LEarning and action alliances for NexuS EnvironmentS in an uncertain future

LENSES

WP4

D4.2 Framework for Participatory System Dynamics Modelling (PSDM) implementation in LENSES case studies

Alessandro Pagano (IRSA), Raffaele Giordano (IRSA), Ivan Portoghese (IRSA), Marco Berardi (IRSA), Pompilio Vergine (IRSA), Stefania Santoro (IRSA)

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Project coordinator

Project partners

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Lead Authors	Alessandro Pagano (IRSA), Raffaele Giordano (IRSA), Ivan Portoghese (IRSA), Marco Berardi (IRSA), Pompilio Vergine (IRSA), Stefania Santoro (IRSA)
Email	alessandro.pagano@cnr.it
Contributions from	DRAXIS, Pilot Leaders
Internal Reviewer 1	Cem Cetinkaya (EA-TEK)
Internal Reviewer 2	Nikolaos Nikolaidis, Maria Lilli (TUC)

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Executive summary

The activities detailed in the present Deliverable are oriented to support reaching one of the main objectives of the LENSES project, which is to shift from individual (or sectoral) perspectives to the definition of a holistic system picture - based on the WEF Nexus approach - ultimately identifying suitable actions to drive the system towards sustainability. In this direction, Participatory System Dynamics Modelling (PSDM) is considered as an effective and straightforward methodological approach to: i) support better understanding the WEF systems under investigation, ii) help building a shared understanding of the main challenges for the area as well as of the most important dynamics that can affect those challenges; iii) help in the identification of leverage points and in the design of policies and actions for a sustainable Nexus management; iv) help understanding system state and potential evolution under different (future) conditions. The use of a participatory approach, deeply rooted in the LAAs activities, should guarantee the long-term involvement of stakeholders in LAAs and enhance a cross-sectoral knowledge fertilization process.

This ambitious goal requires the definition of a solid methodological approach to PSDM building. Indeed, PSDM requires on the one hand the use of sectoral models and data (e.g., hydrological models, climate data, environmental economics, etc.) which in the present project are provided through the LENSES Observatory (see D7.1), but on the other hand the integration with expert knowledge collected through the LAAs. State-of-the-art methods for stakeholders' engagement in modelling exercise are being adopted for this purpose. The PSDM can help model and visualize the state and potential evolution of key indicators under different conditions (see D4.1 for further details).

The present Deliverable provides an updated description of the framework described in draft form at M18, with insights on the implementation of the framework in the LENSES pilots. It mainly provides details on the multi-step framework that has been proposed for PSDM development, also giving some evidence and lessons learned from the activities performed in the pilot areas so far. It therefore drives an interested reader through the suggested steps for building PSDM based on a sequence of both desk and participatory activities, providing the necessary methodological support and a detailed structure of the activities. The proposed approach aims to be general and replicable, although flexibility is needed (and encouraged) to customize the approach to the specificities of the area under investigation (including, e.g., the needs and attitude of the involved stakeholders).

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Report on Framework for PSDM implementation in LENSES case studies

1. Purpose of the deliverable

The present deliverable details the activities performed mainly within Task 4.2, but in tight cooperation also with other WPs, such as WP2 (Learning and Action Alliances), WP3 (Policy perspectives) and WP8 (Pilot implementation). The Task 4.2 aims to support shifting from individual or sectoral perspectives to different WEF Nexus issues, towards the definition of a holistic frame. For this purpose, PSDM exercises are performed in pilot areas to support building a comprehensive (and shared) view of the WEF systems under investigation. The use of a participatory approach, deeply rooted in the LAAs activities, supports the long-term involvement of stakeholders in LAAs and enhances a cross-sectoral knowledge fertilization process.

The development of PSDM benefits from the integration of sectoral models and data (e.g., hydrological models, climate data, ecosystem services assessment, etc.) provided also by the LENSES Observatory (WP7) and performs an integration with expert knowledge collected through LAAs (WP2). State-of-the-art methods for stakeholders' engagement in modelling exercise are adopted.

The present deliverable mainly includes details on the definition of a common framework for PSDM development, with some evidence and lessons learned from the activities performed in the pilot areas. The framework has been updated and revised throughout the project duration and is a key component of the guidelines for replication (D4.3). Information collected and analysed in LAA activities has been used to produce the present revised version of the framework. It is worth to mention here that the PSDM framework is central also in the 'sister' project REXUS (in which the same research group is involved), and in this direction the synergies and the potential for mutual learning opportunities were maximized while keeping the LENSES specificities.

The deliverable is structured as follows. The following Section 2 provides a short review of relevant literature dealing with PSDM. Section 3 provides a summary of the proposed LENSES framework for PSDM implementation, with full details on the main methodological aspects. The state of activities in the LENSES pilots is then discussed in the Section 4, where details from some relevant pilots are also discussed. A critical analysis of such experiences is then proposed in the Section 5, which also provides information on how the framework could be customized/adapted to pilot specificities. Lastly, Section 6 includes some conclusions and details on future activities.

2. Background information

2.1. An overview of PSDM

Systems consist of the whole of closely interacting elements and their interactions. System Dynamics Models describe the assumed/perceived underlying (material, informational, social, …) structure of largely closed real-world systems. In SD terms, a causally closed system is a system which controls action based on the results from previous action (Forrester, 1987) which means that closed systems generate their own behaviour endogenously over time (Pruyt, 2013). However, SD is often used to deal with complex real-world issues that are not fully closed nor entirely open.

Systems consist of elements and relations between (some of) these elements. Models are simplified representations of issues or systems. They consist of variables and links between variables. In SD models, diagrammatic distinctions are made between different types of variables (stocks, flows, auxiliaries, parameters and constants). Underneath, stocks are integral equations of the flows, flows and auxiliaries are equations of other variables and parameters/constants, and parameters/constants assume (constant) values over a simulation run. The structure of a model –i.e. different types of variables, their links, and the feedback loops they form, together with their underlying equations and values– determines the behaviour of the system (Forrester, 1987; Sterman, 2000).

System Dynamics (SD) basically comprises a series of tools and methods to describe, model, simulate and analyse dynamically complex issues and/or systems taking jointly into account the processes, information, organizational boundaries and strategies (Elsawah et al., 2017; Pruyt, 2013). Both qualitative and quantitative approaches exist in SDM, whose use depends on analysis objectives, employed methodology and addressed audience (Brychkov et al., 2022). Basically, **qualitative** SDM allows the analysis of the system behaviour with the help of a conceptual (mental) model, often based on CLDs which capture how elements in the system are interrelated by depicting cause-and-effect linkages and feedback loops (Sterman, 2000). The need for qualitative forms of model-building is often dictated by the existence of a large number of 'soft' elements in a system and on 'textual' data obtained e.g., from interviews.

The core building blocks of CLDs are variables and the direct causal relationships between them, which can be either positive or negative (an increase in A causes B to rise or vice versa, respectively) (Sterman, 2000). One key element of CLDs is related to feedback loops. A feedback loop consists of two or more causal links between elements that are connected in a cyclical form. The behaviour of a variable is therefore (partly) caused by its own past behaviour. There are two different types of feedback loops: positive and negative feedback loops. A positive (or reinforcing) feedback loop - in isolation – is self-enhancing and generate exponentially escalating behaviour which could be (extremely) beneficial or (extremely) detrimental. A negative (or balancing) feedback loop – in isolation - generates balancing or goal-seeking behaviour, being sources of stability as well as resistance to change. Feedback loops hardly ever exist in isolation and are often strongly connected with a variation of the relative strength over time. Complex system behaviours often arise due to such shifts in the relative strengths of feedback loops.

Quantitative simulation model mainly derives from a stock-and-flow diagram (SFD) and a set of simulation equations that quantify linkages between different types of variables. The main objectives of quantitative SDM include the elimination of inconsistencies in understanding of general behaviour the system and the empirical testing of hypothesis about system behaviour and all causal mechanisms (Brychkov et al., 2022). A stock variable –also called a level or a state variable– accumulates, i.e., integrates flows over time. During simulation, a stock variable can only be changed by ingoing and outgoing flow variables (also called rates). A stock can be increased by increasing its inflow rate as well as by decreasing its outflow rate.

There is a level of correspondence and competition between CLD and SFD. In most SD applications, both types of diagrams are built because each has strengths and weaknesses, and using both types of diagrams cushions the drawbacks of one or the other type of representation (Elsawah et al., 2017; Mirchi et al., 2012; Winz et al., 2009). Disadvantages of causal loop diagrams are for example that they (i) do not always explain well how flows influence stocks, (ii) could lead to mislabelling of loops, (iii) do not provide a sound basis for the rigorous deduction of behaviour, and (iv) cannot explain some dynamic phenomena. Some disadvantages of stock/flow diagrams are that they (i) make it difficult to grasp feedback loops (ii) make it difficult to grasp models in their totality, (iii) contain too many (technical) details, and (iv) do not allow to explain all dynamic phenomena.

The discussion about the use of qualitative and/or quantitative SD is still alive in the literature. Mainstream system dynamists often start with qualitative SD, then turn to quantitative SD. There are nevertheless system dynamists who prefer qualitative SD modelling –mainly CLDs – over quantitative SD modelling. Proponents of purely qualitative SD modelling argue that if a close representation cannot be reached, the analysis should be restricted to the qualitative level and that qualitative SD modelling is satisfactory when the 'insights from the diagram are so convincing [or] uncertainties in the numerical data are so great that a quantified model may contain such uncertainties and inaccuracies that it is not worth the effort of building'. Other arguments pro qualitative SD are that it is useful (i) for describing a problem situation and its possible causes and solutions, potential risks and uncertainties, hypotheses and constraints; (ii) to 'capture intricacies of circular causality in ways that aid understanding'; (iii) as a medium by which people can externalize and share their mental models and assumptions; (iv) for the 'inference of modes of behaviour by assisting mental simulation of maps' ; (v) to show people the dynamic system they are part of and to propose solutions. However, there are also good arguments against purely qualitative modelling and in favour of qualitative-quantitative-qualitative modelling, namely that: (i) maps are misleading and unreliable; (ii) they do not enable estimation of the scale or speed of change of key items ; (iii) feedback based insights can often be difficult things for people to understand and believe in ; (iv) they are 'less likely to lead to commitment, consensus or system changes than quantitative models'. The question to be asked in each and any case is thus whether the additional effort of quantitative modelling is justified given the time and resources available (Chen & Wei, 2014; Meinherz & Videira, 2018; Pruyt, 2013).

Particularly when approaching sustainable environmental management issues, an approach that accounts for dynamic connections between social and ecological systems, integrates stakeholder deliberation with scientific analysis, incorporates diverse stakeholder knowledge, and fosters relationships among stakeholders that can accommodate changing information and changing social and environmental conditions is needed. Participatory System Dynamics Modelling (PSDM) provides such a framework (Stave, 2010). (Voinov & Gaddis, 2008) describe participatory modelling as "… *the process of incorporating stakeholders, often including the public, and decision makers into an otherwise purely analytic modelling process to support decisions involving complex environmental questions*".

The 'participatory' component to SDM is therefore not unusual, and PSDM refers to the use of a system dynamics perspective in which stakeholders participate to some degree in different stages of the process, including problem definition, system description, identification of policy levers, model development and/or policy analysis (Stave, 2010). PSDM enables a collective way of developing a system model, known as group model building (GMB), based on the idea that 'effective learning from models occurs best, and perhaps only, when the decision-makers participate actively in the development of the model' (Brychkov et al., 2022; Sterman, 2000). SDM is therefore often also highly interactive, i.e., a high degree of participation of decision-makers and stakeholders is desirable and often necessary. A participative/interactive process allows 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; Pruyt, 2013). SDM are often created using multiple streams of information including quantitative data, written records, and information contained in the mental models of both individuals and groups (Vennix & Gubbels, 1992) and can also help build social capital among stakeholders. To maximize the learning value of simulation models, it is important to allow enough time for debriefing that leads to curiosity about system behaviour. To maximize social capital development, it is important to build enough time into the problem structuring and model conceptualization phases for stakeholders to articulate their mental models and examine those of other participants (Stave, 2010). Ultimately, one of the key benefits of PSDM is participant learning about system connections and feedback, both about the system and about other participants (Stave, 2010).

Stakeholders can help to analyse the system elements and their interactions, as well as to structure, categorize and debate these interacting elements. Storytelling and narratives can help better understanding specific loops as well as the whole system. Working in groups, they further socialize the originated stories and system maps in a multi-stakeholder environment to overcome possible mistakes and discrepancies of their system visualizations. These activities are iterative so the products they derive become dynamic tools rather than static objects of analysis.

2.2. PSDM frameworks

The present section focuses on the analysis of relevant frameworks that have been developed in the recent scientific literature for supporting the implementation of PSDM approaches.

A very basic starting point is the work by (Sterman, 2000) detailed also in (Pruyt, 2013), which summarizes a SDM process based on the following phases:

1. Problem identification: identifying and articulating the issue to be addressed;
2. Model conceptualization: developing a causal theory about the issue;
3. Model formulation: formulating a SD simulation model of the causal theory;
4. Model testing: testing the model to assess whether it is fit for purpose;
5. Model use, quite often model-based policy analysis: using the model to design and evaluate structural policies to address the issue.

The first stages of the above process are qualitative, as is the interpretation of outcomes of SD-based policy analysis. SD model formulation, simulation, and model-based policy analysis on the other hand relate to, or require, quantitative models. A key phase is the conceptualization phase which captures the feedback structure and is based on the following steps:

i) determine the purpose/objective of the model;
ii) define the model boundaries and identify the most important variables
iii) construct a conceptual model of important mechanisms and feedbacks in the system
iv) formulate a causal theory, aka dynamic hypothesis, i.e. a hypothesis on how (problematic) behaviour is generated by the model structure.

Although the division of the modelling process in these phases can be convenient for approaching SD, it should not be considered as a phase-to-phase waterfall process. SD modelling is extremely iterative in nature as every phase in the process may reveal the need to revise the model structure and modelling is an explorative process of knowledge generation (Pruyt, 2013). In practice, any of these phases is revisited several times during a SD modelling project, starting with a small model that is gradually extended until it is good enough for the purpose at hand. Indeed, from a learning point of view, SD modelling processes are more important than the models resulting from these modelling processes (Forrester, 1990).

A relevant framework for integrating sectoral models and stakeholder knowledge in Nexus management, with a focus on transboundary areas, has been detailed by (De Strasser et al., 2016). The methodology consists of six steps and based on the integration between a desk study of the basin, and a set of activities where stakeholders were actively involved, and a more in-depth analysis of nexus interlinkages was made. Basically, the process includes the following steps. The steps 1 to 3 are the core of the desk study, which then feeds into the steps 4-6.

- Step 1—Socio-Economic and Geographical Context Step, which aims at characterizing the basin conditions and its economic context and determining the level of dependency of riparian countries on the basin's resources, mainly based on the assessment of resources security and on the identification of strategic goals, development policies and challenges.
- Step 2—Identification of Key Sectors and Key Actors to be included in the nexus assessment.
- Step 3—Analysis of Key Sectors. Understanding how the sectors use resources, their socio-economic value and what are the rules, plans and regulations associated with them. The step comprises both a resource flows analysis and a governance analysis.
- Step 4— Intersectoral Issues Step. This mainly takes place in a participatory workshop, which defines how each sector will interface the others in the nexus dialogue. Intersectoral issues are explored from sectoral perspectives as participants are divided into thematic groups—water, energy, food/land and ecosystems—according to their expertise or area of interest. Key policies, sectoral plans and data sources are presented and validated by local actors, who also provide expert judgment for prioritization of issues. An opinion-based questionnaire is used to collect the different perceptions of sectors and countries.
- Step 5—Nexus Dialogue. This can be considered the core of the nexus assessment because it is the moment where intersectoral issues are discussed having all concerned sectors around the table. A shared understanding of the nexus is built, and the interlinkages identified in Step 4 are jointly prioritized and combined into thematic "nexus storylines". Next, the relevant future tendencies (climate change, socio-economic trends) are identified jointly with participants and the effects that these will have on intersectoral issues are discussed.
- Step 6—Solutions and Benefits. Following the discussion on intersectoral issues, possible solutions are discussed. They can be of two kinds: (a) Synergetic: when two or more sectors cooperate on actions and projects that create multiple benefits. (b) Sectoral: when the action of one sector has side benefits on other sectors or at least minimizes the negative impact on other sectors. Technical solutions as well as policy interventions are considered.

The key elements of the process are: a) Indicators, used at different stages to substantiate the analysis of the basin, including spatial screening indicators, sectoral indicators and basin-specific indicators focused on interlinkages; ii) Factual questionnaire distributed to the participants to the workshop and local experts to collect basic information on the state and uses of resources as well as issues in the areas of water, energy, food/land and ecosystems; iii) Workshop, with several sessions where participants engage in the nexus assessment process directly; iv) Opinion based questionnaire to gather the opinions of stakeholders involved in the process and compare the different perspectives between sectors and countries on various issues.; v) Follow-up meeting, as a discussion with authorities on how the findings and solutions included in the assessment relate to policies or programs in the countries, and what could be done to address the identified intersectoral issues.

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A valuable approach for PSDM implementation in Nexus-related issues has been proposed by (Purwanto et al., 2019), mainly focused only on the co-definition of CLDs. For the purpose, a one-day GMB workshop on WEF security nexus was conducted, preceded with a series of formal and informal meetings with all potential committees and participants to clarify the aims and objectives of the GMB exercise. The main session of GMB workshop focused on the development of the integrated WEF security CLDs in the local context.

Similarly, (Herrera & Kopainsky, 2020) proposed a multi-step approach to characterize the resilience mainly in terms of food security. A series of participatory and desk activities has been designed, to overcome one limit of the sectoral literature and of the SD practice, which is the need for a generic structure for designing replicable and comparable processes.

A participatory modelling procedure for SDM has been also proposed by (Gallagher et al., 2020) and relies on an iterative process between stakeholder engagement (based on five participatory workshops, bilateral meetings and expert interviews) and desk research was performed to identify and quantify the mechanisms underlying trade-offs between national level energy security and economic growth and local level food security, the priority risks (scenarios), and potential actions (interventions).

The proposed analysis approach comprises also three specific aspects:

1. Qualitative data analysis. A substantial amount of qualitative data was collected during the project and analysed to support the choice of indicators to represent stakeholder priorities and identified risks of concern, scenario formulation, resilience analysis design, and in the discussion of results.
2. Scenario analysis. Framework conditions were changed, and different simulations compared. Particularly the authors identified two baseline scenarios (with and without a dam), and additional scenarios for adaptation (an alternative cropping scheme) and mitigation (environmental flow standards), identified by stakeholders' groups.
3. Resilience analysis. Given uncertainties in stakeholder discussions and model calibration, the model- based scenario analysis was integrated with a resilience analysis. The impact of external disturbances (related to climate change impacts and population change) were measured through specific properties (hardness and elasticity).

A script for the whole process of stakeholders involvement in the discussion of a Nexus problem, including the development of CLDs has been developed by (Kimmich et al., 2019) and available online (https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029%2F2019EF001311&file=eft2_607-sup-0001-2019EF001311-SI.pdf). The script includes, for each phase of the activity, timing, materials needed, a detailed description of the steps and the guiding questions to be used by the facilitators.

It is worth to mention here that the IRSA research Team involved in the LENSES has an extensive experience on PSDM and already proposed a framework for PSDM, fully detailed in (Pagano et al., 2019) and summarized in the following Figure 1. The mentioned framework has been firstly proposed within the NAIAD project (H2020, Grant Agreement No 730497) when it was basically used to define a structured participatory approach to Nature-Based Solutions co-design, co-evaluation and implementation.

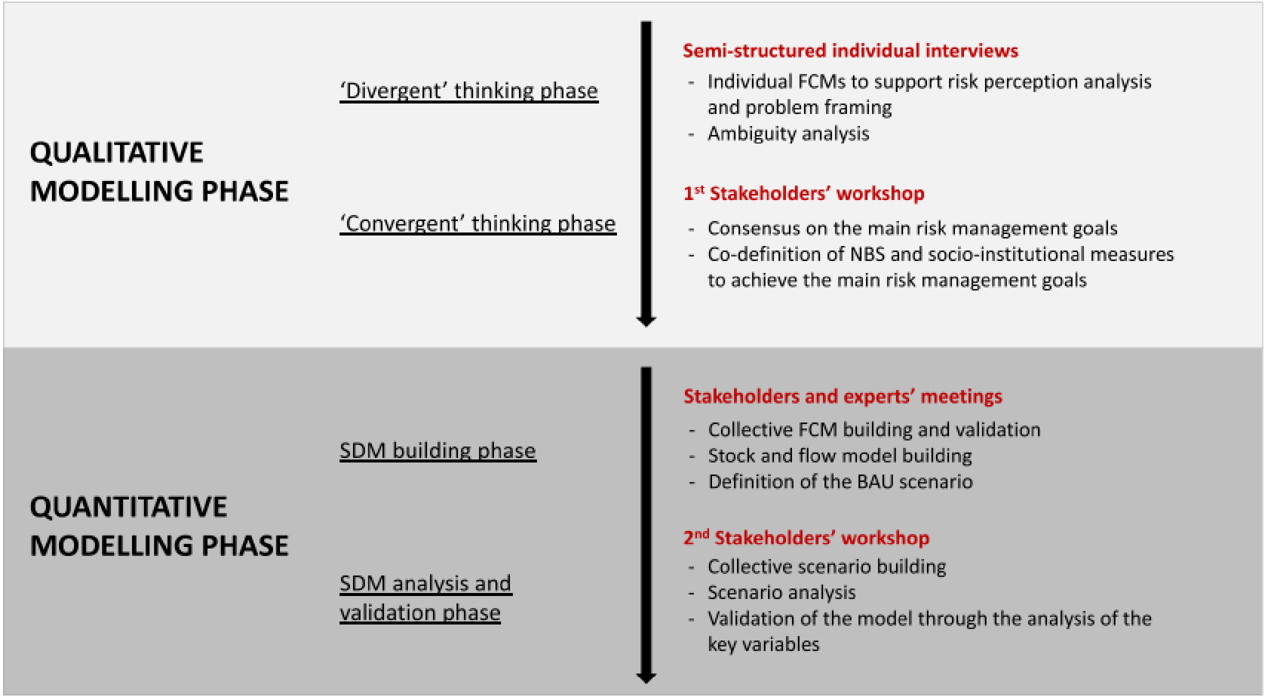

Figure 1 Overview of the main phases of the process (Pagano et al., 2019)

The framework comprises two main phases, identified as 'qualitative' and 'quantitative' modelling phases. The 'qualitative modelling phase', described in detail in (Santoro et al., 2019), is based on the use of Fuzzy Cognitive Maps (FCM) to elicit and structure stakeholders' risk perception, knowledge, and problem framing. It was closed with a stakeholder workshop, organized with a twofold objective: i) to identify the most important risk management goals, and the most suitable and effective measure(s) to achieve these goals; ii) to support building an aggregated version of the FCM. The 'quantitative modelling phase' mainly refers to the transition from a FCM to a stock and flow model, which requires a huge effort from the analysts. Targeted meetings and interviews were then used for the validation of specific parts of the model. Stakeholders were then involved in a second workshop, which was used for scenario analysis and validation.

3. Description of the framework

The present section provides a general description of the PSDM framework that has been developed and implemented in the LENSES pilot areas. It directly responds to the need to have a structured and replicable procedure for project activities in pilot areas (and beyond) and aims to provide both theoretical and practical guidance to use PSDM approaches for Nexus studies.

The proposed framework derives on the one hand from the experience of the IRSA research team in previous projects dealing with PSDM (detailed in the Section 2) and on the other hand from the activities that the same research group is currently carrying out in the 'sister' project REXUS (IRSA team is working on PSDM-related activities along with the University of Cambridge). The LENSES framework has been therefore aligned as much as possible with the one proposed in the REXUS project (and fully detailed as well also in an analogous REXUS Deliverable), with the aim of enhancing synergies as much as possible, although with some adaptations due both to the interactions with the other WPs and, clearly, to the specificities of the LENSES pilot areas.

The factors that represent a potential synergy between the two projects, as far as the PSDM framework is concerned, can be summarised as follows:

i) as the framework has been adapted and updated throughout the project duration based on the feedback from pilot areas, the structure of the framework benefits from feedbacks and lessons learned from several case studies, covering multiple challenges, scales, physical and socio-institutional contexts. This aspect will be also useful to support a wider uptake of the methodology after the projects' end, in different contexts.
ii) although the 'Nexus' analysed in both projects is slightly different (with a focus on Energy in REXUS and on Ecosystems in LENSES), the activities in all pilots suggested that in most cases all dimensions are part of the Nexus system being analysed, as all sectors are somehow inextricably connected to the others although with a variable 'configuration' and relevance in each area. A common approach based on the role of resources security and ecosystem services production, has been therefore proposed in both projects (as detailed in the D4.1) and represents a key element of the proposed PSDM framework.

The main differences are, instead related to the following issues:

i) PSDM tools in REXUS have been developed in tight connection with other tools and methods (e.g., the coupled resource stock flow analysis, the Sankey diagrams and the Metamodel). The PSDM in LENSES is being developed to work, where possible, as a central model for aggregating different forms of knowledge and, in particular, multiple sources of information from sectoral models. Basically, the development of 'quantitative' PSDM will be particularly oriented to integrate the evidence of sectoral models, enhance scenario analysis and support visualization of results, helping the integration of multiple aspects ranging from the biophysical to the socio-institutional realm. This role is crucial to support Tasks that take place in the second half of the project (e.g., Task 4.3 PSDM for scenario analysis, Task 3.3 Policy scenarios).
ii) PSDM is one of the key tools used in LENSES for involving stakeholders in co-designing, testing, and evaluating different intervention scenarios for Nexus resilience building. The development of transformative (visionary) scenarios for resilience building through the integration of explorative models and participatory scenarios development is the foundation of the co-creation process in the LAA. In this direction the integration with the WP3 (Lead by IRSA team as well) is crucial and will be oriented to identify collective solutions and enhance evidence-based "multi-objective policy design" to reach regional or national goals.

In general, it is worth to remark that the framework should be interpreted as a general guidance with enough flexibility to be adapted to the needs and specificities of pilot areas, and therefore should be modified and tailored according to local needs and opportunities. Therefore, the framework detailed in the present section is also the result of several revisions throughout the project duration based on the feedback and evidence from the activities in pilot areas. In this direction, as already mentioned, the cross-fertilization between the LENSES and the REXUS projects contributes to provide a value added to the outcomes.

The proposed framework for PSDM implementation comprises multiple steps and basically describes a highly iterative process, as it involves constant iterations with other WPs and should be adapted to the state of pilot activities. An overview of the proposed framework is provided in the following Figure 2, while further details on the different steps are provided afterwards. The framework is based on a series of '*desk*' and '*participatory*' activities (in blue and green boxes, respectively), and multiple interactions with the activities performed in other WPs (highlighted in the other boxes). Desk activities are directly performed by the analysts, while participatory activities are performed with the stakeholders (including e.g. interviews and exercises during the workshops).

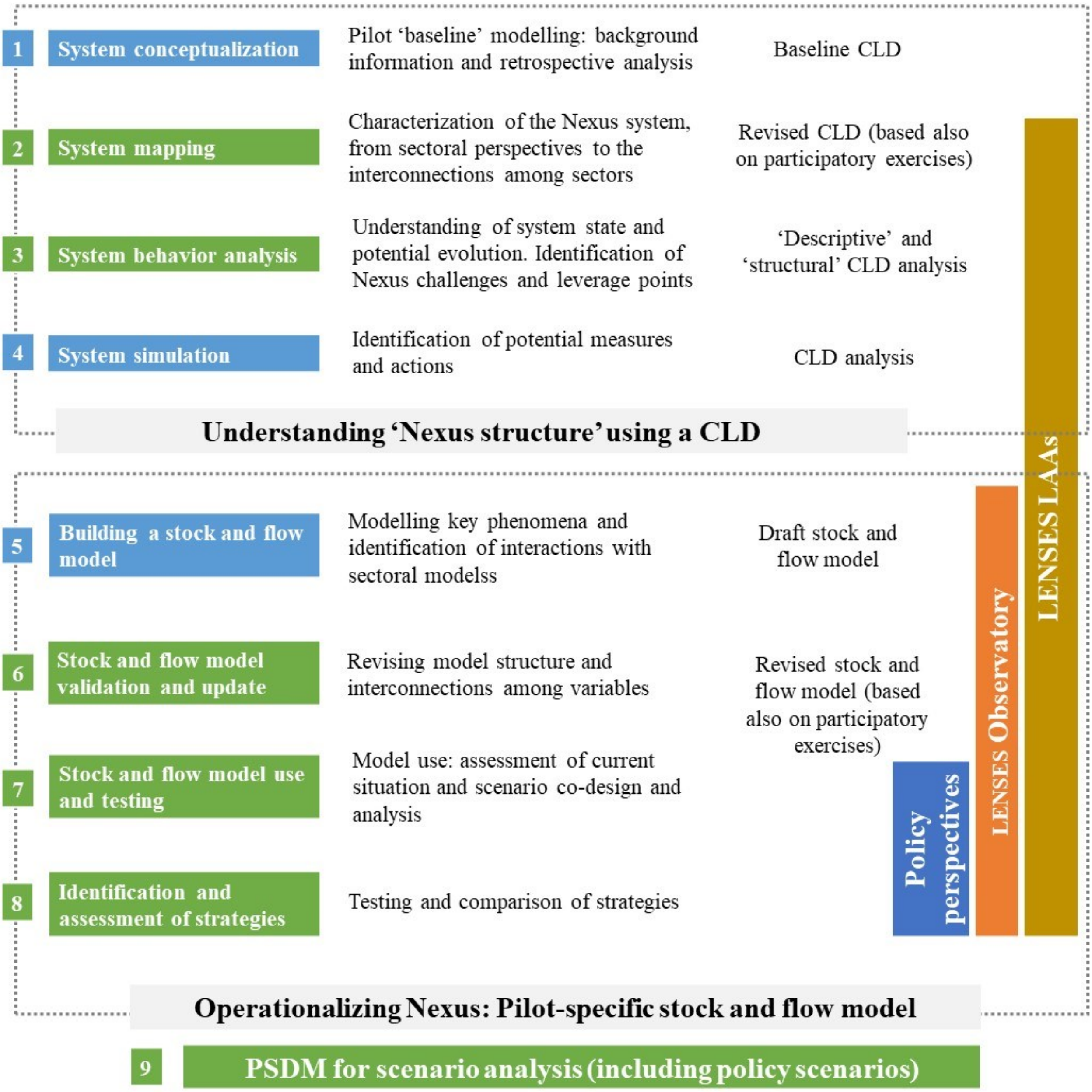

Figure 2 Overview of the steps of the LENSES PSDM implementation framework and of the key interactions with other activities.

The framework basically comprises two major modelling phases. The first one (steps 1-4) is broadly defined as 'qualitative', and oriented to provide an improved understanding of the 'Nexus structure' based on the definition of Causal Loop Diagrams in each pilot area. The second one (steps 5-8) is defined as 'quantitative' and oriented to produce a more operational approach to Nexus, based on the development of pilot-specific stock and flow models (in a subset of pilots). One additional phase (#9), based on the use of PSDM for scenario analysis) can be performed based on both a qualitative and a quantitative PSDM, clearly with specific limitation and potential outcome.

As already mentioned, the framework should be interpreted as flexible enough to be customized to specific pilot needs (in terms also of structure and evolution of the activities) and that it is meant to be implemented with a variable level of detail in each pilot area. Therefore, not all pilots will be involved in all steps of modelling, and not all pilots will be involved necessarily in the 'quantitative' modelling. A detailed view of the current and 'expected' level of implementation of PSDM activities in pilot will be proposed further in the text.

A description of the main methodological aspects for each phase is provided in the following.

Step 1. System conceptualization (Pilot 'Baseline' Modelling).

The first step of the framework aims at providing a basic understanding of each pilot area and is mainly based on the information included in the Baseline description (D8.1). Bilateral meetings have been also performed at the beginning of the process with pilot leaders, to get further insights into the main Nexus challenges and strategic objectives for the area according to their knowledge. The specific target of PSDM for each pilot area has been also preliminary defined at this stage.

The main purpose of this step is to set the context of the analysis and to preliminarily select the main challenges of the pilot, based on the retrospective analysis of the area, of the key policies (both implemented and planned) and of the evidence from previous projects and activities (including inter-sectoral conflicts). During this step, the analysts identify the focus of pilot activities and define the modelling objective (and boundaries), building a preliminary SDM based on the use CLDs, which need to be iteratively updated based on the evidence of participatory activities or results from sectoral models. The accuracy of the modelling performed during this step is fundamental to facilitate the stakeholder engagement and to enhance the effectiveness of the whole process.

Building CLDs is particularly useful, as they allow describing a complex system based on three elements: nodes, connections, and feedback loops. The nodes represent variables in the system (which can be either biophysical or not). The connections (or edges) represent causal influence from one node to the other. Connections have a polarity which can be either positive (i.e. the variable they connect increase or decrease together) or negative (i.e. the variable they connect change in opposite directions). Feedback loops (which can be also colour coded and annotated with small arrows and a specific '+' or '-' symbol) can be either reinforcing (R, or positive) or balancing (B, or negative). In a reinforcing loop, change in one direction is compounded by more change. Balancing loops, in contrast, counter change in one direction with change in the opposite direction. A reinforcing loop shows exponential growth (or decay); a balancing loop tends to produce oscillation or movement toward equilibrium[1] (Barbrook-Johnson & Penn, 2022; Sterman, 2000).

[1] https://thesystemsthinker.com/causal-loop-construction-the-basics/

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 feedback loops are usually focused around a ‘core system engine’, which is a set of nodes that are the core of the system, and strongly hint at dynamics in the system. CLDs are therefore typically useful to think at a slightly higher level, bringing together feedbacks and thinking about how these might play out together. The focus on feedbacks means the CLDs are a structured way of looking at a system, which can be performed at a different level of detail and complexity (Barbrook-Johnson & Penn, 2022).

CLDs can be used in many ways. Most fundamentally, they are a way of visualising and exploring mental models. Exploration of the full map can be done in many ways, but typically with a qualitative analysis of the core engine and of the main feedbacks. It represents a hypothesis of the feedback structure of the system and serves as a tool for the creation of a shared understanding of the system amongst members of a discussion group. CLDs are often an intuitive precursor to ‘quantitative’ System Dynamics models, used before the conversion to stock and flow diagrams and differential equations (Barbrook-Johnson & Penn, 2022). To some extent, CLDs can also provide insights into the future evolutions of the system, including rather basically the time dimension (through delays) and allowing scenario analysis (see Step 8).

As far as the Step 1 is concerned, the ‘baseline’ version of the CLD is mainly built on scientific knowledge (which is typically used for drawing well-known connections between e.g., biophysical variables) and on the evidence included in the D8.1 for each pilot area. At this stage it is crucial that the variables are clearly expressed as things that can go up or down and should be precise. ‘Container concepts’ such as ‘Technology’ which can mean many different things should be avoided and connections added (if needed) to make the diagram clearer or easier. This step is useful to make a hypothesis on the structure and content of the core system engine which can be either a variable at the centre, or a set of key variables which interact in ways that drive system behaviour. The engine will be the focus of the map as a whole and will be one of the main focuses for exploring feedbacks. At this stage, it is useful to develop ideas about the variables might be connected (Barbrook-Johnson & Penn, 2022). In general, the structure of the CLD has been built trying to keep the different domains of analysis ‘separated’ (e.g., in sub-models), but also clearly highlighting interconnections and interdependencies. For the purposes of the LENSES project, the baseline version of the models has been revised, updated and modified also through the interaction with pilot team leaders, as detailed in the following section.

Some relevant guidance, which can help dealing with CLD development, analysis and update, can be found at https://thesystemsthinker.com/.

Step 2. System mapping

Both Steps 2 and 3 of the proposed framework are heavily based on participatory activities, as the knowledge provided by stakeholders can help revising/improving the ‘Baseline’ CLD developed in the Step 1 and identifying key variables for the analysis. Steps 2 and 3 are tightly interconnected.

Specifically, the Step 2 aims at defining a comprehensive picture of the study area and of the main interdependencies among sectors, based on a revised version of the CLD, which accounts for the information provided by local stakeholders. The purpose is to elicit and structure stakeholders' understanding about current issues and objectives (mainly focusing on sectoral, but also thinking about cross-sectoral objectives and implications), building the 'narrative of the present', ultimately creating a picture of the system that reflects stakeholders' perception and knowledge. The main result is the identification (and discussion) of cause-effect connections between key variables, with a few significant upgrades with respect to the Step 1: i) some additional arrows can be drawn, to reflect 'hidden' interconnections or perceived interdependencies according to the stakeholders; ii) some arrows might be removed, in case a cause-effect chain has been wrongly identified in Step 1; iii) new variables can be added, in case relevant elements have not been included into the picture; iv) variables can be removed, in case they are not perceived as relevant for describing system dynamics; v) relevant balancing or reinforcing loops are selected in the CLD.

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 among stakeholders (Stave, 2010; Scrieciu et al. 2021).

The main scope of this phase is thus 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) using the potential of CLDs; iii) co-define selected variables/indicators that can help describing key elements, such as the level of achievement of the selected needs under different conditions (including selected scenarios) and the state of the key ecological resources.

This step of the analysis is strongly participatory and based on two different activities:

A. Individual interviews with key stakeholders, for the identification of basic cause-effect chain affecting the main security dimensions (water, energy, food, ecosystems security). Key measurable variables are also defined with stakeholders, and then translated in the form of scientific indicators by the analysts. The format of interviews does not make any reference to scientific indicators, to allow stakeholders without a technical or scientific background to contribute. Analysts are then required to perform a desk activity to 'translate' the measurable quantities identified by the stakeholders into the form of scientific indicators. Details have been provided in the D4.1.
B. Participatory exercises during a Workshop/focus group, oriented to co-define Nexus interactions, focusing on sectoral interdependencies and causal connections. Details on the polarity and weight of the connections can be asked during this phase, with specific exercises. This phase can be completed with the support of geographical maps, and therefore used to provide also spatial information on the main issues and challenges for the study area. Specific activities could be also performed to refine, select and prioritize the selected indicators. This phase is highly relevant to identify the main variables the model should be focused on.

The activity (A) is performed referring to the sector (or domain) the interviewee is mostly related to. Basically, the rationale of the interview was to identify critical connections between the sectoral security level, and the level of satisfaction of the main needs expressed by the stakeholders, identifying all the most influential processes (both natural and anthropic), barriers and drivers. The adopted approach is theoretically centered around the role of Ecosystem Services (ESs). The analysis was mainly focused on the current system state ('Business-as-usual') and expected system evolution under current major drivers (e.g. climate change, economic conditions, etc.).

Just to make an example, referring to the 'water' domain, one of the elements mentioned in connection to the 'water security' is the 'availability of surface water', and one of the related needs is the 'irrigation water demand'. In this regard, the key ecosystem resource bridging the need and the security objective can be a relevant surface water body (e.g. a river or a reservoir), with its capacity to produce a multiplicity of ESs (e.g. regulating – Hydrological cycle and water flow regulation; provisioning – water provisioning for agriculture). The capacity to produce such ESs depends on both natural (e.g. physical flows/recharge) and anthropic processes (e.g. management scheme or access to the same resource from different users). Furthermore, the capacity to produce ESs for achieving the needs related to the sectoral security can be also affected by other elements, that have been broadly classified as either 'barriers' (e.g. institutional fragmentation, sectoral regulation, etc.) or 'drivers' (e.g. climate change impacts).

Similarly, within the 'food' sector, a key element for guaranteeing 'food security' is the 'agricultural productivity' and one key related need is the 'profitability of agricultural practice'. Besides water, one of the main ecological resources for agriculture is 'agricultural land', which provides multiple ESs (e.g. provisioning - Cultivated terrestrial plants for nutritional purposes). The capacity to produce such ESs is conditioned by multiple natural and human processes (e.g. the agricultural practices used that may affect soil quality), as well as by barriers (e.g. lack of knowledge on innovative agricultural practices or poor spatial planning) and external drivers (e.g. market conditions).

This step of the framework is useful for identifying the main dynamics to represent and analyze through the PSDM. The use of a semi-structured interview allows on one hand to have a structured and coherent approach to expert knowledge elicitation, but on the other to guarantee enough flexibility and simplicity also to 'non-technical' stakeholders. The role of ESs has not been explicitly introduced yet in some of the models, as this requires actions from the analysists, while currently the main aim is to provide a representation of the stakeholders' perspectives.

One key outcome of this step is the identification with the stakeholders of a set of indicators, that can be relevant to describe both the current state of the pilot area and its potential evolution under different scenarios. Such indicators should be (ideally) considered as a reference for the selection and implementation of relevant models, and for co-evaluate relevant scenarios with the stakeholders.

Just to make an example, based on those proposed for the Step 2, the 'availability of surface water' can be described based on the 'water level (or volume) in reservoirs' and the 'Number, capacity and density of water reservoirs'; the related need 'irrigation water demand', e.g. through the variable 'Water use efficiency in agriculture: water volume pumped/used per unit area (or farmer)'. Similarly, the 'agricultural productivity' can be described through variables such as 'Agricultural yield per hectare' or 'Water use efficiency in agriculture: agricultural production per water volume pumped/used'; the related need 'profitability of agricultural practice' e.g. through the variable 'Economic efficiency per crop and cultivated area'.

A revised version of the CLD was therefore drawn at the end of the 1st stakeholder workshop and, subsequently, formalized by the analysist using the Vensim software and/or the kumu.io platform (https://kumu.io/). The CLD produced during this step was then validated through the support of case study leaders or, if necessary, with targeted interviews (in case clarifications on specific parts of the CLD were needed). However, as already mentioned, 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.

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It also worth mentioning here that LENSES participatory activities are performed in coherence with the Guidelines for stakeholder engagement and with the Gender Action Plan.

Step 3. System behavior analysis

The third step of the proposed approach is oriented to perform a comprehensive analysis of the CLD, based both on a 'descriptive' and on a 'structural' analysis. In particular, the aim of this step is to get information on the system under investigation, mainly based on the description of the CLD structure, on its current state and potential evolution under variable conditions (including potential policy actions). During this step, stakeholders might also contribute to the selection of the most important variables and to describe key dynamics to understand.

This step represents a critical bridge in supporting the transition from 'sectoral' perspectives to the definition of a holistic 'Nexus' picture.

Although CLDs only include qualitative information, their analysis can help deconstructing system interactions and better understand behaviors that might often be unpredictable and counterintuitive (Murphy and Jones, 2021). As already mentioned, the step 3 comprises two intertwined activities, which can be broadly identified as a '*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 the identification and description of key 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 support the screening of potential **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 1 shows the centrality measures adopted in the proposed approach and their relevance.

Table 1 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.	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.	Elements with high eigenvector centrality are the leaders of the network.

The measures can be calculated either in weighted or in unweighted 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.

In the present approach, the Nexus challenges are identified considering the elements characterized by high values of centrality measures while also having multiple intersectoral connections and/or dependencies.

Following the identification of the Nexus challenges, key feedback loops related to or describing those challenges are isolated and analyzed. As already mentioned, feedback loops represent a key component and organising structure for complex system. 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 to identify the elements that could provoke change. System archetypes can be also used in this analysis (Vennix, 1996; Egerer et al. 2021).

To support policy design, a **leverage analysis** is also proposed in direct cooperation with the WP3. It basically consists of the identification of potential leverage points through the joint analysis of feedback loops and centrality measures. 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; 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, potentially enhancing the transition towards Nexus sustainability. By integrating the loop analysis and the centrality measures, our approach aims at supporting the identification of the leverage points and 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.

Step 4. System simulation

The Step 4 is referred to as 'model simulation' and is interconnected to the Step 3. In fact, CLDs can be used for understanding the main criticalities of a system as well as for performing a preliminary evaluation of the impact that actions/measures might have on the system, relying on the analysis of centrality measures and on the information provided by the feedback loops analysis. Basically, the system can be analyzed considering e.g., the introduction of new variables (or new arrows) representing actions of potential measures, the change of weights for specific connections, etc.

The system simulation is highly relevant to provide insights into system state and expected evolution, and for feeding the discussion with stakeholders on the relevance (and potential implications) of specific strategies. The system simulation step can be performed relying on CLDs, although the limitations discussed before related to the use of qualitative modelling tools should always be taken into account. Nevertheless, even more importantly, a CLD can represent a robust 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).

Step 5. Building a stock and flow model.

The fourth step aims at translating the qualitative model (CLD) built in steps 1 to 4, into a quantitative model (stock and flow). This step is mainly based on desk activities and require a significant effort from the analysts, as the transition towards a quantitative model is not always straightforward.

A System Dynamics model is mainly made up of stocks and flows, plus the factors which affect flows. Stocks represent any entity which accumulates or depletes over time and take numerical values. A flow is the rate of change in a stock and is usually represented by a differential equation. These equations may be relatively simple and based on standard operations (e.g., addition, subtraction, multiplication, division, and sometimes exponents), or be more complex involving functions and parameters which moderate how variables interact. A simulation can be run by choosing a starting point (i.e., a set of stock values) and computing how stock values change through repeated time steps (Barbrook-Johnson & Penn, 2022).

One of the key advantages of using this kind of SD models is that various things can be represented in stocks and flows, which don't even have to be fully or precisely quantifiable, rather just provide a reasonable and meaningful trend over time. This is particularly true when 'soft' (unquantified) factors, such as social ones, are introduced into the models, which also require extra effort and care to be incorporated (Barbrook-Johnson & Penn, 2022).

In general, the stock and flow model should try to model the whole system but focusing on specific sub-parts of a system or particular issues or problems, which may persist despite the presence of dynamics and interventions. The use of CLDs or stock and flow models depends on the process that is being implemented and on the purpose of the modelling efforts (Barbrook-Johnson & Penn, 2022).

The transition from a CLD to a stock and flow model is not always straightforward but is often useful to add order to an often 'chaotic' process by emphasizing the difference between information and material flows, and the importance of unit consistency throughout a diagram.

The conversion process includes the following steps (detailed at this website):

- Specify the Units of All CLD Variables

  Specifying the units of all CLD variables helps thinking about the causal loop in a more rigorous way, and this is an important step toward stock and flow thinking. Furthermore, it helps determine which variables are going to involve time and will therefore likely (but not necessarily) be flows, and it provides the basis for determining what variables are missing and will need to be added later in the conversion process.

- Identify and Create the Stocks

The next step is to determine which CLD variables are stocks, which is facilitated by the definition of units helps facilitate this process by indicating which variables involve time and, therefore, are probably flows. Any additional stocks that might be needed can be also added at this stage.

- Identify and Create the Flows

  Once the stocks have been identified, the flows can be easily identified as they are simply the variables that add to or subtract from the stocks.

- Connect Flows to Stocks and Stocks to Flows (if Necessary)

  The first task in this step is to connect all flows to the stocks that they influence. If the flow has a negative effect on the stock (i.e., it is associated to a reduction of the stock), then it is an outflow; if it has a positive effect (i.e. it is associated to an increase of the stock), it is an inflow. Once all flows have been connected to their corresponding stocks, certain stocks might need to be connected to flows, in case they influence one or more flows through an information link.

- Add and Link Remaining CLD Variables

  In this step, any CLD variables that have not been previously identify as stocks or flows should be added. These “auxiliary” variables are of two types: ‘constants’ in case their value does not change at all over the time period considered, and variables that simply represent calculations based on stocks and flows. These variables should be then connected to the variables that they influence and to those that they are influenced by.

  Although the first version of the stock and flow diagram is done at this stage, the conversion process is iterative and further rounds of defining and creating variables are usually needed before the diagram can be considered complete.

- Define Stocks and Flows and Check Units

  Formally defining variables entails specifying the equation that allows calculating the value of a specific variable given its initial value and the values of the other variables in the diagram. A good practice is to start with the stocks, which are usually the easiest to define as they are calculated by adding the effects of the inflows and the outflows to the amount already in the stock. The next step is to define the flows and then check the units they use. Defining units for the flows may also lead you to discover other variables that need to be included in the diagram.

- Create and link any additional variable

  Once stocks and flows have been determined and associated to the proper units, other variables need to be examined. The process for defining the remaining variables and checking for unit consistency is the same as the one described above for defining the flows. Although the conversion can be considered complete at this stage, the model still is not calculable.

During this step of the process, the analysts should also understand to what extent information on the key variables can be derived from available models and datasets. In this direction, the role of the LENSES Observatory is crucial as well as the direct interaction with pilot leaders. Efforts are being made in all case studies to benefit from existing models (such as e.g., hydrological or water allocation models) including key information in the stock and flow models. In particular, the outcomes of the participatory exercises are highly useful This phase of the analysis is particularly challenging, and several interactions (and model updates) are needed to ensure that the available results and information are adequately considered and carefully translated into the stock and flow sets.

Step 6. Stock and flow model validation and update.

The process described at the previous Step 5 is mainly based on 'desk' activities, and on the translation made by the analyst of the CLD into the stock and flow model form. However, the proposed approach requires that a validation of the stock and flow model is performed with stakeholders/expert. However, dealing with the structure (and the equations) included in a stock and flow model might be not always easy in particular for non-technical stakeholders. In this regard, the proposed framework suggests a 'simplified' model validation, to be performed focusing on a subset of key stocks and flows, which may have some uncertainty or ambiguity.

This step of the analysis should be based on two different activities:

- Individual interviews (optional) with selected stakeholders or with pilot leaders, for the analysis, validation and (potential) revision of sub-models or specific parts of the stock and flow model. This step will be ideally performed, if needed, between the 1st and the 2nd WS, in case any element of the model needs further clarification.
- Participatory exercises during the 2nd or 3rd Workshop, oriented mainly to discuss collectively specific parts of the model or sub-models. Specific attention should be given to: 1) the connections and influences between stocks and flows; 2) the cross-sectoral influences and interdependencies.

The role of case study leaders is also central for this activity, as the expert knowledge they provide could significantly help improving the quality of the model. The expected output of this step is a revised version of the stock and flow model, particularly as far as the variables and connections are concerned.

The process of model validation and update also requires the use of formal tools for model analysis, such as the sensitivity analysis. This can provide a deeper understanding of model characteristics, in particular as far as the role (and relevance) of subsets of variables is concerned.

Step 7. Stock and flow model use and testing.

This step of the analysis is, instead, more focused on the 'computational engine' of the stock and flow model. It should be strongly participatory and based on specific exercises to be performed during the 2nd or 3rd Workshop, followed by desk activities.

An overview of the (potential) activities – and related objectives – that can help completing this Step follows:

- Identification of the Business-As-Usual (BAU) condition. The analysis of the outputs of the stock and flow model, with particular reference to the key variables/indicators, help ensuring that the model is able to describe the state of the system in the future assuming that no changes occur to input variables. This analysis can be performed considering both the evidence from models or data, and the stakeholder knowledge.

- Following the analysis of the BAU condition, stakeholders should be involved in the co-design of potential scenarios. The objective is to focus the analysis on the most interesting or impactful scenarios. Multiple techniques could be used for the purpose, such as the co-development and analysis of the Behaviour Over Time (BOT) graphs for key variables under different conditions which has a proven effectiveness in actively engaging stakeholders (Calancie et al., 2018; Elias, 2012).The creation of BOT graphs could provide insights and inform future modelling and data collection priorities, though an effective integration of multiple perspectives and a better understanding of what the (intended or unintended) consequences of any action could be. Basically, the facilitator can ask stakeholders (individually or in groups) to draw the graph for each variable over time under different conditions, such as (see also Figure 3): 1) desired future, i.e. defining the evolution of the variables as the stakeholders would like; 2) most likely future, i.e. defining the evolution that the variables is expected to have according to stakeholders; 3) feared future, i.e. the 'worst-case' evolution of the variables. This activity could be also performed using semi-structured interviews. Such graphs should highlight - if possible - specific points and thresholds. In case the graphs drawn by the different groups on the same variables do not show great differences, they can be almost directly used to represents the variable's BOT. In the case of large differences, the different interpretations should be discussed with all stakeholders to reach a shared view.

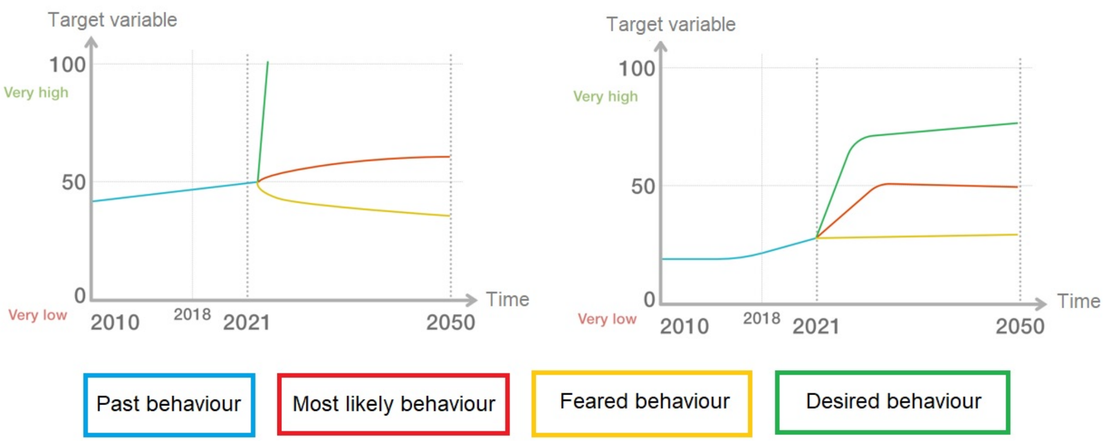

Figure 3 Graphical example of how the BOT can be drawn for key variables.

- One of the key aspects to consider in the participatory modelling exercises is the opportunity for integration of the SDG targets into the modelling approach, which can be useful to make explicit the SDG implications linked to different scenarios (see also Step 8).

Some desk activities, based on the evidence of this step, will be needed to revise the model before it can be considered complete.

Step 8. Identification and assessment of strategies

This step of the framework, to be performed during either the 2nd or the 3rd stakeholder WS, is mainly based on the identification of the most relevant scenarios that should be investigated through PSDM. Stakeholders, decision- and policy-makers will be involved in co-designing different intervention scenarios for Nexus resilience building. Such scenarios will include a multiplicity of conditions, including climate change scenarios along with sectoral and cross-sectoral policies. The impacts of specific behaviors (e.g. from different groups of stakeholders) will be also taken into account. Ultimately, in cooperation with the other WPs, a suitable ‘strategy’ for increasing the resilience of the Nexus in individual pilot areas will be defined. For this step, the direct cooperation with the WP3 (in particular, with reference to the Task 3.3 on Policy scenarios) is crucial for the identification of barriers, side-effects and potential policy resistance mechanisms, ultimately suggesting the most suitable policy interventions.

Step 9. PSDM for scenario analysis (including policy scenarios)

A scenario represents a change in the model, which should be mainly performed varying the state of input variables, but also potentially modifying the structure of the model (i.e. with a connection added or removed). The purpose is to represent some intervention or difference in the system, mainly related to different policy options or changing boundary conditions. Model outputs should thus represent hypothetical futures, or qualitative forecasts of the types of patterns and dynamics we might see.

Scenario analysis will be performed using both qualitative and quantitative PSDM tools (i.e. CLDs or stock and flow models) to explore a wide range of conditions (e.g. technology transitions, changes in land use, climate change, demographic change, etc.) and a multiplicity of measures (including socio-environmental policies) defined at the step #8. While CLDs can provide a qualitative (yet robust) overview of the potential evolution of system variables (e.g. through the detailed analysis of feedback loops), stock and flow models can help quantitatively simulate the evolution of variables under different conditions (including e.g. the change of drivers and different actions/strategies). Transformative (visionary) scenarios for resilience building will also take place in the LAAs, with a focus on solutions and “multi-objective policy design” to deliver the desired DOs and specific regional or national goals.

4. Implementation of the framework in the LENSES pilots

4.1. Overview

The present section provides a summary of the level of implementation of the PSDM framework by the end of the project (Table 2). In case the target level of PSDM implementation is defined as ‘quantitative’, i.e. the development of a stock and flow model is foreseen, the ‘qualitative’ model (i.e. the CLD) will be also available, and used as a basis for building the stock and flow model. The activities aim to contribute, to variable extent, to all pilot areas. The level of implementation of the PSDM, extensively discussed with pilot leaders, mainly depends on the goal of pilot activities, on the scale of analysis and on the main challenges emerged in the pilot areas. The level of PSDM implementation in pilot areas might thus change by the end of the project.

Table 2 Target level of PSDM-related activities implementation in the LENSES pilot areas.

Pilot area	Target level of PSDM implementation
Pinios (GR)	Quantitative analysis: stock and flow
Doñana (SP)	Quantitative analysis: stock and flow

Tarquinia plain (IT)	Quantitative analysis: stock and flow
Menemen (TR)	Qualitative analysis: CLD
Deir Alla (JR)	Qualitative analysis: CLD
Hula Valley (ISR)	Qualitative analysis: CLD
Koiliaris (GR)	Quantitative analysis: stock and flow

Ideally, the PSDM approach will be proposed in a 'quantitative' form in 4 pilot areas (Pinios, Doñana, Tarquinia plain, Koiliaris), while the framework will be implemented until the development of a 'qualitative' model in the other three pilots. Some of the elements that conditioned the level of implementation of the PSDM framework in pilot areas are:

- Relevance and potential of the proposed approach with respect to the main challenges of the case studies. As already detailed the use of PSDM has a relevant potential in studies oriented to assess problems at a strategic level (e.g. highlight potential conflicts or the impacts of policies/actions), rather than in very local studies (such as e.g. the introduction of technological innovations). This aspect directly affects the contribution of PSDM to the local challenges.
- Level of participation of stakeholders to modelling activities. The key value added of using PSDM is the direct involvement of stakeholders in modelling activities, which might not be immediate and straightforward as in every participatory process. This may also depend on the case studies specificities (e.g. existing conflicts, stakeholder attitude), but may also depend on external conditions (e.g. the pandemic partially conditioned the organization of physical meetings). The effectiveness of participation may also depend on other factors, such as the education level of stakeholders, the technological preparedness, and the familiarity with conceptualization. These factors should be carefully considered when developing and implementing the approach.
- The development of a fully quantitative PSDM in different pilots is a time-consuming task, as the model needs to be carefully customized according to pilot specificities and needs. In this regard, we decided to make efforts towards the definition of a 'shared' baseline stock and flow model, capable to describe in a rather general way the main interconnections that characterize 'Nexus' system, complemented by a series of site-specific sub-models.
- Language 'barrier'. The interaction with stakeholders should preferably be performed in the local language, as this allows a broader participation also from non-technical ones. This implies that the participatory exercises need to be performed by the pilot leaders, after a 'training' phase and – where possible – with the external support of WP4 Team. This adds another layer of 'complexity' in the effective implementation of the PSDM approach.
- Integration with other models and data. The integration of the scientific information available in the different pilots is a critical task, as different sources of information might be available (with variable spatial and temporal resolution) and a specific processing (and typically, aggregation) need to be performed. In particular, the interaction with WP7 has been relevant in this direction, as the information derived from hydrological and water allocation models has been included to a large extent into the PSDM.

- Scale and scope of the analysis. SDM is mainly used to support policy- and decision-makers at planning or strategic level. Therefore, it might have a limited applicability and relevance for some pilot areas, depending on the scale of the analysis and the specific focus of the 'Nexus' problem.

Full details on the implementation of the proposed framework in some of the LENSES pilots, with a discussion on key methodological issues that might be relevant for the replication and wider uptake of the approach, follow.

4.2. Software for PSDM implementation

Currently, several software packages are available for the development of System Dynamics Models. An interested reader can find an overview of the main specificities of each software at the following link: https://systemdynamics.org/tools/core-software/.

For the purposes of the LENSES project, we mainly used two software packages:

- **VENSIM** (from Ventana Systems), which is one of the most widely used for constructing CLDs and stock and flow models. It includes a learning edition of the software, which is free for academic use.
- **Kumu**, a web-based tool that provides a straightforward approach for stakeholder mapping, systems mapping, social network mapping, community asset mapping, and concept mapping.

Basically, the VENSIM tool provides a solid and almost 'standard' approach to SDM building, with several functions that are highly useful for supporting the analysts in model building, revision, validation and for scenario analysis. Nevertheless, based on our experience, it is not straightforward to use for people that are not fully familiar with SDM and not user-friendly (unless an interface is built). Conversely, Kumu provides a rather simple yet highly visually effective approach to CLD building, which includes some functionalities related to the computation of graph theory metrics on CLDs and the visualization of causes-uses trees and feedback loops directly on the diagram. The stock and flow models are being developed in VENSIM.

4.3. Pinios pilot area

Overview

The Pinios River Basin (PRB) is located in central Greece and is one of the most productive basins of Greece and the national WFD pilot basin. PRB presents highly diversified geological and hydrological conditions, while the absence of rational water resources governance and management generally manifests in a major problem, which is the **high water consumption and groundwater over-abstraction for irrigation** (full information is available in the D8.1). Irrigation constitutes the dominant water user and irrigation requirements are satisfied both by groundwater and surface water.

Within the LENSES project, two areas of the PRB are analyzed, namely the Agia watershed and the Pinios River Delta (PRD).

Regarding specifically the Agia watershed, one of the main issues is the intensification of irrigation started in the 1970s with major impacts on the GW resources. Most of these GW wells are private and operated by small groups of farmers and, only marginally, by the Municipality of Agia. The construction of small, private reservoirs at the mountainous part of the watershed, driven by the expansion of (mainly) chestnuts and to lesser extent of apple cultivation, is also taking place. Water resources are, in general, considered sufficient but issues can arise with the peak irrigation demand in hydrologically poor years.

Regarding the agricultural sector, the transition to orchards, mainly apples and cherries, started in the late 1960s and currently, a huge demand is related to the chestnuts whose cultivation is being expanded in the mountainous part of the watershed with a tendency to further develop in the plain area. Agriculture is affecting groundwater quality since locally high NO_3 concentrations are observed in the plain part of the watershed. Furthermore, the increased salinization locally observed in groundwater is attributed to irrigation water return flow caused by irrational irrigation practices and fertilization malpractices.

In the PRD irrigation needs are partially satisfied by the GW, which is characterized by a high number of shallow, small diameter groundwater wells (auger wells). Currently, it is a complementary resource. Pinios River surface waters serve a significant part of the irrigation needs, especially at the western and southern part of the deltaic plain. The surface water is collected through temporary diversion dams and distributed through irrigation networks. The capillary rise of groundwater from the phreatic aquifer currently integrates irrigation needs as well. Annual crops dominate the area (more specifically, corn, cotton, and wheat), with an increasing presence of sunflower areas, primarily used for energy production. Moreover, kiwi fruit cultivation is expanding significantly the last years and it constitute the most dynamic crop of PRD.

From the environmental point of view, PRD constitutes a very significant area. However, the conversion of the natural landscape to agricultural land has gradually affected the ecosystem, as well as the expansion of the touristic sector. Regarding groundwater, salinization phenomena are observed, while locally high NO_3^- and NH_4^+ concentrations in the phreatic aquifer have been monitored in the context of previous studies.

Qualitative PSDM – CLD development

A preliminary version of the CLD model has been prepared for the whole basin, but including some of the key specificities of the two sub-areas. A more specific characterization of the Agia and the PRD will be performed in the stock and flow model development phase. Due to the complexity of the final CLD, it has been structured in the form of sectoral sub-models (1. Water; 2. Land/Food; 3. Ecosystems), yet with a clear identification of the cross-sectoral interconnections (also through 'shadow variables', i.e. variables that have already been included somewhere in the model and are duplicated for visualization purposes). Clearly, the division into sectoral sub-model is mainly meant to facilitate the visualization of the model, and should not be interpreted as a rigid separation of model components, as many items are included in different sub-models and correlated to multiple variables.

After the definition of the baseline version of the model, an upgrade has been performed based on the results of a set of interviews that have been conducted by the SWRI team with 19 local stakeholders. The model is presented in the following Figure 4 to Figure 6, where a preliminary distinction between variables has been performed mainly to facilitate reading. In particular, variables in **red** refer to elements mainly belonging to the class of 'socio-institutional variables' (e.g. 'Lack of trust in institutions', 'institutional coordination and legislation framework') and include also policy actions (e.g. 'Public participation', 'Training on good practices'). Although the activities were not yet oriented to define solutions, some potential actions/measures that were already mentioned have been included in **blue**. All other variables are in **black** or in **grey** (the latter class include 'shadow' variables). Due to the complexity of this model, the Figures refer directly to the revised version of the model, in which the main variables that have been added or revised following the stakeholders' interviews have been underlined.

Concerning mainly the **water sector,** one of the key issues highlighted by several stakeholders (e.g. farmers) is the lack of water for irrigation, described in the model e.g. by the variables 'SW use for irrigation', 'GW use for irrigation', 'Water demand for irrigation'. This issue has been mainly related to water quantity, but some stakeholders mentioned issues regarding the low quality of available water ('SW quality', 'GW quality'). This problem is heavily conditioned on the one hand by the poor state (and very limited maintenance) of irrigation infrastructures and systems ('infrastructure state and performance') and, on the other hand, by the lack of coordinated planning and agricultural policies as well as by the absence of an effective legislation (e.g. 'Land use planning', 'Lack of control', 'Institutional coordination and legislation framework'). Referring specifically to the GW, one of the main issues that has been highlighted is the decrease, in some areas, of the 'GW level', which causes a significant raise of 'GW cost' (with direct cascading impacts in the food/land sub-model). Other factors, such as the lack of adequate 'Water consumption monitoring' and the limited 'Efficiency of SW pricing' directly contribute to worsen the situation.

The innovation in water sector, mainly as far as new dams and reservoirs ('Small reservoirs and barriers') is concerned, is limited by a conflict with ecologists. Indeed, the presence of barriers and constructions within the river creates serious impacts to ecosystem, such as e.g. the reduction of species. However, the presence and availability of water infrastructures is a crucial asset for the development of a productive and sustainable agricultural sector (in terms of 'Agricultural productivity' and 'Economic sustainability of agriculture'), and more in general for the economic and 'Community well-being' over the area. Furthermore, the whole PRB may also benefit from a potential 'river diversion' plan (from the Acheloos river) that is being heavily questioned.

Regarding specifically the '**food/land sector**', intensive and irrational agricultural practices in 'Irrigated areas' are heavily impacting the area (e.g. in terms of 'Nitrate pollution' due to the 'Use of chemicals and fertilizers'). In this direction the innovation in some practices (e.g. the transition to kiwi) might have benefits. There is a limited political will to shift towards more sustainable practices to avoid conflicts with farmers ('Promotion of rainfed or low-water demand crops'), which would require additional 'Training on good practices' and 'Awareness on sustainable water management and water conservation'.

As far as the organization and structure of the agricultural sector is concerned, one of the key issues that was raised during the interviews was the lack of coordination and organization in a structured form of farmers, summarized through the variable 'Coordination among farmers – Consortia'. Several stakeholders highlighted that the very limited capacity of farmers to collaborate within an established structure, coupled with other issues such as the high level of 'Land fragmentation' over the area, is having manifold impacts on the agricultural sector and cascading effects on the other sectors. Among the others: i) it is limiting investments, and therefore the innovation capacity of the system (e.g. the improvement of the infrastructural system); ii) it is reducing the sustainability of agricultural activities as, for example, the negotiation on the price of products is harder to be performed by individual farmers. In general there is a low level of 'Awareness on sustainable water management and water conservation' for farmers, who do not have proper incentives to innovate (e.g. 'Subsidies' and 'Training on good practices').

Referring to the **'ecosystem' sector,** one of the issues that emerged from the interviews on the environmental condition is related to the problem of poor 'soil quality', which depends e.g. on the increase of 'soil pollution' and 'soil erosion' and on the loss of 'soil fertility'. Huge impacts are related to agricultural activities and 'livestock grazing', but many stakeholders mentioned the increasing lack of 'Effective waste management, which is also worsened by the 'tourism' activities and by the 'urbanization'. More in general, both the changes to the river course (e.g. small dams) and the increasing urbanization and encroachment of natural landscape are causing the fragmentation of habitats. Furthermore, the interventions in the riverbed as well as the action on riparian habitats and forests are affecting the state of ecosystems, in particular as far as the 'flora and fauna conservation' is concerned. In addition, the interventions along the natural river course for managing irrigation water is mentioned with regards to the implications to the ecological flow of the river 'ecological flow', since natural discharge may be minimized and allow sea water encroachment at considerable distances inland, potentially also affecting GW quality at the PRD.

In addition, the issue of energy has been mentioned, mainly as far as the impact of the increasing cost of energy on irrigation and agricultural practices is concerned. However, some stakeholders expressed increasing concerns related to the development of RES in highly productive areas.

The impacts of 'Climate change' are rather evident, in terms of increase of both frequency and intensity of extreme events ('Floods frequency and severity', 'Drought frequency and severity'), although still a low awareness (due also to the very limited exchange of knowledge and information) characterize some groups of stakeholders such as farmers. Recently, there were some events, mainly related to CC that have been increasingly affecting the agricultural sector. Among the others, the spring 'frost' that heavily impact agricultural productivity, the increasing air temperature and the strong variability of conditions in neighboring areas.

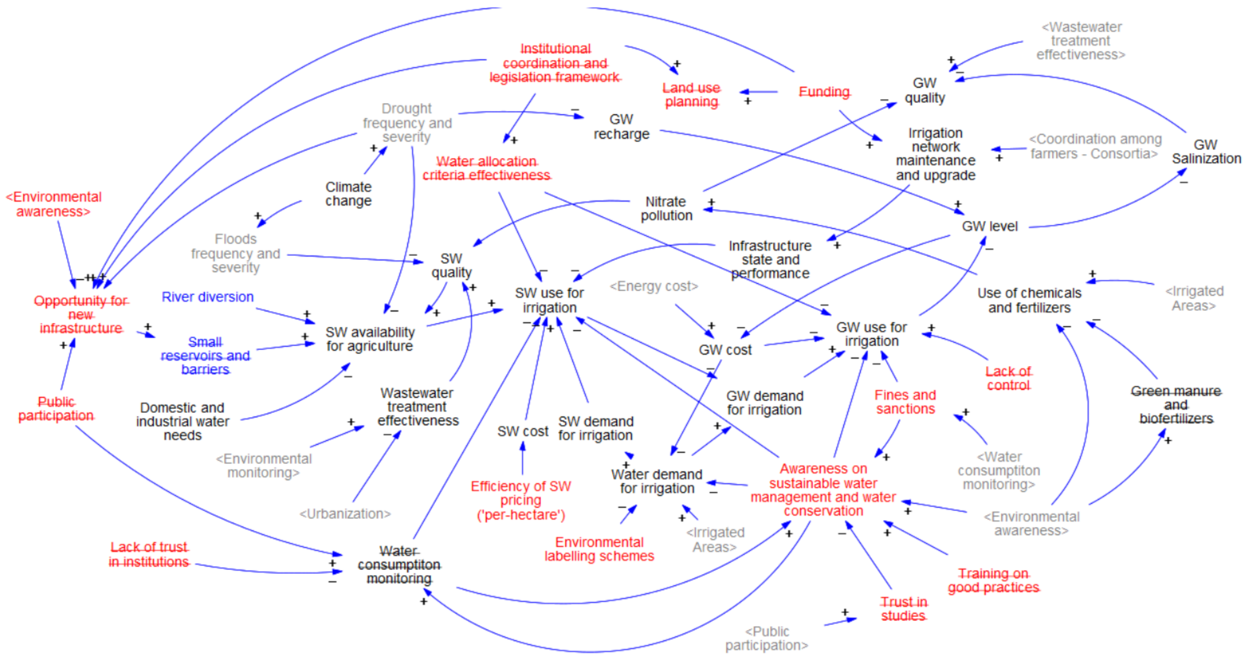

Figure 4 'Water' sector sub-model developed for the Pinios pilot area.

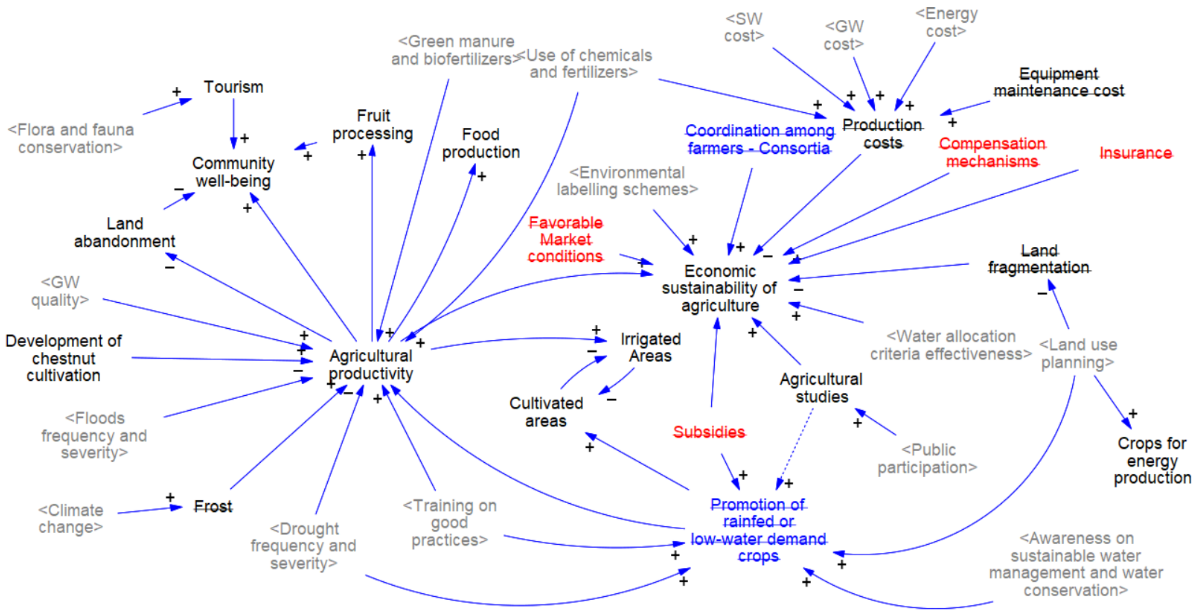

Figure 5 'Food' sector sub-model developed for the Pinios pilot area.

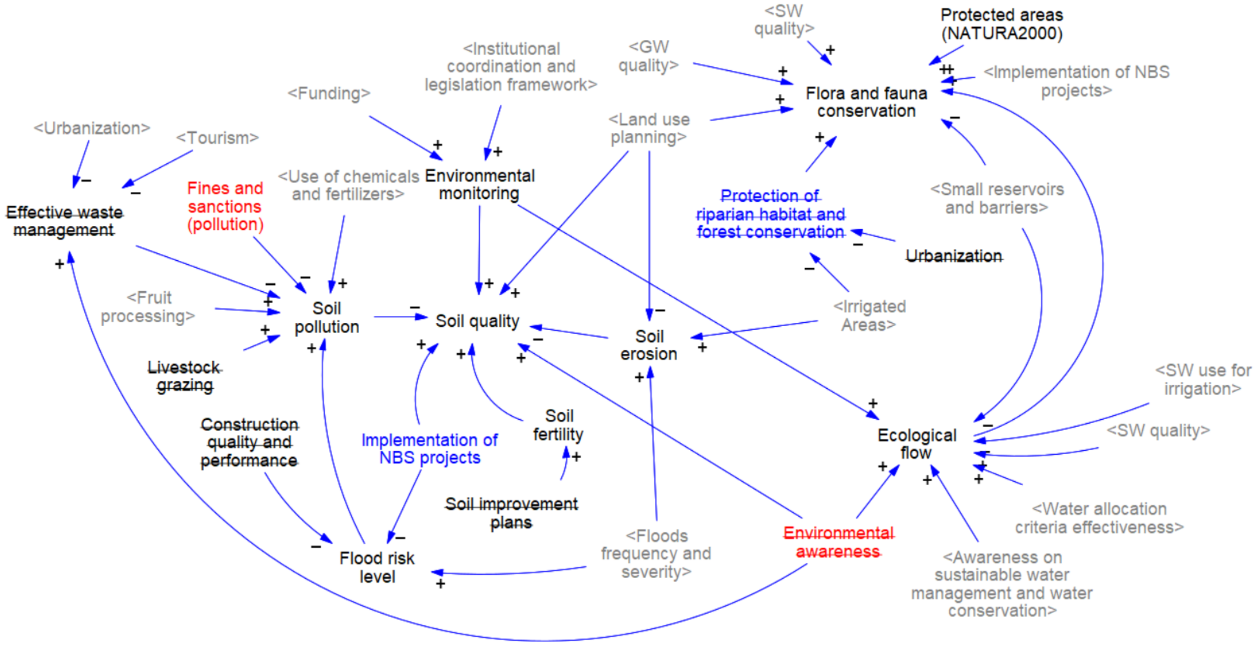

Figure 6 'Ecosystems' sector sub-model developed for the Pinios pilot area.

A significant common denominator across the three examined sectors is mulching and management of soil water retention capacity through irrigation programming. This is manifested at the 'implementation of NBS projects' of the ecosystems' sector, but also closely related to the water sector 'GW/SW use for irrigation' and the food sector 'awareness of sustainable water management/training on good practices.

Useful insights on some central aspects of the model can be provided by the analysis of the 'causes trees' and 'uses trees', i.e. the chains of variables affecting and being affected by the target variables. Although focusing on individual variables and a limited number of connections may cause the ‘loss’ of the whole picture, this is a really useful exercise to focus on specific parts of the whole model.

One variable has been extracted and analyzed to provide details on how this function can be used to better understand the model. Particularly, referring mainly to the ‘water’ sector sub-model, the ‘SW use for irrigation’ has been identified as target variable. Causes and uses trees are represented in Figure 7 a) and b).

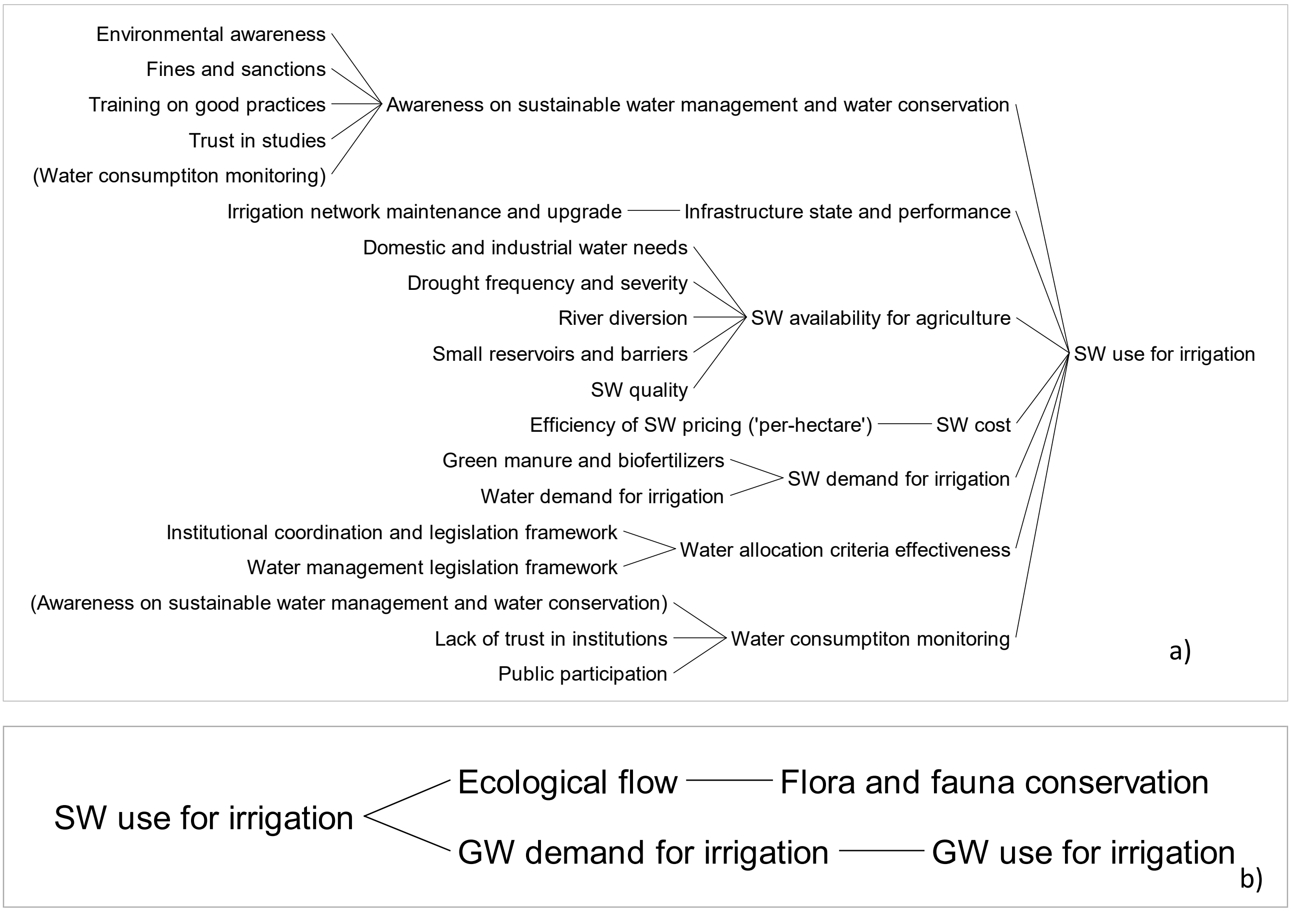

Figure 7 Causes and uses trees for the variable ‘SW use for irrigation’ for the Pinios pilot

The analysis of the causes and uses trees confirms that the issue of SW use for irrigation is multifaceted and depending on several aspects, ranging from merely technical ones (such as e.g. the ‘infrastructure state and performance’), to economic ones (‘SW cost’, which depends on the pricing criteria used), to socio-institutional ones (e.g. the ‘water consumption monitoring activities’ or the ‘water allocation criteria effectiveness’). Interestingly, a key role is played by the ‘awareness on sustainable water management and water conservation’, which is directly dependent on the ‘environmental awareness’ level, and directly offers multiple possibilities for acting on the system through specific policies (e.g. through ‘fines and sanctions’, or through ‘training on good practices’). A high level of interdependency of this variable on other sub-models is also clear as, for example, the dynamics of agriculture and irrigation practices (‘SW demand for irrigation’ and ‘SW availability for agriculture’). An overview of the causes trees also highlights the complexity of this dynamics, which depends – among others – on changing climatic conditions (‘Drought frequency and severity’) and on infrastructural measures to potentially increase SW availability (e.g. ‘river diversion’ and ‘small reservoirs and barriers’). In other words, the role of external drivers needs to be jointly analyzed with users’ behaviors and with technical considerations, to have a clear idea of the SW use dynamics and potential evolution. Similarly, it is also evident that the 'SW use for irrigation' has multidimensional impacts that are particularly important in the environmental realm, as it affects the 'GW demand for irrigation' as well as the 'Ecological flow', with an indirect impact on 'flora and fauna conservation' over the area.

The CLD had to undergo several iterations, following the participatory activities organized in the case study area, and was finally translated into the Kumu version. The 'Kumu' version of the CLD thus takes into account information coming from interviews and workshops that have been performed with the support of pilot leaders, including specific activities oriented to validation. The final version of the CLD is presented in the following Figure 8. The model is available at the following link: PINIOS CLD.

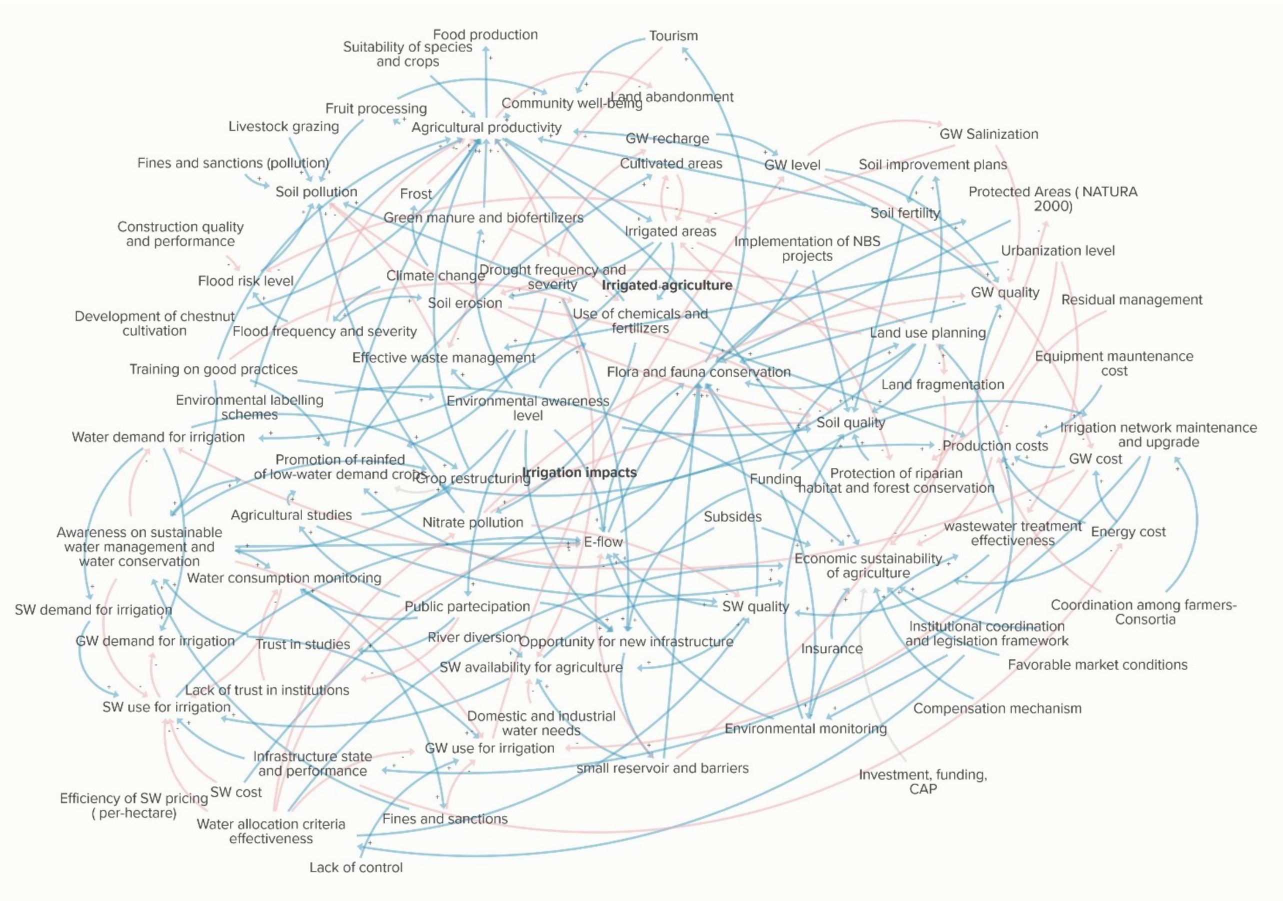

Figure 8 Revised version of the CLD developed for the Pinios pilot (KUMU). Blu arrows are used for a (+) connection, red arrows for a (-) connection.

Following the approach detailed in Section 3, the CLD has been explored using graph theory measures. 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 identifying Nexus challenges.

The analysis highlights that a key challenge for the Pinios area relates to the role of agricultural activities, and to the impacts that the unsustainable management of natural resources may have on the system. In fact, among the high-ranked variables in terms of Centrality Degree, the analysis highlights the fundamental role of 'Agricultural productivity' (Degree centrality 19, Betweenness centrality 0.098) and of the 'Economic sustainability of agriculture' (Degree centrality 13). There is a strong interconnection between water and agriculture, as well as between agriculture and the state of the environment as the impacts of intensive agriculture on the availability and state of natural resources is high. This emerges from the high centrality of 'Awareness on sustainable water management and water conservation' (Degree centrality 12), 'Irrigated areas' (Degree centrality 9, Betweenness centrality 0.095), 'SW use for irrigation' and 'GW use for irrigation' (Degree centrality 9 and 7, Betweenness centrality 0.050 and 0.064 respectively), 'Use of chemicals and fertilizers' (Degree centrality 8, Betweenness centrality 0.033). An interplay between human activities (mainly agriculture) and the state of the environment is also evident, as highlighted by the high centrality of 'Flora and fauna conservation' and 'e-flow' (Degree centrality 10), and 'Soil pollution' (Degree centrality 8). Rather central problems also emerge, such as for example the low 'Environmental awareness level' (Degree centrality 9), the inefficient 'Land use planning' (Degree centrality 9), and the need to improve 'Water allocation criteria effectiveness' (Degree centrality 7).

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

Table 3 Nexus challenges for the Pinios case study.

Nexus challenges	Centrality measures
Agricultural productivity and sustainability	High centrality degree, High betweenness centrality
SW and GW use for irrigation, water allocation criteria effectiveness	High centrality degree, High betweenness centrality
Use of chemicals and fertilizers in agriculture	High centrality degree, High betweenness centrality
Flora and fauna conservation	High centrality degree
Ecological flow	High centrality degree

During the 1st stakeholder workshop (21/11/2022), a specific activity was performed in order to find an agreement on a set of three main challenges for the area, defined starting from the results of the first round of interviews with the stakeholders. In particular, the selected challenges were defined as: 'Achieving and maintaining sufficient quantity and good quality of water resources', 'Sustainability of the agricultural sector' and 'Protection and restoration of ecosystems'. The results of the model are in good agreement with the challenges directly identified by the stakeholders for the pilot area.

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 whose role looks highly relevant with respect to the abovementioned Nexus challenges. It is worth mentioning that the CLD is highly complex and includes several additional feedback loops, which further suggest a high level of interdependency among sectors.

The 'Irrigated agriculture' feedback loop represented in Figure 9 (a balancing loop) suggests that the increase in 'Agricultural productivity' may have a direct effect on further increases in the 'Agricultural areas'. This may cause an increase in the 'Use of chemicals and fertilizers', with a cascading impact on the 'Nitrate pollution' level over the area. The increased load of nitrates may cause a reduction in 'GW quality', which can seriously affect irrigated agriculture and pose a limit to the 'Agricultural productivity' with a negative impact on the sector.

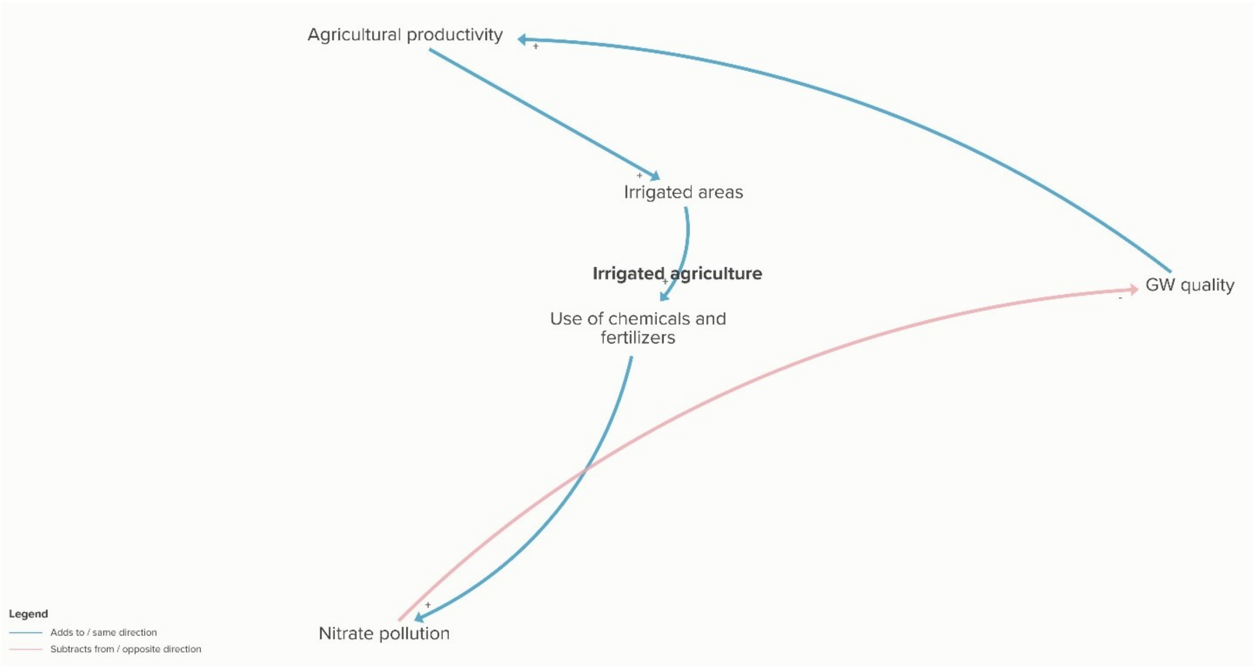

Figure 9 Focus on the 'Irrigated agriculture' feedback loop in the Pinios CLD (KUMU)

Starting from the identification of challenges and from the analysis of key feedback loops, the approach detailed in the methodological section has been then used for the leverage analysis. In particular, the closeness centrality - which identifies elements that can easily affect most of the network and usually have a high impact on what is happening across the system – is used to support the leverage analysis. Interestingly, the analysis suggests that the high-ranked variables mainly include socio-institutional measures, such as mainly the 'Environmental awareness level' (closeness centrality 0.265). Some potential leverage points are directly related to the agricultural sector and the implementation of good practices ('Training on good practices' 0.255, 'Awareness on sustainable water management and water conservation' 0.199), others to the socio-institutional frame ('Funding' 0.215, 'Institutional coordination and legislation framework' 0.203, 'Land use planning' 0.202, 'Public participation' 0.191). The analysis thus suggests that acting on the agricultural sector with both technical and/or 'soft' measures might have a significant impact on the system, affecting multiple dimensions including the profitability/sustainability of agricultural activities, as well as the state/use of water resources.

A summary of the results of the leverage analysis is provided in Table 4.

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

Nexus challenges	**Leverage points**
Agricultural productivity and sustainability	Environmental awareness level Training on good practices Funding Land use planning Awareness on sustainable water management and water conservation
SW and GW use for irrigation, water allocation criteria effectiveness	Environmental awareness level Training on good practices Land use planning

Use of chemicals and fertilizers in agriculture	Environmental awareness level Training on good practices
Flora and fauna conservation	Land use planning Environmental awareness level
Ecological flow	Environmental awareness level Training on good practices

Quantitative PSDM – stock and flow development

The present subsection provides information on the development of the stock and flow model for the Pinios pilot area, as it is currently the most advanced. It is worth to remark here that, although stock and flow models definitely aim to represent pilot-specific dynamics and reflect local specificities, efforts are also being made to develop a shared 'core' engine. This is reasonable, from the analyst point of view, for several reasons. First of all, as many of the dynamics that relate resources (e.g. the water demand for irrigation and for drinking purposes, the interplay between surface water and groundwater, the impacts of agricultural activities on the state of ecosystems, etc.) can be expressed through rather generic equations that come from the scientific knowledge. Local differences can be taken into account rather easily both customizing the equations as needed (even de-activating some dynamics if not relevant) and setting the initial state of variables in a way that properly represents the local conditions (e.g. the current ratio of SW versus GW use for irrigation). Second, as many of the sectoral inputs that are used for the development of the stock and flow models come from the same tools and models, such as water allocation tools (e.g. WEAP), hydrological models (e.g. SWAT), or climate projections. Therefore, the definition of some input variables and the way they are used is similar also for different pilots. Lastly, the shared components of the stock and flow model can be more easily used as a starting point for replication within LENSES and beyond.

The stock and flow model has been designed to simulate over 30 years with a monthly time step. The duration of the simulation depends on the identification of a relevant (and significant) time step to account for the main changes that may occur in the system (ranging from the impacts of CC to the changes in agricultural areas, to the implementation of NbS), but can be easily modified. The time step has been selected considering its relevance to describe with enough detail some key phenomena (e.g. monthly variation of water demand) and the coherence with the time step used in other models (e.g. water allocation). Increasing the time step (e.g. seasonal or annual) would result in a potentially relevant loss of information at least for some dynamics, while reducing it (e.g. daily) would add limited information in terms of quality of the outputs while potentially increase the computational burden.

The model has been also organized in the form of sub-models, for a twofold reason. On the one hand, to simplify the visual structure of the whole model, without compromising the description of interconnections (as the use of 'shadow' variables can transfer information among sub-models). On the other hand, to facilitate users interested in getting insights into a specific sector to focus on that sector only. The sectors were identified as: 'water', 'agriculture' and 'ecosystems' (see Figure 10, Figure 11 and Figure 12 respectively). An additional sub-model is identified as 'ESS' and mainly aims at providing a specific description of the evolution of ESS production in different scenarios. One of the expected evolutions of the model is the development of a user-friendly interface, where the user can modify the state of input variables and drivers and visualize relevant results (in form of graphs or tables) without accessing the model and its equations.

Although SDM tools do not have an explicit spatial nature, spatial information can be managed in different ways. The stock and flow model above is based on the use of 'subscripts', which allow a single variable to represent many different things. We basically identified two areas of interest ('Delta' and 'Agia') and some input variables have specific values for the two areas of interest. An alternative option is to create sub-models specifically for different areas of interest (which should have homogeneous characteristics), paying attention to the mutual influences and interdependencies.

It is worth noting that the stock and flow does not aim to fully describe in quantitative form the complexity of the CLD. It rather aims to provide insights into the main dynamics affecting the key challenges identified for each case study. In this case, specifically, the focus of the water sub-model is on water use for different purposes (with a focus on agriculture) and the impacts of human activities (mainly agriculture) on water quality; agriculture sub-model is mainly built around the productivity and sustainability of the main crops for the area, with also a focus on the impacts of the adopted practices on water resources and on the environment; the ecosystems sector is focused on the main impacts of human activities and resources use on the state of the environment.

The following Figures provide an overview of the sub-models as they have been developed so far. Updates will occur before the last stakeholders' workshop, where the results of the model will be presented and discussed.

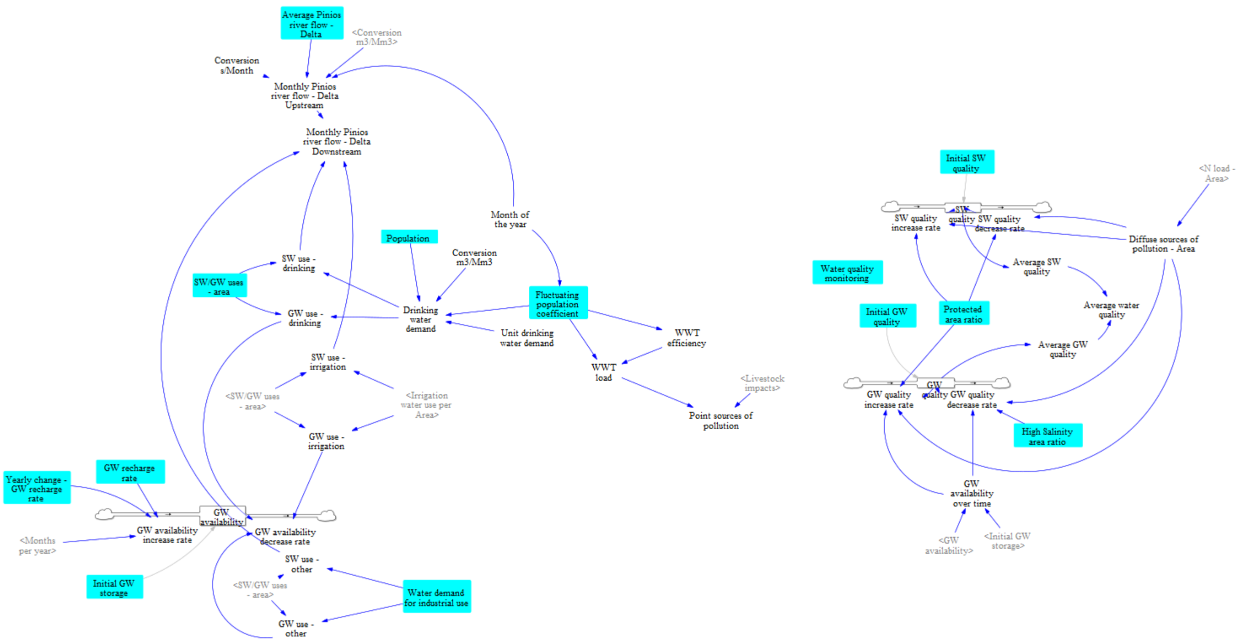

Figure 10 View of the 'Water' sub-model for the Pinios pilot stock and flow model

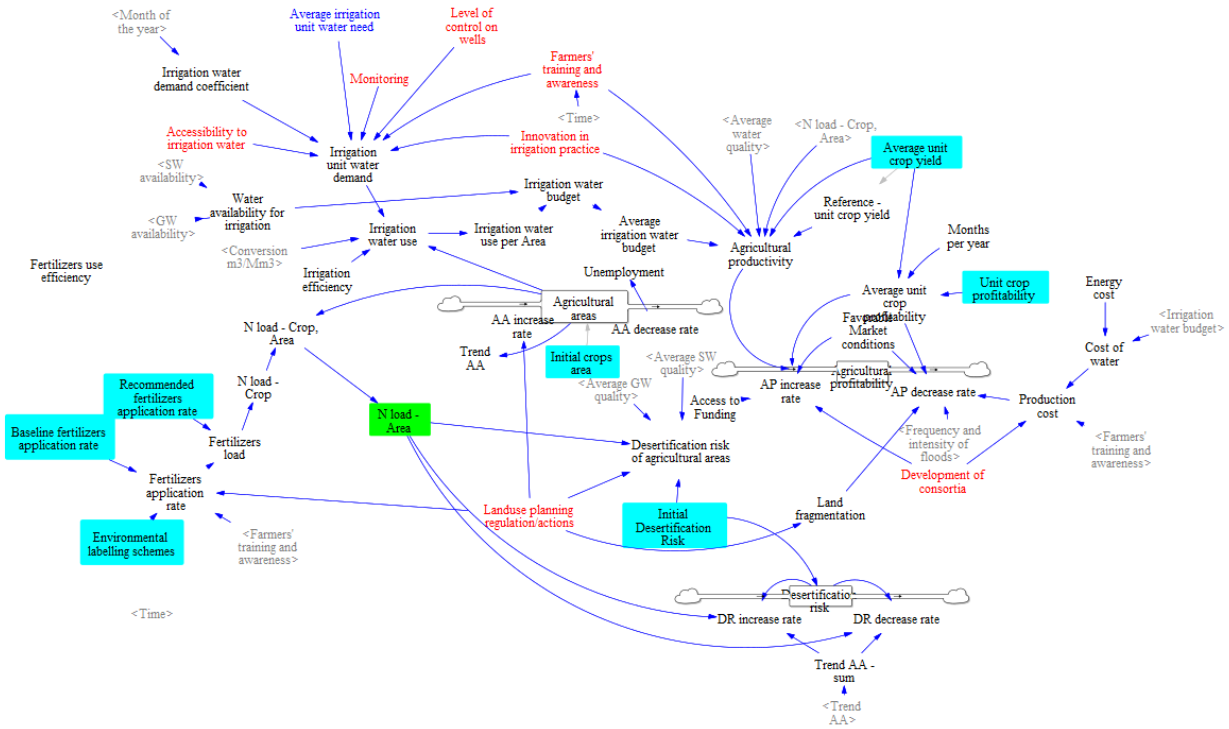

Figure 11 View of the 'Agriculture' sub-model for the Pinios pilot stock and flow model

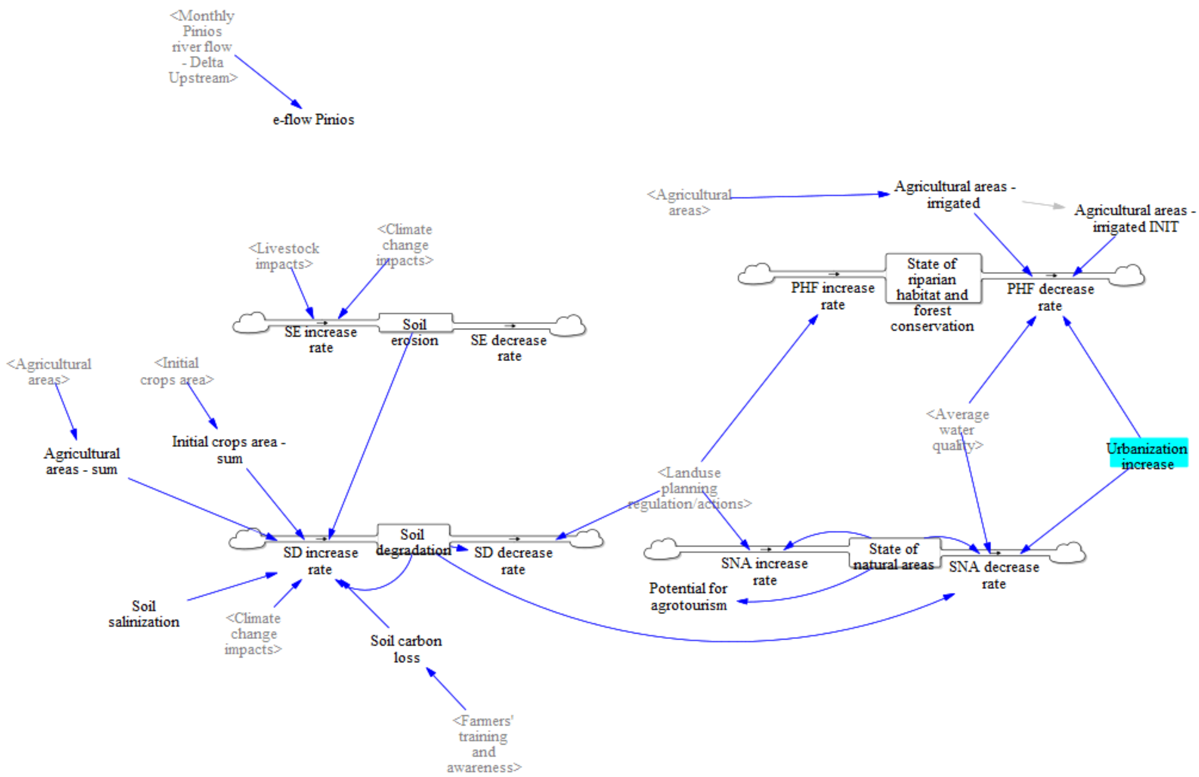

Figure 12 View of the 'Ecosystems' sub-model for the Pinios pilot stock and flow model

A full description of the content of the stock and flow model is out of the scope of the present Deliverable. Nevertheless, it is worth highlighting in the following some key features of the model, focusing on a particularly relevant part related to the irrigation water use and presented in Figure 13.

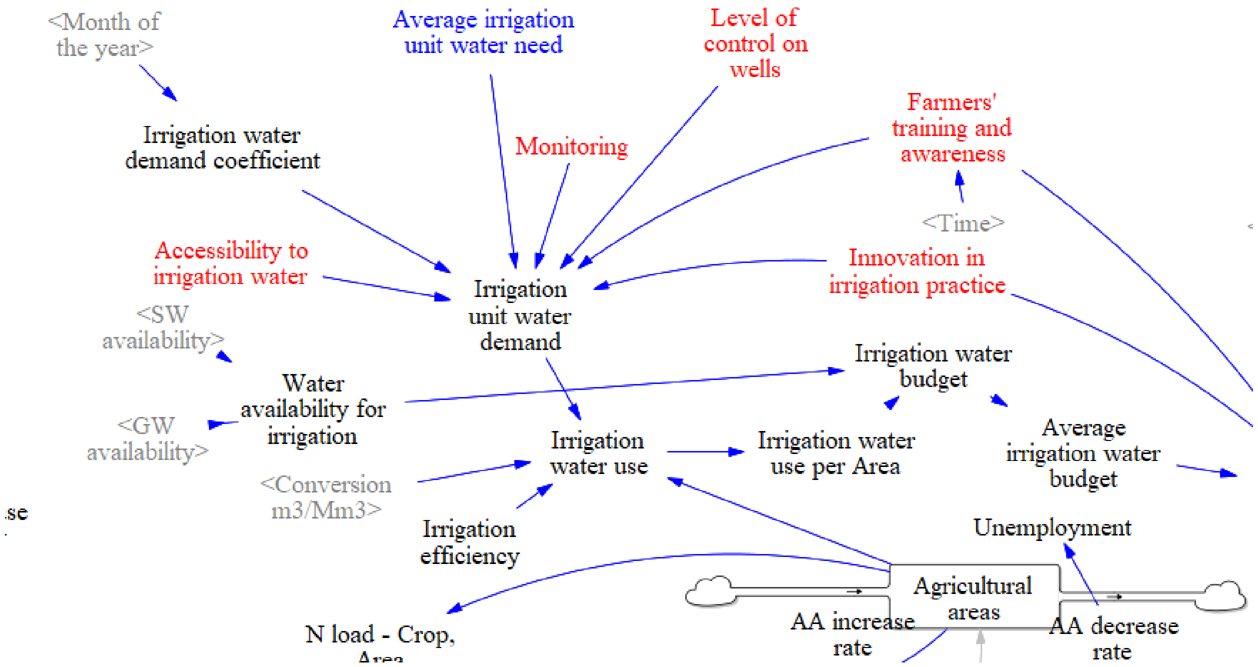

Figure 13 Part of the Pinios pilot stock and flow model, focusing on the water use for irrigation

Input variables are variables with no incoming arrows. For the sake of simplicity, some input variables are in red and represent inputs mainly related to the socio-institutional realm. A constant value is assigned to all input variables, along with units. For example, the 'Average irrigation unit water need' (the values assigned are in Table 5) represents typical yearly irrigation requirements in [m^3/ha] for each relevant crop of the area (Apple fruit trees, Stone fruit trees, Cereals, Corn, Nuts, Forage, Cotton, Olives, Other trees, Other crops). Data from other models (or from observations) are being used as inputs, following consultation with case study leaders. The irrigation unit water need is distributed throughout the year considering the 'Irrigation water demand coefficient', and can be either increased or reduced considering the role of other aspects that have been mentioned by the stakeholders, including e.g. the 'Farmer training and awareness' and the 'Innovation in irrigation practice'.

Table 5 Average yearly irrigation unit water needs (in m^3/ha) for relevant crops in the study area.

Table | Average irrigation unit water need

File View Window

Time (Time)	0
Average irrigation unit water need[Pome fruit trees] : prova	4200
Average irrigation unit water need[Stone fruit trees] : prova	4200
Average irrigation unit water need[Cereals] : prova	0
Average irrigation unit water need[Corn] : prova	4840
Average irrigation unit water need[Nuts] : prova	3300
Average irrigation unit water need[Forage] : prova	4030
Average irrigation unit water need[Cotton] : prova	3730
Average irrigation unit water need[Olives] : prova	1130
Average irrigation unit water need[Other trees] : prova	4200
Average irrigation unit water need[Other crops] : prova	0

Going further into details, the 'Irrigation unit water demand' is described using the following equation:

Average irrigation unit water need[Crop](1+(1-Innovation in irrigation practice)+(1-Monitoring)+(1-Level of control on wells)+(1-Farmers' training and awareness))*Irrigation water demand coefficient*Accessibility to irrigation water*

The variables in red are not active (i.e. the numerical value assigned is not affecting the computation) in the 'baseline scenario', but interesting scenario analyses can be performed assuming changes in one (or more) of those variables. Just to make an example, an increase in the level of 'Farmer training and awareness' can be considered to show that individual awareness and behaviour can increase (or reduce) the demand of water for irrigation.

The 'Irrigation water use' (expressed in Mm^3) considers on the one hand the 'Irrigation unit water demand' and, on the other hand, the 'Agricultural areas' (in ha). It then basically provides an overview of total irrigation water use per crop, per area of interest based on the following equation:

*Agricultural areas [Crop,Area] * Irrigation unit water demand [Crop] * (2-Irrigation efficiency[Area]) * "Conversion m3/Mm3"*

An example of output for the irrigation water use is plotted in the following Figure 14. The Figure highlights both the effect of seasonal variation of the use of water for irrigation, and the specific impacts of individual crops in the areas of interest. The reduction of irrigation water use over time shows the impact that could be achieved with a change in 'Farmer training and awareness level'.

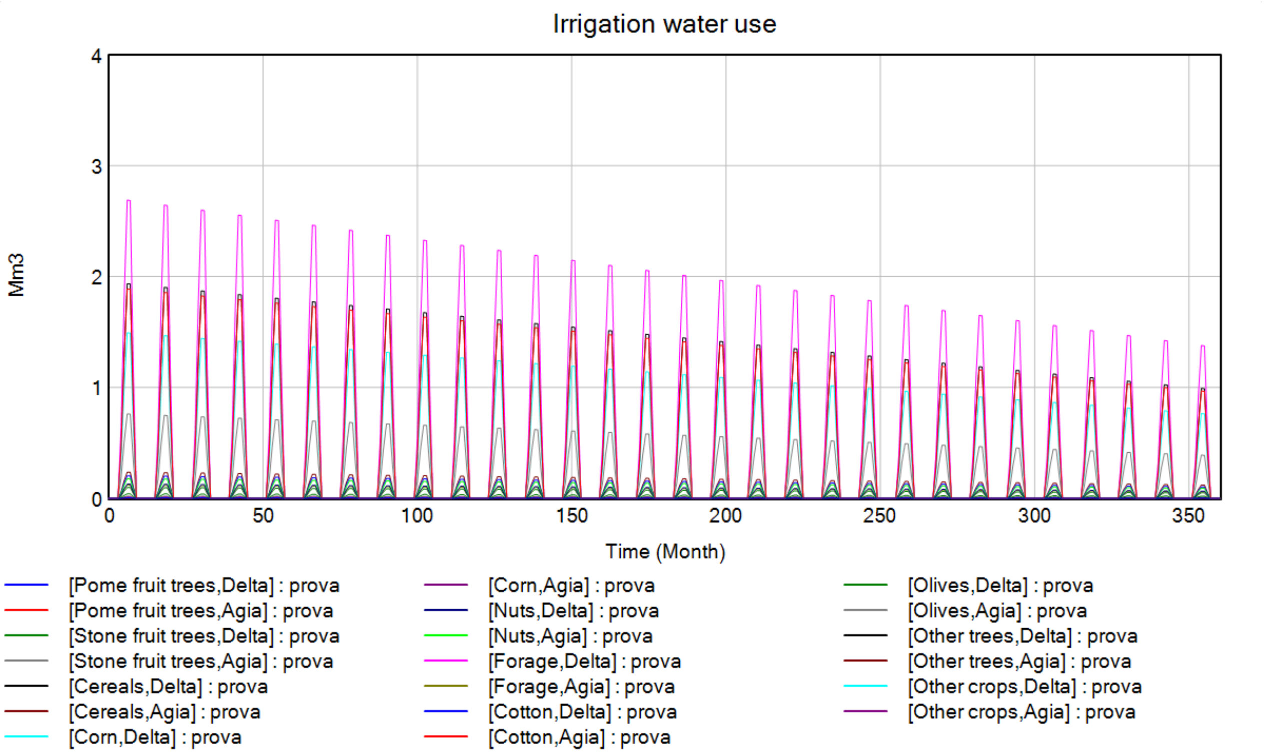

Figure 14 Output for the Irrigation water use

The variable 'Irrigation water use per area' (Figure 15) provides an aggregated overview of irrigation water use in the two areas of interest.

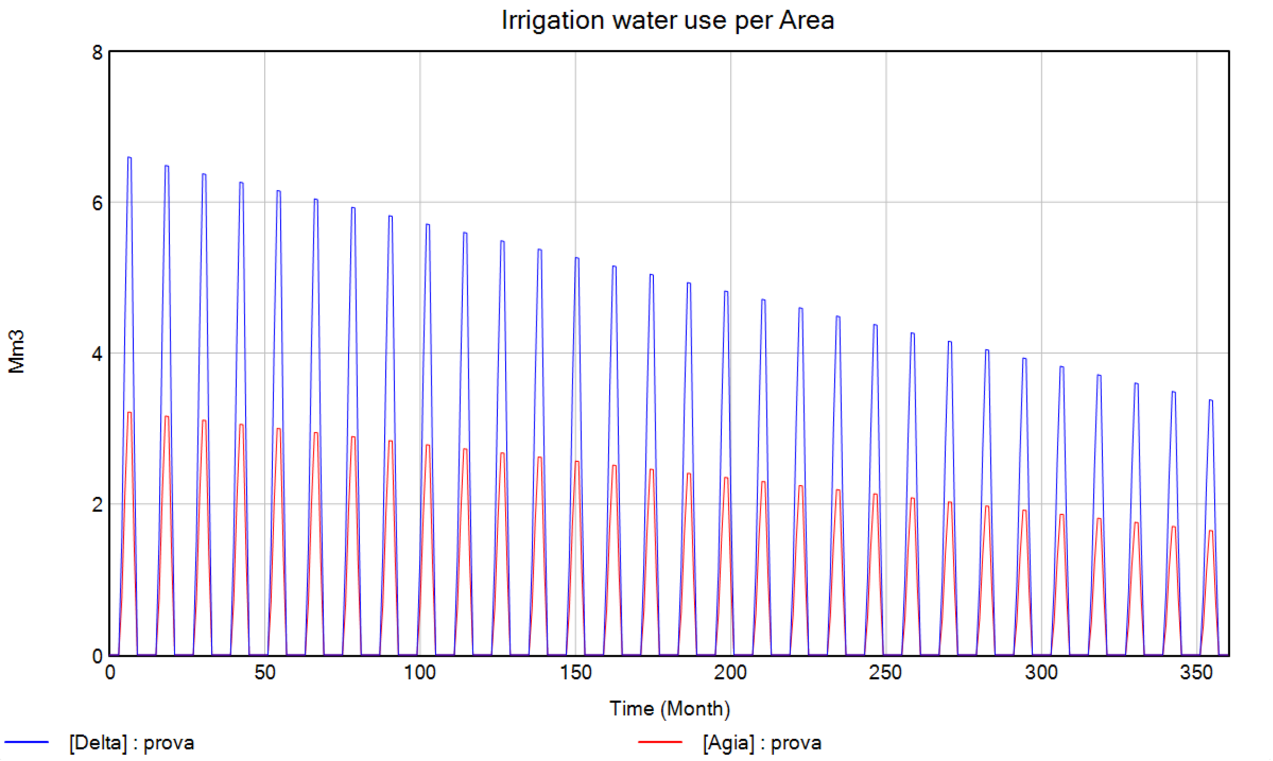

Figure 15 Output for the Irrigation water use per area of interest

It is worth highlighting, going back to Figure 10 that the 'Irrigation water use per area' is present as *shadow variable* in the water sub-model, as it is used to compute a simplified water balance in the areas of interest (along with the water for drinking and industrial purposes), given the 'SW/GW use ratio'.

The model is currently being revised and further developed with the support of the pilot leaders, who are helping in the collection and integration of data from other tools and models (as well as from the LENSES Observatory) and providing expert knowledge for validating at least the key variables. The ambition is to use the stock and flow model to support the 'what-if' scenario analysis in the last stakeholder workshop. This task can be achieved either running the model and discussing results, or using the model in real time with stakeholders. The latter option would require the development (ongoing) of a user-friendly interface, with a straightforward identification of inputs (e.g. sliders for input variables) and outputs (graphs or tables for the relevant variables to discuss). During this stage, effort will be made to align the variables with 'Nexus'-relevant indicators (Details in D4.1).

4.4. Tarquinia pilot area

The preliminary version of the model built for the Tarquinia pilot area has been described in full details into the first version of the D4.1 ('Report on PSM and SNA. Identification of DOs, NRQs and NIs'). Starting from the mentioned CLD, an analysis of the causes trees and uses trees has been performed focusing on the variable 'Irrigated areas' and is summarized in the following Figure 16 a) and b).

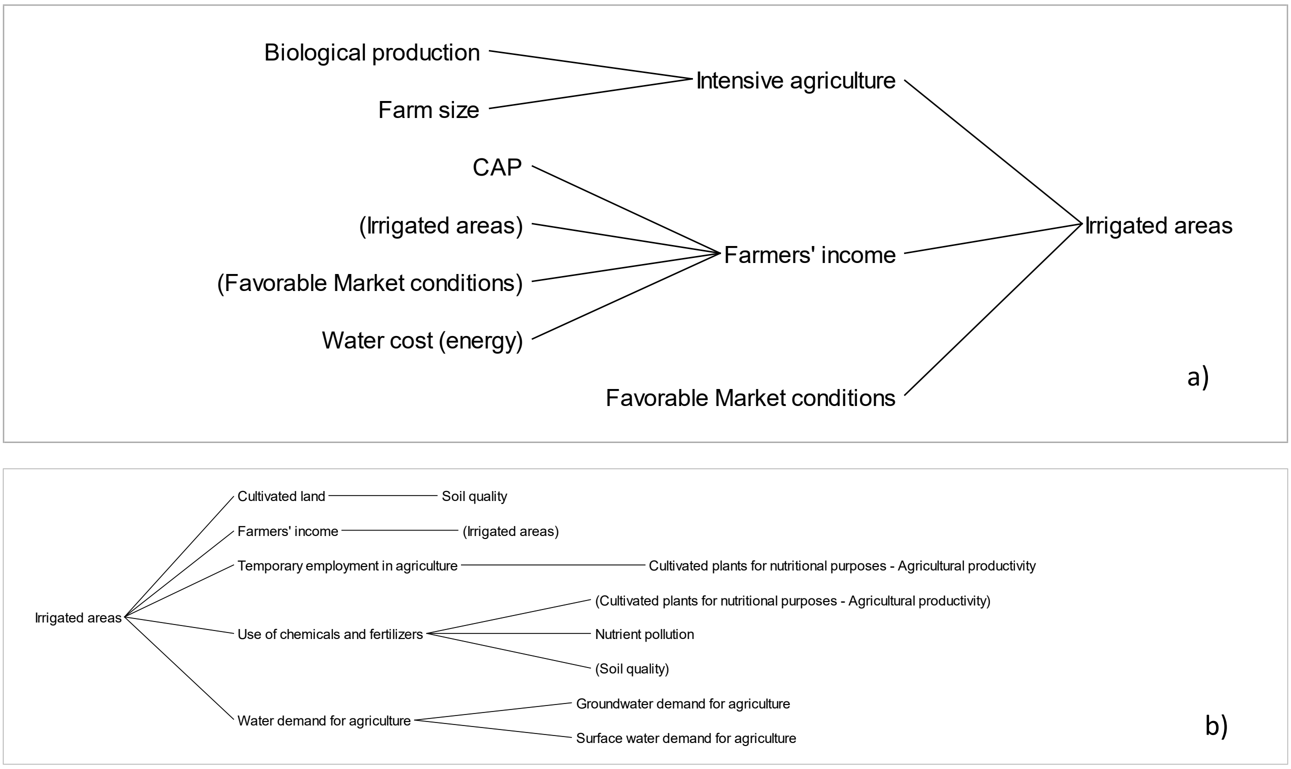

Figure 16 Causes and uses trees for the variable 'irrigated areas' for the Tarquinia pilot

The dynamics of agricultural practices, which ultimately affect the 'Irrigated areas' depend on a multiplicity of factors but are definitely dominated by the profitability of agriculture (represented through the 'Farmer income'), which is affected -among the others - by the CAP and by the favorability of current market conditions. The role of 'Water cost', mainly dependent on energy cost, is also becoming crucial. The 'farm size' and the development of 'biological production' are also conditioning the development of 'intensive agriculture'. The variation of 'irrigated areas' has several impacts that mainly relate to i) the crucial role of the activity for the local economy (e.g., considering the direct dependence of farmers' income and of temporary employment); ii) the water demand for agriculture, ii) the amount of chemicals and fertilizers that are used over the area.

The CLD was presented during the stakeholders' workshop that was organized on May the 26th 2022 in Tarquinia, along with the key evidence from the interviews. This step was highly useful on the one hand to get preliminary feedback on the main results of the first step of the participatory process, which was performed based on individual interactions with stakeholders and, on the other hand, to start feeding the Nexus dialogue.

The Workshop was organized identifying two main challenges for the area, as resulted from the background analysis and the interviews:

1) **Sustainable agriculture** (including the issues of groundwater protection and food production)

2) The **protection of the system lake-river-coast and ecosystem conservation** (for valuing landscape).

Based on these challenges, the activities for the workshop (designed and carried out in close cooperation with the CREA Team and ECOADAPTA) were mainly oriented to:

- Identify and locate on a geographical map the main elements that characterize the area (using cards with a predefined set of resources, pressures, impacts,)
- Draw and characterize the main interconnections and interdependencies between such elements, identify chains of cause-effect relationships.

More specifically, stakeholders were guided in the discussion through the following questions/activities:

- *What are the main activities that are affected and are affecting the main challenges for the Tarquinia area*? This step was completed using a specific set of cards representing socio-economic activities. The analysts then provided a summary of the main elements located on the map (e.g. removing duplicates) to simplify the view and tried also to provide a simple ranking of the elements.
- Similarly, for the other type of cards (human and natural resources, pressures and impacts), both a geographical mapping and conceptual mapping exercise was performed, followed by a simple ranking and a discussion of the main interconnections.
- Lastly, any additional variable that was considered relevant and that could have an impact on system state was also added at this stage.

The key elements of the discussion were the characterization of the meaning and of the strength of the identified connections.

The following pictures (Figure 17 and Figure 18) were taken during the above phases of the 1st WS and refer respectively to the geographical mapping exercise and to the ‘conceptual’ mapping activity.

Figure 17 Participatory geographical mapping for the Tarquinia pilot

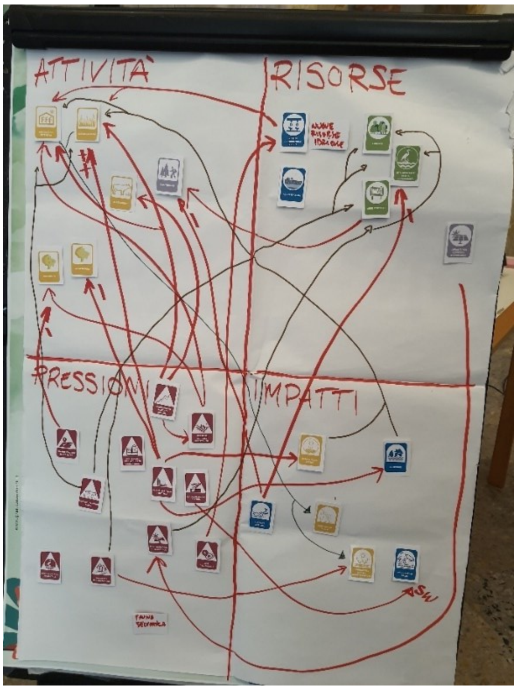

Figure 18 Participatory conceptual modelling for the Tarquinia pilot

The final version of the CLD was then translated into the Kumu version, to take advantage of the main features of the software (including among the others, the computation of graph theory metrics). The 'Kumu' version of the CLD has been further revised, to account for additional information coming from other phases of the participatory process. In particular, interviews and workshops have been performed with the support of pilot leaders also to better understand the potential impacts of Nature-based Solutions on the most relevant challenges for the area, and to highlight the major barriers to their implementation. The final version of the CLD is presented in the following Figure 19, and is available at the following link: [TARQUINIA - CLD]

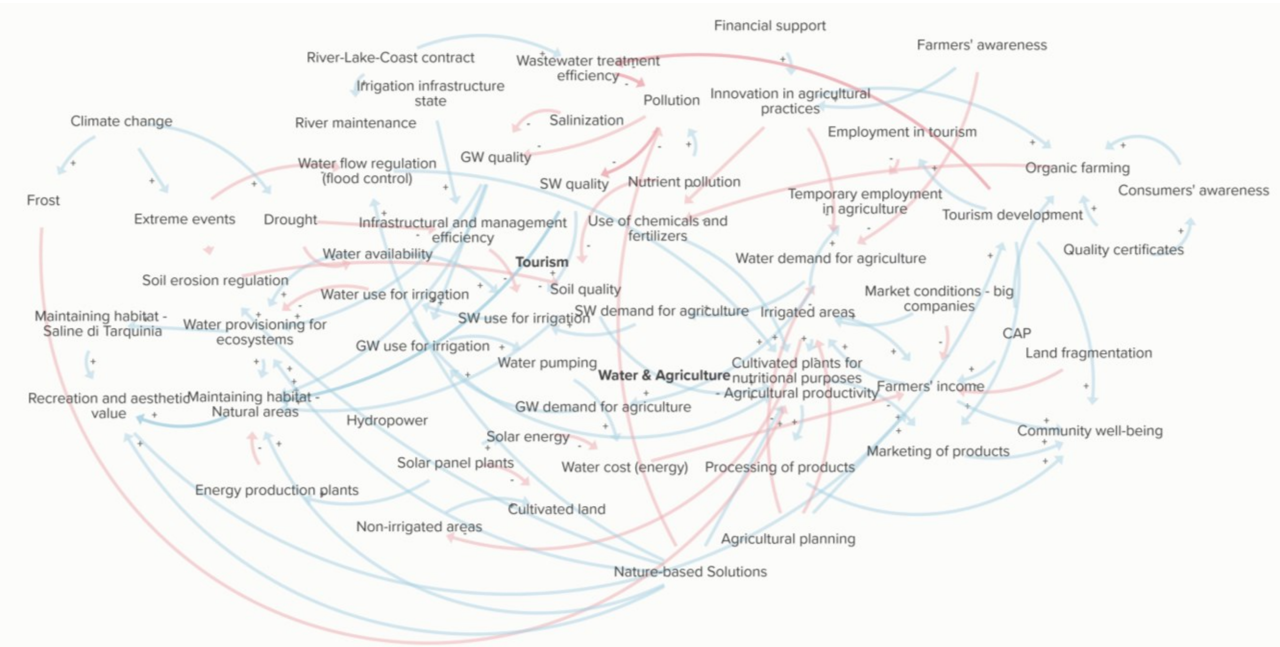

Figure 19 Revised version of the CLD developed for the Tarquinia pilot (KUMU)

Following the approach detailed in Section 3, the CLD has been explored using graph theory measures. 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 identifying Nexus challenges.

The analysis highlights that a key challenge for the Tarquinia plain mainly relates to the role of agricultural activities, and its interdependencies with the water sector and with the socio-economic conditions of the area. Among the high-ranked variables in terms of Centrality Degree, the analysis highlights the role of 'Irrigated Areas' (Degree centrality 8, Betweenness centrality 0.112), 'Agricultural productivity' (Degree centrality 9) and 'Farmers' income' (Degree centrality 8, Betweenness centrality 0.110). There is a strong interconnection between water and agriculture, as the impacts of irrigated agriculture on the availability and state of natural resources is high. This also emerges from the high centrality of 'Water demand for agriculture' (Degree centrality 6) and 'GW quality' (Degree centrality 5, Betweenness centrality 0.120). It is worth to consider that, although (to date) the water availability over the area has never been a relevant issue, there are increasing concerns mainly due to the impacts of climate change (note: some interviews have been performed after a rather long – and quite uncommon - dry period in the area). Conversely, there is evidence of the severe impacts on GW quality due to the heavy use of chemicals in agriculture in many irrigated areas. A relevant interconnection between human activities (mainly agriculture) and the environment is also evident, as highlighted by the centrality of 'Maintaining habitat – Natural areas' and 'Water provisioning for ecosystems' (Degree centrality 6 and 5 respectively, Betweenness centrality 0.106 and 0.09 respectively, Eigenvector centrality 0.078 and 0.066 respectively), 'Pollution' (Degree centrality 5, Betweenness centrality 0.150) and 'Recreation and aesthetic value' (Betweenness centrality 0.150, Eigenvector centrality 0.088). A central issue is also the 'Wastewater treatment efficiency' (Betweenness centrality 0.120, Eigenvector centrality 0.044), which significantly affects the state of water bodies and natural areas, in particular in case the load is extremely high. The analysis also shows that potential central role of some measures that might be considered for improving system state (e.g. 'Organic farming' and 'Innovation in agricultural practices' with Centrality degree 5) and, particularly, 'Nature-based Solutions' (Centrality degree 7) positively affecting multiple sectors/dimensions.

A summary of the main Nexus challenges and related centrality measures is provided in the following Table 6.

Table 6 Nexus challenges for the Tarquinia plain case study.

Nexus challenges	Centrality measures
Agricultural productivity	High centrality degree
GW quality	High centrality degree; high betweenness centrality
Maintaining habitat – Natural areas	High centrality degree; High betweenness centrality; High eigenvector centrality
Wastewater treatment efficiency	High betweenness centrality; high eigenvector centrality
Farmers' income	High centrality degree; high betweenness centrality

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 whose role looks highly relevant with respect to the abovementioned Nexus challenges. It is worth mentioning that the CLD developed for the Tarquinia area includes several feedback loops, and that many of those feedback loops have a very high number of connections. This further highlights the complexity of the study area as well as the high level of interdependencies among sectors.

The ‘Tourism’ feedback loop represented in Figure 20 (a balancing loop) suggests that the uncontrolled ‘Tourism development’ (which currently is not enough supported by infrastructure planning and management) is responsible for a reduction in ‘Wastewater treatment efficiency’, which causes an increased level of ‘Pollution’ over the area. The malfunctioning of wastewater treatment plants is due indeed to the higher load that directly depends on the population fluctuations. This heavily affects the level of ‘SW quality’, whose degradation is directly responsible for a decrease in the state of ‘Natural areas’, which affects the ‘Recreation and aesthetic value’ of the whole area. As the ‘Recreation and aesthetic value’ of the area is reduced, this might negatively affect the ‘Tourism development’. Although this might help stabilizing the dynamics described by the analyzed loop, it might also have a negative impact in terms of well-being of local communities which significantly rely on the role of tourism. A more sustainable tourism development model should thus be pursued.

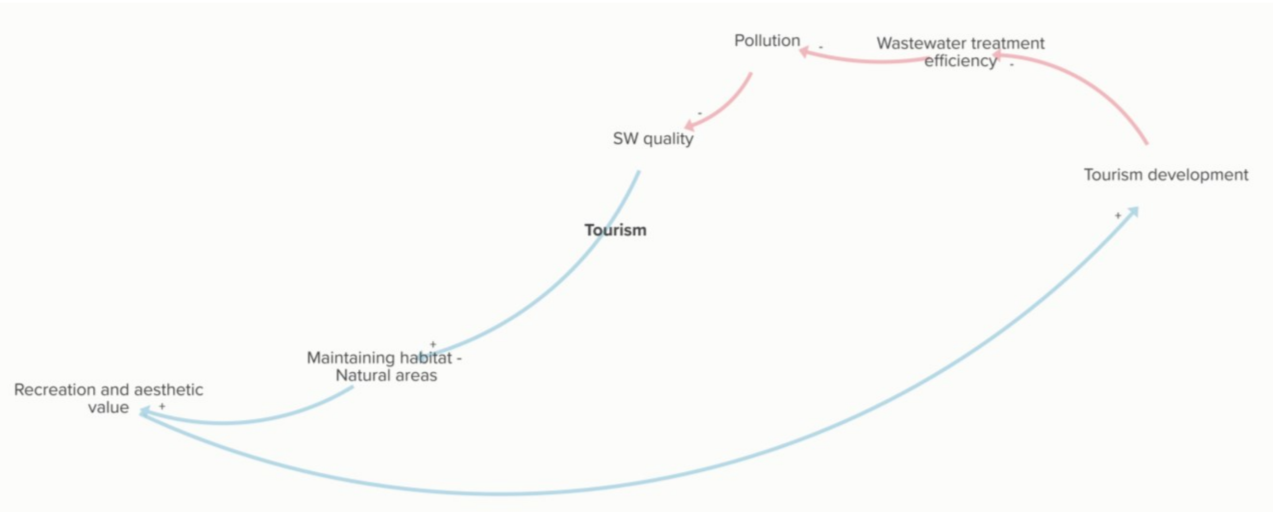

Figure 20 Focus on ‘Tourism’ feedback loop in the Tarquinia plain CLD (KUMU)

The ’Water & Agriculture’ feedback loop (balancing) in Figure 21, directly relates to the interplay between water resources demand (and use) for agriculture and the sustainability/profitability of agricultural practices. An increase in ‘Irrigated areas’ (as well as the transition to crops that typically require higher volumes of water) caused an increased ‘Water demand for agriculture’, with a cascading impact on the ‘GW demand for agriculture’ (and, similarly on ‘SW demand for agriculture) and an increase in ‘GW use for irrigation’. This causes an increased ‘Water pumping’ with a cascading effect on the ‘Water cost (energy)’, which ultimately causes a reduction of ‘Farmers’ income’. The analysis of the loop again suggests that attention should be given to the development of sustainable (yet profitable) agricultural development models.

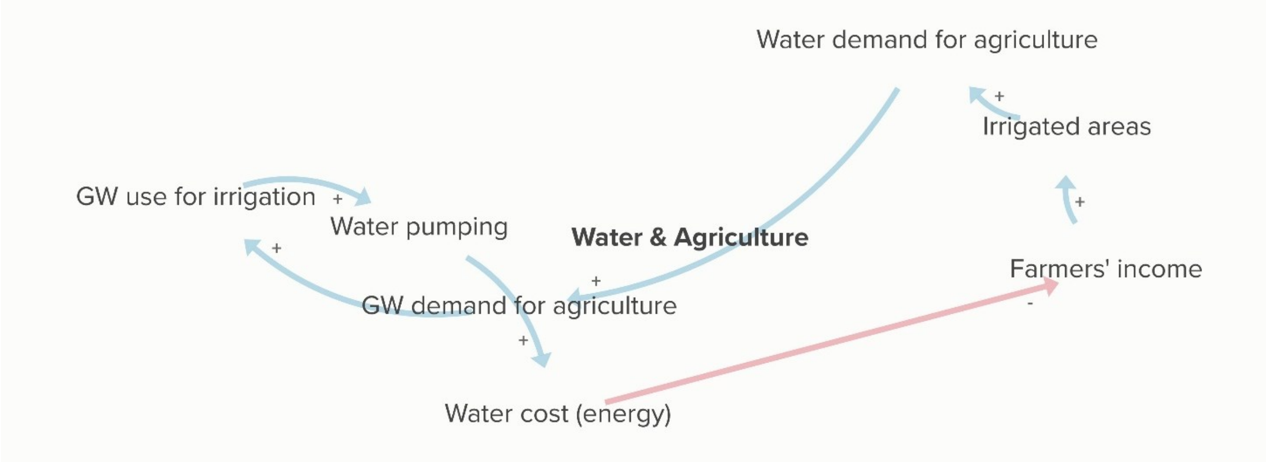

Figure 21 Focus on 'Water & agriculture' feedback loop in the Tarquinia Plain CLD (KUMU)

Starting from the identification of challenges and from the analysis of key feedback loops, the approach detailed in the methodological section has been then used for the leverage analysis. In particular, the closeness centrality - which identifies elements that can easily affect most of the network and usually have a high impact on what is happening across the system – is used to support the leverage analysis. The variable characterized, by far, by the highest value of closeness centrality is 'Nature-based solutions', showing the high potential of a series of combined measures to affect the state and potential evolution of the system, targeting many of the main challenges. The variables characterized by the highest closeness centrality are all related to the agricultural sector, which thus have a lot of potential leverage points to act on the state of the system. Those variables – besides the 'Irrigated areas' (0.198) - include 'Innovation in agricultural practices' (0.193), 'Agricultural planning' (0.179), 'Farmers' awareness' (0.175), 'CAP' (0.171) and 'Use of chemicals and fertilizers' (0.159). The analysis thus suggests that acting on the agricultural sector with technical and/or financial measures might have a significant impact on the system, affecting multiple dimensions including the profitability/sustainability of agricultural activities, the state of water resources and water bodies and, consequently, the state of natural areas.

A summary of the results of the leverage analysis is provided in Table 7.

Table 7 Results of the leverage analysis for the Tarquinia plain case study.

Nexus challenges	**Leverage points**
Agricultural productivity	Innovation in agricultural practices Agricultural planning Farmers' awareness CAP Use of chemicals and fertilizers Nature-based Solutions
GW quality	Innovation in agricultural practices Farmers' awareness Use of chemicals and fertilizers River-Lake-Coast contract Nature-based Solutions
Maintaining habitat – Natural areas	Nature-based Solutions Innovation in agricultural practices

Wastewater treatment efficiency	River-Lake-Coast contract Tourism development
Farmers' income	Innovation in agricultural practices Agricultural planning CAP Market conditions – big companies

4.5. Menemen pilot area

Menemen plain is part of the Gediz river basin and represents the area with the highest agricultural potential. Agricultural activities are mainly related to cotton, wine and maize, and irrigation based on furrow irrigation for about 98% of plots (open channel). Drip irrigation is used only for vineyards and vegetables. In general agriculture is crucial for the area and for local development but needs to be sustainable and efficient. The expansion of irrigated areas requires that water availability and use efficiency increase accordingly, as currently the main challenge is related to the **poor planning and irrational use of available resources**.

Irrigation is mainly based on SW from the 'Gediz river' rather than on GW (ratio 90-10 %), through a series of 'Dams and reservoirs'. WUA manage water allocation and distribution ('Water use for irrigation'), with a currently poor level of 'Farmers' WUA efficiency'. In general, a rather poor planning of agricultural and irrigation practices is acknowledged ('Agriculture planning'), which is reflected for example by the 'Soil salinity' caused by the excessive 'Water use for irrigation' in summer. The high 'Soil salinity' has a cascading impact e.g., on the 'Agricultural productivity'. Similarly, the high 'GW level' (particularly in the lower area) is causing 'Drainage problems in plots', again with sever impacts on the 'Agricultural productivity'. Furthermore, there is a widespread unconscious and excessive water use, also due to the low level of 'Environmental awareness' and producers in the outlet parts of the irrigation network cannot access sufficient irrigation water. Producers who cannot reach the irrigation water they need must obtain water from the drainage channels by pumping.

'Agricultural sustainability' is increasingly under threat due to issues with 'Agricultural productivity' e.g., due to the 'Soil fertility' loss and, more in general, to the impacts related to the increasing population (and related 'Urbanization'), 'Industrial activities', increasing 'Use of agricultural inputs' and related costs. Consequently, the 'Environmental conditions' of the area seriously decreased over the years, particularly in terms of biodiversity. Climatic fluctuations (and 'Climate change') and environmental effects seriously contribute to disrupt the balance in the ecosystem. The following CLD (Figure 22) includes a preliminary description of the pilot area based on the Baseline documents. All variables are in **black**, except for socio-institutional variables, which are represented in **red**.

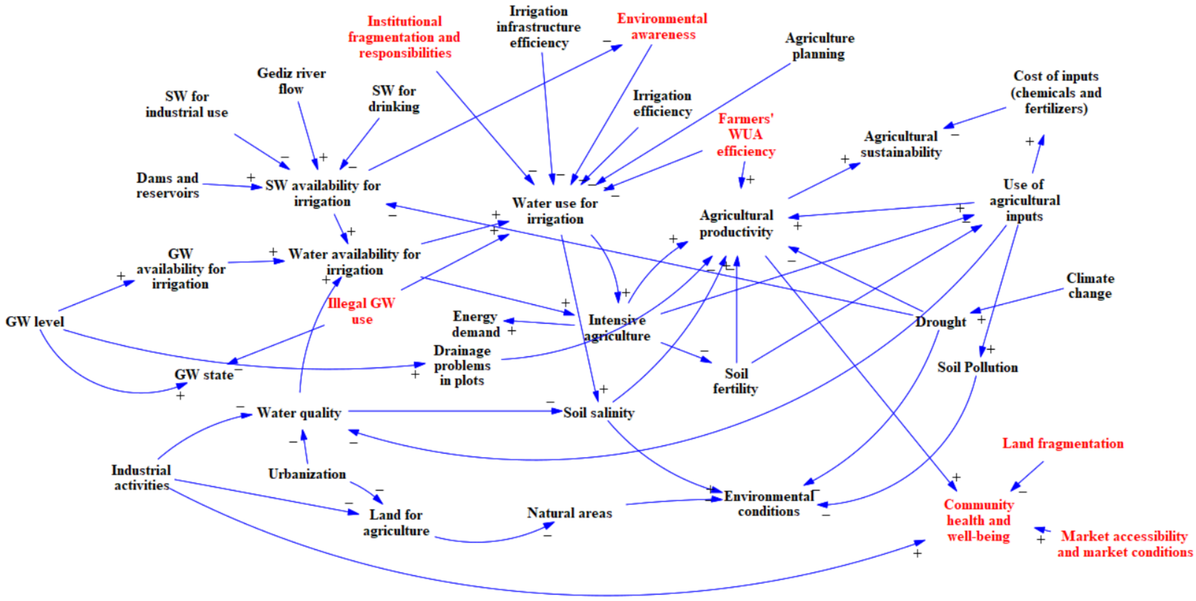

Figure 22 Preliminary 'Baseline' version of the CLD developed for the Menemen pilot

Following the 1st stakeholder meeting (which was organized in December 2021) and a preliminary round of interviews (21 participants were consulted), a few elements emerged that allowed better focusing and characterizing the pilot area. In particular, based on the interview framework, this phase of consultation was mainly oriented to characterize the main needs (and, potentially, the related barriers) for the different Nexus domains.

Referring to the water domain, the most important issues identified by the stakeholders are related to **water quantity and water quality**, mainly as far as **irrigation activities and water allocation planning** are concerned. The losses of water irrigation system and limited efficiency were also mentioned as highly relevant. In general, the role of climate change and related impacts are associated to heavy impacts on water resources.

Similarly, in the ecosystem's domain the impacts of climate change are perceived as highly relevant. Land use (and cover change) are heavily impacting the **state of the environment**, which is also threatened by the progressing **soil degradation**. The significant water demand for productive activities also creates a potential imbalance for environmental flow.

In the agricultural field, the main need identified by the stakeholders is related to **irrigation water accessibility**. Other issues that were mentioned as rather important are **the land fragmentation** and the decrease of rural population, as well as the increasing impacts of climate change on agricultural activities. The role of specific policies and subsidies has been already identified as highly relevant to solve sectoral issues. Based on the evidence from stakeholder consultation, the CLD has been revised as in the following Figure 23. Variables added based on the evidence of participatory exercises have been underlined, while **purple** connections were added based on the information provided by the stakeholders.

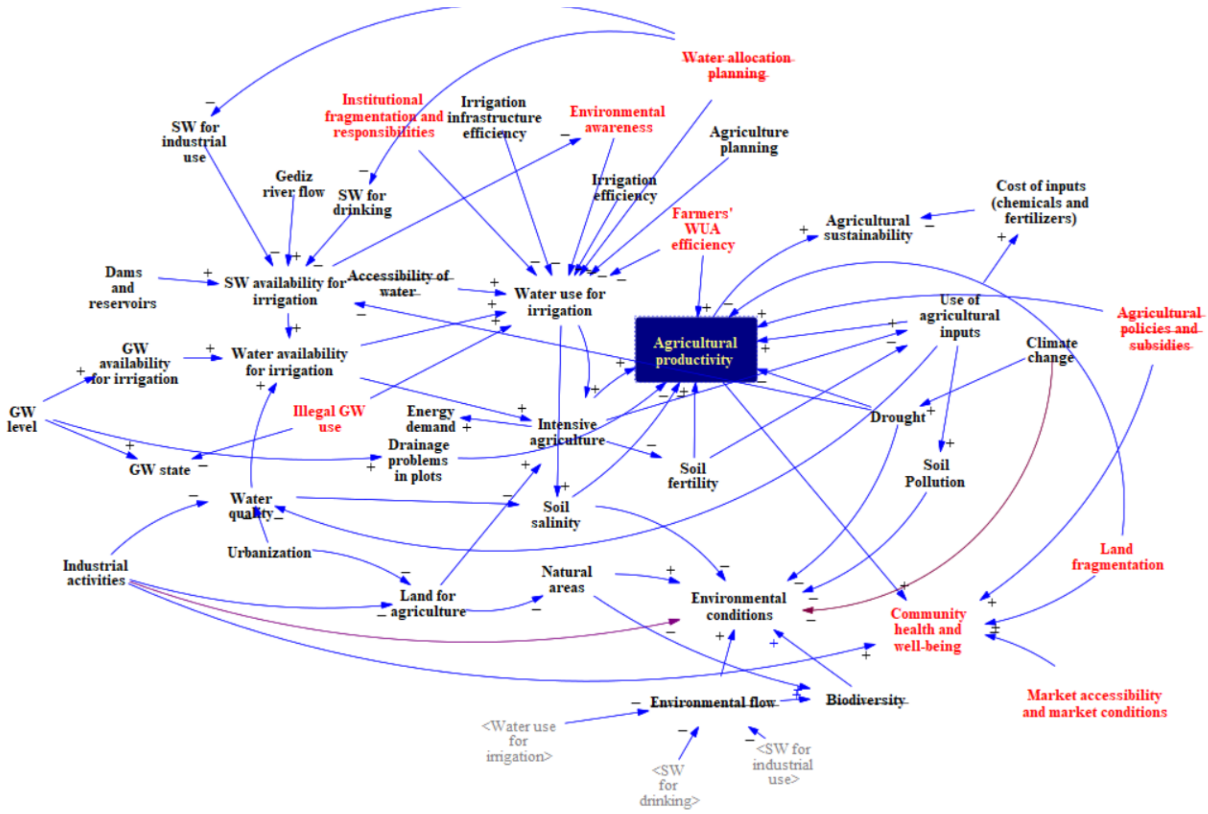

Figure 23 Revised version of the CLD developed for the Menemen pilot

The analysis of 'causes trees' and 'uses trees' has been performed with reference to the Menemen CLD, focusing on the variable 'Water use for irrigation', which has been considered as target variable. Causes and uses trees are represented in Figure 24 a) and b). As highlighted for the Pinios model, the problem of 'water use for irrigation' is again multifaceted and depending on a multiplicity of aspects. Basically, it directly depends on technical aspects that are reflected by the 'water availability for irrigation' and the 'accessibility of water'. However, a strong dependency is also evident on other variables that describe the socio-institutional conditions and constraints, such as the 'Farmers' WUA efficiency', the 'Illegal GW use' and the 'Institutional fragmentation'. Similarly, there are manifold impacts connected to the 'water use for irrigation', ranging from the 'Environmental flow' (which has cascading impacts on both 'biodiversity' and 'environmental conditions'), to the 'Soil salinity', to the development of 'intensive agriculture' (which is also related to other aspects such as the energy demand and the increasing use of chemicals in agriculture).

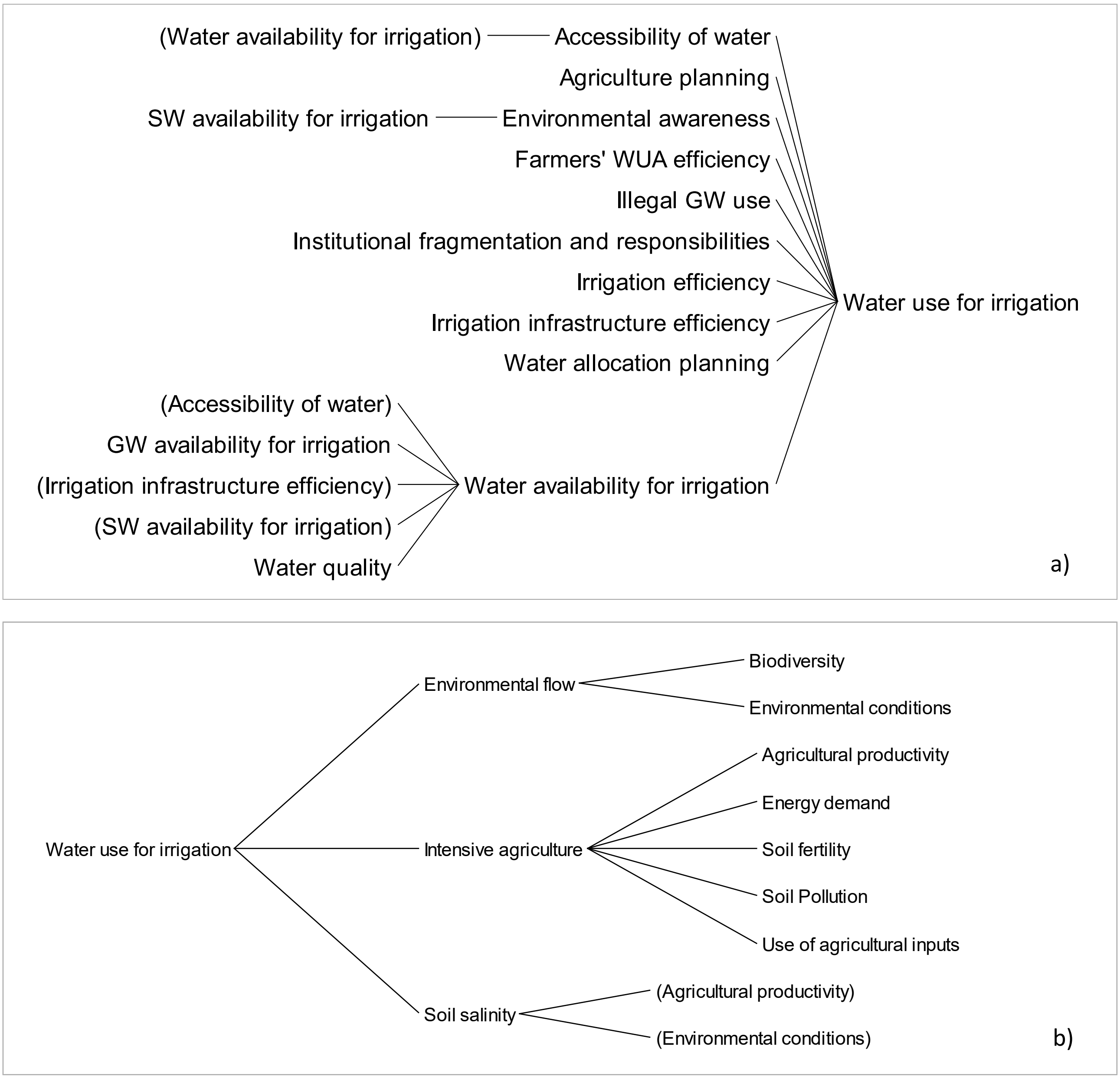

Figure 24 Causes and uses trees for the variable 'SW use for irrigation' for the Menemen pilot

The final version of the CLD was then translated into the Kumu version, to take advantage of the main features of the software (including among the others, the computation of graph theory metrics). The 'Kumu' version of the CLD has been further revised, to account for additional information coming from other phases of the participatory process. In particular, interviews and questionnaires have been performed by the pilot leaders mainly to better understand the potential impacts of Nature-based Solutions on the most relevant challenges for the area, and to highlight the major barriers to their implementation. The final version of the CLD is presented in the following Figure 25, and is available at the following link: MENEMEN - CLD.

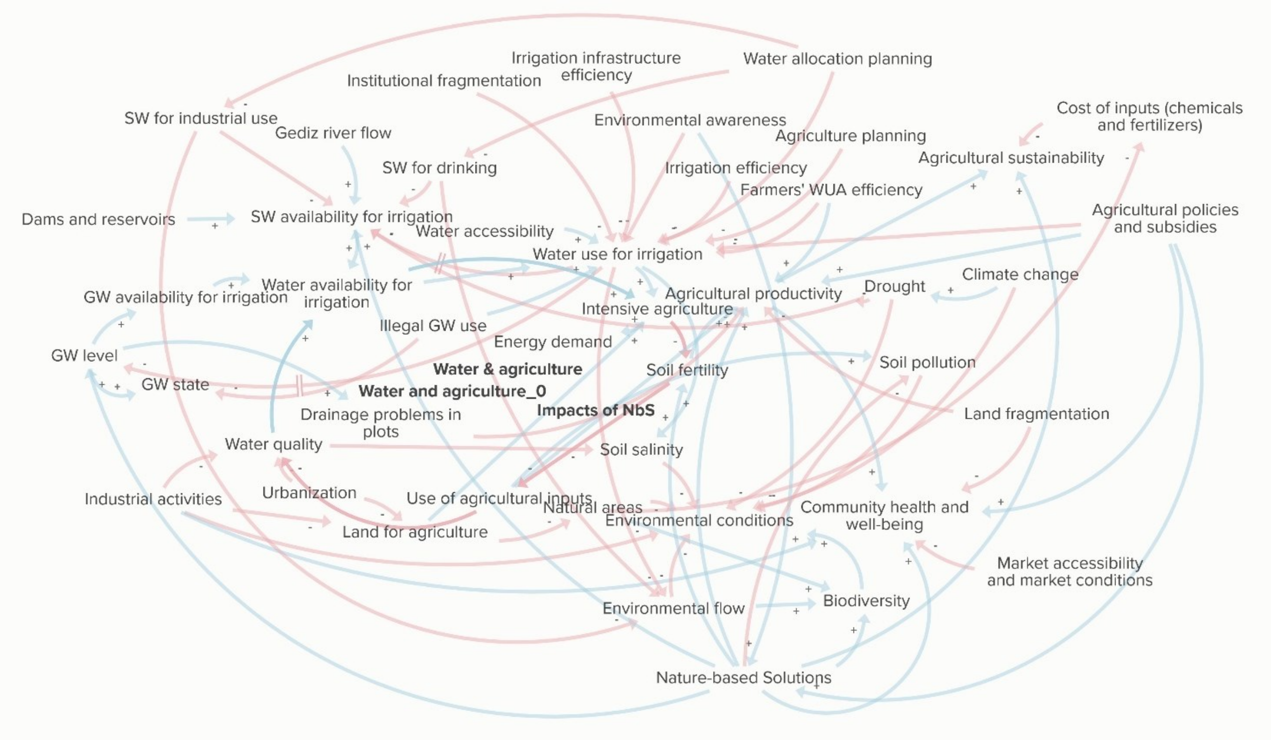

Figure 25 Revised version of the CLD developed for the Menemen pilot (KUMU)

Following the approach detailed in Section 3, the CLD has been explored using selected graph theory measures. 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 identifying Nexus challenges.

The analysis clearly highlights that the key challenge for the Menemen area is related to the interplay between water resources availability and use and agricultural practices. Going further into details, the high-ranked variables in terms of Centrality include on the one hand 'Water use for irrigation' (Degree centrality 16, Betweenness centrality 0.169, Eigenvector centrality 0.048), 'SW availability for irrigation' (Degree centrality 9, Betweenness centrality 0.099) and 'Water quality' (Degree centrality 5, Betweenness centrality 0.041), on the other hand 'Agricultural productivity' (Degree centrality 11, Eigenvector centrality 0.113), 'Agricultural sustainability' (Eigenvector centrality 0.092), 'Intensive agriculture' (Degree centrality 6, Betweenness centrality 0.094, Eigenvector centrality 0.062) and 'Community health and well-being' (Degree centrality 6, Eigenvector centrality 0.08). The analysis also shows that the role of environmental issues is highly relevant, as the 'Environmental conditions', along with the 'Environmental flow' are among the high-ranked variables (Degree centrality 8 and 5, Eigenvector centrality 0.08 and 0.03 respectively). Additionally, the decrease of 'Soil fertility' (Betweenness centrality 0.063, Eigenvector centrality 0.048) is mainly due to agricultural malpractices and could directly have a cascading negative impact on the agricultural productivity and sustainability on the long term. It is worth highlighting that the role of 'Environmental awareness' is also crucial (Betweenness centrality 0.056), as its low state in current conditions is also a serious limit for the sustainable development of the area, as it affects both the uncontrolled water demand for irrigation and the limited uptake of Nature-based Solutions. Interestingly, the role of Nature-based Solutions, that have been identified and discussed as key measures for the area is also rather central (Degree centrality 10), as they are highly interconnected with several variables belonging to multiple sectors. Among the main bottlenecks or barrier related to the main challenges of the system, besides the 'Environmental awareness' the analysis attributes a central role to the excessive 'Use of agricultural inputs'.

A summary of the main Nexus challenges and related centrality measures is provided in the following Table 8.

Table 8 Nexus challenges for the Menemen case study.

Nexus challenges	Centrality measures
Water use for irrigation	High centrality degree; high betweenness centrality, High eigenvector centrality
Agricultural productivity	High centrality degree; high eigenvector centrality
Intensive agriculture	High centrality degree; High betweenness centrality; High eigenvector centrality
Environmental conditions	High centrality degree; high eigenvector centrality
Soil fertility	High betweenness centrality, high eigenvector centrality

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 one loop whose role looks highly relevant with respect to the abovementioned Nexus challenges.

The 'Water & Agriculture' feedback loop represented in Figure 26 (a balancing loop) is central for understanding the interplay between water resources state and agricultural activities, and for understanding system state and evolution with respect to some of the main challenges identified above. An increase in 'Water use for irrigation' (due e.g., to the lack of planning of agricultural activities at regional scale) can facilitate the development of 'Intensive agriculture', which has a detrimental impact on 'Soil fertility'. As the soil fertility decreases, the increased need for 'use of agricultural impacts' has a cascading negative impact on 'water quality'. The reduction of water quality causes a reduction of 'water availability for irrigation', which then poses a limit to the use of water for irrigation and, ultimately, to the development of agricultural sector.

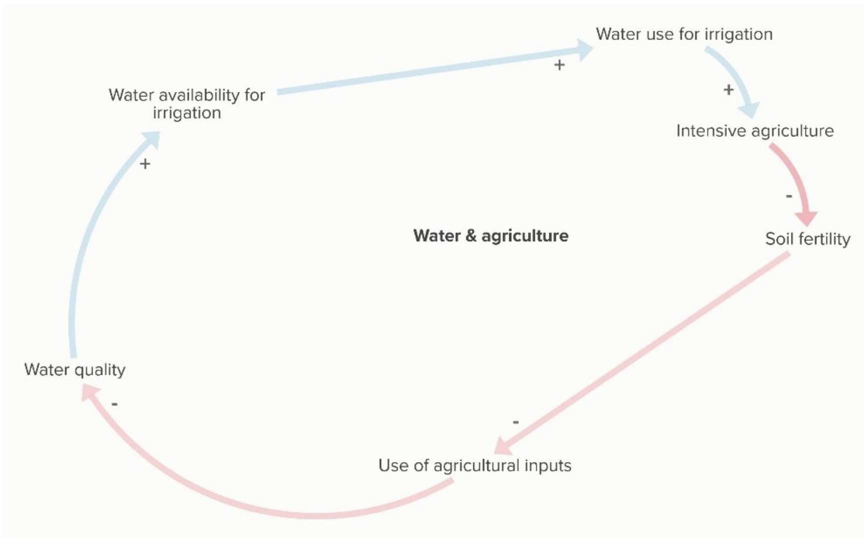

Figure 26 Focus on 'Water & agriculture' feedback loop in the Menemen river basin CLD (KUMU)

As detailed in the methodological section, 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 – is used to support the leverage analysis. The variable characterized by the highest closeness centrality value is represented by the ‘Nature-based Solutions’ (Closeness centrality 0.304), which can directly intervene on multiple variables within the above loop e.g., guaranteeing an improvement in ‘Water quality’ through the potential that several NbS have in terms of pollutants removal, as well as an increase in ‘Water availability for irrigation’ and an increase in ‘Soil fertility’. Among the high-ranked variables in terms of Closeness centrality, a key role is played by ‘Agricultural policies and subsidies’ (0.264) which can directly impact the ‘Water use for irrigation’ but also facilitate the implementation of ‘Nature-based Solutions’ (e.g. supporting the uptake of sustainable irrigation and agricultural practices) with positive effects on all Nexus sectors. Among the potential leverage points, it is worth also to highlight the role of ‘Environmental awareness’ (0.240), that can contribute both to reduce ‘Water use for irrigation’ and to facilitate the introduction of ‘Nature-based Solutions’. Similarly, an improved ‘Water allocation planning’ (0.229) can help optimizing the use (and state) of water resources in all productive sectors. This result shows that besides ‘structural’ actions, there are a few policy and economic initiatives that can be rather easily implemented for supporting the sustainable development of the area, while guaranteeing the well-being of local communities.

A summary of the results of the leverage analysis is provided in Table 9.

Table 9 Results of the leverage analysis for the Menemen case study.

Nexus challenges	Leverage points
Water use for irrigation	Water allocation planning Nature-based Solutions Farmers’ WUA efficiency Agricultural policies and subsidies
Agricultural productivity	Farmers’ WUA efficiency Agricultural policies and subsidies Nature-based Solutions
Intensive agriculture	Nature-based Solutions Agriculture planning Illegal GW use
Environmental conditions	Nature-based Solutions Use of agricultural inputs
Soil fertility	Nature-based Solutions Use of agricultural inputs

4.6. Koiliaris pilot area

The Koiliaris River watershed 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 uses are related to intensively grazed shrubland and pasture; olive, citrus groves, vines, and vegetables; and mixed forest. The drainage network consists mainly 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. Full details on the area are provided in the D8.1.

The main challenge for the area is the **development of sustainable agricultural activities**. Although water is relatively abundant (currently) over the area, it is poorly managed. The specific challenge for the water sector is therefore to improve water resources management of the watershed, considering both the biophysical conditions (e.g. seasonal fluctuation of the spring flow and impact of drought periods, as well as infrastructure conditions and efficiency) and the socio-institutional frame (e.g. lack of a single managing authority for water resources). In general, the main issues for irrigation are the need to use water of low quality because of high salinity, and the competitive water uses between irrigation, tourism, and local drinking water use, which also cause insufficient water supply in some areas. Regarding the food/land sector, the key issues are related to the high level of fragmentation, which gives no economy of scale, the low level of profit with key products such as citrus and olive oil, the lack of training and knowledge for farmers, which reflects also in the development of unsustainable agricultural practices.

In this framework, **avocado farming** is becoming increasingly relevant for the area as it is a dynamic new crop with good price. In terms of water quantity, it mainly relies on drip irrigation and faces issues with the lack of infrastructures which causes impacts on irrigation particularly during drought periods. However, the main issue is related to water quality, as the high Cl concentration may affect the quality of production.

The area is also affected by significant environmental/ecosystem challenges, and particularly: i) there are significant livestock impacts especially in NATURA areas; ii) there is a significant erosion rate due to land use practices (tilling) even in areas with high slope; iii) urbanization associated to ineffective (or unavailable) sewage systems are impacting the springs; iv) the intensive agriculture requires heavy fertilization, pesticide and herbicide applications; v) abandoned terraces contribute to erosion and soil degradation.

The evidence from the baseline description of the Koiliaris area has been summarized in the CLD proposed in the following Figure 27. The CLD mainly represents bio-physical dynamics and preliminarily includes socio-institutional variables. Following the colour-code used in the other Figures, variables are typically in **black**, while shadow variables are in **grey**. All variables defining socio-institutional aspects are identified in **red**, while potential measures/solutions preliminarily identified have been included in **blue**.

The CLD is based only on the preliminary information on the pilot area, integrated with background scientific information provided by the TUC team, which has been particularly active over the area in the last few years (Lilli et al., 2020; Tzanakakis et al., 2020).

On the 26th of October 2022 an in-person meeting has been organized at TUC, in order to perform a validation of the most relevant dynamics described by the model. The validation was mainly performed considering three steps: i) the identification of key challenges for the area, with the selection of the most important variables to analyse (target variables) and their short description; ii) a systematic analysis of the 'causes trees' and 'uses trees', i.e. the chains of variables affecting and being affected by the target variables; iii) a preliminary selection of potential feedback loops to be further analyzed. An additional activity was specifically oriented to discuss the models available from the TUC for the area (e.g. Karst-SWAT), and how the results of those models can be integrated into a quantitative stock and flow model.

The following Figure 28 represents an example of the step ii) of the analysis, with the isolation of the causes and uses trees for the variable 'Soil degradation'. The same analysis has been performed for the following additional target variables, directly contributing to produce a revised version of the model represented in Figure 29: a) environmental conditions (renamed from 'state of natural areas' in the previous version); b) agricultural productivity; iii) irrigation water budget; iv) livestock grazing; v) biodiversity; vi) agricultural sustainability.

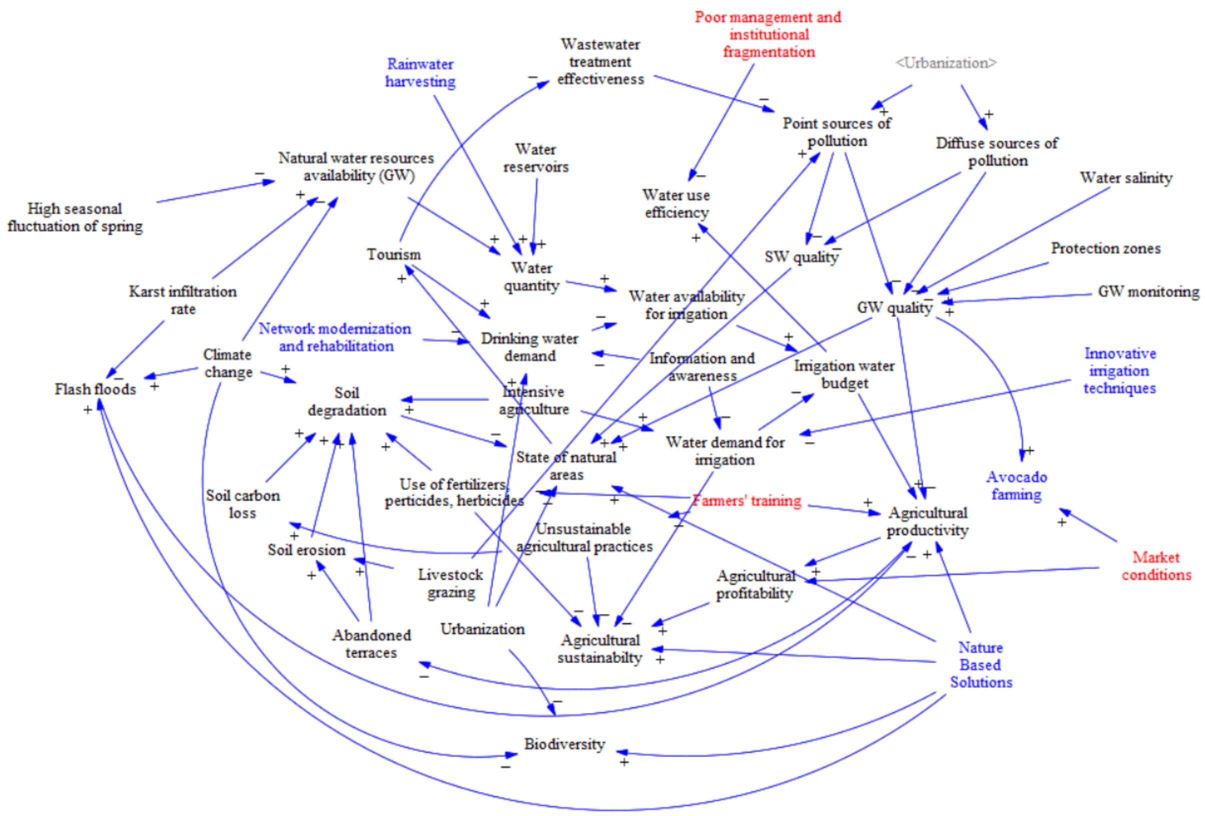

Figure 27 Preliminary 'Baseline' version of the CLD developed for the Koiliaris pilot

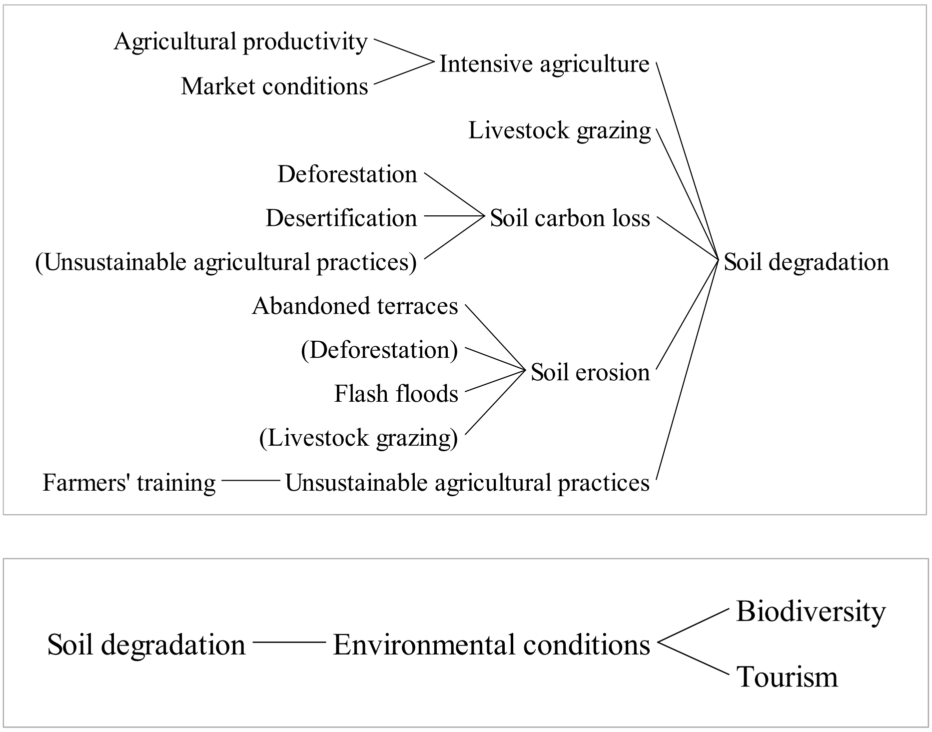

Figure 28 Causes and uses trees for the variable 'Soil degradation' for the Koiliaris pilot

The variables represented in red in the Figure 29 mainly identify the key socio-institutional variables that emerged from the analysis and that need to be further described and analysed. In this direction, we decided to develop - in parallel – a more detailed CLD focusing specifically on the analysis of farmers' behaviour in terms of innovation adoption. This should clearly provide an overview of the opportunities and bottlenecks related to innovation in agricultural practices.

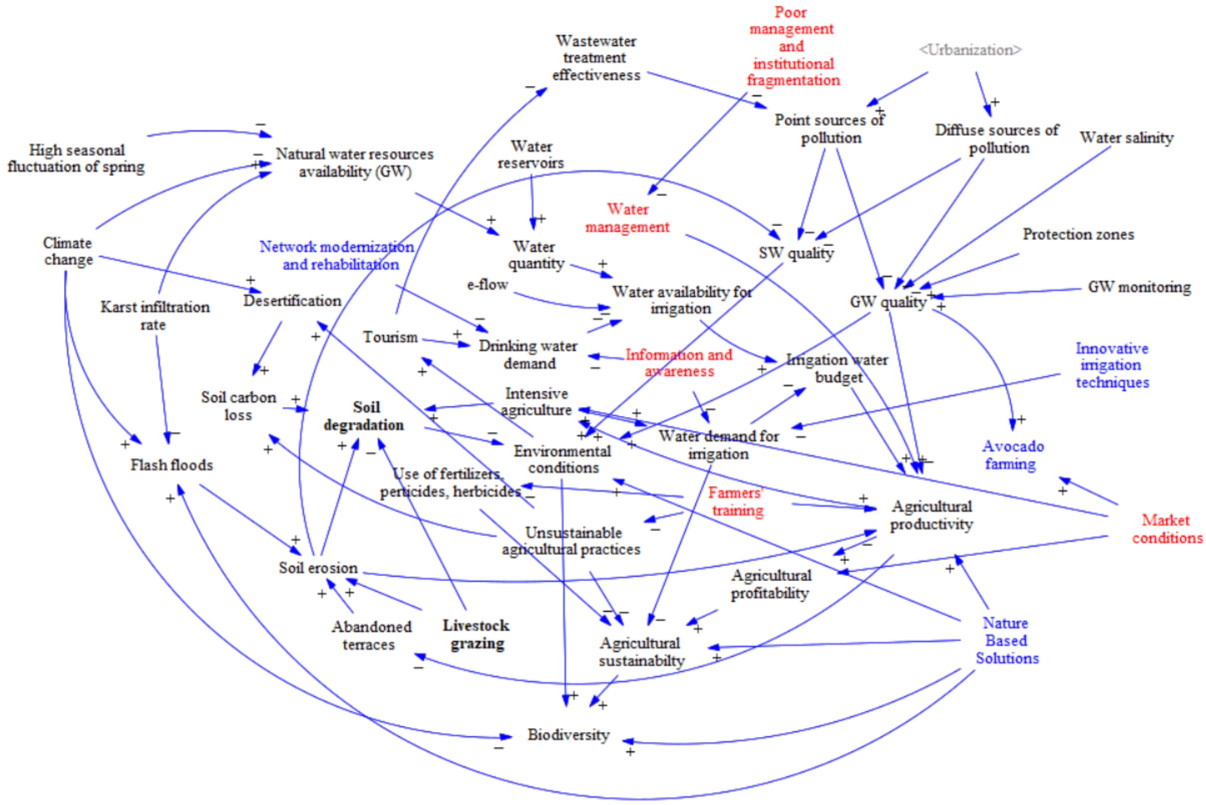

Figure 29 Revised version of the CLD developed for the Koiliaris pilot (VENSIM)

In order to improve the quality of information related to the socio-institutional aspects, a specific framework for interviewing the local farmers has been proposed. The format chosen for the first step of participatory activities, which has been performed on the 25th October 2022 with the direct support of the TUC team, was the **focus group**. Basically, the local pilot leaders identified two different groups of avocado farmers (which are getting increasingly central for the agricultural activities in the area), one organized in the form of an association/cooperative and the other one operating independently. The key information collected during the focus groups, mainly concerned the current state, barriers and potential for innovation in avocado farming (e.g. the role of land fragmentation). Particular attention has been given to the perceived gaps to be filled to substitute the current irrigation practice with innovative ones. Specific reference has been made to a couple of barriers, i.e. the lack of knowledge/expertise and the lack of fundings. Referring to knowledge gaps, details have been asked on knowledge/information needed, knowledge/information providers and forms of knowledge/information sharing to support innovation uptake. The relationships with other farmers and the influence of their form of aggregation have been also discussed. Referring to the lack of funding, information were asked on the main economic barriers (i.e. the perceived risk of reduced yield in case of innovation, or the costs for introducing the innovation) and the information needed to reduce the perceived risk of reduced yield. The evidence from the focus groups (which was performed in the local language) has been included in the final version of the CLD.

The final version of the CLD was then translated into the Kumu version (Figure 30), to take advantage of a few features that the software has (including among the others, the computation of graph theory metrics). The model is available at the following link: KOILIARIS - CLD

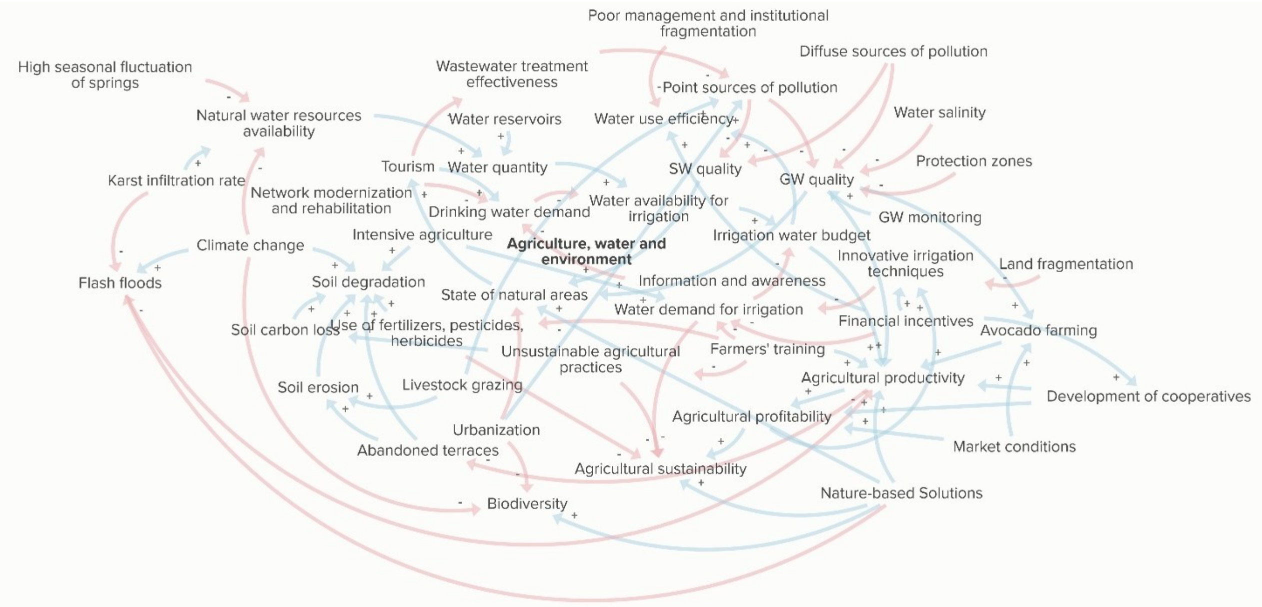

Figure 30 Revised version of the CLD developed for the Koiliaris pilot (KUMU)

The CLD has been explored through the analysis of selected graph theory measures, following the approach described in the Section 3. As already mentioned, 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 identifying 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 direct 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 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 10.

Table 10 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

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 Figure 31 (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'. This can drive a decrease of 'Agricultural profitability'. As lower profits can hamper the spread of innovation in agriculture, a reduction 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.

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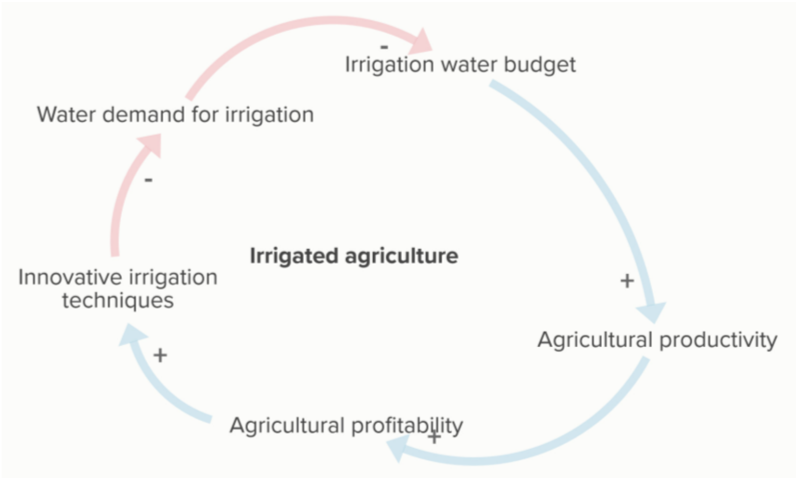

Figure 31 Focus on 'Irrigated agriculture' feedback loop in the Koiliaris river basin CLD (KUMU)

Among the other loops present in the map, a balancing one named as 'Agriculture, water and environment' is shown in Figure 32, 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' because 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 of the attractiveness of the places for 'Tourism'.

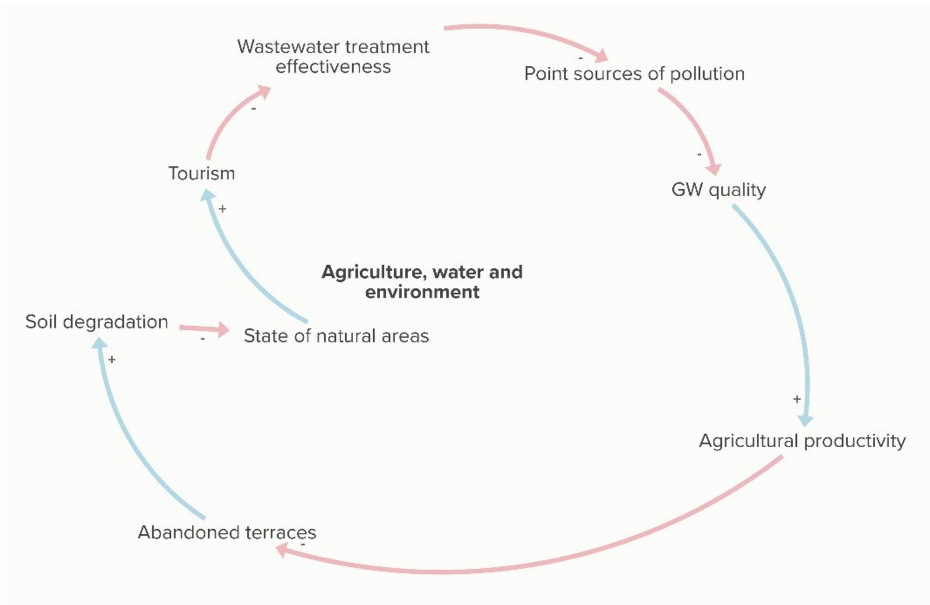

Figure 32 Focus on 'Agriculture water and environment' feedback loop in the Koiliaris river basin CLD (KUMU)

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 11.

Table 11 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 cooperatives Avocado farming
Soil degradation	Nature-based solutions Reduction of unsustainable agricultural practices Farmers' training
State of natural areas	Nature-based Solutions Protection zones Reduction of intensive agriculture
GW quality	Reduction of the diffuse sources of pollution Protection zones GW monitoring
Irrigation water budget	Farmers' training Network modernization and rehabilitation

4.7. Deir Alla pilot area

Overview

The Jordan valley is water-scarce, energy-poor, and home to a rapidly growing population. A relevant part of the population lives in rural areas and depends primarily on agriculture, mainly as livestock keepers and smallholders of farm households. Agriculture is thus still an essential source of employment in rural communities. The study area is located below sea level, and this makes it warm in winter. Water for irrigation is available from the King Abdullah Canal, other dams, aquifers, and artesian wells.

Modern methods of farming have vastly expanded the agricultural output of the area. The overall efficiency of the Jordan Valley irrigation system is high; however, on-farm efficiency is still below 50 % in many cases. The quantity of freshwater available for agriculture is on a continuous decline, and its quality is continuously deteriorating due to the increased rate of its mixing with treated wastewater of high salinity, which has already resulted in increasing soil salinity.

Water management in Jordan is supply-based and, despite significant improvements in water-supply infrastructure, a critical and severe supply-demand imbalance remains. Jordan has been subjected to additional water stress due to the influx from neighboring countries impacted by political instability in the region. Finally, the potential decreasing precipitation in Jordan due to climate change could worsen the existing problems.

The area experiences pollution mainly due to wastewater, insecticides, and plastic. Salinization, soil-quality deterioration, and lack of fertility are emerging in many areas. It is expected that water consumption for potable, domestic and industrial purposes will increase at the expense of irrigated areas and that increased quantities of wastewater will be mixed with irrigation water for agriculture. An increase in the number of dams is also expected, along with an increase in cultivated lands.

PSDM

The following Figure 33 includes an overview on the CLD developed at the end of the process described in the Section 3. The model is available at the following link: [DEIR ALLA - CLD]

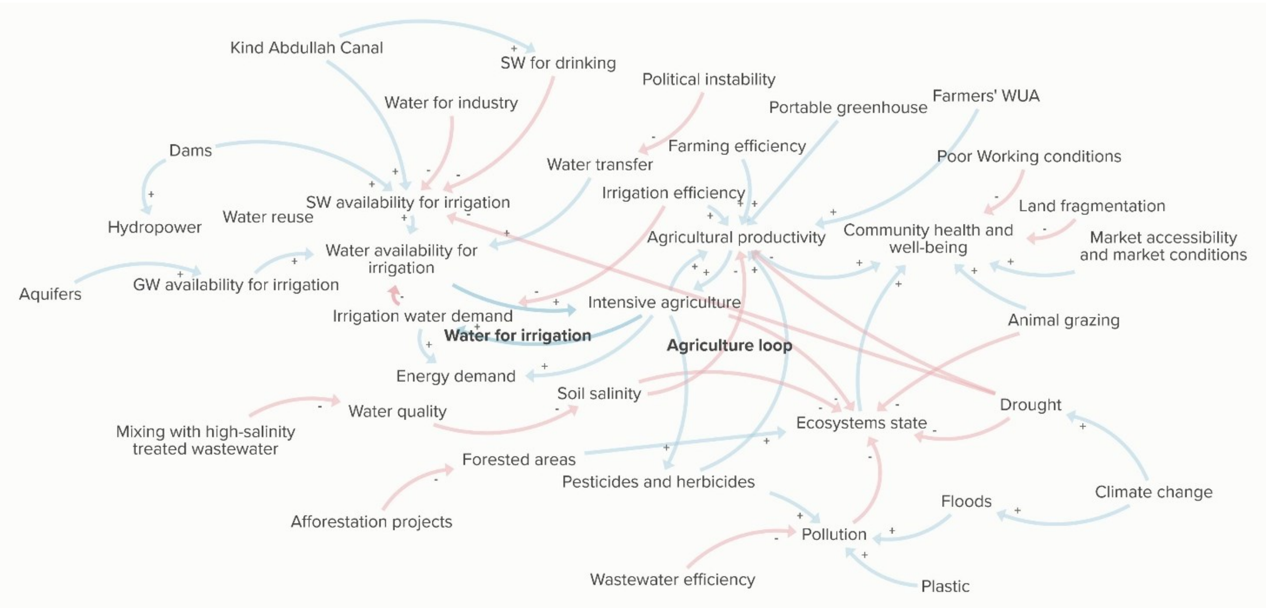

Figure 33 Revised version of the CLD developed for the Deir Alla pilot (KUMU)

The CLD has been analyzed using graph theory measures, following the approach described in the Section 3. As already mentioned, 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 identifying Nexus challenges.

The analysis suggests that a central role in the CLD is played by water and, in particular, by water use for irrigation purposes. Both the 'SW availability for irrigation' and the 'Water availability for irrigation' have a high centrality (Degree centrality 7 and 5; Betweenness centrality 0.035 and 0.065 respectively). Agricultural activities are also vital for the area, as confirmed by the centrality of 'Agricultural productivity' for 'Community health and well-being' (Degree centrality 6 and Betweenness centrality 0.053; Degree centrality 5, respectively). The centrality analysis also reveals a critical role of 'Ecosystems state' (Degree centrality 5) and the threat of 'Soil Salinity' (Betweenness centrality 0.014) and 'pollution' phenomena (Degree centrality 5).

A summary of the main Nexus challenges and related centrality measures is provided in the following Table 12.

Table 12 Nexus challenges for the Deir Alla case study.

Nexus challenges	Centrality measures
Agricultural productivity	High degree centrality; high betweenness centrality
SW availability for irrigation, Water availability for irrigation	High degree centrality; high betweenness centrality
Ecosystems state, Soil salinity	High degree centrality; high betweenness centrality
Community health and well being	High degree centrality

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 those more relevant for the Nexus challenges.

The analysis of the loops highlights a couple of rather simple loops that need to be taken into account for the analysis. With specific reference to Figure 34a, a balancing loop refers to the 'Water for irrigation' dynamics. It basically highlights that an increase in 'Water availability for irrigation' might increase the role of 'Intensive agriculture' which produces, as a result, an increase in 'Irrigation water demand' which ultimately reduces the water availability for irrigation. An imbalance might be caused by external elements that can interfere with the loop. Among the others, all the elements that can affect the water availability for irrigation (e.g. droughts or other water uses, as well as water reuse and water transfer initiatives). The dynamic described by the loop has also relevant impacts on the rest of the system, such as the 'ecosystem state', which is directly affected by 'intensive agriculture' practices. This also relates to the role of the reinforcing loop in Figure 34b, which basically shows that an increase in the use of 'Pesticides and herbicides' might increase the 'Agricultural productivity' and, in cascade, push towards a further development of 'Intensive agriculture'. The impact would be a further increase in the use of chemicals, with a detrimental effect on the ecosystems state due to an increase in the level of pollution.

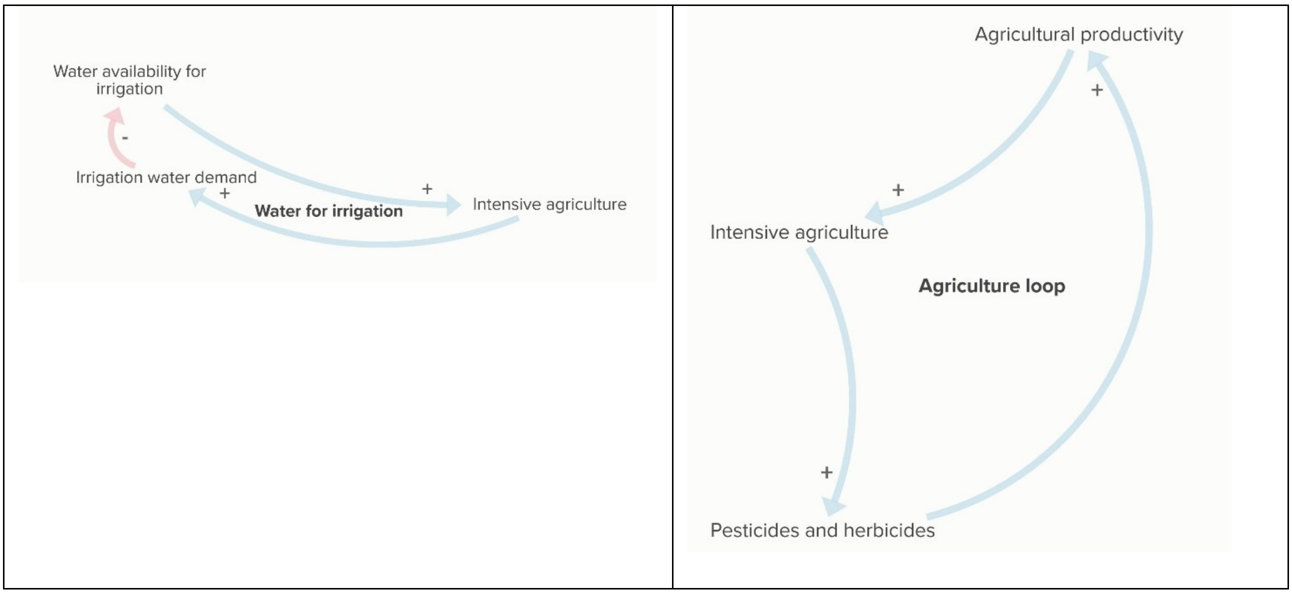

Figure 34 Focus on the main loops for the Deir Alla pilot (KUMU): a) 'Water for irrigation' loop, b) 'Agriculture' loop

The identification of potential leverage points for the system is based 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.

Besides highlighting the crucial role of some external drivers on system evolution (e.g., 'climate change' and 'drought' both have a closeness centrality equal to 0.155), the analysis shows some potential points of intervention. Acting on the 'intensive agriculture' (closeness centrality 0.176) and related impacts could be highly effective, provided that suitable actions are identified (e.g., identification of new/different crops and more sustainable practices). Among those, increasing the 'irrigation efficiency' (closeness centrality 0.133) and reducing the use of 'pesticides and herbicides' (closeness centrality 0.199) are potentially the most impactful actions. Interestingly, additional measures that can positively impact system state and evolution are related to the development of 'Farmers' WUA' (closeness centrality 0.104), to the increase of 'farming efficiency' (closeness centrality 0.104) and to 'portable greenhouse' systems (closeness centrality 0.104)

4.8. Doñana pilot area

Overview

As detailed in the baseline description, the water resources - both superficial and groundwater - play a key role in the Nexus management in the area. The water resources are crucial for the quality of the ecosystem and for agricultural production. The Doñana social-ecological system (southwestern Spain) provide numerous ESs which rely upon the use of water resources for being produced and used. External drivers, such as climate change and market demand, are exacerbating the conflicts over the use of water resources, creating clear trade-offs between the local conservation of the ecosystem and the global market values of such ESs

PSDM

A description of the preliminary version of the CLD developed for the Doñana pilot area has been provided in the D4.1 and summarized in the present section. The following Figure 35 includes an overview on the CLD developed at the end of the process described in the Section 3. The model is available at the following link: DONANA - CLD.

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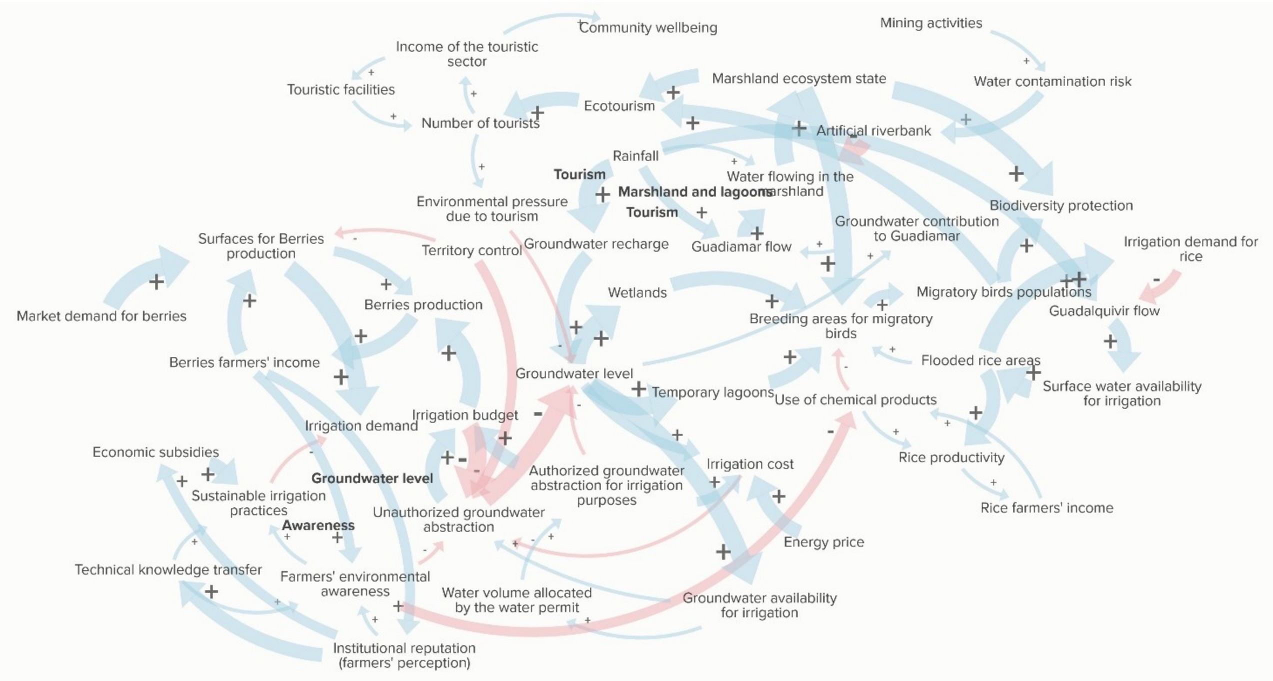

Figure 35 CLD for the Doñana case study

The CLD maps the complex web of interactions among the different elements affecting the sustainable WEFE Nexus management. The links are characterized by different weights, representing the strength of the causal connection, and assigned accounting for the stakeholders' perception.

Three main ecological resources contribute to the production of the ESs, namely the Guadiamar River, the Guadalquivir River and the different aquifers. Specifically, the Guadiamar River - in natural conditions - contributes to the periodic flooding of the Doñana marshland and, in doing so, increases the quality of the ecosystem and protects biodiversity. The Guadalquivir River is currently used to provide surface water for agricultural production. Finally, the aquifers have a twofold role. On the one hand, they are used for providing water for irrigation purposes - i.e. water provisioning for agriculture. On the other hand, the aquifers feed the several wetlands dislocated at the margins of the main marshland. Those wetlands play a key role in biodiversity conservation since they are used as breeding areas by several species of migratory birds - e.g. water provisioning for the ecosystem. This complex wetland system is at risk of extensive ecological damage. According to Green et al (2023) groundwater withdrawals are worse than previously thought, reaching up to 20 m, and have phreatic levels have been lowered from 0.5 to 2 m in some areas. The impacts of groundwater abstraction are particularly strong in temporary ponds and marshes. Another issue that is pointed at and that has been previously underestimated, are the impacts of the use of agrochemicals for irrigated crops, both on GW and SW.

The CLD clearly shows that one key aspect is the conflict over the use of water resources between agricultural production and ecosystem conservation. The first conflict to be analyzed is the one related to the use of groundwater for irrigation. The study area is characterized by five aquifers, among which the aquifers "La Rocina", "Almonte" and "Marismas" have been officially declared as overexploited (bad quantitative status). This area is characterized by large and intensively cultivated farms, mainly with berries (i.e. strawberry, blueberry, raspberry and blackberry). During the interviews, we learned that the main water source for irrigation is the groundwater since the irrigation network distributing surface water (from the river Guadalquivir) is absent in this part of the study area. Berries are considered highly remunerative crops in the area. Therefore, farmers tend to increase the areas used for berry cultivation (intensive agriculture). This, in turn, provokes an increase in the water demand and, thus, the use of groundwater for irrigation purposes. The farmers' perception of the GW as a reliable and almost infinite water resource activates the loop.

Illegal pumping of the GW for irrigation purposes is also a key behaviour within the farming dynamics. This behaviour is provoked by the need to obtain more water volume in order to increase agricultural production. The key variable in this section of the CLD is the "irrigation budget". Farmers perceive the allocated water volume - i.e. the water permits - as not enough for meeting the irrigation demand due to the intensive agriculture. The excessive exploitation of GW for irrigation purposes is negatively affecting the level of the GW, thus, reducing its contribution to the temporary lagoons and wetlands that represent key resources for the migratory birds. Maintaining the quality of the ecosystem and preserving the biodiversity plays an important role in producing the cultural ES and, thus, in the increase of eco-tourism. Moreover, the GW low level is negatively affecting its contribution to the Rocina stream flow, with a negative impact on the process of the winter flooding of the Doñana marshland and, consequently, on the state of the ecosystem.

The Guadiamar river flow is a key resource for the marshland ecosystem. The winter flooding of this river is the main source of water for the ecosystem. Two main human interventions are reducing the Guadiamar contribution to the marshland ecosystem, i.e. the channelization of the river and the creation of several barriers along the river course. The first intervention dates back in the Sixties and it aimed at reclaiming land for agricultural production. The second intervention was implemented after the collapse of the dam that was storing mining waste (with high concentration of heavy metals and other toxics) from Aznalcollar mining area. However, the barriers create obstacles to the natural flow of the Guadiamar water into the small channels. Although some restoration activities have been performed, the combination of the reduction of the autumn rainfall due to the impacts of climate change and the barriers along the Guadiamar river are drastically reducing the contribution of this river to the quality of the marshland ecosystem.

The last ecological resource playing a key role in the achievement of nexus security is the Guadalquivir river, whose water is used for irrigating the rice plantation. As shown in the model, rice cultivation is a key economic resource for the local wellbeing. Due to the situation of droughts in recent years, the Guadalquivir river Basin Authority has been systematically reducing the water quotas for rice cultivation, which halved what was previously been allocated per hectare in a normal year. Without compensation to rice farmers, the current situation is that of a negative impact on the local wellbeing. The response of many farmers has been to sell their water permits[2]. Therefore, changing the crop is still considered a highly conflictual solution. However, the rice cultivations do not directly affect the Doñana ecosystem, because the Guadalquivir river is not directly connected with the marshland and/or the wetlands. The areas flooded for rice cultivation contribute to the ecosystem functioning because they are used as breeding and feeding areas by the migratory birds when there is a lack of water in the marshland and in the wetlands of the Doñana park. However, the combined impacts of the reduced rainfall and the excessive use of surface water for irrigation purposes are reducing the river flow and, consequently, it is allowing sea tidal intrusion in the river. This process is increasing the salinity of the river, whose quality is often not good for rice cultivation. Farmers are requiring the provision of more water of better quality. Therefore, there is the risk of an increase in the use of groundwater for rice cultivation, which could provoke a further increase in the pressure on the local aquifers (unlikely).

[2] https://elpais.com/espana/andalucia/2023-06-14/primera-venta-masiva-de-agua-en-andalucia-1333-piscinas-olimpicas-entre-sevilla-y-almeria.html

Tourism is also relevant over the area, yet with two different dynamics. Ecotourism mainly occurs inside the protected area, while seasonal tourism in the coastal village of Matalascañas. The latter uses GW from the protected area for its supply (drinking, swimming pools, hotels, etc.). Measures are being implemented to replace groundwater pumping that supplies Matalascañas with surface water from the Palos drinking water treatment plant.

The CLD has been analysed to detect the main Nexus challenges. To this aim, the Centrality degrees of the Graph Theory were implemented. The following Table 13 shows the Nexus challenges.

Table 13 Nexus challenges for the Doñana case study.

Nexus challenges	Centrality measures	Intersectoral interactions and meaning
Groundwater level	Centrality degree Closeness degree Betweenness degree	Water – water body Ecosystem – impacts on the wetlands lagoons and marshland Food – irrigation This variable is characterized by several direct and indirect connections. Moreover, it can rapidly affect the state of the other variables in the system (closeness). Finally, it could be a bottleneck for the system change (betweenness).
Unauthorized groundwater abstraction	Centrality degree Closeness degree	Water – impacts on the water body Ecosystem – negative impacts on the wetlands, lagoons and marshland. Food – irrigation efficiency This variable is characterized by several direct and indirect connections. Moreover, it can rapidly affect the state of the other variables in the system (closeness).
Mashland ecosystem state	Centrality degree	Water – water body Ecosystem – biodiversity protection Food – it is affected by the irrigation This variable is characterized by several direct and indirect connections.
Breeding areas for migratory birds and biodiversity protection	Centrality degree	Water – it is affected by the state of the water bodies Ecosystem – biodiversity protection Food – it is affected by the rice production (flooded areas) This variable is characterized by several direct and indirect connections.
Farmers' environmental awareness	Closeness degree	Water – it affects the irrigation demand in several ways

		Ecosystem – it affects the state of the water bodies Food – irrigation efficiency This variable can rapidly affect the state of the other variables in the system (closeness).
Tourism, Ecotourism and environmental pressures	Betweenness degree	Water – it is affected by the state of the water bodies and it could affect the groundwater level (overexploitation) Ecosystem – it is affected by the state of the ecosystem resources Food – no impacts This variable could act as a bottleneck for the system change (betweenness).

As shown in the table, the Nexus challenges have been selected among the most central elements in the CLD and have multi-sectoral impacts.

The CLD has been analysed to detect potential leverage points, i.e. elements in the system that can accelerate the impacts of policy interventions for addressing the above-mentioned nexus challenges. To this aim, the loops incorporating the challenges were isolated and discussed. However, since some of the challenges are connected, they have been merged in the loop analysis for detecting the leverage points, as shown in following.

The state of the value "groundwater level" is affected by several loops. The first one is a reinforcing loop connecting the farmers' income and the berries production areas (Figure 36). An increase in the farmers' income could lead to an increase in the berries areas. The groundwater level should act as a limiting factor, balancing the previously described reinforcing loop. As shown in the Figure, the decrease in the groundwater leads to a reduction in the water volume allocated to irrigation. In turn, this should lead farmers to reduce the berries areas to keep the irrigation demand at a sustainable level. However, the market demand is leading farmers towards an overexploitation of the resources through often unauthorized abstraction. The overexploitation of the groundwater is causing the degradation of different ecological resources, i.e. the temporary lagoons and the wetlands. The reduction of the groundwater level is also negatively affecting the Doñana marshland ecosystem state due to the limited contributions of groundwater to the Guadiamar baseflow.

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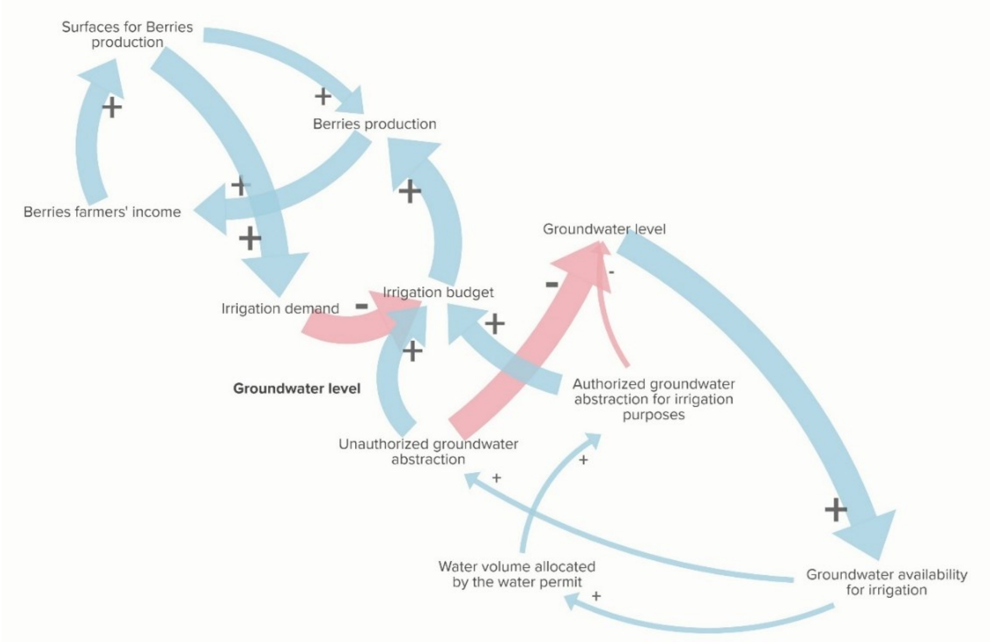

Figure 36 CLD for the Doñana case study: focus on the 'Groundwater level' loop

The loop analysis allows us to detect the leverage points. Firstly, to address this Nexus challenge, interventions should be implemented to limit the connection between farmers' income and the increase in berries areas. According to the developed CLD, this could be achieved by reducing the pressure of the market – i.e. consumers' behaviour, certificate of sustainability, etc. Secondly, interventions are needed to reduce the irrigation demand. Potential interventions are related to the adoption of innovative, more sustainable, irrigation practices. Thirdly, the farmers' behaviour represents a key leverage point, with specific reference to the unauthorized groundwater abstraction. Potential interventions are related to the enhancement of territory control and the increase of the farmers' environmental awareness. However, acting exclusively on these two elements could lead to a decrease in the farmers' perception of the institutional reputation which, in turn, could lead to a decreasing effectiveness of the technical knowledge transfer.

The following Figure 37 shows the loops affecting the dynamic evolution of these two interconnected challenges. The state of the ecosystem elements – i.e. wetlands, temporary lagoons and the Doñana marshland – strongly affects biodiversity protection with specific reference to the breeding areas for migratory birds. The key element affecting these variables is the rainfall. Climate change impacts are reducing the water inflow in the water bodies due the decreasing precipitation. Rainfall cannot be considered as a leverage point because no interventions can be defined to change the state of this variable. Therefore, the key points of intervention to address this challenge concern the conservation of the groundwater level and the increase of the Guadiamar contribution to the marshland. Concerning the first point, interventions are needed to reduce the exploitation of groundwater for irrigation purposes, as already discussed previously. To increase the contribution of the Guadiamar river to the marshland, interventions are needed to renaturalize the riverbanks. However, those interventions might lead to an increase in the water pollution risk.

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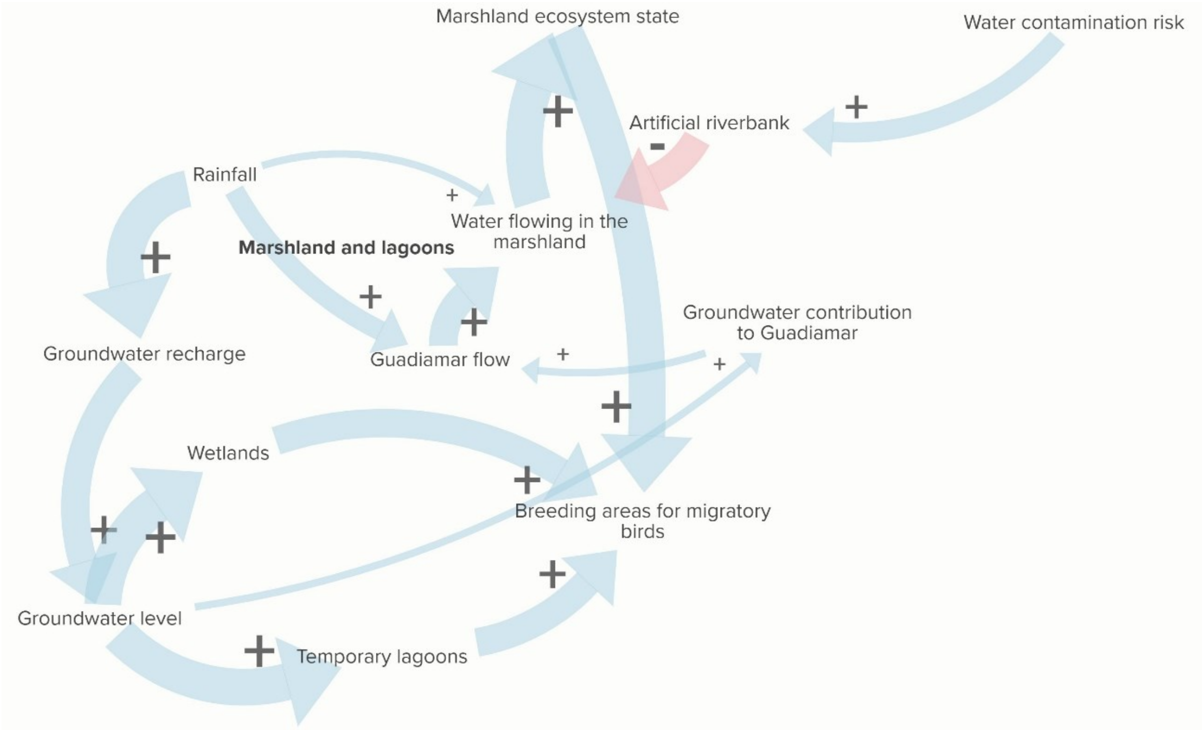

Figure 37 CLD for the Doñana case study: focus on the 'Marshland and lagoons' loop

As shown in the following Figure 38, the Farmers' environmental awareness could play a key role for the sustainable management of the WEFE nexus. Firstly, it affects the farmers' attitude towards the unauthorized use of groundwater for irrigation that, in turn, could significantly reduce the pressure on the groundwater. However, the dynamic evolution of the variable "Farmers' environmental awareness is affected by several limiting factors. For example, acting exclusively on the farmers' awareness could be ineffective due to the high influence of the variable "Farmers' income", as it affects the value of the institutional reputation that plays a key role in facilitating the adoption of innovative irrigation practices.

The analysis of this loop allows us to determine that, to be effective, any policy intervention aiming at increasing the farmers' environmental awareness should account for the need to keep the farmers' income at a satisfactory level.

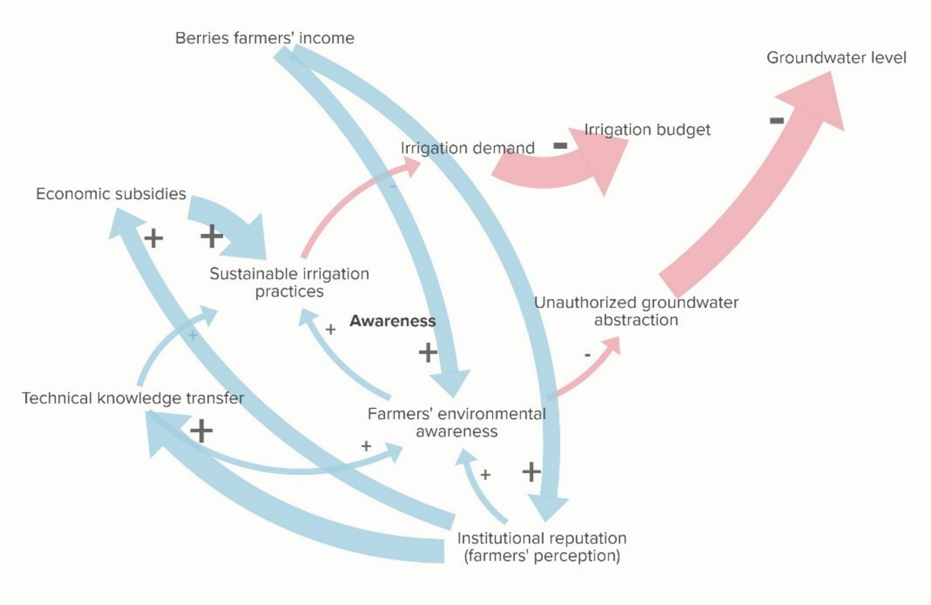

Figure 38 CLD for the Doñana case study: focus on the 'Farmer awareness' loop

The eco-tourism is a key economic resource for supporting the community wellbeing, although touristic activities might have severe impacts on the state of the system. In particular (Figure 39), an uncontrolled development of the touristic infrastructures could lead to an ever-increasing number of tourists and, thus, to an increasing pressure on the environmental resources, such as the groundwater. The analysis of this loop suggests that addressing this challenge requires interventions for deleting the connection among the number of tourist and the pressure on the environmental resourses.

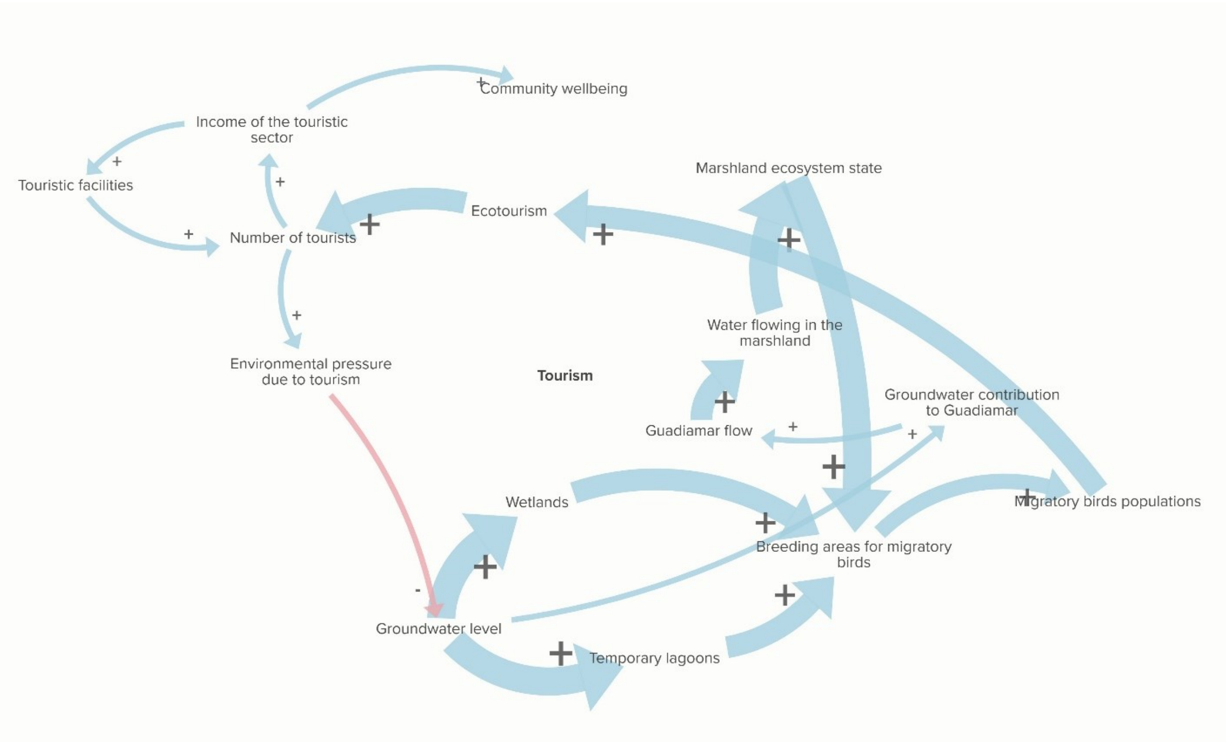

Figure 39 CLD for the Doñana case study: focus on the 'Eco-tourism' loop

4.9. Hula Valley pilot area

Overview

The interplay between agriculture and water resources has been historically challenging for the area, as well as for the well-being of local farmers' communities. Desalinated seawater is solution currently one key element to support local economy, and also a cause for the surge in water prices in the last few years. Though desalination plants successfully helped tackle the climate-change-induced water crisis, it generated some side effects. Rising water prices put farm production, especially in some areas, at the limit of profitability, and sustainability. Collapse of the local farming economy can have tremendous social consequences, and reduce the resources for financing public services to treat and maintain, among others, environmentally important services.

The role of water resources is central for the area as their availability can help farmers dealing the increasing water prices and with the reduction in the near future (e.g. the discharge of the Jordan River is expected to be significantly reduced, and the rainfall is already decreasing. Under such conditions, agro-voltaic technologies can support reducing water use while generating solar power (with related economic and environmental benefits), that can ultimately enhance the sustainability of agriculture. Similarly, the role of agriculture is also crucial to guarantee crop quality and quantity. The role of agricultural ecosystems is also central mainly for reducing carbon footprint related to agriculture.

PSDM

The following Figure 40 includes an overview on the CLD developed at the end of the process described in the Section 3. The model is available at the following link: HULA - CLD

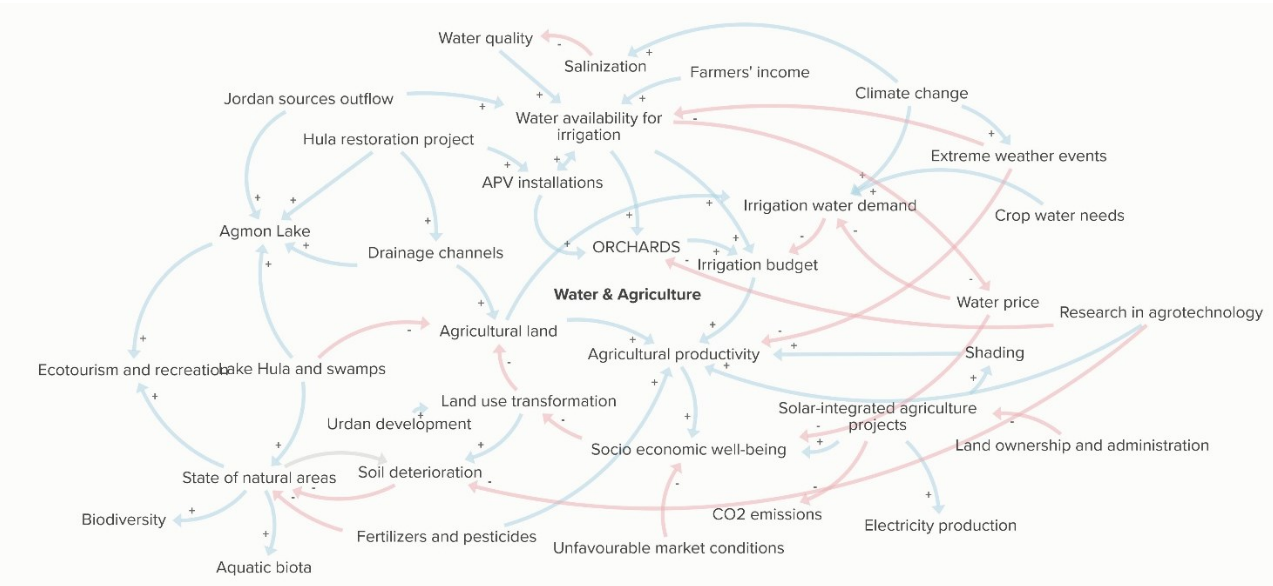

Figure 40 Revised version of the CLD developed for the Hula Valley case study (KUMU)

The CLD has been analyzed using graph theory measures, following the approach described in the Section 3. As already mentioned, 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 identifying Nexus challenges.

The analysis suggests that the interplay between water resources and agricultural activities has a central role in the CLD. The variables characterized by the highest centrality are indeed 'Water availability for irrigation' (Degree centrality 8, Betweenness centrality 0.07) and the 'Irrigation water demand' (Degree centrality 5), along with 'Soil deterioration' (Betweenness centrality 0.086). The importance of agricultural activities is confirmed by the centrality of 'Agricultural productivity' (Degree centrality 7, Betweenness centrality 0.081) for the 'Socio-economic well-being' (Degree centrality 5 and Betweenness centrality 0.146), and by the increasing 'Land use transformation' (Degree centrality 4, Betweenness centrality 0.142). The centrality analysis also suggests a critical role of the 'Solar-integrated agriculture projects' (Degree centrality 5).

A summary of the main Nexus challenges and related centrality measures is provided in the following Table 14.

Table 14 Nexus challenges for the Hula Valley case study.

Nexus challenges	Centrality measures
Agricultural productivity	High degree centrality; high betweenness centrality
Water availability (and demand) for irrigation	High degree centrality; high betweenness centrality
Soil deterioration	High betweenness centrality
Socio-economic well-being	High degree centrality; high betweenness centrality

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 those more relevant for the Nexus challenges.

The analysis highlights a loop that is interesting to take into account for the analysis. With specific reference to Figure 41, a balancing loop directly relates to the 'Water & Agriculture' dynamics. It basically highlights that an increase in 'Agricultural land' directly increases the 'Irrigation water demand' which produces, as a result, a potential reduction in the 'Irrigation budget'. If the irrigation budget is reduced, this may result in a reduction in the 'Agricultural productivity', with a subsequent negative impact on the 'socio-economic well-being' of local communities. The reduction of well-being could drive towards an increase in 'Landuse transformation' with, finally, a reduction of the 'Agricultural land'. This dynamic may thus negatively affect at least two of the identified challenges, i.e. the agricultural productivity and the need to guarantee the well-being of local communities.

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, has been then used for the identification of potential leverage points for the system.

The analysis highlights that a key point needing intervention is the 'Water availability for irrigation' (0.234). It is crucial to work on the irrigation water balance both guaranteeing an increased water availability and a reduction in water demand (e.g. improving irrigation infrastructures or working on crop water needs). In this direction, the role of the Hula restoration project (Closeness centrality 0.216) as well as of the 'Drainage channels' (Closeness centrality 0.213) looks central from the analysis. The 'Solar-integrated agriculture projects' are also high ranked in the analysis (0.205), showing a potential for positively impacting the Nexus challenges over the area. Other elements that can contribute to the identified Nexus challenges are also the 'Research in agrotechnology' (0.185) and the 'Land ownership and administration' (0.154). It is worth noting that a major driver for the system is Climate change (Closeness centrality 0.234). This reflects the increasing concerns that CC impacts may have on the system and the need for prioritizing potential adaptation and mitigation measures.

A summary of the results of the leverage analysis is provided in Table 15.

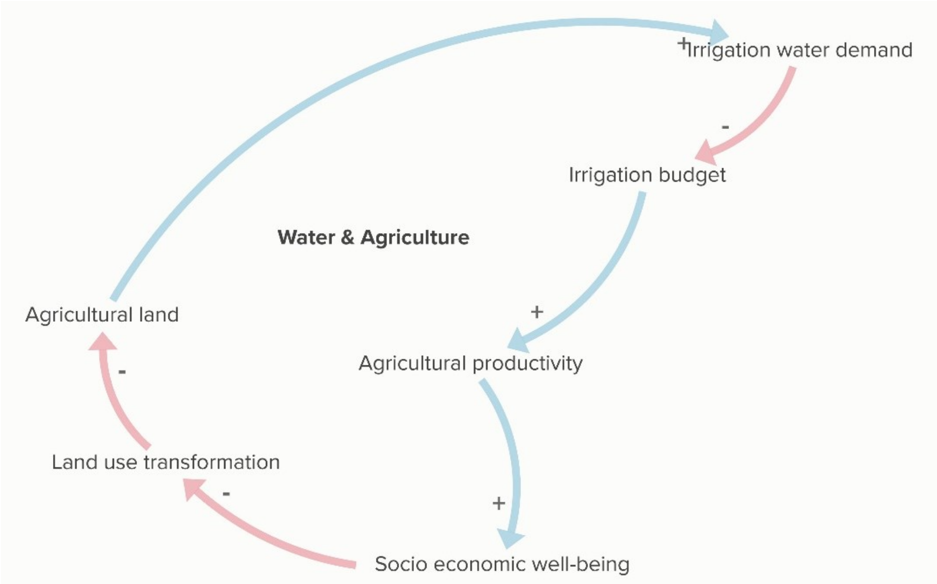

Figure 41 Focus on the main loops for the Hula Valley pilot (KUMU): 'Water & Agriculture' loop

Table 15 Results of the leverage analysis for the Hula Valley case study.

Nexus challenges	**Leverage points**
Agricultural productivity	Solar-integrated agriculture projects Research in agritechnology Land ownership and administration
Water availability (and demand) for irrigation	Hula restoration project APV installation
Soil deterioration	Research in agrotechnology Hula restoration project
Socio-economic well-being	Solar-integrated agriculture projects Research in agritechnology Market conditions

4.10. Summary of the main activities in pilot areas (until M30)

The present section provides a basic summary of the activities related to the PSDM development in all pilot areas. In part of the case studies, the IRSA team joined in person project activities, directly supporting pilot leaders in the organization of the participatory exercises oriented to PSDM development and review. In other pilots, an external support (including training) was provided to pilot leaders, and feedbacks collected from them. This is needed considering e.g. the 'language' barrier.

- Pinios.
  - Support to the preround of semi-structured interviews (12/2021 - 03/2022), to identify the main sectoral issues and cross-sectoral interdependencies.
  - Field visit in the study area (joint LENSES-REXUS activity) in September 2022.
  - Support to the preparation of the 1st stakeholder workshop/focus group (November 2022). PSDM-related activities are oriented to the presentation, discussion and revision of the CLD developed so far.
  - Support to the activities of the 2nd stakeholder workshop/focus group (May 2023). Identification of challenges, obstacles, risks, strengths/opportunities, indicators. Presentation of preliminary PSDM results.

  - *Ongoing*: development of the stock and flow model, presentation of PSDM results and scenario analysis during the 3rd WS (*tbd*).

- Doñana.
  - Field visit in the study area in November 2021.
  - Participation to the round of semi-structured interviews (11/2021), to identify the main sectoral issues and cross-sectoral interdependencies. Attention has been given to a better understanding of the perception of the local situation from specific groups of stakeholders (e.g., berry farmers).
  - Participation to the 1st stakeholder WS in October 2022. The results were collected and used to update the PSDM.
  - Support to the preparatory activities of the 2nd stakeholder WS and participation to the WS and to focus groups (scheduled in December 2022).

  - *Ongoing*: development of the stock and flow model, presentation of PSDM results and scenario analysis during the 3rd WS (*tbd*). These activities are being partially developed within a PhD thesis.

- Tarquinia.
  - Field visit in the study area in December 2021
  - Participation to the round of semi-structured interviews (12/2021), to identify the main sectoral issues and cross-sectoral interdependencies. Attention has been given to a better understanding of the perception of the local situation from specific groups of stakeholders (e.g., farmers).
  - 1st stakeholder workshop in May 2022, mainly oriented to perform a participatory mapping exercise and a review/validation of key cause-effect connections.
  - 2nd stakeholder workshop in May 2023, mainly oriented to receive feedback on the preliminary evidence from modelling results and finalize the identification of the main challenges for the area.

  - *Ongoing:* Development of the stock and flow model, with integration of sectoral models (e.g. SWAT) and climate projections. These activities are being partially developed within a PhD thesis.

- Koiliaris.
  - Support to the first round of semi-structured interviews performed by the local team.
  - Interviews and focus groups with stakeholders were performed in October2022, followed by a field trip in the study area.
  - CLD revision and validation with the support of the pilot leader (TUC) in October 2022, along with an analysis on how sectoral models could be integrated in the PSDM.
  - Support to the focus groups activities performed in October 2023.

  - *Ongoing*: development of the stock and flow model, presentation of PSDM results and scenario analysis during the 3rd WS (*tbd*).

- Menemen. Support to the preparation of interviews and of the stakeholder workshop/focus group, organized in November 2022 (based on two separate events targeting different groups of stakeholders).

- Deir Alla. Feedbacks were collected mainly through the interaction with case study leaders, that were in direct contact with relevant stakeholders throughout the project.

- Hula Valley. Feedbacks were collected mainly through the interaction with case study leaders, that were in direct contact with relevant stakeholders throughout the project.

5. Lessons learned from the LENSES pilots

The present section provides some details on the main lessons learned (so far) from the LENSES pilot areas, as far as the PSDM development and implementation process is concerned. The evidence from pilot areas, mainly in terms of barriers encountered and opportunities emerged, is highly relevant for updating and revising the framework throughout the LENSES projects.

- Identification of key stakeholders, for adapting and customizing the approach. Typically the PSDM process could be used for multiple purposes ranging from the analysis of a system for designing interventions to the development of a shared understanding and ownership of a problem amongst stakeholders, and can be developed at multiple levels, also considering the specificities of the stakeholders' groups involved. Their clear identification drives the approach and supports an effective planning and adaptation of the steps to be implemented.

  > The evolution of project activities soon highlighted that in most of the LENSES pilots a central role is played by farmers. This is particularly true e.g. for the Koiliaris, where farmers are directly involved in the transition towards a more sustainable agriculture but show some 'resistance' to change, or for the Doñana, where the berry cultivation is one of the key activities but also a relevant stressor for the whole basin. Also where small-scale activities are being performed, performed at 'plot' level (e.g. Deir Alla, Hula Valley), the role of farmers is crucial as they are directly interested in the potential uptake of measures and solutions tested within the project.

This required an adaptation of some activities, which need to be explicitly oriented to better understand, analyze and model the behavior of farmers. Specific interviews, more focused on the farmers' perspective, have been developed and performed in some pilot areas and specific sub-models directly describing farmers' behavior are being built (e.g. Doñana).

- The involvement of stakeholders should be continuous throughout the project duration and requires (among the others) also the regular presentation of project results, explicitly highlighting the contribution of participatory activities, and an analysis of the evidence from stakeholder consultation at each step. This helps increasing the willingness to participate and guarantees the development of a sense of ownership of modelling outcomes.

The organization of workshops (e.g. in Tarquinia) took explicitly into account the activities already performed with stakeholders: i) the presentation of project results, before the beginning of participatory exercises, clearly described the results obtained, based on the preliminary stakeholder consultation phases; ii) the definition of the 'challenges' for the area was based on the evidence collected through individual interviews with stakeholders; iii) the modelling activities did not start from the scratch, but even the supporting materials (e.g. cards) were customized to reflect the information provided by the stakeholders e.g. during the interviews.

- The definition of the specific aim of the SD models that are being built is fundamental. This is an 'iterative' process as well, as the priorities and needs might be different for diverse stakeholders and may become clearer as the participatory process evolves. Ideally, the focus of modelling activities should become clear no later than at the end of Step 3.

In the activities performed in the Tarquinia plain, the role of the agricultural sector has been considered central for the area from early project stages as it is widely considered one of the most productive plains in Italy. However, based also on stakeholder consultation activities, the tight interconnection it has with ecosystem state and environmental conditions gradually emerged. Indeed, the need to consider the whole area as an integrated environmental system, involving the lake, the river, the sea but also including the urban area and the agricultural land is widely acknowledged, and shows increasing positive impacts on agricultural activities. These impacts range from the improvement of soil and water quality to the opportunities of valuing local agricultural productions in a safe and controlled environment.

- The spatial dimension and spatial scale of the analysis needs to be carefully considered for different reasons.
    - First, as already mentioned, the main issue is that SDM does not immediately an inherently deal with spatial information. Anyway, the spatial dimension can be considered in multiple ways, and this is crucial specifically when dealing with the need to adapt input data for the SDM (particularly from the 4th Step on). 'Aggregating' spatial data is an effective option, but this can clearly limit the quality and the level of detail of results. Working with distributed or semi-distributed information and data is also an option, although this can become unsustainable from the computational point of view.

The development of 'lumped' models based on some degree of aggregation of spatial information over 'homogeneous' areas in the pilot site is a good option to keep track of rather detailed spatial information. This is particularly true, e.g. for the Tarquinia pilot and for the Doñana pilot, where the high complexity of the hydrogeological context, the level interaction among multiple physical

elements (e.g. SW and GW systems, natural areas, agricultural areas, the coast, and additional features such as either the saltworks for Tarquinia or the Marshland for the Doñana) and distribution of activities, resources and challenges over the area require some level of simplification of the spatial data, although the risk of over-simplification should be carefully avoided.
Particularly in the Tarquinia area, the Team is also working with specific (sectoral) models, such as SWAT. Although the use of such models can definitely help having a more precise overview of the state and evolution of the area under different scenarios, the integration of results into the PSDM requires some level of 'abstraction' and a potential loss of information.

- Second, the scale of the analysis directly affects the specific contribution that can be provided by PSDM, which is typically more suitable for supporting decisions and policies at a strategic/planning level (thus on a larger scale). The contribution to very specific or local problems (e.g. technological innovation) needs to be carefully identified.

This scale issue emerged in the LENSES project for some pilot areas (mainly Deir Alla and Hula Valley) which are mainly working at plot scale and proposing innovative practices that can have a positive impact on the Nexus optimization. The purpose of PSDM, in such pilots, could be mainly related to the identification of potential barriers and opportunities for the wider uptake of such practices, including the role of specific policies, and to the assessment of their potential impact on Nexus system at a different level.

- <u>Integration of data, models and information</u>. The integration of data and sectoral model into the PSDM needs to be tackled carefully, particularly when moving to the 'quantitative' modelling part. In the current phase of the project, we are approaching the issue and dealing with some preliminary considerations, such as the input (and output) data format, the spatial and temporal scale of data, the use of scenario analysis combining evidence from different models.

6. Conclusions

The work described in the present deliverable is central to WP4 activities, as it helps developing an improved understanding of complex Nexus systems, based on the development of a common framework for implementing Participatory System Dynamics Modelling. PSDM is used, within the LENSES project, in conjunction with other tools and methods, to describe the different forms of interaction amongst socio-economic and institutional actors, and to describe how they impact the production and provision of ESs under different scenarios, ultimately affecting the effectiveness of the Nexus sustainable management.

The core of the present Deliverable is the methodological framework for building, developing and implementing PSDM in all LENSES pilot areas (and beyond). It is based on two main phases, namely a 'qualitative' modelling phase based on CLD development, and a 'quantitative' modelling phase based on the development of stock and flow models. It comprises a series of desk activities (where the role of the analysis is central for building or validating models) and participatory exercises (needed to include explicitly stakeholders' knowledge into the picture and to co-design scenarios and solutions). It is meant to be 'modular' as the level of implementation of PSDM can be variable from site to site, and flexible enough to guarantee space for tailoring the approach to pilot needs. The framework has been built starting from relevant scientific literature and capitalizing the experience of the research group involved in previous projects (NAIAD) and in the 'sister' project (REXUS).

The present Deliverable also discusses the state of activities in the LENSES pilots, with a clear identification of the expected level of PSDM implementation. Reflections and lessons learned from the activities performed so far have also been included.

It is worth to remark here that the main element of innovation in the proposed approach is the strongly participatory nature of the activities proposed. In this regard, the experiences in several case studies are revealing that stakeholders are actually surprised by the complexity of the models produced, and attracted by the possibility of better understanding the multiple interconnections and implications that underlie the system considered, also going beyond the sectoral perspective they are used to consider. However, building (or validating) SD models in a participatory way is not straightforward, as a basic knowledge of a few key concepts or rules is required, which is not easy to achieve in the limited time that is available during a workshop or a focus group. A careful customization of the approach and adaptation of the format of participatory exercises on a case-by-case basis is therefore necessary. In general, the feedbacks obtained through participatory exercises were highly valuable and gave the opportunity to guide discussions and knowledge exchange processes in a structured and systematic way.

The proposed approach is meant to be directly used in other case studies and guarantees flexibility for the implementation in variable conditions. It should not be considered as a fixed structure, rather as an opportunity for developing SD models with a strongly participatory nature, in a structured and replicable form.

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