. Loops affecting the dynamic evolution of the energy production.

Table 7
Nexus challenges for the Jucar case study and leverage points.

Nexus challenges	Leverage points
Soil degradation and desertification	Protection of soil natural cover Sustainable agricultural practices Territory controlFarmers’ environmental awareness
Jucar baseflow	Innovative irrigation system Institutional reputationFarmers’ environmental awareness
Albufera wetland state	Sustainable agricultural practices Return flowProtecting the agricultural practices
Unauthorized groundwater abstraction	Innovative irrigation system Farmers’ incomeFarmers’ environmental awareness
Energy production	Innovative irrigation systemAlternative energy sources

leverage points. Most of the discussion was focused on changing processes and flow of resources. From the transformation point of view, it is worth noting that the activation of most leverage points claims for the implementation of practical measures. However, the adoption of these measures on a large scale requires changes in the political system.

5. Discussion

The present work proposes a framework based on the use of CLDs for supporting the transition from Nexus thinking to Nexus doing in complex environmental systems. More specifically, the different steps of the methodological approach help achieving some relevant objects for Nexus analysis, such as: i) improved system conceptualization and mapping, for a structured description and overview of the complexity of Nexus systems; ii) system analysis, for the identification of Nexus challenges and of sectoral/cross-sectoral conflicts in the system, as well as for supporting the identification of potential leverage points for policy implementation; iii) system designing, for understanding, through model simulations, how the system could evolve in different conditions.

Table 8
Jucar leverage points clustered according to Meadows (1999) and O'Brien and Sygna (2013).

Leverage point	System change and sphere of transformation	Explanation
Protection of soil natural cover	Shallow Practical	It provokes a change in the feedback, reducing the strength of the link between the agricultural activities and the soil degradation.Moreover, it requires adopting a technical response.
Sustainable agricultural practices	Deep Personal	It requires changing the farmers' mind-sets and paradigms and involves learning processes. As results of this learning process, farmers' belief about the most effective agricultural practice could change, enabling the adoption of these practices at large scale.
Territory control	Shallow Political and practical	It requires changes in the process of monitoring the territory and the use of water for irrigation purposes.Moreover, it requires a change in the political and legal system enhancing the institutional capacity to control the activities carried out in the territory.
Farmers' environmental awareness	Deep Personal	It requires changes in the farmers' mind-sets and paradigms.
Innovative irrigation system	Shallow Practical and Political	It requires changes in the processes related to the irrigation practices, reducing the strength of the connection between irrigation and groundwater depletion. From the *sphere of transformation,* the leverage points require changes in the political system – e.g., incentives for enabling the adoption of the irrigation practices.
Institutional reputation	Deep Political	It requires changes in mind-sets and paradigms.Moreover, activating this leverage point requires changes in the political system.
Return flow	Shallow	Activating this leverage point requires changing the material flow.A technical/practical response is required to activate this leverage point.
Protecting the agricultural practices	Shallow Political	It requires changing the irrigation process.Moreover, it requires changes in the political system.
Farmers' income	Shallow Practical	It requires changing the flow of economic resources.It requires the adoption of practical measures to keep the farmers' income at a sustainable level.
Alternative energy sources	Shallow Practical and political	It requires changing the energy production process.Activating this leverage point requires both the adoption of practical solutions and changes in the political system.

A shared understanding of the Nexus is promoted, and collective decision-making is encouraged, enhancing the effectiveness and acceptance of Nexus management strategies. In particular, policy-makers can more easily preliminary understand their potential impacts – as well as side effects and unintended consequences – on the system as a whole, overcoming the 'silo thinking'.

This section aims to discuss if and to what extent the described methodological approach is suitable to enable the transition from Nexus thinking to Nexus doing by overcoming the barriers described in the introductory section. The main barriers and the pros and cons of the adopted methodology are described in the following sub-sections.

5.1. Engaging stakeholders in the Nexus management: the foundation for trandisciplinarity

One of the key objectives of this work is to enhance the stakeholders' understanding of the Nexus complexity by engaging them in different participatory activities. Stakeholder engagement serves as the foundation for transdisciplinary processes, as it facilitates knowledge exchange, builds trust, and lays the groundwork for co-creation. A critical analysis of the experiences carried out in the case studies allows us to draw interesting conclusions concerning the main barriers encountered during the engagement process and how we tried to overcome them.

Firstly, creating a heterogeneous group of stakeholders, and engaging participants representing the different Nexus sectors is key to the success of the participatory process. To achieve this, the SET network analysis was instrumental in identifying the most representative stakeholders. Nonetheless, the composition of the stakeholder group attending the participatory modelling workshop could not be completely satisfactory. For example, the energy sector was often underrepresented, as energy utilities tend to operate on a much larger scale and are less attuned to local perspectives. This underrepresentation can lead to the misrepresentation of key issues in the model. To mitigate this risk, we integrated knowledge from multiple sources collected throughout the modeling process—literature reviews, expert consultations, and stakeholder feedback—into the final models. In both case studies, extra-participatory activities with selected stakeholders were organized to supplement knowledge-gathering and finalize the models. The participatory CLDs, therefore, remain "living models," adaptable to new insights gained during the participatory process.

Secondly, participatory modelling is a long exercise, and it requires going through different phases. Maintaining momentum is challenging but essential for ensuring long-term participation. Two actions were taken in this work to achieve this objective. On the one hand, efforts were carried out to identify the main stakeholders' needs and concerns in the early phases of the participatory exercise. This ensured that the engagement process was directly relevant to the stakeholders' priorities and demonstrated its practical significance beyond academic research. On the other hand, feedback was continuously exchanged between researchers and stakeholders concerning model development and validation. By involving stakeholders in ongoing discussions and iterative refinements of the CLD, their interest and ownership in the process were strengthened. Several issues concerning the CLD were discussed with the stakeholders, contributing to increasing the stakeholders' interest in model development and use.

Finally, navigating ambiguity and conflicting perspectives proved to be a critical challenge.. Participants often brought different, sometimes contradictory, perspectives. Ambiguity was encouraged during the participatory activities because it represented the richness of the participants' knowledge. However, a synthesis among the different perspectives was needed to develop the CLD. Where possible, differences in perspectives were explicitly included in the CLD, such as incorporating alternative causes for the same effect. In cases where conflict persisted, focused discussions were organized during workshops to resolve specific issues. If consensus remained elusive, we, as analysts, relied on complementary knowledge gathered in other phases of the process to make informed decisions. This approach balanced inclusivity with the need to ensure the model's coherence and robustness.

By addressing these challenges, the stakeholder engagement process established a strong foundation for advancing toward transdisciplinary collaboration. It not only ensured the inclusion of diverse perspectives but also created an environment where stakeholders could collectively explore and address the complexity of the Nexus system.

5.2. Moving toward transdisciplinarity: Co-creation of Nexus knowledge

The WEFE nexus approach distinguishes itself from the previous integrated frameworks because of the holistic perspective adopted in analysing the interconnections among the different sectors. Enabling the implementation of the Nexus approach requires moving beyond interdisciplinarity—which integrates knowledge across disciplines—toward transdisciplinarity, where the co-creation of knowledge takes center stage.. Transdisciplinarity builds upon stakeholder engagement, as it facilitates collaboration between scientists and stakeholders to map and analyze the complex web of connections across policy sectors. This progression from engagement to transdisciplinarity is essential for addressing the complexity and interconnectedness of Nexus systems.

Central to our approach was the use of System Dynamic Modelling (SDM) and Causal Loop Diagrams (CLD), which were co-created with stakeholders through a participatory mapping exercise. The CLD served as a tool to integrate diverse perspectives and knowledge from multiple sectors, moving beyond disciplinary silos. This process enabled the identification of key interconnections across sectors and highlighted the interdependencies inherent in the WEFE Nexus. For example, stakeholders' insights were critical in identifying the impacts of agricultural practices on water availability and quality, as well as their cascading effects on energy and ecosystem services.. The CLD analysis then focused on identifying the critical relationships between sectors, enabling the mapping of challenges that lie at the heart of the Nexus. Graph theory measures such as centrality were applied to identify elements with high intersectoral connections, which were subsequently defined as key Nexus challenges.. Following this, the loop analysis further examined how these interconnections influence the system's dynamic behavior, offering insights into how these challenges could evolve over time. By integrating these analytical tools into a participatory process, the transition to transdisciplinarity became more structured and actionable.

However, the maps obtained at the end of the participatory mapping exercise in the case studies were rather complex and difficult to understand by the stakeholders. When requested to provide feedback on the mapping exercise, most of the stakeholders expressed a rather high skepticism on the usability of the obtained map to support the policy-making process. In response, the subsequent loop analysis significantly enhanced the clarity and readability of the CLD, fostering more effective engagement from stakeholders in defining potential Nexus interventions.

While stakeholder participation and knowledge integration are fundamental to transdisciplinarity, the co-creation process is not immune to challenges. Power dynamics and epistemic differences among stakeholders can influence the outcomes of participatory exercises. For instance, in the Jucar River Basin case study, the underrepresentation of the energy sector in the stakeholder group led to gaps in the initial CLD. These gaps were addressed through the integration of insights from literature reviews and expert input, demonstrating the need for complementary knowledge sources to ensure a robust transdisciplinary approach..

The effectiveness of transdisciplinary processes also hinges on the balance between stakeholder contributions and expert facilitation. While stakeholders provide invaluable contextual knowledge, analysts play a critical role in synthesizing diverse inputs and guiding the co-creation process. To align with the principles of transdisciplinarity, this synthesis must be transparent and iterative, with continuous feedback loops to validate and refine the models. Such iterative processes are vital for ensuring that the outcomes of transdisciplinary collaborations are both inclusive and scientifically robust.

By advancing from stakeholder engagement to transdisciplinarity, this work underscores the importance of integrating scientific and local knowledge systems. The participatory approach not only supports the transition from Nexus thinking to Nexus doing but also enhances the potential for designing policies that address intersectoral trade-offs and synergies holistically.

5.3. Enhancing the stakeholders' understanding: Bridging complexity and usability

Enhancing stakeholders' understanding is a critical objective of this work, as it enables them to grasp the complexity of Nexus systems and actively engage in co-developing sustainable policies. This section examines how the methodological tools employed—such as System Dynamics Modelling (SDM), Causal Loop Diagrams (CLDs), and centrality measures—facilitate this process and discusses the balance between expert interpretation and transdisciplinarity principles (Coletta et al., 2021).

The capability of SDM – and, particularly, of CLDs – to support the active participation of stakeholders in modelling activities has been already highlighted in the scientific literature (see e.g., Pluchinotta et al., 2021). A significant potential in Nexus studies has been also recently discussed (e.g., Bahri, 2020; Zhang et al., 2021; Bache and Reynolds, 2022). The present work confirmed, through experiences in different environments, some of the main advantages related to application of QSDM techniques such as flexibility, transparency and adaptability, and potential for testing and learning. SDM and centrality measures play a pivotal role in improving stakeholders' comprehension of system dynamics. These tools allow the visualization and analysis of interconnected elements, feedback loops, and trade-offs within Nexus systems. By applying graph theory measures (e.g., centrality) and conducting loop analysis, key leverage points and intersectoral challenges were identified and communicated to stakeholders. For example, the identification of high centrality variables in the Jucar River Basin case study—such as unauthorized groundwater abstraction—enabled stakeholders to understand how localized interventions could yield broader system-wide benefits. This structured analysis not only clarified system behaviors but also empowered stakeholders to contribute meaningfully to identifying potential interventions.

Participatory processes were integral to enhancing understanding by making complex systems more accessible. The co-development of CLDs with stakeholders ensured that their perspectives and knowledge were reflected in the system representation, fostering ownership and engagement. However, the complexity of the resulting maps often exceeded stakeholders' ability to intuitively interpret them. This limitation was mitigated by breaking down the CLDs into more comprehensible segments, focusing on key feedback loops and leverage points. For instance, stakeholders in the Koiliaris River Basin were presented with simplified sub-maps during workshops, which facilitated discussions about agricultural productivity and irrigation practices.

The role of the expert filter in interpreting complex systems warrants careful consideration. While expert interpretation is essential for analyzing intricate dynamics, it introduces the risk of diminishing stakeholder agency, potentially conflicting with the principles of transdisciplinarity. To address this, the interpretation process in this work was designed to be iterative and transparent. Stakeholders were regularly involved in validating the analysis, reviewing the identified leverage points, and refining the model. This iterative feedback loop ensured that expert interpretations were aligned with stakeholder insights and priorities, thereby maintaining the inclusivity central to transdisciplinarity.

Nevertheless, a balance must be struck between accessibility and scientific rigor. While efforts were made to simplify the CLDs for stakeholders, some degree of abstraction is unavoidable in modeling complex systems. This raises the question of how much simplification is acceptable without compromising the model's utility. In this context, the inclusion of diverse knowledge sources—scientific, local, and experiential—proved instrumental in bridging the gap between technical analysis and stakeholder usability. Future iterations of the methodology could explore enhanced visualization tools or gamified interfaces to further support stakeholder understanding.

Finally, enhancing understanding is not only about tools but also about fostering a learning process. Stakeholder engagement in the modeling process encouraged dialogue, mutual learning, and the development of shared mental models of the Nexus system. This shared understanding is critical for designing policies that account for the interdependencies and trade-offs across sectors. The co-creation process itself becomes a vehicle for building the capacity of stakeholders to address complex challenges collaboratively.

In summary, improving stakeholders' understanding involves more than simply presenting tools and results; it requires an inclusive, iterative process that respects the diversity of knowledge systems while ensuring that technical insights are accessible and actionable. By integrating stakeholder feedback at every stage and maintaining transparency in expert interpretation, this work aligns with the principles of transdisciplinarity and underscores the importance of bridging complexity and usability in Nexus management.

5.4. Bridging the gaps among different disciplines including the social science

The lack of transdisciplinary methods for analysing the Nexus connections has been discussed as being a key barrier to overcome. Most of the existing frameworks focus exclusively on technical aspects related to Nexus management, neglecting the importance of the socio-economic elements of the system. The approach adopted in this work puts emphasis on the impacts that social dynamics could have on Nexus management, with specific reference to both individual and collective behaviors. Bringing the human decisions and actions, and the main drivers affecting those actions, into the Nexus analysis, the adopted methodological approach contributes to overcoming the hypothesis of the stationarity of the human dimensions, which is rather common in technically-oriented frameworks (Sivapalan et al., 2012).

However, the current version of the analytical framework is still considering the human dimensions from a qualitative point of view. This makes it difficult to fully integrate the human/social elements with the technical aspects related to the management of the environmental resources. Efforts are required to qualitatively assess the impacts of individual and collective behaviour on the WEFE Nexus management. To this aim, in the future development of this work, QSDM will be integrated with an Agent-Based Model (ABM). Moreover, as already mentioned, further developments of this work need to be based on a deeper integration between social science and modelling efforts.

5.5. Supporting the definition of Nexus policies

The analysis conducted in the case studies illustrates that the proposed methodology offers valuable insights to support the design of policy interventions in complex environmental systems using a Nexus perspective. By incorporating the diverse viewpoints of stakeholders and recognizing the intricate interconnections among sectors, this approach enables policy-makers to make more informed decisions regarding key system challenges and policy priorities.

One of the most significant contributions of the methodology lies in its ability to combine loop analysis with leverage point detection using graph theory measures. This approach allows the identification of critical elements within the system where policy interventions could be most impactful. For example, in the Jucar River Basin case study, the Causal Loop Diagram (CLD) identified vital connections between water resource management and energy production, highlighting areas where targeted interventions could alleviate pressure on both sectors.

A key advantage of the methodology is its capacity to support a trade-off analysis, which stakeholders identified as one of the most valuable outcomes. The complex interconnections revealed by the CLD helped uncover potential conflicts between policy measures. For instance, increasing water use efficiency in agriculture may unintentionally reduce water availability for energy production. This trade-off analysis enables policy-makers to foresee such unintended consequences and balance interventions across sectors to avoid negative ripple effects in the system.

In addition to trade-off analysis, stakeholders emphasized the importance of the leverage point detection process. By identifying key elements in the system where change could yield the most significant impacts, the methodology helps prioritize where policies should be implemented. For example, in the Jucar case, water use efficiency emerged as a high-leverage area, where small adjustments could lead to significant improvements across the Nexus.

However, it is important to emphasize that while the leverage analysis and trade-off identification provide a solid foundation for decision-making, these tools are not a silver bullet for solving complex Nexus challenges. Instead, they offer a structured means to identify critical system elements that require further exploration and discussion with stakeholders. In some cases, as observed in the Jucar River Basin, the initial CLD may not fully capture key issues—such as the underrepresentation of energy-related challenges—due to the composition of the stakeholder group. In these instances, the intervention of analysts and the use of supplementary knowledge from literature reviews allowed for a more comprehensive leverage point analysis, ensuring that important system elements were accurately represented.

Furthermore, the identification of leverage points is not a one-size-fits-all solution. As Murphy and Jones (2020) note, the same graph theory measures can highlight both opportunities for change and barriers, depending on the system's dynamics. This underscores the need for continuous collaboration between analysts and stakeholders to validate the robustness of the model and ensure that leverage points reflect the system's true nature.

Finally, the methodology's ability to identify trade-off-free leverage points is critical for facilitating effective policy implementation. By recognizing which interventions can be made without undermining other sectors, policy-makers can design more coherent and sustainable policies. The loop analysis, combined with stakeholder input, enables a nuanced understanding of where interventions can produce the greatest benefits while minimizing negative outcomes.

5.6. Considering the dynamic evolution of intersectoral connections

The existing Nexus analytical frameworks assume a rather static approach to the detection and analysis of the synergies and trade-offs among the sectoral policies. However, policy implementation is a process that could have different stages for different policies. Moreover, the effects of the policy implementation could arise in different time steps for different policies. Therefore, the dynamic evolution of the policy implementation process needs to be accounted for. By introducing the delays in the CLD analysis, the methodological approach enhances the quality of the trade-offs analysis, accounting for those emerging in different time steps. Moreover, the loop analysis allowed us to detect and analyse trade-offs due to indirect connections.

However, policies can have different impacts in different spatial locations. Thus, the analysis of the trade-offs among different sectoral policies claims geographically-based methods. The methodological approach described in this work is not yet capable of addressing spatial-related issues. To this aim, efforts have been carried out to integrate spatial mapping and the system mapping, as shown in Fig. 14.

As shown in the map, a geographical location was also assigned to the elements of the system map. This is particularly relevant as some phenomena are relevant only for a part of the river basin (e.g., the non-authorised pumping occurs in the upper part of the Jucar only). However, the subsequent CLD analysis is still lacking a geographical dimension, that will be more explicitly taken into account in the Quantitative SDM.

Fig. 14. Integrating System mapping and Spatial mapping in a participatory exercise in the Jucar River Basin.

6. Conclusions

The present work contributes to the debate concerning the lack of practical implementation of integrated frameworks for the sustainable management of natural resources, specifically through the lens of the WEFE Nexus approach. By recognizing the need for a holistic, multi-resource perspective, we identified key barriers to adopting the WEFE Nexus in policy-making and proposed a multi-step methodological framework based on Qualitative System Dynamics Modelling to address them. The framework's strength lies in its ability to integrate scientific and local knowledge to map complex intersectoral interactions within the Nexus system. The coupling of loop analysis with graph theory measures for the identification of Nexus challenges and leverage points represents an important methodological innovation. These leverage points, identified through centrality and other graph theory metrics, are valuable for supporting the design of effective policies aimed at accelerating sustainable changes in the system.

However, the current findings remain preliminary, and the full potential of the methodology has not yet been realized in terms of direct policy outcomes. While the results of the leverage point analysis provide a solid foundation for understanding key areas of intervention, the usability of this analysis for co-designing Nexus policies with decision-makers and stakeholders will be further evaluated in the second round of workshops. These future workshops will help test whether stakeholders can meaningfully engage with the leverage points identified and whether these can indeed support policy development in practice.

Additionally, the transition from thinking to action—or from conceptualizing the Nexus system to implementing changes—remains a significant challenge. While the current framework offers qualitative insights into Nexus dynamics, the development of a Quantitative System Dynamics Model will be essential to support simulation and scenario analysis. This will enable decision-makers to test and compare different policy interventions in a systematic way, providing a more concrete tool for guiding action.

Thus, while the present work lays important groundwork by offering a structured approach to Nexus challenges and identifying leverage points, further steps are needed to fully bridge the gap between system analysis and real-world implementation. Future efforts will focus on enhancing the usability of the model for stakeholders and developing quantitative tools to support the simulation of policy scenarios, marking the transition towards effective Nexus governance. Moreover, efforts will be carried out to integrate social science and system modelling aiming at enhancing the effectiveness of the stakeholders' engagement process.

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CRediT authorship contribution statement

Raffaele Giordano: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Anna Osann:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Esteban Henao:** Writing – review & editing, Validation, Methodology. **Maria Llanos López:** Writing – review & editing, Validation, Formal analysis. **José González Piqueras:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition. **Nikolaos P. Nikolaidis:** Writing – review & editing, Validation, Methodology. **Maria Lilli:** Writing – review & editing, Validation, Methodology. **Virginia Rosa Coletta:** Writing – review & editing, Validation, Methodology. **Alessandro Pagano:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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