from
Nexus Thinking to
Nexus Doing

REXUS

MANAGING RESILIENT NEXUS SYSTEMS THROUGH
PARTICIPATORY SYSTEMS DYNAMICS MODELLING

Deliverable 4.1 – Report on PSM and SNA. Identification of DOs, NRQs and NIs.

WP4 – Advancing Nexus Thinking

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1 Introduction

1.1 The objectives of the deliverable

The present deliverable summarizes the methodological approach and the main results obtained in selected pilots concerning the activities of Task 4.1 'Nexus structure and Nexus Indicators'. The main objective of this task is to describe the complex set of interactions (both formal and informal) among different stakeholders and decision-makers involved in Nexus management, as well as the mutual dependencies and connections among multiple resources and different sectors. The results of these preliminary analyses are being used for supporting the Participatory System Dynamics Modelling (PSDM) activities (within Task 4.2).

As further described in the text, stakeholders-based methodological approaches have been implemented in this task. Specifically, Participatory Social Mapping exercises (PSM) based on Social Network Analysis (SNA) have been mainly used for the purpose of describing the network of interactions among different stakeholders. The rationale here is that the interconnections among the different actors involved in the management/use of ecological resources, and/or benefitting from the production of Ecosystem Services (ESs), can affect the Nexus sustainable management. Moreover, as pointed out by Bodìn (2017), the functioning of ecosystems and the production of ESs depend on the fitting between the socio-economic and ecological networks - i.e. the network connecting ecological resources and processes in order to produce certain ecosystem services. Therefore, a socio-ecological network analysis approach was adopted in this work (Bodìn 2017), using SDM tools.

Qualitative SDM tools (Causal Loop Diagrams) are used to support individual problem understanding and analysis, and are specifically oriented to the identification of Nexus Domain Objectives -DOs- (i.e. water, energy and food security) and of Nexus Resilience Qualities (NRQ). Specifically, the Causal Loop Diagrams have allowed mapping the complex web of interactions among ecological resources and processes, human activities, and the production and flow of ecosystem services for the achievement of the Nexus Domain Objectives and to avoid trade-offs hampering the Nexus resilience. The proposed methodology has been implemented in three different case studies (Lower Danube, Pinios and Nima Cauca) which are detailed in the present Deliverable. Lessons learned will be then used for replication in other pilots and relevant results included in other deliverables (mainly D4.2, D4.3 and D4.5).

The activities performed are explicitly oriented to support stakeholder participation, which is key to identify relevant WEFC Nexus Indicators (NIs) with specific reference to the main socio-economic variables, which will be then used to assess the current state of Nexus systems and to analyse their potential evolution in different scenarios accounting for the stakeholders' knowledge.

2 Description of the methodological approach

2.1 Rationale

Both the concepts of 'Nexus' and 'resilience' are not new. Nexus thinking was first conceived at the WEF (2011), and most authors identify the flagship publication by Holling (1973) as the onset of resilience thinking insofar it became relevant in a WEF nexus context. The essence of the nexus is about interconnections between different sectors (water, energy and food systems, ecosystems), whereas resilience is about the capacity of a system to respond to threats and retain its ability to deliver benefits (Lawford et al. 2013; Grafton et al. 2016). The interplay between Nexus and resilience has recently received increasing attention, as summarized in a recent review by (Hogeboom et al. 2021) which highlighted the key interconnections of resilience thinking and WEF Nexus based approaches.

Particularly, the Authors highlighted a few promising research avenues and knowledge gaps, fully in line with the REXUS objectives/approach proposed within the WP4:

1) **improving the understanding of resilience in the WEF nexus across scales, sectors, domains, and disciplines**, basically with relying on a better understanding of the WEF nexus dynamics, paying attention to the boundaries of the analyzed (sub-)systems, and more comprehensive cross-sectoral investigations, ultimately with a better understanding of the implications of cross-scale dynamics or interventions and the implications of interventions in WEF systems (e.g. trade-offs).
2) **developing tools and indicators to measure and assess resilience of WEF systems**. Several tools—meaning methods, models, and frameworks—are being developed to overcome this gap. Two directions of development can be identified. The first is the development of tools to improve the understanding of cross- sector, cross-scale, cross-domain, and complex dynamics. Proposed examples are e.g. scenario building, trade-off analysis, integrated assessment modeling, environmental footprinting and agent-based modeling. The second direction is to develop tools and methods that support more consistent policy formulation. Broadly accepted indicators for resilience are rare, however some examples are the Nexus City Index and the WEF nexus index (Schlor et al. 2018).
3) **bridging the implementation gap brought about by (governing) complexity**. Barriers include a lack of data, knowledge and observability that match the level of complexities involved, physical challenges of managing resources over a large area, and a lack of public and private investments. Most often, however, governance is underscored as impeding factor for practical uptake of resilience and nexus thinking.
4) **integrating or reconciling resilience and nexus thinking**. Elements common to both the nexus and resilience thinking are the application of systems thinking, taking an integrative management perspective and considering complex dynamics across scales, domains and sectors. Also, the notion of enhancing security appear to be a common connection between nexus and resilience discourses.
5) considering other development principles and frameworks toward solving WEF challenges **beside and beyond resilience, including control, efficiency, sustainability, and equity.** We see a need to address the trade-offs and synergies between multiple development objectives and their implications, including control, efficiency, robustness, sustainability, equity, and fairness, to enrich policy design frameworks with perspectives from beside and beyond the resilience rationale. Researchers are therefore heeded to critically examine the desirability of WEF system resilience.

The Nexus approach is also inextricably connected to the concept of resource security. Both the negative environmental impacts and insecurity of water, energy and food supply are expected to worsen in the near future, driven by population growth, increasingly resource- intensive lifestyles and vulnerabilities to disruptive shocks including climate change (Hoekstra and Wiedmann, 2014; Steffen et al., 2018). Reaching the UN's Sustainable Development Goals (SDGs), including those on food (SDG 2), water (SDG 6) and energy (SDG 7), require substantial, if not transformative efforts across the actor landscape (FAO et al., 2017; United Nations, 2018; IRENA, 2019). Nexus thinking advocates that water, energy and food systems should be viewed collectively and holistically in order to reach water, energy and food (WEF) security (WEF, 2011)

From the methodological point of view, it has been decided to adopt an **ecosystem services-based (ES-based) approach,** with a direct engagement of stakeholders, to better capture the existing connections between Nexus and resilience concepts. In this direction, the Nexus can be considered resilient if, under internal and external stressors (e.g. climate change, increase of the demand, etc.), the three main security dimensions (i.e. Water Security, Food Security and Energy security) are guaranteed by a healthy ecosystem, which is capable to produce the needed services.

The adoption of an ES-based approach allows to identify and analyse in an integrated way the social factors (e.g. such as skills, management regimes and technology) and ecological functions related to the production of the needed ecosystem services, including non-linear feedbacks, trade-offs, and interactions related to nexus management.

Within this framework, the main scope of the activities performed within the Task 4.1 is to actively engage stakeholders for the analysis of the complex and non-linear connections among the socio-ecological elements affecting the Nexus resilience. Concerning the stakeholders' engagement activity, two main phases have been identified: 1) elicitation and structuring of the stakeholders' perception about the Nexus resilience; 2) mapping the interaction among agents and resources through the ES-based approach.

2.2 Overview of the approach

The activities have been carried out during the first year of REXUS for the purposes of the present deliverable, in line with the program of WP2 and WP6. Given the significant differences in pilot state, targets and objectives, the structure detailed in the following has to be considered as a general reference rather than a fixed protocol. These activities integrate desk activities and participatory exercises and have been based on the following structure:

- **Baseline analysis**: a description of pilot state, challenges and issues to be tackled. It consists of a "Factual analysis" (details are provided in D 6.1) performed by the pilot leaders (in cooperation with key stakeholders of the area) and the most relevant elements, for the purposes of the present work are: i) the description of the current state of energy, food, water and environmental security; ii) the availability of natural resources; iii) the main pressures and hotspots in the area; iv) the relations that exist within the region strategic goals, policies and challenges. Basically, the content of the baseline analysis has been used to: i) preliminarily identifying the key challenges and current system state; ii) building a draft of SD models for individual pilots, highlighting the main challenges and potential options.
- **'Opinion-based interviews'**: individual semi-structured interviews have been performed with key stakeholders, in order to capture differences in sectoral perspectives, with an explicit focus on sectoral objectives, state, pressures, etc. Such interviews were highly useful to help identifying potential ambiguities in perceptions and analyzing the sources of ambiguity (conflicts). Full details on the interviews are provided in the Annex 1, which includes an 'easier' version of the format that has been mainly used for stakeholders without a technical background.
- **Desk activities**. Based on the results of the interviews, the baseline SD models have been edited in order to explicitly incorporate local knowledge, thus reflecting the stakeholders' perception of system state and key determinants. This task was mainly focused on: i) the analysis and translation in SDM form of the key processes involving natural resources and ES production, as described by the stakeholders; ii) the analysis of main variables identified by the stakeholders to understand system state and evolution, to be translated in the form of scientific indicators.
- **1st workshop**: The 1st workshop has not been performed yet in any pilot, but is being planned/scheduled in several pilots. The objectives, for the purposes of the WP4, will be: i) the analysis and validation of SDM (at least with specific reference to key connections); ii) the support to Nexus dialogue, based on the analysis of key intersectoral connections and dependencies; iii) a decision-actors mapping exercise using PSM and SNA techniques; iv) the selection and ranking of a relevant subset of key indicators.

Given the strongly participatory nature of the REXUS project and the multiple activities that are planned throughout project duration, the results proposed in the present work should not be considered as final. Rather this should be considered as a 'living' and dynamic document, which proposes a methodological approach to be followed to support integrated modelling in REXUS pilots (and beyond). Updates and evidence from other case studies will be mainly provided in the D4.2, D4.3 and D4.5.

The processes derived from the completion of this set of activities are comprised in three different approaches:

1) Participatory Social Mapping and Social Network Analysis (described in section 2.3)
2) Participatory System Dynamics Modelling (Nexus Structure, see section 2.4)
3) Identification of Nexus Domain objectives, Nexus Indicators and Nexus Resilience Qualities (see section 2.5)

2.3 Participatory Social Mapping and Social Network Analysis

These activities have contributed to the detection and analysis of potential barriers to the Nexus sustainable management and resilience accounting for the complex web of interactions among different socio-economic and institutional actors, and the ecological resources and processes affecting the production of Ecosystem Services (ES) for the achievement of the Nexus objectives. ESs, defined as the benefit we receive from a well-functioning ecosystem, are a key element of the Nexus security (i.e. maintenance of the quality and quantity of the supply of water, energy, food and ecosystem functions) (IISD 2013). The key assumption here is that the different forms of interactions amongst socio-economic and institutional actors impact the production and provision of ES and, in doing this, affect the effectiveness of the Nexus sustainable management. Ineffective interactions can create conditions hampering cross-sector coordination and collaboration in the Nexus management (Weitz et al. 2017).

In the past, interdependencies among different sectors - i.e. water, energy, ecosystem and food - have been neglected in sectoral policies, leading to persistent trade-offs among policies and conflicts over the use and management of different resources. Increasing pressures due to global changes - i.e. climate change impacts and economic development, increasing exploitation of resources and population growth - are exacerbating the conflicts in the Nexus management. In order to reduce conflicts and strengthen the synergies among different sectors, the Nexus should be governed with a focus on the interactions between policy fields and not on policy fields in isolation (Pahl-Wostl 2019). Addressing security from the perspective of the Water-Energy-Ecosystem-Food nexus refers to reducing trade-offs to acceptable levels and to enhancing synergies between efforts to simultaneously increase water, energy, and food security to sustain human-wellbeing, economic production and environmental integrity. The focus on trade-offs and synergies analysis for the sustainable management of the Nexus puts forward a system perspective and emphasizes the role of ES as a way to operationalize it. The ES approach: i) tries to capture the nexus interactions and governance deficits by analysing actors-ES network; ii) encourages negotiation and cooperation among ES users; iii) supports the integration of fragmented institutional settings; iv) contributes to operationalizing the nexus in terms of trade-offs and synergies; and v) facilitates the alignment between the governance framework and the ecological processes. Adopting an ES-based approach in the analysis of the socio-economic and institutional interactions means that actors are not linked exclusively through formal interactions. Informal - and often hidden - interactions happen in the biophysical system, e.g.

using the same resources or competing for the ES.

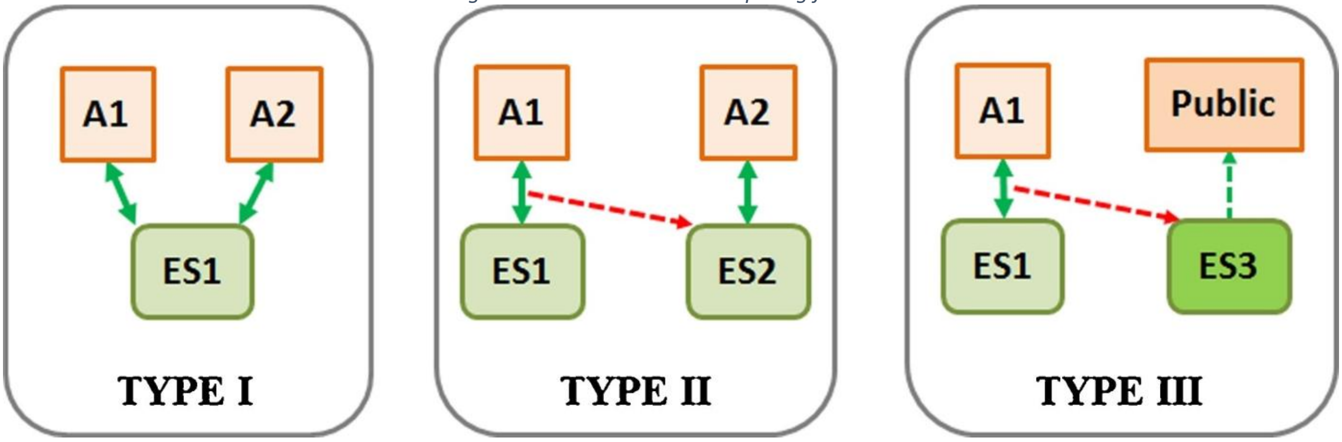

Figure 1 shows the potential interactions among decision agents/users and ES.

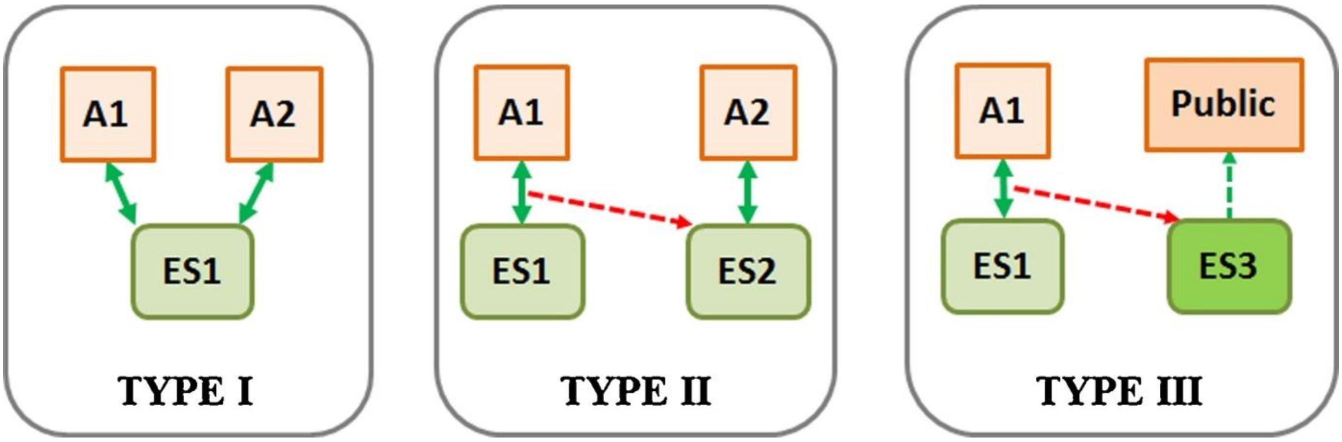

Figure 1: Graphical representation of potential interactions among ESs and their users (from Pahl-Wostl 2019)

In the first case, different users use the same resources and/or benefit from the same ES. In the second case, by using ES1 user A1 affects the capability of the ecological resource to produce ES2, creating a potential conflict with user A2, which is supposed to benefit from ES2. Finally, in the third case, the use of ES1 by A1 affects the availability of a public good hampering its capability to provide ES to a large public. The trade-offs in the Nexus management are often caused by interactional conditions such as those of type I and III. Trade-offs and conflicts among different agents in Nexus management are often caused by actors that are linked via interactions in the biophysical system (through ecological resources and processes), that do not have a formal correspondence in the network of socio-institutional interactions (Pahl-Wostl 2019).

A key factor that distinguishes environmental problems - such as the inadequate Nexus management - from many other collective action problems in general is that environmental problems are inevitably tied to the complex structures and processes of boundary-spanning ecosystems (Bodìn 2017). Addressing environmental issues requires a clear understanding of the ecosystem structure and of the mutual interaction between the natural system (e.g. natural species and ecological processes) and the socio-economic systems (i.e. stakeholders, their incentives and management actions (Bodìn 2017). However, to date, ecological and socioeconomic networks have largely been considered in isolation from each other (Dee et al. 2017). Approaches based on Social Network Analysis (SNA) have been frequently adopted to analyse the structure of the interactions among institutional and non-institutional actors and to detect barriers hampering effective collaboration in decision-making (Calliari et al. 2019; Giordano et al. 2021). However, SNA neglects the interdependencies between the social and ecological systems.

In this work, a socio-ecological network analysis approach for ES was adopted. In this network, nodes representing ES can be connected to an element of the ecological network (e.g. a specific ecological resource) and to a socioeconomic network (e.g. establishing which stakeholders benefit from a service, and which entities manage the service):

- The socio-ecological network is centered around the ES of interest and, in a first step, uses ecological networks to identify which ecological resources and processes, directly and indirectly, contribute to the ES production and provision. In the ecological network, the nodes represent the ecological components - e.g. resources, species, etc. - and links describe the processes happening within the ecological network. The ecological network helps identify critical dependencies that affect ES.
- As a second step, the social network can specify who benefits from an ES, which entities manage the services, and how those individuals and organizations interact. Moreover, in this work we also considered the stakeholders and decision-makers exerting pressure on the ecological resources needed for the ES production. Interactions within a social network influence the impacts of management actions on the ES provisioning. Moreover, social interactions influence knowledge exchange between different stakeholders involved in decisions, governance of natural resources, and defining which policy objectives should be pursued. Finally, the interactions in the social networks determine how people value, use and demand different ES (Dee et al. 2017).

Previous works dedicated to the development of the socio-ecological networks mapped the relationships among the agents managing or using the ecological resources, benefitting from the ES or creating pressures on the ecosystem (e.g. Bodìn 2017; Dee et al., 2017; Pahl-Wostl 2019). However, the production and flow of ES do not rely exclusively on the potentialities of the ecological resources and processes. Three systemic filters - i.e. infrastructures, institutions and individual perceptions - influence the processes of ES mobilization, realization and flow (Anderson et al. 2021). In this work, the socio-ecological network aims at mapping also the relationships involving: i) the agents responsible for the development and maintenance of the infrastructures for the ES fruition - e.g. transportation infrastructure for the ES related to tourism; ii) agents influencing the institutional framework related to ES flow. Finally, the socio-ecological network should account for the role of agents' perceptions in influencing the actual use of a specific ES. Infrastructures - green, blue and grey - play a key role in the ES production and flow. Therefore, this work is based on the analysis of the socio-ecological-technical network.

The socio-ecological-technical network was adopted in this work with the aim of investigating to what extent the lack of effective interactions among stakeholders and decision-makers affects the production and provision of ES, i.e. detecting key barriers to the ES production and provision, due to the misfit between the social and the ecological network. We assume that managing ecological resources for ES production is a complex task, whose effectiveness exceeds the capacity of a single decision-maker and requires collaboration among different decision-makers (Therrien et al. 2019). We refer to two kinds of collaborations in decision-making, i.e. coordination and cooperation. Coordination describes a situation where all or most actors agree on what they want to accomplish and getting there is more a matter of coordinating the actors' different activities in an efficient way. Cooperation corresponds to problems where actors display different opinions and interests and addressing a specific issue would require necessarily negotiations to reach common agreements. The network of interactions among decision-makers and stakeholders should assume different configurations to enable coordination or cooperation. In the first case, two decision-makers should have strong connections with a third one, operating at a higher administrative level. Effective cooperation among two different decision agents requires direct connections between them, allowing information exchange and negotiation over the goals to be achieved.

The following Table 1 describes the different steps of the adopted methodology.

Table 1: Overview of the main steps of the proposed methodology

Step	Objective	Adopted method
ES definition	To identify the key ES that ought to be produced in order to guarantee a satisfactory level of security in the Nexus domains	Individual semi-structured interviews with key stakeholders in the different Nexus domains were carried out. ES needs were detected in the stakeholders' narratives.
Ecological network	To build the network of ecological resources and processes affecting the ES production and provision.	A combination of stakeholders' knowledge elicitation and analysis and literature review was adopted in this step to identify the ecological resources and define the different connections.
Social network	To build the network connecting the different stakeholders and decision-makers involved in ES production, provision and use.	The results of the individual interviews were used to map the different interactions among the stakeholders and decision-makers. Different kinds of interactions were mapped: i.e. information sharing, regulating, controlling, resources sharing.
Barriers detection	To detect and analyse barriers to ES production and provision due to misalignment between social and ecological networks.	The socio-ecological network analysis was used to identify and analyse potential misfits between the social and ecological network hampering the ES production and provision.

The results of the stakeholders' interviews were used to identify the key ES and to start building the ecological network. Specifically, as shown in the framework used for the interviews in the pilot areas (Annexes 1A and 1B), stakeholders were asked to specify the key goals to be achieved for the Nexus security and to specify the ecological resources having the potentiality to produce the ES for the achievement of those objectives. Ecological processes and connections among resources and ecological components were defined referring to both the stakeholders' knowledge and the literature review.

The identification of the key ecological resources and processes allowed to identify the decision agents and stakeholders (agents from now on) that need to be accounted for in the analysis. In this phase, we considered: i) agents responsible for the management of the ecological resources; ii) agents whose decisions/actions affect the ecological processes; iii) agents befitting from the ES provision; iv) agents exerting pressure on the ecological resources. The next step concerns the mapping of the social network. To this aim, both the baseline description of the different pilots and the results of the individual interviews were used.

Finally, the analysis of the socio-ecological network allowed us to detect the key barriers hampering the ES production and provision due to the misfit between the ecological and social networks. Specifically, the structure of the social network was analysed and its capability to enable coordination or cooperation among agents sharing the same resources or using the same ecosystem service was assessed. The misfit between the social and ecological network can be either horizontal - i.e. lack of alignment of social and ecological connectivity - or vertical

- i.e. across different network layers (Bodìn 2017). The impacts of these misfits in the socio-ecological network on the production and provision of the needed ES for the Nexus security were analysed and discussed.

2.4 Participatory System Dynamics Modelling (Nexus Structure)

System Dynamics Modelling (SDM) is a methodology and mathematical modeling technique to frame, understand and discuss complex issues and problems (e.g. complex environmental systems). It is widely used for policy analysis and design, and represents a holistic and cost-effective modelling approach. For the purpose of the REXUS project, it is used as an integrated modelling tool, for representing Nexus systems as complex socio-ecological systems, i.e. based on the strong interaction among networks of agents (described through PSM and SNA methods) and natural resources.

SDM comprises a set of conceptual tools that enable the understanding of the structure and dynamics of complex systems as well as rigorous modelling methods for building formal computer simulations of complex systems and using them to design effective strategies (Sterman 2000). It aims to capture the key variables and relationships of a system, understand their interdependencies and predict their behaviour over time. If dynamic behaviour arises from feedbacks within the system, finding effective policy interventions requires understanding the systems' structure. SDM is highly effective in the analysis of complex ('wicked') problems relying on the integration of qualitative ('soft') and quantitative ('hard') variables, where hard variables describe attributes or relationships in a problem regulated by bio-physical laws and based on quantifiable algebraic operators, and soft variables are typically intangible, and relate to attributes of human behaviour or effects that variations in such behaviour produce (Pluchinotta et al. 2021). SDM is well suited to the analysis of problems whose behaviour is governed by feedback relationships over a long-time horizon. It establishes a 'business as usual' state of the system and then scenarios can be analyzed based on specific hypothetical inputs such as future policy interventions.

Among the key benefits of SDM highlighted in the scientific literature, a key role in many applications is given to the active stakeholder participation, flexibility, ease of uptake, transparency and adaptability, potential for integrating sub-models, foresight, and ongoing testing and learning (Pluchinotta et al., 2021). Participatory approaches in SDM (PSDM) facilitate collaboration among stakeholders by integrating their local knowledge and perceptions of the investigated problem, along with potential solutions (e.g. Winz et al. 2009, Coletta et al. 2021). PSDM identifies the use of a SD perspective in which stakeholders actively participate in different stages of the modelling process, including problem definition, system description, identification of policy levers, model development and/or policy analysis. PSDM is more than simply eliciting knowledge, rather involves building shared ownership of the analysis, problem, system description, solutions and a shared understanding of the tradeoffs among different decisions

As aforementioned, SDM comprises a broad class of methods and tools, which can be basically divided into 'qualitative' (Causal Loop Diagrams) and 'quantitative' (Stock and flow models). Basically:

- **Causal Loop Diagrams (CLDs)** provide a graphical representation of the system under investigation, focusing on the relationships among different variables. The direction of the connections between such variables defines the causal dependency, being positive (+) if the variables change in the same direction (i.e. they both increase or decrease) or negative (-) if they change in the opposite direction (Sterman, 2000) A strength of the relationships can be shown, as well as time delays. Combinations of positive and negative causal relationships can form either reinforcing ('R') and balancing ('B') feedback loops. Reinforcing loops represent growing or declining actions, while balancing loops represent a mechanism of self-correction that contrasts and opposes change, and their analysis is crucial to describe the expected dynamic evolution of variables (Sterman 2000, Coletta et al. 2021).

- **Stock and flow models** describe the behaviour of complex systems over time using feedback loops, stocks, flows and modifiers. Stocks characterise the state of the system at a point in time, keeping a memory of it. Flows affect the stocks via inflow or outflow and interlink the stocks within a system. Flows correspond to the change per period of time that increases or decreases levels in the system. Both physical laws and intangible issues (e.g. perception of a given system) are jointly considered, with specific attention to their potential interconnections and mutual influences.

An increasing number of studies on the WEF nexus has been conducted from global to local and even household scale based on System Dynamics Modelling (see among the others Sušnik 2018; Laspidou et al. 2020; Purwanto et al. 2021; Sušnik et al. 2021). SDM is particularly relevant for Nexus problems, as such models facilitate knowledge integration across many domains, shedding light on the interactions between social and natural systems and how these might be influenced by public policy (Gallagher et al. 2020). Gallagher et al. (2020) described an experience implementing one such analysis in the Mekong river basin, a paradigmatic example for international Nexus research. Causal Loop Diagrams, scenario modeling and an innovative resilience analysis method were developed to identify and test water-energy-food risks in northeastern Cambodia, supporting a deeper understanding of complex system transitions. As highlighted by the authors, a key lesson learned is that the use of participatory and systems-thinking informed approaches can make a positive contribution to anticipating and responding to risks that emerge from nexus relations, without the need for 'perfect' data. González-Rosell et al. (2020) recently performed an analysis based on SDM coupled with relevant regional level Nexus-related indicators to assess the impact of water pricing policies on e.g. over-utilisation of resources, unit economic profit from agriculture and water productivity, environmental sustainability. Sušnik et al (2021) used SDM (performing both qualitative and quantitative assessment, with the support of local stakeholders) to offers insight for policy and decision making at national level (in Latvia), hinting at policy options to pursue, and highlighting those to avoid. While useful in academic understanding of WEF nexus systems, a main criticism to SDM (Sušnik et al. 2021) is the lack of impact assessment of potential or likely policies across the nexus. A critical factor contributing to this is the difficulty to translate policies, objectives, and targets into a representative modelling framework, and then to make modelling output understandable to policy makers.

The value added of SDM use for REXUS mainly lies in the use of a holistic approach to system analysis which helps overcoming 'silo-thinking' (i.e. the sectoral fragmentation), highlighting the high interconnectedness among sectors (water-energy-food- -ecosystems) and among the multiple agents involved in/impacted by Nexus resources management. Besides supporting the Nexus thinking phase, PSDM will help supporting "Nexus doing" by finding barriers and action points within the system structure where nexus policies - that have the potential to change the problematic trend to a more desirable one – should be implemented.

In the following, a summary of the main advantages (+) and limitations (-) related to the use of SDM is proposed:

- (+) System dynamics is an appropriate modeling approach for sustainability questions because of the capability to support long-term perspective and feedback dynamics.
- (+) The modelling can be performed at different level of detail, depending on the objective, the scale, the stage of the analysis (e.g. preliminary screening vs. detailed assessment). Both qualitative and quantitative models can be used.

- (+) Differently from sectoral approaches (e.g. water balance models), SDM integrates multiple classes of variables/information in the same model (e.g. physical variables along with socio-economic variables). The stakeholders can be directly involved in model building and validation (PSDM).
- (+) SDM has been widely adopted for exploratory scenario analysis.
- (-) SDM does not have an explicit 'spatial' nature – i.e. it uses and provides aggregated information rather than spatial data.
- (-) SDM is more useful at a strategic/planning/policy design level rather than to support 'final' implementation.
- (-) The integration with sectoral models may not be straightforward.

2.5 Identification of Nexus Domain objectives (DOs), Nexus Indicators (NIs) and Nexus Resilience Qualities (NRQs)

Moving from 'Nexus Thinking' to 'Nexus Action' requires multiple efforts. One means of integrating sectors, which are characterized (and measured) through different units and time scales, is through the development and integration of indicators (see e.g. de Strasser et al. 2016, Albrecht et al. 2018). Existing indicators for individual components (or sectors) of the Nexus are rather abundant and widely known, such as e.g. Global Food Security Index (Rosegrant and Cline 2003), Water Exploitation Index, Energy Supply or Demand Index (Kruyt, 2009) as well as those proposed by the World Bank of by the FAO (e.g. AQUASTAT). Attempts have been made in order to develop a composite index approach (Shu et al., 2021). Among others, the Pardee RAND Food-Energy-Water Security Index (FEW Index) has been developed comprising three sub-indices (for food, energy, and water) (Willis et al. 2016). The index combines these sub-indices using an unweighted, geometric mean. Although natural resource security can be described through many dimensions (including scarcity, stress, supply reliability, supply diversity, sustainability, environmental impact, and equity), the resource sub-indices in the FEW Index include the *availability* and *accessibility* dimensions. Availability reflects whether the population is provided adequate resources to support needs for dietary requirements, sanitation, and productivity. Accessibility considers how the distribution of those resources across society occurs. Particularly for water, another dimension is considered (*adaptive capacity*) which reflects to what extent the system can absorb long-term changes and adapt to short-term disruptions. Examining the FEW Index provides a picture of the state of availability and accessibility of these resources worldwide. The WEF Nexus Index has been developed (WRC Report no. 2959/1/19) following the methodology developed by the European Commission JRC Competence Centre on Composite Indicators and Scoreboards. This composite indicator comprises three resource sectors i.e. Water, Energy and Food as equal pillars/sub-indices. Each resource sector is, in turn, characterized by 'access' and 'availability' sub-pillars (no weights are assigned). Based on a review of 87 globally available indicators, 21 relevant indicators have been included into the WEF Nexus Index (https://wefnexusindex.org/) which has been determined for more than 180 countries (Simpson et al. 2022). Information provided by indicator, and particularly by composite indicators such as the WEF Nexus Index should not be viewed as an end, but rather as an entry point into the structure of the Nexus. Such indicators can also catalyze, or be utilized in parallel with, complementary quantitative and qualitative nexus assessments[1]. Other attempts toward the development of composite performance indicators are available in the recent literature (e.g. El-Gafy, 2017, Giupponi and Gain 2017, de Vito et al., 2017).

Giupponi and Gain (2017) presented a comprehensive indicator-based approach for the assessment of **water, energy and food security**, with reference to the **Sustainable Development Goals** of the United Nations. This should provide a tool to monitor progress, compare different geographical areas, highlight synergies and

[1] https://www.water-energy-food.org/resources/tool-wef-nexus-index

conflicts amongst and within the three dimensions of the WEF Nexus, ultimately providing support for improved—more effective—management strategies to meet the goals. The Authors propose a method to aggregate indices in a single WEF security index, by means of a multi-criteria approach. The main ambition is to provide a transparent and reproducible GIS-based approach to assess the state of WEF spatial indicators, which could be adopted in the future to monitor the progresses in meeting the SDGs, allowing to compare different geographical areas and highlighting synergies and conflicts amongst the three dimensions of the WEF Nexus.

Identifying and using suitable indicators to support the transition towards 'Nexus Action' is crucial, as indicators can be used (with different purposes and variable level of detail) in multiple phases of the process (see e.g. de Strasser et al., 2016). Particularly, indicators could be highly useful to support the analysis of the study area (ranging from the bio-physical to the socio-economic side) and for the identification of the 'nexus issues' as well as for supporting the assessment of 'nexus solutions', focusing on interlinkages (such as multiple uses of resources, negative impacts, trade-offs and dependencies between sectors). Both factual and opinion-based information can be collected and elaborated, also through the use of indicators (de Strasser et al., 2016).

Typically, although indicators can be rather effective and synthetic, a few limitations exist, such as:

- They often aim to be applicable across nations allowing intercountry comparison, without taking explicitly into account local specificities and differences (e.g. between countries with a different level of industrialization).
- Many indicators in Nexus studies have been developed for a specific scale or context, for example river catchments or irrigated agriculture. Some indicators are composite and focused on Nexus at higher scale (e.g. country) such as Pardee Rand and (Giupponi and Gain 2017). Specific indicators have been also proposed for specific areas, such as the Mediterranean area.
- Most of the available indicators somehow include the constraints imposed by availability of the other two WEF resources, but do not explicitly consider the feedback effects on those resources which are essential for a comprehensive Nexus analysis (Shu et al. 2021).
- A 'prescriptive' use of indicators should be avoided, giving more space to flexibility and adaptability, although indicators must be consistent and the unambiguous (de Strasser et al. 2016).
- Actions to reduce one indicator may have unintended consequences for other indicators, and therefore building a network map of the key interactions between indicators and whether interactions are likely to be positive or negative is crucial for an effective WEF Nexus analysis (Shu et al. 2021).

Starting from this short summary of the literature and the main current limitations, one of the objectives of WP4 within REXUS is to develop an innovative methodological approach for identifying indicators that are significant for the pilot areas and useful for supporting decisions and actions at a relevant scale. A key issue is, considering the gaps discussed above, finding a balance between the need for avoiding a 'prescriptive' use of indicators and the opportunity of considering the wide body of consolidated indicators, already used worldwide. For this reason a combined 'top-down' (based on the review of available indicators) and 'bottom-up' (based on the elicitation of stakeholders knowledge) process has been designed. This follows previous experiences (see e.g. Gallagher et al., 2020) which highlights the importance of co-identifying suitable indicators, in order to correctly represent priorities and identify risks of concern. REXUS aims to support a knowledge co-production method that enables diverse stakeholders to be actively involved in identifying suitable indicators and inflection points while creating new understanding of trade-offs from multiple actors' perspectives and momentum for seeking solutions (as in Gallagher et al. 2020).

It is worth highlighting that indicators are not being defined and used in isolation, rather are being directly connected with models (particularly PSDM). Such coupling is needed for using WEF Nexus indicators to describe both a baseline system state and a predicted state reached via simulation (Hoolohan et al. 2018). This step is also needed to make indicators useful for supporting Nexus operationalization. Indicators have been classified, for the purpose of the REXUS project in three broad categories, which are defined in the following:

- **Nexus Domain Objectives (DOs)**. The World Economic Forum's primary area of concern regarding the WEF nexus was initially water security, hence it is termed by some as the **WEF security nexus**. However, as explained e.g. by Pahl-Wostl (2017), since then the concept's use has broadened to address interdependencies and integration to achieve resources security for societal well-being. In this context, DOs defines sectoral objective(s) related to the **security of the resources** (water, land/food, energy, ecosystems), being the '*access*', '*utilization*' and '*availability*' the main security-related properties that stand out, constituting the core elements of WEF. The 'availability' element concerns the distribution, processing or production of food, energy conversion and renewable and non-renewable sources, and water abstraction, distribution, or treatment, whereas the 'access' involves purchase, self-production, and food, energy, and water aid. Finally, the 'utilization' entails the consumption of food, addressing the nutritional value, and energy and water use.
- **Nexus Indicators (NIs)** .The WEF nexus is the study of the connections between different resource sectors (typically water-energy-food), together with the synergies, conflicts and trade-offs that arise from how they are managed, i.e., water for food and food for water, energy for water and water for energy, and food for energy and energy for food. Efforts to attain a goal in one sector (i.e. a DO) affect (or are affected by) efforts in other sectors, and the total demand for key resources may degrade the resource base and underlying ecosystems. Basically, NIs should support **measuring the linkages between the constituent sectors**, e.g. measuring water for energy, water for food, energy for water, etc. (Simpson et al., 2022) NIs should also **show how goals across sectors are integrated to make the SDGs more cost-effective and efficient**, reduce the risk that SDG actions will undermine one another, and ensure sustainable resource use (Weitz et al., 2014).
- **Nexus Resilient Qualities (NRQs).** In an uncertain and complex world, unforeseen shocks and disasters can proliferate across scales and systems in unexpected ways, reducing system performance. The general notion of resilience describes 'the capacity of a system to cope with shocks', and specifically *resilience thinking* emphasizes the need to design, develop and manage systems for resilience such that they can sustain their function when facing inevitable disturbances. Resilience and Nexus thinking are two relevant frames to help deliver on the grand development challenges of **reaching WEF security for all while sustaining that security under threats** (Hogeboom et al., 2021). However, developing tools and indicators to measure, monitor, model and evaluate resilience in the WEF nexus remains as an under-represented theme in the current research landscape. This observation can be explained partially by the complexity of both concepts, which makes it difficult (if not impossible) to capture resilience in the nexus using a limited number of methods and indicators.

From the methodological point of view, the knowledge co-production process ('bottom-up' phase) for indicators identification has been mainly based (so far) on individual interviews, as detailed in the framework proposed in the Annex 1 A and B. Basically, the idea is - at least at this stage - to avoid any direct reference to scientific/technical indicators, as this could be challenging for many stakeholders (even with a technical background) and impose a limit to creativity knowledge production. Stakeholders are thus indirectly driven towards the identification and characterization of key (measurable) quantities that could be relevant according to their own problem perception. This step of analysis does not require that the identification of the variables is accurate or detailed, rather aims to select the most relevant elements to consider, model and visualize. More specifically, each stakeholder is first assigned to a specific domain (water, energy, food, ecosystem - depending on her/his role and interest) and is then asked, in the first part of the interview, to identify the main **needs** that should be achieved to guarantee the resource security for that domain. A couple of specific questions are then oriented to understand how that level of achievement can be described and **measured** (e.g. which variables or parameters should be taken into account) and to describe the current level of satisfaction of those needs. Lastly, a reflection is required on the main barriers and challenges that may limit the satisfaction of the mentioned needs, as well as on the role that can be played by external drivers (specifically, the climate change). The evidence from the interview is then summarized in the form of a Table, which includes also a classification of the indicators according to their potential representativeness as **DOs** and **NIs**.

In summary, the rationale behind the interview structure is to have on the one hand a clear identification of the key measurable quantities (i.e. indicators) useful for a characterization of each sector, and on the other hand a simple description of the dynamics that affect their state and evolution. In particular, the main processes that include the mentioned variables are identified, and this is reflected in the PSDM building. The identification of NRQ is directly connected with the analysis of the main dynamics from the PSDM.

The measurable variables/concepts identified by the stakeholders through the interviews should be then related to the scientific indicators ('top-down' phase of the process). This step is being performed by the analysts, who should match the measurable quantities identified by the stakeholders with scientific indicators selected from a list that summarizes some of the available indicators from the scientific and technical literature. A specific activity during the 1st Workshop (to be performed yet in all pilots) will be dedicated to the selection of a subset of relevant measurable quantities, as well as to the validation of the selected indicators. A summary of the whole process is proposed in the following Figure 2.

The Annex 2 includes a list of indicators available in the scientific/technical literature that will be related to the main measurable variables and concepts identified by the stakeholders in pilot areas. This list does not aim to be exhaustive, rather at providing a comprehensive enough list of the indicators most commonly used in sectoral and Nexus studies. A classification is also proposed, mainly used to identify the main dimension the indicators contribute to.

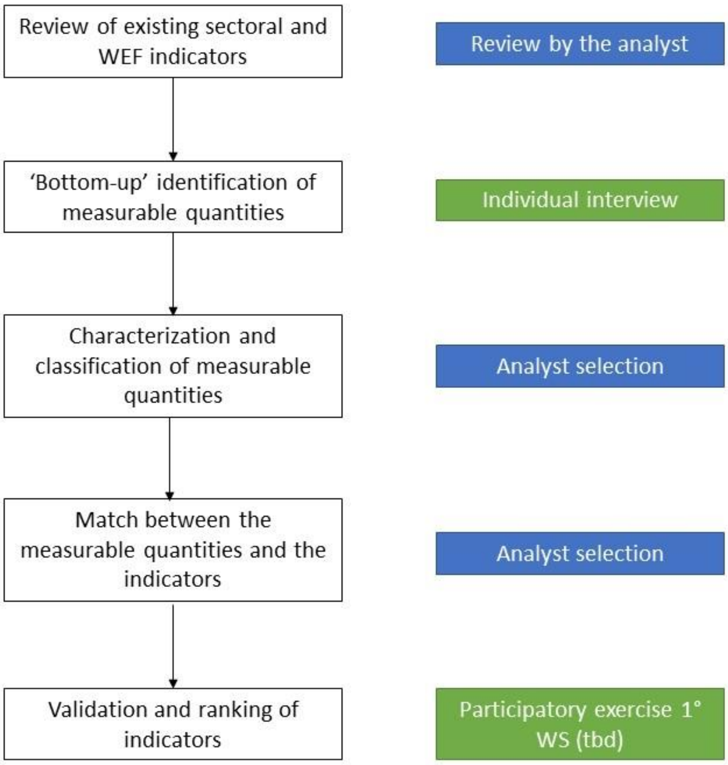

Figure 2: Overview of the process adopted for indicators identification

3 Results: Implementation in pilots

3.1 The Lower Danube

The preliminary results of the implementation of the methods y in the Lower Danube pilot refer to the baseline description (D6.1) and to the results of the first round of interviews carried out with the local stakeholders. The Lower Danube pilot is characterized by the presence of a key ecological resource - i.e. the Danube river - whose potential to produce and provide ES for the community's well-being is jeopardized by the implementation of sectoral policies - e.g. energy production, flood protection, ecosystem regeneration, fish farming incentive, agricultural production, etc. - that are creating trade-offs. Therefore, the main goal of the REXUS implementation in this pilot is to detect and analyse these trade-offs, and to contribute to the definition of multi-sectoral policies for the provision of ES for the Nexus security.

Following the REXUS guidelines for stakeholder engagement, the first round of semi-structured interviews was carried out in the pilot with the aim of collecting stakeholders' knowledge concerning: i) the most important ES to be produced for the Nexus security and the local development; ii) the key ecological resources and ecological processes needed for the ES production; iii) the key actors interested/involved in the ES production and provision; iv) the infrastructures needed for the actual use of the ES, and v) the main barriers hampering the ES production processes. The results of the interviews were used for mapping the socio-ecological network of interactions (see section 3.1.1.) and structuring the sector-based qualitative models (see section 3.1.2.) .

3.1.1 The socio-ecological-technical network

As already described in section 2, this phase of the analysis aims at identifying barriers to ES production and provision due to the structure of the interactional network among the different decision-makers and stakeholders. To this aim, the ecological resources and processes for the production of the ES in the Lower Danube were defined along with the agents using/managing the resources, and benefitting from the ES or exerting pressures on the ecological resources. Moreover, the socio-ecological-technical network maps the interactions among the agents responsible for the development/management of the infrastructures needed for the ES flow and use.

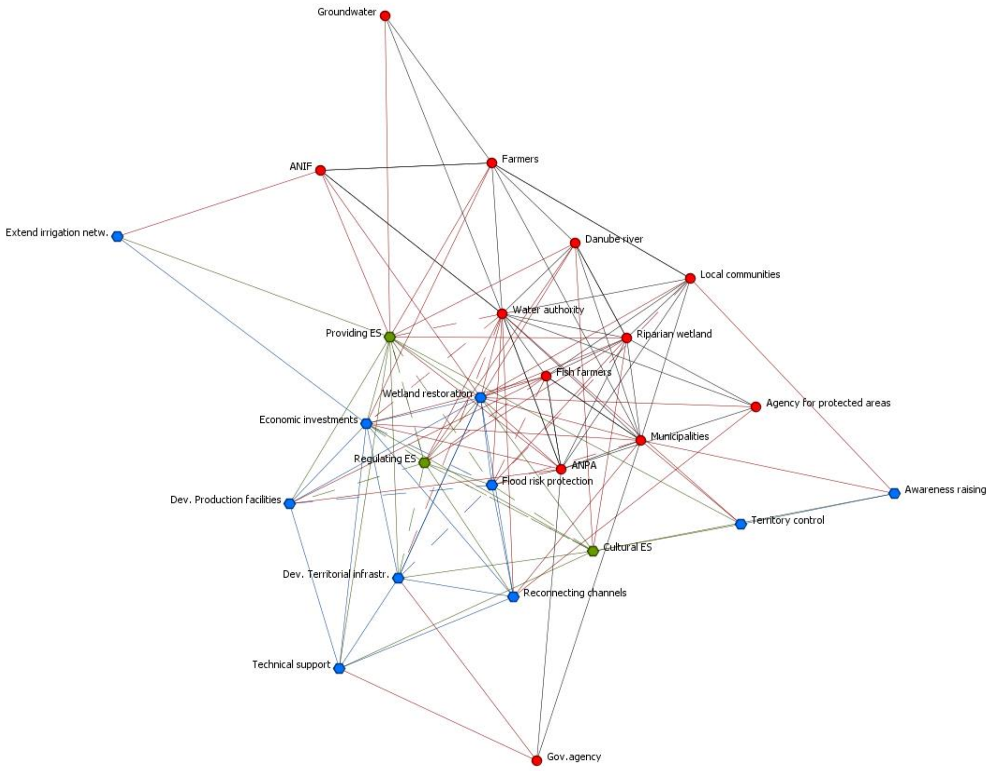

Figure 3: Socio-ecological-technical network for the Lower Danube pilot

Figure 3 shows the socio-ecological-technical network developed for the Lower Danube pilot. For sake of simplicity, in this map, we considered the three main categories of ESs, as expressed by the stakeholders, i.e. the Providing ESs, the Regulatory ESs and the Cultural ESs. The different ESs are specified further in the text (see the Section 3.1.2). The map shows the different ecological resources needed for producing the expected ESs and the processes - both ecological and human - that ought to be activated. The map also shows the connections among the different agents in terms of interactions in the use/management of the resources. In order to facilitate the detection of potential trade-offs due to the lack of effective interaction, the map also shows the tasks that the different actors are expected to carry out for producing ESs.

Following the methodological approach described in (Giordano et al. 2017), the network is composed of three meta-networks, i.e. the agent X agent, the agent X tasks and the task X task networks. Specifically, the agent X agent network describes the interaction among the different agents. In order to account for the role that ecological resources play in the production and provision of ES, we considered the ecological resources as agents in the model. This is also in line with the approach used in developing the Agent-Based Model (ABM), in which ecological resources are also considered as agents in the model (see e.g. Castlla-Rho et al. 2015). Therefore, the 'agent X agent' meta-network is composed of both human and ecological agents. The 'agent X tasks' network shows who is expected to do what, concerning the production and use of ESs. Finally, the 'tasks X tasks' network shows the interdependences among the different tasks. Negative connections (the dotted lines on the map) mean that the implementation of a specific task could negatively affect the implementation of the other tasks. To facilitate the analysis, the production of the ESs is considered as a task. The ecological processes are considered as tasks carried out by the ecological resources. Unfortunately, the results of the interviews did not allow us to assign a weight to the different connections, representing their importance.

The network shows the centrality of the ecological resource "Riparian wetland" in producing the three classes of ESs. The key process (task) allowing the production of the above mentioned ES is the wetland restoration since, currently, most of the lands along the Danube riverbank are used for either farming activities or pasture. As shown in Figure 4, the restoration of the riparian wetlands can be achieved through the implementation of two human-induced processes, i.e. reconnecting the Danube river to the riparian wetland and the land use change. Referring to the three key filters for the ES production and provision (see section 2.2), the process of "reconnecting the river" requires the development of the connecting channels, which is an infrastructural intervention. The Regional branch of the Water Agency is responsible for implementing this intervention (agent X task meta-network). The land-use change requires the adoption of an institutional process related to the revision of spatial planning. The local municipalities are responsible for this institutional process. However, issues related to the different perceptions of the landowners - i.e. the regional branch of the Water Agency, the fish farmers and the municipality - concerning the ES to be produced could affect the land-use change process. The regional branch of the Water Agency perceives the wetland restoration process as a key measure for reducing the flood risk, with the main goal of reducing flood damage. This goal is incompatible with the economic investments needed to produce the ESs perceived by the fish farmers and by the National Agency for Aquaculture (ANPA). These investments are meant to enhance fish production and cannot be exposed to flood risk. The dotted (negative) links among the related tasks - i.e. developing production facilities, developing territorial infrastructures and flood protection - show this conflictual situation in the map of interactions.

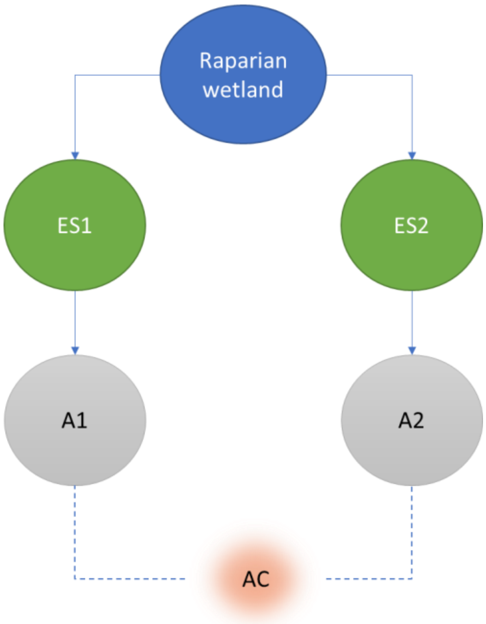

Figure 4: Example of lack of coordination affecting ES production through the riparian wetland in the Lower Danube pilot

The two ESs are mutually exclusive because of the perceptions of the two benefitting agents, i.e. the regional branch of the water agency and the ANPA. The water agency perceives the restoration of the riparian wetland as a flood risk mitigation measure. Therefore, these areas are going to be flooded in case of heavy precipitation, provoking economic damages in case of the presence of productive facilities for fish farming activities. This is a clear example of a vertical misfit between the ecological and social networks (Bodìn 2017). There is only one ecological resource, managed by two different agents capturing different aspects of the riparian wetland. This condition would require the presence of a mediating agent operating at a higher administrative level, capable to activate cooperation among the two benefitting agents to find a consensual solution. In this regard, it is worth remembering that coordination in collective decision-making corresponds to the situation where agents display different opinions and interests. Currently, the coordination agent does not exist, and the two agents have a weak connection mainly related to the allocation of water volume by the water agency. This interaction mechanism hampers the reaching of a common agreement concerning the ES to be produced through the restoration of the riparian wetland.

During the interviews, many stakeholders described the wetland restoration as a great opportunity to increase the eco-touristic flow in the area. Therefore, they expect the riparian wetlands to produce cultural ecosystem services. However, the restoration of the riparian wetlands could be not enough for producing cultural ES. Territorial infrastructures, such as transportation networks and accommodation facilities, are needed to enable the effective production of the cultural ES. The development of such territorial infrastructures requires the intervention of the municipalities and the use of dedicated funds (economic investments in the map). Most of the local mayors that were interviewed during the field trip described difficulties in interacting with the governmental agencies managing funds for the local development. This lack of interactions is negatively affecting the capabilities of the mayors in activating resources and projects for the development of territorial infrastructures. Moreover, the community’s perception of the local environment and the rather low level of awareness of the potential impacts of its behaviour - i.e. illegal wastes disposal - on the quality of the environment could have negative impacts on the effectiveness of territorial infrastructures in enabling the production and use of the cultural ES. Two key interactions are missing here between the municipalities and the local communities, i.e. the control of the territory and the awareness-raising initiatives. The first interaction is a regulatory interaction, whereas the second one is a knowledge sharing interaction. Both of them could contribute to changing the community’s behaviour. This, in turn, could lead to the effective implementation of the territorial infrastructures for the production of the cultural ES.

The key role played by infrastructures in enabling the ESs flow, making them actually usable, is evident in the process for the production and use of the ES “Water provisioning for agriculture”. The study area is characterized by high availability of water. As many stakeholders told us during the interviews, even in case of a drought period, the quantity of water available does not represent a limit to food production. The dimension of the water security affecting the Nexus here is the water accessibility (Weitz et al. 2017) because the lack of adequate infrastructures reduces the possibility for farmers to access the water for irrigation. The existing irrigation network was abandoned after the collapse of the communist regime and was rarely maintained in the early 90s. As a consequence, the current state of the irrigation infrastructure makes not affordable the use of water for irrigation. The agency for rural development (ANIF) is implementing projects for the renovation of the irrigation network, based on the existing demand for water. That is, ANIF is primarily renovating the infrastructure for providing water for irrigation in the areas where there is a high water demand from farmers. As described further in the text (see section 3.1.2), irrigation demand is mainly expressed by big farmers, because small farmers consider the irrigation tariffs (mainly energy cost) unsustainable. Therefore, the interaction between ANIF and the small farmers is missing in the socio-economic network. This missing connection hampers the effectiveness of the infrastructure development - reducing the coverage of the irrigation network - and, hence, the flow of the ES.

Another key barrier hampering the development of the irrigation network is due to land fragmentation. Most of the land is divided into small parcels owned by small farmers that are reluctant to cooperate with each other. As we learned during the interviews, this behaviour is mainly due to a reaction after the collapse of the communist regime. Small farmers - and specifically those old enough to have a vivid memory of the communist regime and the imposition of collectivization - are against any form of collective actions. The lack of strong social capital within the community of small farmers is reducing the process of forming Water Users Associations (WUAs). As we learned during the interviews, WUAs could easily access water for irrigation since they have to cover only 50% of the energy, whereas small farmers have to cover 100% of the energy costs. Therefore, the lack of farmers' social capital is affecting the production of water demand for irrigation and, thus, the effectiveness of the project for renovating the irrigation network.

The lack of strong social capital within the community of small farmers reduce their capability to access the market for agricultural product. This, in turn, affects the farmers' income and their capability to cover the water fees, as required by the ANIF. To summarize, the lack of interactions between ANIF and the small farmers and the low level of social capital within the small farmers are barriers to the development of infrastructures needed for the production and flow of the ES related to the irrigation.

Main findings

The implementation of the approach based on mapping the socio-ecological-technical connections in the Lower Danube pilot allows to draw preliminary conclusions concerning the main collaborative barriers hampering the Nexus management. The production and mobilization of ESs for the Nexus security and resilience require an effective interaction network among the different agents - institutional and non-institutional - that should fit with the ecological and technical processes needed for producing such ESs. The following Table 2 summarizes the main findings in terms of key barriers to the ESs production and mobilization due to ineffective interactions.

Table 2: Overview of the main barriers related to ESs production and mobilization in the Lower Danube pilot

Detected barrier	**Involved actors**	**Impact on ESs**
Lack of coordination	Municipalities, Water agency and ANPA	The lack of a coordinating actor affects the conflicts for the land-use change.
Lack of control	Municipalities and communities	The municipalities have a rather low level of territory control, affecting the effectiveness of the territorial investments.
Lack of awareness-raising campaign	Municipalities and communities	Local communities' behaviour could reduce the effectiveness of the territorial investments for eco-tourism.
Lack of technical support	Municipalities and Governmental Agency for local development	Small municipalities need technical support for funding opportunities for local development.

Lack of farmers' social capital	Community of small farmers, ANIF	The lack of cooperation within the community of small farmers is negatively affecting the implementation of the irrigation network renovation project.
Lack of interaction between ANIF and small farmers	ANIF, small farmers	Similarly to the previous barrier, the lack of interaction between ANIF and small farmers is negatively affecting the implementation of the network renovation project.

The impacts of these barriers on the ESs production for the Nexus security and resilience will be analysed and discussed in the next section, dedicated to the development of the System Dynamic Model. This model allow to investigate to what extent the detected collaborative barriers can hamper Nexus security and resilience. Besides, it enables to identify the key elements affected by these barriers and, in doing so, to define policy interventions for overcoming the collaborative barriers.

3.1.2 Participatory System Dynamic Modelling

A round of semi-structured interviews was carried out involving key stakeholders in the study area, as shown in the following Table 3.

Table 3: List of the stakeholders interviewed in the Lower Danube pilot

Stakeholder	Role
ANPA (National Agency for Fishery and Aquaculture)	Supporting the fish farmers and regulating the aquaculture activities
Hydroelectrica	Company managing the Iron Gate dams for the production of electricity
Fish farm Garla Mare	Fish farming activities (water user)
Mayoralty of Gârla Mare, Calafat, Bistret, Bechet, Corabia, Turnu Magurele, Zimnicea	Municipality – local development
Farmers	Water users
Research Institute Dăbuleni – Crops on sandy soils	Research centre - agriculture
Romanian Waters National Administration - Jiu River basin Administration	Water resources management – water permits
University of Craiova – Faculty of Agriculture	Research centre - agriculture
National Agency for Environment Protection	Natural resources conservation
National Agency for Land Improvement (ANIF)	Irrigation network improvement

The interviews aimed at gathering the stakeholders' understanding of: i) the key ES to be produced in order to achieve a satisfactory level of security in the different Nexus domains; ii) the ecological resources and processes needed for the ES production; iii) the main pressures on the ecological resources; and iv) the main barriers hampering the effective ES production and mobilization.

This case study is characterized by a key ecological resource - i.e. the Danube river - having great potential to produce a wide range of ESs. However, key issues need to be addressed for sustainable Nexus management. Most of these issues are already described in the pilot baseline description (please, refer to the D6.1). The results of the interviews allowed us to complete the knowledge gathering process and structure it in the CLD, as described further in the text. Following the framework for the interviews, three main classes of ESs were detected in the stakeholders' argumentation, as shown in the following table:

Table 4: identification of the key ES and ecological resources for the Nexus security (Lower Danube)

Ecosystem Service type	ES description	Resources involved	Nexus security	Main beneficiaries
Regulating	Flood control	Riparian wetland	Water security	Water Agency
	Bank erosion reduction	River flow	Water security / Ecosystem security	Transportation companies
	Soil degradation and desertification mitigation	River water and aquifer	Food security	Farmers
Provisioning	Water for Irrigation	River water and aquifer	Food security	Farmers
	Water for energy	River water	Energy security	Hydroelectric company
	Maintaining nursery populations and habitats	River water and riparian wetland	Ecosystem security	Local community Ecosystem
	Feed for grazing livestock	Riparian wetland	Food security	Local community
	Reed production	Riparian wetland	Ecosystem security	Ecosystem
	Fish production	Riparian wetland	Food security	Fish farmers
Cultural	Recreation and aesthetic value	Riparian wetland River water	Ecosystem security	Local community Tourists
	Ecotourism	Riparian wetland River water	Ecosystem security	Local community Tourists

The Table 4 shows the ESs mentioned by the stakeholders during the first round of interviews. Most of the stakeholders consider the provisioning ES as key for guaranteeing the nexus security. This is specifically true for food security and ecosystem security. The stakeholders' narratives about the nexus of security and resilience were built around the central role played by the Danube river. This is somehow shown also in the table: most of the ESs mentioned by the stakeholders are water-related ESs. However abundant the water resources are in the area, their potential to produce and mobilize ESs is hampered by the lack of effective policies and infrastructures. As already described in section 3.1.1, three key filters need to be activated in order to effectively produce ESs, i.e. institutions, infrastructures and perceptions. This section describes the modelling approach adopted in this pilot for analysing the role of these filters in affecting Nexus security and resilience.

To this aim, the results of the interviews were structured in Causal Loop Diagrams to describe the cause-effects web of non-linear connections affecting the production of ESs, according to the stakeholders' problem understandings. For sake of clarity, the whole model has been split into different sub-modules, describing the main issues related to ESs production. The following Figure 5 shows the sub-module related to the perceived role of the riparian wetlands in producing ES.

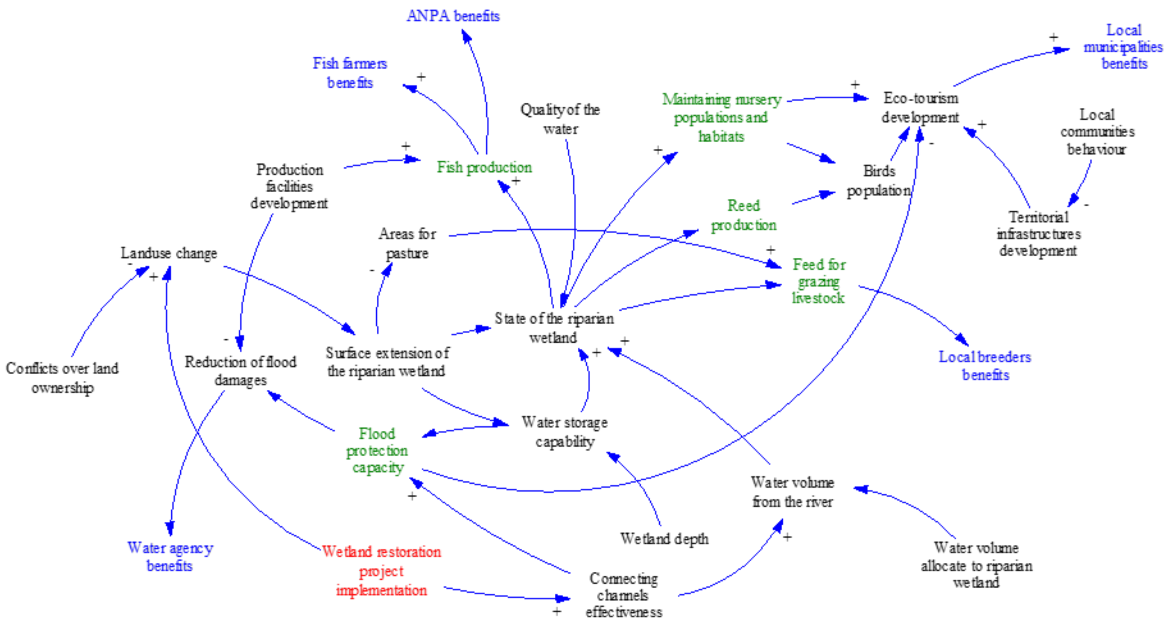

Figure 5: Sub-model focusing on the role of the riparian wetland to produce ESs in the Lower Danube pilot area

As shown in the Figure 5, the riparian wetlands are perceived by the stakeholders as key resources for nexus security. Specifically, wetlands are supposed to contribute to food security by increasing aquaculture production, which in turn, would contribute to the community's well-being. Moreover, wetlands are expected to play a key role in enhancing biodiversity and, thus, attracting eco-tourists. Finally, the wetlands are supposed to produce regulating ES, i.e. flood risk reduction. As shown in the table, different stakeholders will benefit from the production of these ESs.

However, at the current stage, most of the former riparian wetlands are used either as pasture areas or as agricultural land. During the communist regime, the wetlands were disconnected from the Danube river and dried up for increasing agricultural production. Only a few pristine wetlands still exist but, due to the limited connections with the Danube river, they are in a fairly bad status from the ecological point of view. The lack of functioning infrastructures capable of bringing water to the fish ponds is perceived as a strong barrier hampering the aquaculture activity in the area. Therefore, the production of the different ESs is negatively affected by the fairly bad state of the existing wetlands. A project for restoring riparian wetlands is currently under discussion at the national level. The project is supposed to improve the connectedness between the river and the former wetlands, through the realization of new - or renovation of existing - channels. As shown in the model, the project is expected to have a positive impact on the variable “state of the riparian wetland”. This, in turn, could increase the wetlands’ potential to produce the ESs. However, the actual production and mobilization of these ESs are hampered by different barriers. Firstly, high level conflict among different institutional actors - namely the Water Agency, the ANPA and the municipalities - is hampering the land-use change process for the increase of the wetland area extension. The conflict is due to the different perceptions about the wetlands’ role, and the benefits that these actors are expecting to receive. The Water Agency considers the riparian wetlands as a key measure for reducing flood risk in the area, requiring the wetlands to be freely floodable in case of flood episodes. This would represent a risk in the case of fish farming production facilities installed in the wetlands. Those facilities are needed for the effective production of the fish production ES. Therefore, the ambiguity concerning the perception of the ES to be produced by the restored wetland is hampering the implementation of the renovation project.

Similarly, the improvement of the wetland state through the implementation of the “wetland restoration project” could create the condition for the development of eco-tourism initiatives in the area, with great benefits for the local communities. However, as already described in section 3.1, the effective production of the ES for the eco-tourism initiatives requires the development of territorial infrastructures - e.g. transportation infrastructures, accommodation, etc. - whose effectiveness can be hampered by the local communities’ behaviour. Moreover, a trade-off exists between the use of wetlands as a flood protection measure and the increase of eco-tourism. Additional measures are needed to reduce the damages to the tourism infrastructures in case of a flood.

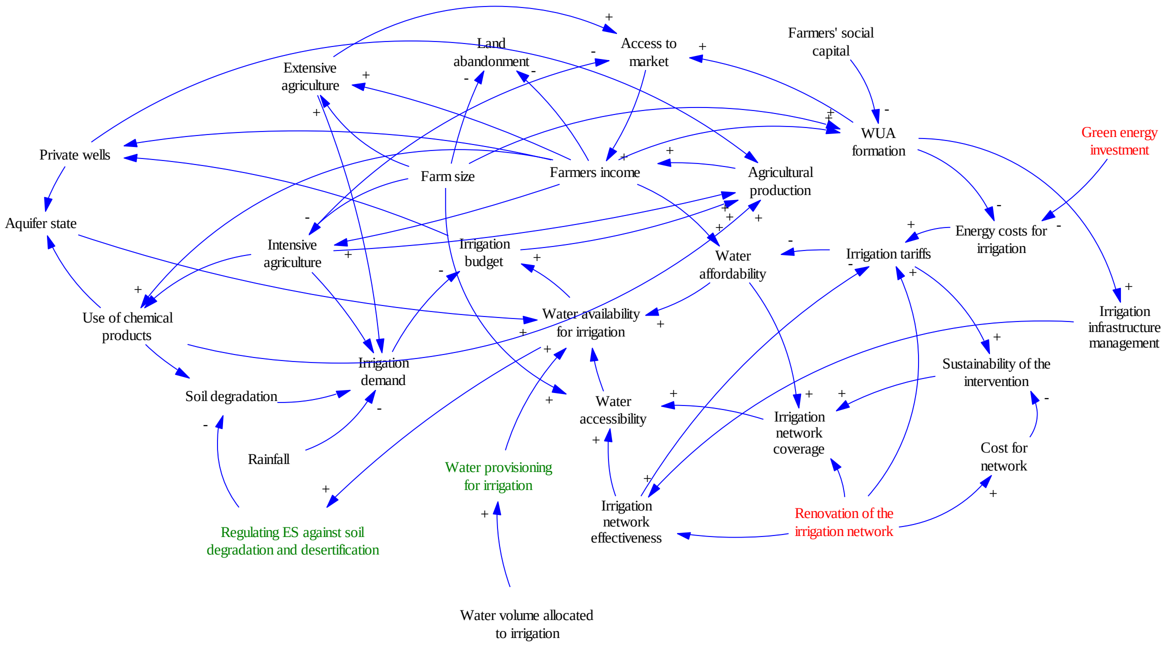

Figure 6: Sub-model focusing on the role of irrigation in the production of ESs in the Lower Danube pilot area

The previous Figure 6 shows the sub-model describing the use of water for irrigation purposes. The main scope of this sub-model is to describe the complex web of interactions affecting the production of the ESs related to food production, namely “water provisioning for irrigation” and “regulating ES against soil degradation and desertification”. As shown in the figure, the central element is not the water volume allocated to the irrigation purposes, as it could be expected. The water volume allocated to irrigation can contribute to the increase of the water availability for irrigation, but instead, water availability is more strongly affected by water accessibility - i.e. the capability of farmers to actually use the available water volume- and by water affordability - i.e. the farmers' capability to sustain the costs related to the use of water for irrigation. Water accessibility is influenced by the irrigation network's effectiveness and coverage. As already described in section 3.1, the existing irrigation network was largely abandoned after the collapse of the communist regime and the current state of the network makes its use rather unsustainable for distributing water for irrigation purposes. In this case, the limiting factor is the lack of infrastructures capable of bringing water to the farmers, rather than the availability of sufficient water volume to satisfy the water demand. Therefore, efforts are required to renovate the irrigation network. It is worth mentioning that the availability of water for irrigation is crucial for reducing soil degradation and desertification. Even the extensive crops in the area - i.e. mainly cereals - need to be irrigated to guarantee a certain level of productivity.

The National Agency for rural development (ANIF) is currently implementing projects for renovating the existing irrigation infrastructure. The agency is prioritizing the areas of intervention accounting for the size of the farms. That is, the interventions are prioritized to provide water to the large farms. Therefore, as shown in the model, the capability of farmers to afford the water tariffs is affecting the implementation of the network regeneration project and, thus, the area covered by the irrigation network. The water affordability variable in the model is affected by the WUA formation process. As described in section 3.1.1, in the case of water distributed to a WUA, the tariff - which is mainly due to the energy cost - is 50% of the one to be paid by small farmers. Therefore, the lack of farmers' social capital is indirectly reducing the water affordability and, thus, the agricultural production. Thus, farmers' income plays a key role in affecting ESs production and mobilization.

During the interviews, we also learned that the farmers' income also influences the land abandonment process. The study area is characterized by two main kinds of farms, i.e. the small farms - mainly used for subsistence agriculture at the family level - and the large farms, frequently owned by foreigner investors and dedicated to extensive agriculture (cereals). The economic sustainability of the small farms depends on the farmers' capability to have access to the market. In many cases, small farmers do not have contact with the distribution network for agricultural products. This negatively affects the farmers' income. Therefore, the likelihood of abandoning the land increases in the case of small farms with limited access to the food market. In the case of small farmers with rather good access to the food market, it is likely to have intensive production of vegetables. In this case, the farmers' income allows them to have their own private wells to guarantee food production even in case of a lack of irrigation infrastructure. Intensive agriculture is having two negative impacts on ecological resources. On the one hand, the use of chemical products - e.g. fertilizers - is accelerating the soil degradation process. On the other hand, the use of groundwater for meeting the irrigation demand is affecting both the qualitative and quantitative state of the aquifer that, in the long term, could negatively affect water availability and, thus, agriculture production. Therefore, the capability of the ecological resources - i.e. the Danube river and the local, aquifer - to produce and mobilize the two key ESs related to food production depends on the availability and accessibility of irrigation infrastructures.

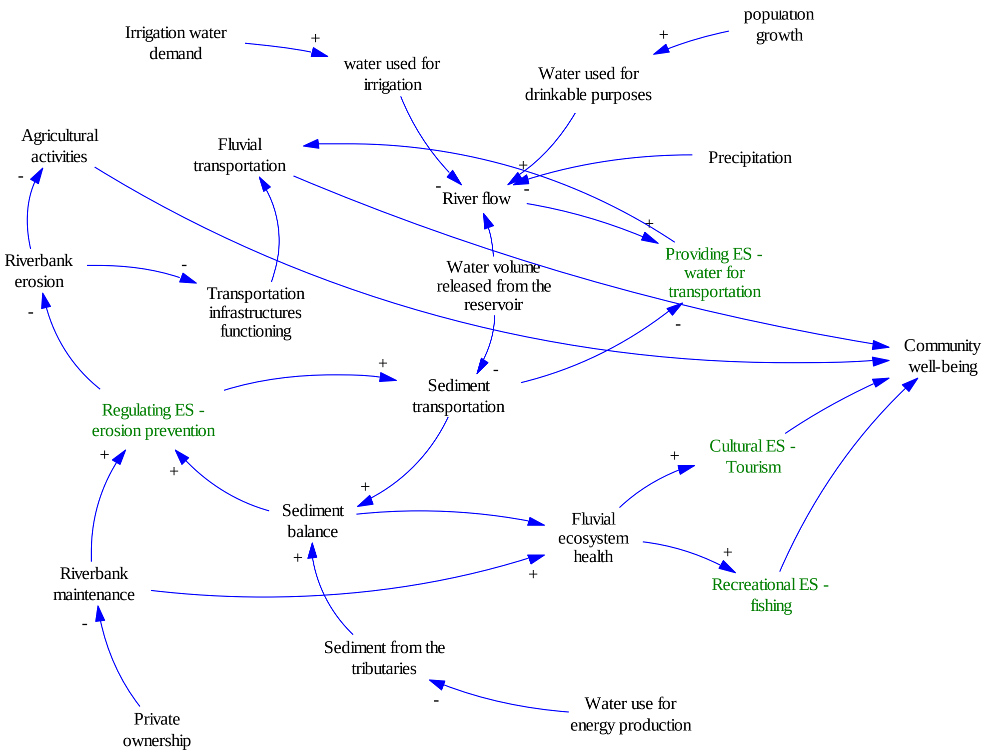

Figure 7: Sub-model focusing on the issue of transportation and sediments in the Lower Danube pilot area

Finally, the Danube River is expected to produce ESs related to fluvial transportation and protection against the riverbank erosion process. The key process here is the river ecosystem equilibrium affected by the management of the Iron Gate dam. The dam produces a sediment deficit, that is also exacerbated by the limited sediment transportation in the Danube tributaries due to the presence of several hydroelectric dams. The sediment disequilibrium is provoking the erosion of the riverbanks and riverbed, with a negative impact on the fluvial transportation (and issues with some types of ships). This is also due to the impacts of the riverbanks' erosion process on the functioning and continuous operation of transportation infrastructures, such as fluvial ports.

Main findings

Coherently with the main findings of the socio-ecological-technical mapping exercise, the participatory modelling approach allowed us to describe a case study in which the Nexus security and resilience is challenged by the lack of coherent and inter-sectoral policies rather than by the lack of ecological resources. Therefore, efforts for optimizing the distribution of the water volume among the different users/uses might be not enough to guarantee Nexus security. Policies are needed to coherently activate the three main filters for the ESs production and mobilization, i.e. Infrastructures, Institutions and Perceptions, as shown in the following Table 5.

Table 5: List of infrastructures, institutions and perception (Lower Danube)

Filter	**Description**
Institution	Coordination among the local institutions Technical support to municipalities Tariffs for irrigation

	Control of the territory
Infrastructures	Irrigation infrastructures Channels connecting the river Territorial infrastructures Production infrastructures
Perception	Community's perception and behaviour Ambiguity in ESs perception and priority

These preliminary findings can be considered as the key challenges to the Nexus security and resilience in the Lower Danube pilot.

3.1.3 Identification of indicators

This phase of the activities aims at collecting stakeholders' perceptions about how to measure the achievement of the main domain objectives and the Nexus sustainable management. Some preliminary analysis of the Nexus resilience qualities has been carried out, but it requires further work using the SDM. Therefore, the final identification of the Nexus Resilience Qualities will be one of the main goals of the first stakeholders' workshop to be organized in this pilot (June/July 2022).

Concerning the domain objectives, we mainly refer to the four security dimensions - i.e. water security, energy security, food security and ecosystem security - that contribute to the Nexus sustainable management.

Concerning water security, the main dimensions are those related to water accessibility which concerns the meeting of irrigation demand. As described previously in the text, the main barriers to the satisfaction of the irrigation demand are not related to the accessibility of the water resources. Water availability is not an issue in this pilot. The effectiveness of the existing irrigation network represents the main issue that needs to be addressed. Most small farmers do not have access to the irrigation network. Therefore, the key indicators are those related to the accessibility and use of water for irrigation purposes. The accessibility of water for domestic use is also a barrier to the local development in some small villages in the pilot area.

Concerning ecosystem security, the main domain objectives are those related to the health of the fluvial ecosystem, which, in turn, is affected by the water volume released by the Iron Gate dam. As already described in the previous section, the management of the dam affects the sediment equilibrium and, thus, the riverbanks' erosion.

Energy security is affected by the affordability dimension. This is specifically valid for the small farmers, that consider the energy costs unaffordable, reducing their capability to access the water resource for irrigation purposes.

Finally, food security depends on the quantity of agricultural production, instead of the access to food. The following table describes the main indicators for assessing the Nexus management in the Lower Danube pilot area.

Table 6: List of indicators identified with the stakeholders in the Lower Danube pilot

Dimension	**Element of the system**	**Indicators**	**Unit**

Water security	Water for agriculture	Agricultural water users Use from surface water Surface water supply Water availability per agricultural area (Water consumption indicator)	% of farmers % of farmers m^3/ha m^3/ha
	Urban water	Piped urban water supply access Urban wastewater collection Access to improved sanitation	% % % of population
Energy security	Affordability	Share of farmers' income spent on fuel and electricity	%
	Disparity	Farmers energy use for each income group	%
	Ecosystem impact (water footprint of energy)	Amount of freshwater withdraw (or consumption) per unit of energy produced or as a percentage of water used for energy production in total water consumption or supply	%
Ecosystem security	River ecosystem	River health index Flow alteration Area affected by riverbank erosion Sediment management	- % ha -
Food security	Food production	Percent of arable land equipped for irrigation Per capita food production variability Proportion of agricultural area under productive and sustainable agriculture Average income of small-scale food producers	% USD per capita % USD

The list of indicators will be discussed and validated during the first stakeholder workshop (which is tentatively being scheduled in September 2022).

3.2 The Pinios River Basin

The preliminary results of the implementation of the REXUS approaches in the Pinios pilot, following the methodological approach detailed above, are based on the integration of the baseline description (D6.1) and the results of the first round of interviews carried out with the local stakeholders, which provided a huge body of knowledge in all Nexus domains. Some basic information were also gathered during the Pinios kick-off meeting, which has been organized online and also included some online questions, exercises and open discussions.

In summary, the Pinios river basin is extremely productive for agricultural activities, although there is absence of rational water resources governance and management, which generally causes high-water consumption and groundwater over-abstraction for irrigation (currently by far the largest water consumer over the area). There is a tight interconnection between agricultural and energy domains, and currently the increasing energy costs for the operation of pumping and irrigation systems are contributing to Nexus challenges. The current agricultural activities are not sustainable and create significant impacts over the environment, so that the Thessaly plain is one of the NVZ (Nitrate Vulnerable Zones) in Greece. A strong conflict on water use is related to environmental flow, which is hardly satisfied at the middle and downstream river sections, due to the high irrigation demand.

A round of individual interviews was carried out by the pilot leader (SWRI) based on the framework developed by IRSA, with the aim of collecting stakeholder knowledge concerning: i) the most important ES to be produced for the Nexus security and the local development; ii) the key ecological resources and ecological processes needed for the ES production; iii) the key actors interested/involved in the ES production and provision; iv) the infrastructures needed for the actual use of the ES; and v) the main barriers hampering the ES production process. The results of the interviews were used to structure the models described in the following.

3.2.1 The socio-ecological-technical network

As already stated previously, the main scope of this phase of analysis is to detect barriers hampering the sustainable management of the Nexus due to lack of effective interaction mechanisms among the different actors. Following the methodological approach described in (Giordano et al., 2017), the analysis of the social network was carried out accounting for three meta-networks, namely Agent X Agent, agent X Task and Task X Task. Even in this case, the lack of stakeholders' inputs concerning the kinds of information to be used for carrying out the different tasks prevented us to build two further meta-networks, i.e. the Agent X Information and the Information X Task. The lack of these meta-networks was accounted for in the analysis of the obtained results.

The following Table 7and Table 8 show the list of agents involved/impacted by the nexus management and the different tasks that, according to the participants in this first round of knowledge collection process, need to be carried out.

Table 7: List of the 'agents' for the Pinios pilot

Agent	**Acronym**
Water directorate of Thessaly	A1
Agricultural University of Athens	A2
Ministry of Rural Development and Food – Directorate of Land improvement and Soil resources	A3
Ministry of infrastructure and Transport	A4
Ministry of Environment and Energy – Directorate of Water	A5
Farmers	A6
University of Thessaly	A7
Agricultural development research organizations	A8
Municipalities	A9
Land improvement organizations	A10
Water utilities	A11
Public Power Corporation	A12
Environmental organizations	A13

Agronomist consultants	A14
Regional Dept. for Environmental and Spatial Planning	A15
Hellenic Land Improvement Service	A16

Table 8: List of the 'tasks' for the Pinios pilot

Tasks	**Acronym**
Technical assistance to farmers	T1
Awareness raising	T2
GW use monitoring and control	T3
Land and soil protection	T4
Land use planning	T5
Farmers' involvement	T6
Agricultural subsidies distribution	T7
Irrigation infrastructure improvements	T8
Environmental resources protection	T9
Water management policies enforcement	T10
Agricultural policies enforcement	T11
Water reservoirs management	T12

The results of the interviews were analysed to define the connections among the elements in these tables. Please, refer to the section on the Lower Danube pilot for a detailed description of the meta-networks. The following Figure 8 shows the network of interactions, as described by the stakeholders involved in the first round of interviews.

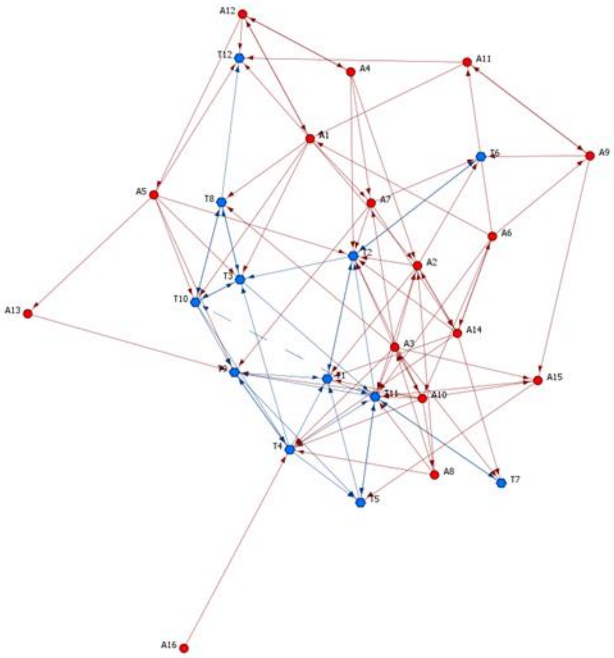

Figure 8: Socio-ecological-technical network for the Pinios pilot

The map of interactions was, then, analysed using the measures of the Graph Theory. Specifically, the centrality degrees of the different meta-networks were calculated (Giordano et al. 2017). The Task X Task network shows the central role played by two tasks, i.e. the technical assistance to farmers and the awareness raising. These two tasks are characterized by numerous connections with the other tasks in the network that need to be carried out in order to achieve a sustainable Nexus management - i.e. agricultural policy enforcement, land and soil protection, and land use planning, just to mention a few of them. This means that if the tasks T1 and T2 are not effectively carried out, barriers emerge hampering the implementation of the other interrelated tasks. However, the Agent X Agents network (Figure 8) shows the limited connections among the agents responsible for carrying out T1 and T2 - i.e. the research actors and the institutional agents – and the farmers. This means that the process of knowledge transfer towards the farmers is hampered by the lack of effective interaction mechanisms. This is also demonstrated by the marginal role played by the task “farmers’ involvement” (T6) in the Task X Task network. Moreover, the lack of farmers’ social capital – as specified by several stakeholders – hampers the knowledge sharing process within the farmers’ community.

Another key barrier detected in the SNA is represented by the limited role played by Land Improvement Service (A16). According to the results of the interviews, this agent possesses key knowledge concerning the best practices for reducing soil degradation and protecting ecological resources. However, this agent is isolated in the Agents X Agents meta-network. The lack of effective connections negatively affects the capability of this actor to carry out the expected tasks.

The land use planning (T5) is characterized by strong connections with other important tasks in the Tasks X Tasks meta-network. Effective land use planning could facilitate the protection of land & soil and environmental resources. Moreover, it facilitates the enforcement of agricultural policy. However, this task is connected only to the agent A15 – Regional Dept. for Environmental and Spatial Planning. The lack of cooperation among the different agents – and specifically the other institutional agents – in carrying out this task represents a barrier that could jeopardize the implementation of the other interconnected tasks. The lack of cooperation among the different institutional agents is also demonstrated by the limited interconnections among these agents in the Agents X Agents network. As many stakeholders pointed out during the interviews, the institutional fragmentation is one of the key issues to be addressed in the pilot. This is specifically true for the water and agriculture management policies, that are connected through a negative link since conflicts emerge quite often during the implementation of these policies.

The following Table 9 summarizes the main barriers hampering the sustainable management of the Nexus due to ineffective interconnections in the socio-ecological network.

Table 9: List of the main barriers from the socio-ecological network (Pinios)

Barriers	Agents involved	Impacts on the Nexus management
Lack of interaction between farmers and institutional actors	Farmers, Institutional actors, Consultants	Lack of knowledge transfer and lack of awareness raising initiatives have impacts on farmers' behaviour.
Isolation of key actor	Land Improvement Service	The lack of interactions between this agent and the rest of the socio-ecological networks negatively affects the knowledge sharing process.
Lack of cooperation in carrying out key task	Institutional agents	The institutional fragmentation hampers the effective implementation of key plans for managing and protecting resources

3.2.2 Participatory System Dynamic Modelling

The REXUS activities in the Pinios pilot included a round of semi-structured interviews, carried out with many stakeholders at different scale/level, as highlighted in the following Table 10. The process is still ongoing, and one large workshop will be organized in the Pinios area in May 2022.

Table 10: List of stakeholders interviewed to date in the Pinios case study

Stakeholder	Role/interest	Main Sector(s)
Water Directorate of Thessaly	Water resources management and allocation in the Thessaly area, water permits	W
Professor of Land Reclamation Works & Irrigation, Vice Rector, Agricultural University of Athens	Research, sustainable development pathways for the area	W
Directorate of Planning and Management of Water Services, General Directorate of Water, Hellenic Ministry of Environment and Energy	Water resources planning and management	W-Ec
Professor of Water Resources Management, Department of Civil Engineering, University of Thessaly	Research, sustainable development pathways for the area	W

Department of Strategic Planning and Policy, Hellenic Agricultural Organization "DEMETER"	Strategic planning, environmental conservation	Ec
Directorate of Land Improvements and Soil Resources, General Directorate of Rural Development, Hellenic Ministry of Rural Development and Food	Rural development and food production	W-F
Lawyer	Sustainable water resources management for agriculture	W-F
Member of the National Association of Land Improvement Organizations, Land Improvement Organization of Naousa, Agricultural producer	Planning of agricultural activities, food production	F
Mechanical Engineer, Energy (SHPP), Department at Public Power Corporation (PPC) – Renewables S.A.	Renewable energy development	En
Management Body of the Ecodevelopment Area of Lake Karla - Thessaly, Professor in Democritus University of Thrace	Research, sustainable management and development of the area	Ec
Renewable Energy Sources company on the field of wind farms	Renewable energy development	En
Agricultural association of Trikala, Geotechnical Chamber, Agronomist and owner of a shop with agricultural supplies	Food production and planning in the agricultural sector	F
Directorate of Agricultural Economy and Veterinary, Regional Unit of Magnesia	Sustainable agriculture and farming	F
Professor of Hydrology and Water Resources, Department of Rural and Surveying Engineering, Aristotle University of Thessaloniki	Research, sustainable water resources management	W
Department of Costing and Pricing of Water Services, Hellenic Ministry of Environment and Energy	Water resources management and allocation, mediation in irrigation water use	W
Civil engineer, Prof. Aristotle University Thessaloniki, UNESCO Chair for Sustainable Development Solutions Network of Black Sea	Research, water resources planning and sustainability	W
Forester, Directorate of Environment and Spatial Planning of the region of Larissa	Local spatial planning, environmental management	Ec
Geologist, Water Resources and Geothermics, Hellenic Survey of Geology and Mineral Exploration	Water resources management, GW state	W
Regional Organization of Land Reclamation of Thessaly	Land reclamation, agricultural activities	F
Professor of Agronomy, Department of Agriculture Crop Production and Rural Environment, University of Thessaly	research, sustainable agriculture and practices	F
Cotton Laboratory at Karditsa and Orchomenos, Hellenic Agricultural Organization – DEMETER	Agricultural production	F

Geotechnical Chamber of Greece – Department of Central Greece	technical advisor, professional license to agricultural engineers, scientific research and innovation	F
Interprofessional Organization of cotton, Local Land Improvement Organization of Titanio	Agricultural production	W-F
Interprofessional Cotton Organization and, Land Organization of Land Reclamation of Titaniou	Agricultural production	W-F
THESGI Farmers' Cooperative of Thessaly	Agricultural production	F
Hellenic Ministry of Rural Development and Food	Agricultural production and rural development	F
Agronomists, Agricultural Association of Karditsa	Agricultural production, technical support and capacity building	F
Local Organization of Land Reclamation of Tavropos, PhD agronomist, cotton grower	Land reclamation, improvement of land farms, maintenance of irrigation systems	W-F
Agriculture Department, Barba Stathis S.A.	Sustainable agricultural production	F
Department of Hydro-Economics and supervision Local Organizations of Land Reclamation, Thessaly's Regional Organization of Land Reclamation	Land reclamation, improvement of land farms, maintenance of irrigation systems	W-F
Professor of Sustainable Water Resources Management, University of Thessaly.	Research, sustainable water resources management	W
Senior Researcher at Chemical, Environmental and Hydraulics Engineering, University of Thessaly	Research, sustainable water resources management	W
Young Farmer	Agricultural production	F
Research Biologist, Greek Biotope/Wetland Centre	sustainable use of renewable natural resources, environmental conservation	Ec
Agronomist, Geotechnical Chamber of Greece, Department of Thessaly; Agricultural Association of Larissa, activist for water resources management improvement of Thessaly	Sustainable use of water resources, with focus on agriculture	W

Basically, the stakeholders involved in the interviews highlighted the central role of two ecological resources mainly related to water (the Pinios river and the aquifers). Several functions are associated with such resources, which are heavily exploited for the productive activities over the area. Different initiatives involve these resources and aim at the development of the area (such as the Karla Reservoir and Acheloos Water Basin Transfer). However, these large scale projects, which at a strategic level aim to increase the amount of freshwater in the Pinios Basin while providing opportunities to augment hydroelectric capacity, are highly contrasted and currently conflicting for different reasons (such as e.g. the potential environmental impacts of projects that may guarantee an increased water availability).

Table 11: identification of the key ES and ecological resources for the Nexus security (Pinios)

Ecosystem Service type	ES description	Resources involved	Nexus security	Main beneficiaries
Regulating	Hydrological cycle and water flow regulation (including droughts and floods)	River, Lake, Reservoirs	Water security, Ecosystem security, Food Security, Energy security	Local community, Farmers, Ecosystem
	Regulation of the chemical conditions of freshwater (SW and GW)	River, Lake, Reservoirs, GW bodies	Water security, Food security Ecosystem security	Local community, Farmers Ecosystem
	Maintaining nursery population and habitats	Forests, River,Lake	Ecosystem security	Local community Ecosystem
	Dilution by freshwater (and marine) ecosystems	River, Lake, GW bodies	Water security, Ecosystem security	Local community Ecosystem
	Regulation of physical, chemical, biological conditions	River, Lake, GW bodies, Soil	Water security, Ecosystem security	Local community Ecosystem
Provisioning	(Surface, subsurface ground) water for ecosystem (non-drinking purposes)	River, Lakes, Reservoirs, GW bodies	Ecosystem security	Ecosystem
	Surface water for energy production (non-drinking purposes)	River, Reservoirs	Energy security	Hydroelectric company
	Cultivated terrestrial plants for nutritional purposes	Agricultural land	Food security	Farmers, Local community
	SW and GW provision for agriculture (non-drinking purposes)	River, Lakes, Reservoirs, GW bodies	Water security Food security	Farmers, Local community
	Animals reared for nutritional purposes	Water and land	Food security	Farmers
	Wind energy, Solar energy	Wind and solar radiation	Energy security	Energy producers, Local community
	Surface water for drinking	Water	Water Security	Local community
Cultural	Recreation and ecotourism	Riparian areas River	Ecosystem security	Local community Tourists

	(Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions)			

Referring to the summary proposed in the Table 11, most of the stakeholders consider the provisioning ES as key for guaranteeing the Nexus security in the Pinios area. This is mainly true for water security and food security. A central role has been definitely attributed to the water resources, both surface water (SW) bodies (the Pinios river, Karla lake and the multiple reservoirs that are located in the basin) and groundwater (GW). This clearly emerges from the table, as most of the ESs mentioned by the stakeholders are water-related ESs. Water is central to support food production (as irrigated agriculture is central in the socio-economic development of the area) and energy production, besides being needed for guaranteeing ecosystem functions. Both SW and GW are increasingly threatened by unsustainable practices and their physical, chemical and biological conditions getting rapidly worse. The role of water-related risks (and therefore the water flow regulation) is another central ES for the area.

The main insights provided by the interviews were structured in the form of a Causal Loop Diagram, which also contains basic information from the baseline description. The CLD does not show a single community view of the issue and may not be representative of either the actual scenario on the ground or of the Pinios River Basin Management Plan. Overall, there were several dominant themes within the CLD, though each of these were derived from slightly different perspectives. The overall picture is one where large scale plans are implemented to address water and electricity shortages through interbasin transfer, while facing challenges due to limited operational and local management. These challenges came in the form of limited maintenance and improvements of infrastructure to facilitate and mediate the flow of resources (energy and water) to and from localities. Without this infrastructure behaviour such as unregulated abstraction and pollution continued to degrade water quality, this behaviour was compounded by a lack of monitoring and law enforcement as well as climate change placing additional pressures on farmers. Considering the complexity of the pilot, and the need for considering different levels of analysis that should be considered, the model is being re-organized considering three different models specifically referring to the strategic, operational and local level.

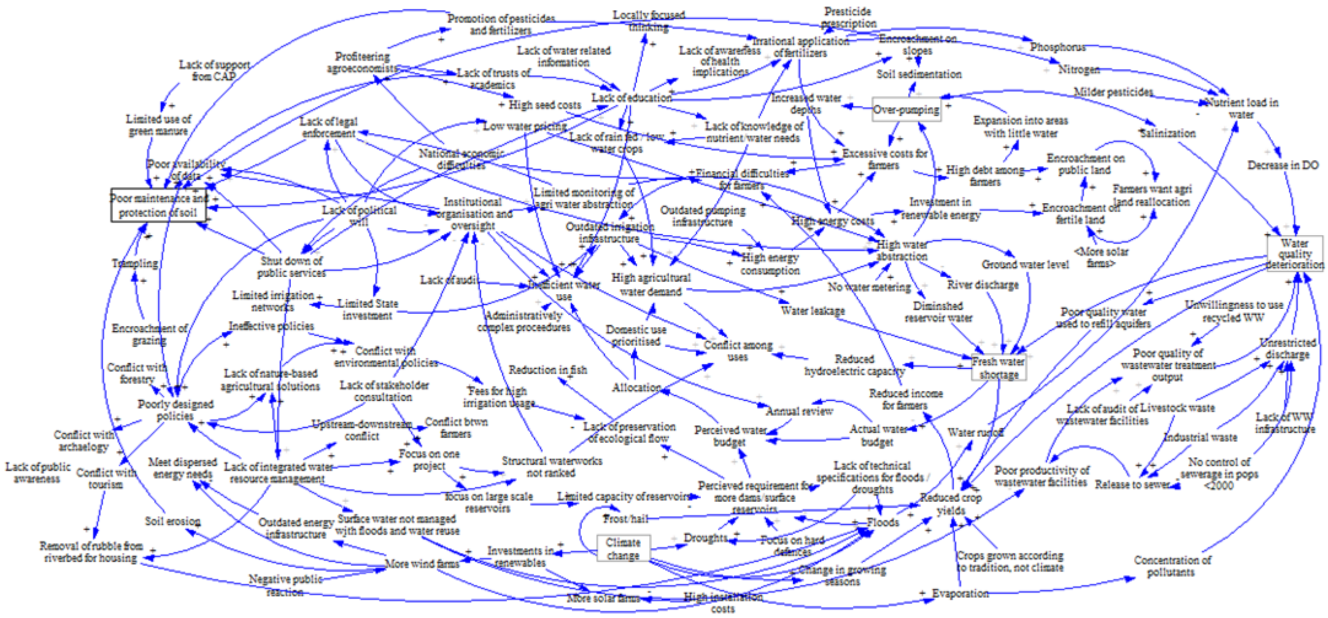

Figure 9: Preliminary CLD developed for the Pinios pilot

As already mentioned, water is central to the Pinios area. This is also reflected by stakeholders' interviews. Water shortage is increasingly an issue over the river basin, due on the one hand to the significant water abstraction rate, mainly related to the agricultural activities performed over the area, and on the other hand to the increasing frequency and intensity of drought phenomena. The low water security is currently related to poor water resources management and limited efficiency in all sectors, but a key role is played by agriculture as it is a dominant economic activity in the area and currently more than 90% of water abstraction is for irrigation purposes. Irrigated agriculture is heavily affected by structural deficiencies, which include specifically the outdated irrigation networks (e.g. open channels are still used over the area) and the limited space for innovation in irrigation systems, also due to the very limited funding and to the complexity of administrative processes. From the administrative point of view it has been highlighted that the water consumption audit in agriculture is not effective, that complex administrative procedures are required (e.g. permissions for water use) and that water allocation is not based on a solid and updated water budget. Many farmers do not have valid water use permits, and no water use meters. Furthermore, the water management legislation framework looks rather complex and old (water distribution is based on a legislation that was instituted three decades ago) and relevant public services (e.g. Hellenic Land Improvement Service) have been closed and not adequately substituted by the Local Land Improvement Organizations. These Organizations, however, have also limited funding through the farmers' fee. The lack of a competent public service that regulates all the different water uses is therefore perceived. Among the policy actions adopted, a high environmental tax has been established in the past, but caused severe conflicts among the stakeholders. Similarly, water pricing strategies were adopted, but resulted inefficient. However, high irrigation fees are expected to be imposed on farmers in favor of environmental protection. It is worth considering also that the spatial dimension needs to be taken into account, as the behaviors in the upstream part of the basin abstract large quantities of water, ultimately limiting the available water in the downstream part. The collaboration in this direction is still hard. As a consequence, the ecological flow in the river is hardly guaranteed.

Besides water quantity, the issue of water quality is also central to water security. Several stakeholders highlighted that point and non-point sources of pollution exist. For example, sewage systems are controlled in cities only while settlements with less than 2000 inhabitants are not adequately monitored. Livestock activities and specific activities (e.g. cheese factories) are (with exceptions) a relevant source of pollution along with agricultural areas, but environmental inspections and monitoring activities are rather limited and fines are rather low (so often it is better to pay fines for some companies than to change operations). Good practices are being increasingly promoted and implemented, although the accessibility to the resources needed is easier for larger companies. A side effect of GW overexploitation is also the salinization of the aquifer, an issue that is increasingly affecting coastal areas.

The overexploitation of GW is currently uncontrolled and resulting in a significant increase of pumping depth (with severe impacts on the agricultural activities as it is related to the energy cost). The severity of the problem increases also as an effect of the limited control and lack of penalties. One solution for the reduction of energy costs and the improvement of *energy security* is the development of RES projects (mainly photovoltaic systems and hydropower plants). However, their implementation is hampered by the limited acceptance of such initiatives by local communities, also considering the need for land (avoiding also the use of highly productive agricultural land) and the impacts on the landscape. A huge barrier is seen in the complexity of licensing procedures for the activation of new hydropower projects and for wind farms, due also to the limited staff working for competent authorities and to the wide political opposition to these projects. In general, stakeholders also perceive that there is an improper strategic planning of RES at spatial scale, resulting in a wrong selection of suitable land or in unintended consequences (e.g. the increase of local runoff due to large photovoltaic plants). However, limited attention has been given, so far, to the indirect benefits that such measures may have (e.g. wind farms may offer indirect flood protection due to the implementation of landscape management practices). More in general, the issue of energy security is rather relevant for the whole country as the entire energy system infrastructure needs upgrading.

Among the technical solutions to improve water security (but also food and energy security), the role of dams and barriers (new ones and an improved operation of the existing ones) has been identified as central, although there is much dispute on the issue. Some stakeholders remarked that the development of dams and barriers has been, so far, rather irrational and not effective and one the strategic objective of EU Green Deal for the Pinios river is the restoration and renaturalization of the water course through their removal. Others highlighted that small-scale reservoirs distributed over the area may provide more efficient water management and support recharge. In general, a huge potential is seen in the rational development of initiatives for multi-purpose SW storage projects, provided that incentives are available along with political will. Among the others, the role of Lake Karla and Plastira (both artificial) is seen as positive for irrigation and other water uses (domestic and hydro-electric), and may also support ecotourism. However, there are also infrastructures (Sykia dam and Pili dam) which have been not completed yet, due to the lack of funding. Impacts on the *ecosystem security* are however associated with dams and other artificial barriers/structures as for example fish populations are affected by constructions and river flow is disturbed by structures and actions. Another technical measure, which is currently highly debated, is the diversion of the Acheloos river which should increase the water availability over the area. However some resistances are mainly related to the perception that such a measure is 'single-sided' and lacking a broader view of the state and evolution of the system. The Acheloos diversion project has some resistance particularly from stakeholders located downstream in the river basin. The lack of a systemic thinking also affects the limited attention to integrated approaches that integrate wastewater reuse and flood-risk reduction measures. Particularly, the role of nature-based solutions is seen as potentially crucial for the development of the area, compared to the role of 'hard' traditional measures. With specific reference to the environmental dimension, the area is characterized by the need for protection of riparian habitats and forest conservation, as the spatial planning has been rather limited and heavy anthropogenic actions (including urbanization) took place. A need for environmental protection is particularly highlighted for the upstream area of the basin and the mountainous forests, which is also affected by erosion (exacerbated by improper agricultural practices and by the increase of areas of rainfed crops). Lastly, an influence of urbanization and natural space encroachment has been highlighted, as a consequence also of tourism expansion.

Food security is fundamental for the development of the area, although significant impacts are associated with the increasing trend in food demand and production. For example, irrational application of fertilizers in the agricultural sector, the improper treatment of agrochemical residues along with poor operation and control of wastewater treatment facilities (e.g. in cheese factories and livestock companies) are affecting the state of SW and GW bodies. Nitrate pollution is becoming severe over the whole area, GW is getting saline close to the coast and SW (affected e.g. by the runoff of agricultural chemicals) is getting not suitable for drinking purposes in specific areas. In general, the problem is perceived also on the socio-institutional side as many barriers exist to sustainable agricultural activities. Particularly, an area-specific rural development plan is missing, there is limited control and supervision by competent authorities, a very limited involvement of farmers in the preparation and development of agricultural studies and plans as well as a limited technical support to them, there is no control in place and non-systematic recording of agricultural area and irrigation water use. Referring specifically to the latter point, having reliable and continuous measurements on crops and crop water needs would be fundamental, but recordings are no more being performed since 2000 (Local Land Improvement Organization). The lack of planning also caused an inefficient development of crops (e.g. the cotton, which caused an increase in water need and is currently being affected by water shortages, but also olive trees which are reducing their yield), a transition from rainfed to irrigated crops without the needed infrastructural development and an expansion of agricultural activities with areas with a low potential. In other words, crops are often selected not considering their adequacy given the system conditions, rather aiming to maximize the profit. This is reducing yields and, ultimately, farmers' profit. Another relevant barrier in this direction is the limited technical knowledge (and support) of farmers, along with a low awareness on key environmental issues: key impacts are related to water use, crop selection and use of fertilizers and pesticides. Fragmentation in roles and responsibilities is increasingly perceived, and impacting agricultural activities (for example, Local Land Improvement Organizations are responsible for channels and Regional Administration for reservoirs maintenance, and there is lack of cooperation between Land Improvement Organizations and Regional authorities in terms of channels maintenance). This also reflects in the limited supervision and sanctions implementation by competent authorities. Agricultural activities are also becoming unsustainable at farm level, as for example, heavily affected by land over-fragmentation, by inefficient maintenance and upgrade of irrigation networks, by the lack of financial analysis at farm level, by a limited uptake of insurance system (difficult to pay as a consequence of the economic crisis). A huge barrier is also seen in the limited tendency of farmers to avoid any form of organization, coordination and mutual support (e.g. limited shared use of agricultural equipment, old machinery). This is also due to the failures of previous experiments. Another barrier to food security and sustainable agriculture at farm level is the limited environmental awareness, and the limited space for innovation, also due to the limited effectiveness of subsidies policy. Just to make an example, the transition to green manure may have manifold impacts including the reduction of water needs and the limitation of soil fertilizers and pesticides. A potential solution is the promotion of innovative environmental labeling schemes, which could support the promotion of sustainable policies (e.g. supporting circular economy schemes).

The role of climate change in this context is definitely perceived as highly relevant, as the frequency and intensity of extreme events (both floods and droughts) is increasing. This will have impacts on all security dimensions, ranging from water (limited availability of water during dry periods), to food (limited productivity and yields as a consequence of extreme weather events) to energy (potential limitation e.g. to HPP mainly due to conflicting uses/needs). Increasing concerns are perceived on the flood impacts in coastal areas (due to both technical and administrative issues).

In general, the analysis of the main interactions that characterize the socio-ecological system, highlighted that critical barriers exist in the institutional network. A lack of political will limits the implementation of innovative projects, and sustainable resources management is affected by the level of bureaucracy and the complex and jeopardized distribution of roles and responsibilities. Currently, the level of participation is relatively low, as no consultation and support structures exist with a direct engagement of stakeholders. This has a cascading impact in the lack of trust in competent authorities and a very limited development of the mentality that would be needed for supporting a sustainability transition.

Main findings

The participatory modelling approach allowed to describe the main characteristics of the Pinios case study, highlighting the main issues and challenges in each sector, and how those can affect the Nexus security and resilience. In the Pinios river basin, the lack of ecological resources (mainly water) is coupled with limiting factors related to the lack of coherent and inter-sectoral policies. The poor governance of the area has been highlighted by several stakeholders as one of the key barriers to sustainable Nexus management. Suitable policies are needed to coherently activate the three main filters for the ESs production and mobilization, i.e. Infrastructures, Institutions and Perceptions, as shown in the following table.

Table 12: List of infrastructures, institutions and perception (Pinios)

Filter	**Description**
Institution	Coordination among the local institutions and lack of coordinated policies Complexity of the legal and institutional framework Poor land management and long-term planning Lack of funding and economic support Control of the territory Lack of trust (in institutions)
Infrastructures	New infrastructures (e.g. Acheloos diversion) Territorial infrastructures(water, energy) Production infrastructures Environmental-friendly measures
Perception	Community’s perception and behaviour (e.g. sense of water ownership at farm level) Lack of information, education and awareness Ambiguity in ESs perception and priority (and related conflicts) Resistance to innovation Lack of cooperation and mutual support

These preliminary findings could be considered as the key challenges to the Nexus security and resilience.

3.2.3 Identification of indicators

As described in the methodological section, interviews have been oriented to identify relevant indicators for measuring the current state and potential evolution of the area under different scenarios. Particular attention has been given to the selection of Domain Objectives (DOs) and Nexus Indicators (NIs). The identification of Nexus

Resilience Qualities (NRQs) will be performed, directly using the SDM and specific exercises, during the first stakeholder workshop which is scheduled, for the Pinios pilot, on May the 17th 2022.

For the definition of DOs, we made reference to four key security dimensions (water, energy, food, ecosystems), highlighting the most crucial issues highlighted by the stakeholders for specific sectors. It is worth to remark that the following Table 13includes a tentative list of indicators suggested in the bottom-up phase of the process. Additional activities, to be performed mainly during the workshops, will be oriented to refine the list (as it currently has been intentionally kept wider to reflect the richness of information collected through the interviews) and to provide information on the most relevant indicators to be used. In the Table, indicators are explicitly related to the main problem/challenge to which they have been related and to the basic processes they refer to (this is needed to directly connect the indicators to the PSDM). Cells are in light blue for indicators that are replicated with reference to different problems/challenges.

In summary, water sector is central for the pilot, as water availability and accessibility are both relevant issues in the Pinios pilot. On the one hand, the availability of water resources is limited and is becoming lower as climate change effects are becoming more evident in the area. On the other hand, the accessibility of the resource is limited because of the inefficiency of the existing irrigation networks is a key issue to address. The overexploitation of GW, along with the intensive and unsustainable agricultural practices are also severely impacting the state of freshwater over the basin. This issue directly relates with the other central sector for the pilot, i.e. the food sector. The Pinios river basin is highly productive and heavily exploited for agricultural activities. However, the sustainability of agricultural activities is not guaranteed both on the economic point of view (as e.g. the water is a limiting factor for production and many policies including CAP are not effective), and on the environmental point of view (the use of chemicals and fertilizers is currently too high).

Energy security is mainly affected by the affordability dimension. This is specifically valid for the farmers, who consider the energy costs unaffordable, reducing their capability to access the water resource for irrigation purposes. Measures to increase energy availability and affordability are being discussed (e.g. multiple hydropower projects) and implemented (particularly, small size hydro) but without a coordinated planning and action.

Table 13 List of indicators identified with the stakeholders in the Pinios pilot

PROBLEM/CHALLENGE	DESCRIPTION - PROCESS	VARIABLES/INDICATORS (SH)	SECTOR (S)	CLASSIFICATION		
Water quantity	Water use for agriculture Water overexploitation and management Water availability	GW level (depth, volume)	W	*state indicator*	DO-availability	
	Water overexploitation and management Water availability	GW level/use vs. annual precipitation (or rate of yearly GW decline)	W-C	*state indicator*	DO-availability/adaptive capacity (Max-Min)	
	Water use for agriculture Water overexplotiation and management	Quantity of pumped water per well/user	W-F		DO-accessibility (Max-Min)	
	Water sector governance	Location of pumps	W		accessibility	

	Water availability	Number, capacity and density of water reservoirs	W-(EN)	*state indicator*	DO-availability/adaptive capacity (Max-Min)	
	Water availability Water sector governance	# of potential beneficiaries/groups (Dams)	W-En-F		accessibility	
	Water availability	SW availability (level, volume) in reservoirs	W	*state indicator*	DO-availability (Max)	
	Water use Soil quality	SW use (mainly agriculture)	W-(F-EC)		DO-availability/accessibility	NI: W-F, W-EN, W-EC
	Water use	River flow in different locations/seasons	W	*state indicator*	DO-availability	
	Water overexploitation and management Water availability	Temporal and spatial variation of GW and SW	W-C	*state indicator*	availability	
	Water use Water overexploitation and management	Water consumption	W-(F-E)		DO-availability/accessibility	NI: W-F
	Water use Water availability	SW/GW consumption	W	*state indicator*	availability/accessibility	
	Use efficiency	Water use efficiency/Water saving rate	W		DO-accessibility (Max-Min)	
	Water use Water availability Use efficiency	Water cost	W		DO-accessibility (Max-Min)	
	Water use Water availability	Water Exploitation Index	W	*state indicator*	DO-availability/accessibility	NI: W-F, W-EN, W-EC
	Water use for agriculture Water overexploitation and management Water availability Use efficiency	Water use efficiency in agriculture: agricultural production per water volume pumped/used	W-F		DO-accessibility (Max)	NI: W-F
	Water use for agriculture Water overexploitation and management Water availability Use efficiency	Water use efficiency in agriculture: water volume pumped/used per unit area (or farmer)	W-F		DO-accessibility (Max-Min)	NI: W-F

	Water use for agriculture Use efficiency	Agricultural production cost per unit area	(W)-F		DO (Min)	
	Water use for agriculture Water availability	Temporal variation of cultivated area per crop over time	(W-)F	*state indicator*		
	Water use for agriculture Use efficiency	Coverage, efficiency and state of irrigation systems	W		DO-accessibility (Max)	
	Water use for agriculture Use efficiency Water sector governance	Water saving rate (policies)	W		DO-accessibility (Max)	
	Water use for agriculture Use efficiency	Energy consumption in agriculture (for irrigation)	W-En-F		accessibility	NI: EN-W-F
	Water use for agriculture Use efficiency	Irrigation cost: energy	W-En-F		DO-access (Max-Min)	NI: W-F, W-EN
	Water use for agriculture Use efficiency	Irrigation water cost per unit of water volume and cultivated land area	W-F		DO-access (Max-Min)	NI: W-F
	Water use for agriculture Use efficiency	Water cost / total agricultural production cost	W-F			NI: W-F
	Water overexploitation and management	Number of farmers associated to water reservoir exploitation	W	-	accessibility	
	Water availability Water-related risks	Hydro-meteorological parameters: precipitation, temperature, rainfall intensity, # of days with high/low T	W-C	*state indicator*		
	Water-related risks	Flood areas per year	(W)-C	*state indicator*	DO (climate-Min)	
	Water-related risks	Compensation level related to flood damages	W			
	Water-related risks	Drought indices	W-C	*state indicator*		

	Water use for agriculture Use efficiency Water sector governance	Land use (with change over time)	W-F (Land)	*state indicator*		
	Water availability Water sector governance	Implementation phase of measures (new reservoirs)	W	-	accessibility	
	Water sector governance	Number of administrative and technical staff	W	-		
Water quality	Ecological state SW and GW deterioration Appropriate quality for (agricultural) use	Water quality parameters	W-EC	*state indicator*	DO-availability/accessibility (Max)	
	SW and GW deterioration	Nitrogen concentration in SW and GW	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	Phosphorous concentration in SW and GW	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	Nitrogen to Phosphorous ratio	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	Dissolved Oxygen concentration in SW and GW	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	Chlorides concentration	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	River flow level in different locations/seasons	W	*state indicator*	DO-availability (Max-Min)	
	Ecological state SW and GW deterioration	Ecological state	W-EC	*state indicator*	DO (Max)	NI: W-EC
	Water sector governance	# Fines per company	W			
	SW and GW deterioration	Electrical conductivity	W	*state indicator*	DO-availability/accessibility (Min)	
	SW and GW deterioration	Turbidity (Secchi disk depth)	W	*state indicator*	DO-availability/accessibility (Min)	

	SW and GW deterioration	Water temperature	W	*state indicator*	DO-availability/accessibility	
Sustainable agriculture	Agricultural productivity Efficient and financially sustainable agriculture	Agricultural production cost per unit area	F		DO (Min)	
	Efficient and financially sustainable agriculture	Water use in agriculture	W-F		DO-accessibility (Max-Min)	NI: W-F
	Efficient and financially sustainable agriculture	Energy consumption in agriculture (for irrigation)	W-En-F		DO-accrssibility (Min-Max?)	NI: EN-W-F
	Efficient and financially sustainable agriculture	Irrigation cost: energy	W-En-F		DO-accessibility (Min-Max?)	NI: EN-W-F
	Efficient and financially sustainable agriculture	Irrigation cost: other (Maintenance, env. fee)	F		DO-accessibility (Min)	
	Efficient and financially sustainable agriculture	Irrigation water cost/Agricultural production cost	W-En-F		DO (Min)	
	Agricultural planning (crops)	Temporal variation of cultivated area per crop over time	F	*state indicator*	DO (Min-Max?)	NI: W-F
	Agricultural planning (crops) Efficient and financially sustainable agriculture	Economic benefit per crop type vs. irrigation water needs	W-En-F		DO	NI: W-F
	Agricultural productivity	Agricultural yield per hectare	F		DO	
	Agricultural productivity Sustainable practices	Agricultural yield vs meteorological data	F-C			NI: F-C
	Agricultural productivity	Quality of agricultural products over time	F		DO (Max)	
	Agricultural productivity Sustainable practices	Type, use and cost of pesticides	F	-	DO (Min)	
	Agricultural productivity Sustainable practices	Use of green manure	F	-	DO (Max)	
	Efficient and financially sustainable agriculture	% of professional farmers	F	-		
	Efficient and financially sustainable agriculture	Average farm size (fragmentation)	F (Land)	*state indicator*		

	Efficient and financially sustainable agriculture	# of active farmers/# of landowners	F (Land)	-		
	Efficient and financially sustainable agriculture	# of submitted applications to funding programs	F	-	DO (Max)	
	Agricultural sector governance	Cost-benefit of EU funding policies	W-En-F			
	Agricultural sector governance	# of approved CAP proposals (e.g. pumping system improvement, young farmers)	F	-		
	Efficient and financially sustainable agriculture	Economic efficiency per crop and cultivated area	F	-	DO (Max)	
Energy efficienc y	Energy efficiency RES	Energy cost (for irrigation)	W-En-F	-	DO-accessibility (Max-Min)	NI: EN-W-F
	Energy efficiency RES	Cost of RES / Cost of conventional energy	EN	-	DO-accessibility (Min)	
	RES	CO2 equivalent emissions savings	EN	-	DO (Max)	
	Energy sector governance	Level of maturity of studies	EN	-		
	Water availability for energy	HPP production (MWh)	EN	*state indicator*	DO-availability (Max)	
	Water availability for energy	# of potential beneficiaries/groups (Dams)	W-En-F	-	DO-accessibility (Max)	
	Energy efficiency RES	Capacity of the energy system infrastructure	EN	*state indicator*	DO-availability (Max)	
	Energy sector governance	Wind farms: time required between approval and installation	EN	-	DO (Min)	
	Energy sector governance	Wind farms: % of successful projects	EN	-	DO (Max)	
	Energy sector governance	Wind farms: power installed per region per year	EN	*state indicator*	DO-availability (Max-Min)	
	Energy efficiency and RES	Areas with PVs	EN-F(Land)	*state indicator*	DO-availability/accessibility (Max-Min)	NI: EN-F

	RES Energy sector governance	RES density per region	EN	*state indicator*	availability	
	Energy efficiency	Energy consumption in agriculture (for irrigation) - unit production	F-EN-W	-	DO-accessibility (Min)	NI: EN-W-F
	Energy efficiency	Energy consumption in agriculture (for irrigation) - unit area	F-EN-W	-	DO-accessibility (Min)	NI: EN-W-F
	Energy efficiency	Energy cost in agriculture (for irrigation) - unit production	F-EN-W	-	DO-accessibility (Min)	NI: EN-W-F
	Energy efficiency	Energy cost in agriculture (for irrigation) - unit area	F-EN-W	-	DO-accessibility (Min)	NI: EN-W-F
Soil quality and degradation	Soil quality	Water use in agriculture	W-F	-	DO-accessibility (Min)	NI: W-F
	Soil quality Soil degradation	Cost-benefit of EU funding policies (sectoral)	EC	-		
	Soil quality	Type and use of pesticides	F-EC	-		
	Soil quality	Soil additives for specific cultivations	F-EC	-		
	Soil quality	Soil parameters (change over time)	F-EC	*state indicator*		
	Soil degradation	Soil erosion	F-EC	*state indicator*	DO (Min)	NI: EC-F
Ecosystem state	Environmental protection & e-flow	River flow in different locations/seasons	W-EC	*state indicator*	availability	
	Environmental protection & e-flow	SW use	W-EC	-	DO-availability/accessibility	
	Environmental protection & e-flow	Ecological flow (over time)	W-EC	*state indicator*	DO (Max)	
	Environmental protection & e-flow	Ecological flow / River flow (over time)	W-EC	*state indicator*	DO (Max)	NI: EC-W
	Pollution control	BOD	W-EC	*state indicator*	DO (Min)	

	Pollution control	Nitrogen, phosphorus and ammonia	W-EC	*state indicator*	DO (Min)	
	Pollution control	Measurements of pesticides	EC	*state indicator*	DO (Min)	
	Pollution control	Measurements of toxicity	EC	*state indicator*	DO (Min)	
	Pollution control	Biological indicators: benthos, plant cover, fish and phytoplankton	EC	*state indicator*	DO (Max)	
	Pollution control	WFD parameters	W-EC	*state indicator*		
	Flora and fauna conservation	Flora and fauna in highly important areas	EC	*state indicator*	DO (Max)	
Governance issues	Water sector governance Agricultural sector governance	Frequency of maintenance of irrigation networks	W	-	accessibility	
	Water sector governance Agricultural sector governance	Availability of equipment and economic resources	W-F	-	accessibility	
CC and extreme events	Water-related risks	Frequency of extreme events	W-C	*state indicator*		
	Water-related risks	Hydro-meteorological parameters: precipitation, temperature, rainfall intensity, # of days with high/low T	W-C	*state indicator*		
	Water-related risks	Distance of constructions from the sea	Land	*state indicator*		
	Water-related risks	Buildings/infrastructure performance	Land	*state indicator*		
	Water-related risks	Flooded areas	W-C	*state indicator*		
	Water-related risks	Compensation level related to flood damages	C			

3.3 The Nima-Cauca River Basin

The preliminary results of the implementation of the REXUS approaches in the Nima-Cauca pilot are based on the integration of the baseline description (D6.1) and the results of the first round of interviews carried out with the local stakeholders. Relevant information also derived from the interaction with the local institutional team responsible for the POT (Territorial Ordering Plan – '*Plan de Ordenamiento Territorial*' in Spanish) preparation, i.e. a strategic planning document for the development of the area which should perform a (participatory) environmental diagnostic of the watershed. Particularly, this diagnostic phase should take into account the desired future land use scenario for the watershed, considering current land use, suitable land use, biophysical characteristics, land use conflicts and causes of natural resources degradation. This analysis should ultimately help to identify required actions and investments that may support a transition towards the watershed's concerted vision of the future.

The pilot is characterized by a main ecological resource - i.e. Nima-Amaime-Cauca river - whose potentialities to produce and provide ES for the community's well-being (ranging from water for drinking purposes to water for energy and agriculture) are currently limited by several pressures (e.g. increased urbanization, limited control and monitoring of the territory, impacts on quality from productive activities and low effectiveness of wastewater treatment plants) which make even more conflicting the contextual use of the resource. The river basin is characterized by two main sub-areas: a mountainous upstream area, that is key to the provision of water-related ES for downstream users and a flat downstream area dedicated mainly to agricultural activities. Particularly the Andean ecosystem is fragile and needs improved conservation. One of the key activities for the socio-economic development of the area is the sugar-cane production, which is however characterized by high impacts on the ecological resources of the area. Therefore, the main goal of the REXUS implementation in this pilot is to detect and analyse those elements potentially threatening the system equilibrium, and to contribute to the definition of multi-sectoral policies for the provision of ES for the Nexus security.

Following the REXUS framework of the stakeholders' engagement, the first round of interviews was carried out by the pilot leader (CIAT) based on the mentioned framework developed by IRSA, with the aim of collecting stakeholders' knowledge concerning: i) the most important ES to be produced for the Nexus security and the local development; ii) the key ecological resources and ecological processes needed for the ES production; iii) the key actors interested/involved in the ES production and provision; iv) the infrastructures needed for the actual use of the ES; and v) the main barriers hampering the ES production process. The results of the interviews were used to structure the models described in the following.

3.3.1 The socio-ecological-technical network

The socio-ecological-technical network for the Nima-Cauca pilot has not been built yet as interviews are still to be completed and the picture would not be comprehensive enough.

3.3.2 Participatory System Dynamic Modelling

The REXUS activities in the Nima-Cauca pilot mainly included a round of semi-structured interviews, carried out with the stakeholders identified in the Table 14. The process is still ongoing, as the REXUS activities are being as much as possible aligned with the activities required for the POT preparation, to avoid any stakeholder fatigue and to benefit from improved interactions. New interviews are therefore foreseen in the upcoming weeks.

Table 14: List of stakeholders interviewed to date in the Nima-Cauca pilot

Stakeholder	Role/interest	Main Sector
Acueducto rural-Upstream area (3 separate interviews)	Water supply and water treatment	W-(Ec)
Grupo de liderazgo social-Amaime	Sustainable development of the area,	W-F-Ec

	provision of services for the community (e.g. cleaning the river, activities of waste management), socio-economic well-being	
Rural community council-Amaime	Sustainable development of the area, provision of services for the community (e.g. cleaning the river, activities of waste management), socio-economic well-being	W-F-Ec
Smurfit Kappa (paper company)	Paper production, ecotourism promotion	Ec-W
Pig farm	Productivity of livestock farming activities	F-W

Following the proposed framework, the interviews aimed at gathering the stakeholders' understanding of the key ES to be produced in order to achieve a satisfactory level of security in the different Nexus domains, the ecological resources and processes needed for the ES production, the main pressures on the ecological resources and the main barriers hampering the effective ES production and mobilization.

As already mentioned, a key ecological resource for the area is the Nima-Amaime-Cauca river, which has a great potential to produce a wide range of ESs. The issue of 'water security', in terms of both quantity and quality of the resource (for drinking purposes, other productive uses and for ecosystem functioning) is central. Relevant conflicts are also related to the use of other natural resources (e.g. the forest) and, more in general, to the need to pursue a more balanced development model of the key productive activities. Such activities, which include e.g. the sugarcane production, the paper production, and the agricultural and livestock farming, need to be more sustainable over the long term since they are perceived as crucial for the socio-economic well-being of local communities, but increasingly impacting on a fragile environment. Particularly, the Andean ecosystems and the forest that are located in the upstream part of the catchment play a key role on the state of the area, particularly in terms of flow regulation. The main issues that need to be addressed for sustainable Nexus management have been already described in the pilot baseline description (D6.1), but the results of the interviews allowed a more detailed knowledge gathering process, integrating the local knowledge and problem perception in the CLD, as described further in the text. The following classes of ESs were detected in the stakeholders' argumentation, as detailed in the following Table 15.

Table 15: identification of the key ES and ecological resources for the Nexus security (Nima-Cauca)

Ecosystem Service type	ES description	Resources involved	Nexus security	Main beneficiaries
Regulating	Hydrological cycle and water flow regulation	River, water springs, forests, Páramo area	Water security, Ecosystem security, Food Security, Energy security	Local community Ecosystem
	Regulation of the chemical conditions of freshwater (SW)	River, wetlands	Water security, Food security Ecosystem security	Local community, Farmers Ecosystem

	Maintaining nursery population and habitats (e.g. *Guaduales*)	Forests, Páramo area, River, wetlands	Water security, Ecosystem security	Local community Ecosystem
	Dilution by freshwater (and marine) ecosystems	River, riparian areas, wetlands	Water security, Ecosystem security	Local community Ecosystem
Provisioning	(Surface, subsurface ground) water for ecosystem (non-drinking purposes)	River, water springs	Ecosystem security	Ecosystem
	Surface water for energy (non-drinking purposes)	River, water springs	Energy security	Hydroelectric company
	Cultivated terrestrial plants for nutritional purposes	Agricultural land	Food security	Farmers, Local community
	Surface water provision for agriculture (non-drinking purposes)	River, water springs	Food security	Farmers, Local community
	Animals reared for nutritional purposes	Water and land	Food security	Farmers
	Mineral substances used for material purposes	Riparian areas	Water security, Ecosystem security	Local community
	Fibres and other materials from cultivated plants, for direct use or processing (*wood for paper production*)	Forest	Ecosystem security, Water Security	Companies, Local community
Cultural	Recreation and ecotourism (Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions)	Riparian areas River, water springs	Ecosystem security	Local community Tourists

The Table 15 shows the multiple ESs mentioned (either directly or indirectly) by the stakeholders during the first round of interviews and integrated with the evidence from the baseline description. Provisioning ES are key for guaranteeing the nexus security over the area, particularly in terms of water use for multiple purposes (including the ecosystem functions), and in terms of agricultural practices. The role of the forest is considered as highly relevant for multiple functions, ranging from the water security (regulation function of extreme floods and role in the hydrological cycle) to ecosystem security. More in detail, the stakeholders' interviews highlighted the central role played by the Nima-Amaime-Cauca river on the state of the area. This is reflected by the table as most of the ESs mentioned by the stakeholders are water-related and involve the river, the riparian areas and wetlands as key resources. The water resources are rather abundant in the area, but the lack of effective policies and infrastructures is currently limiting their access and use for multiple purposes. This is particularly true for the water quality protection (as there is a limited control on the territory and on waste disposal and wastewater treatment processes) and for the access to drinking water, which is increasing following the growing urbanization but limited by structural inefficiency of the available infrastructures. This section characterizes the modelling approach proposed in this pilot, analysing the issues related to Nexus security and resilience.

The evidence from the baseline description along with the results of the interviews (the latter are in orange) were structured in the form of CLDs, to describe the cause-effects web of non-linear connections affecting the production of ESs, according to the stakeholders' problem understandings. Currently, the model included in Figure 10 is not divided into different sub-modules, although the different security dimensions are explicitly identified and characterized by different colors.

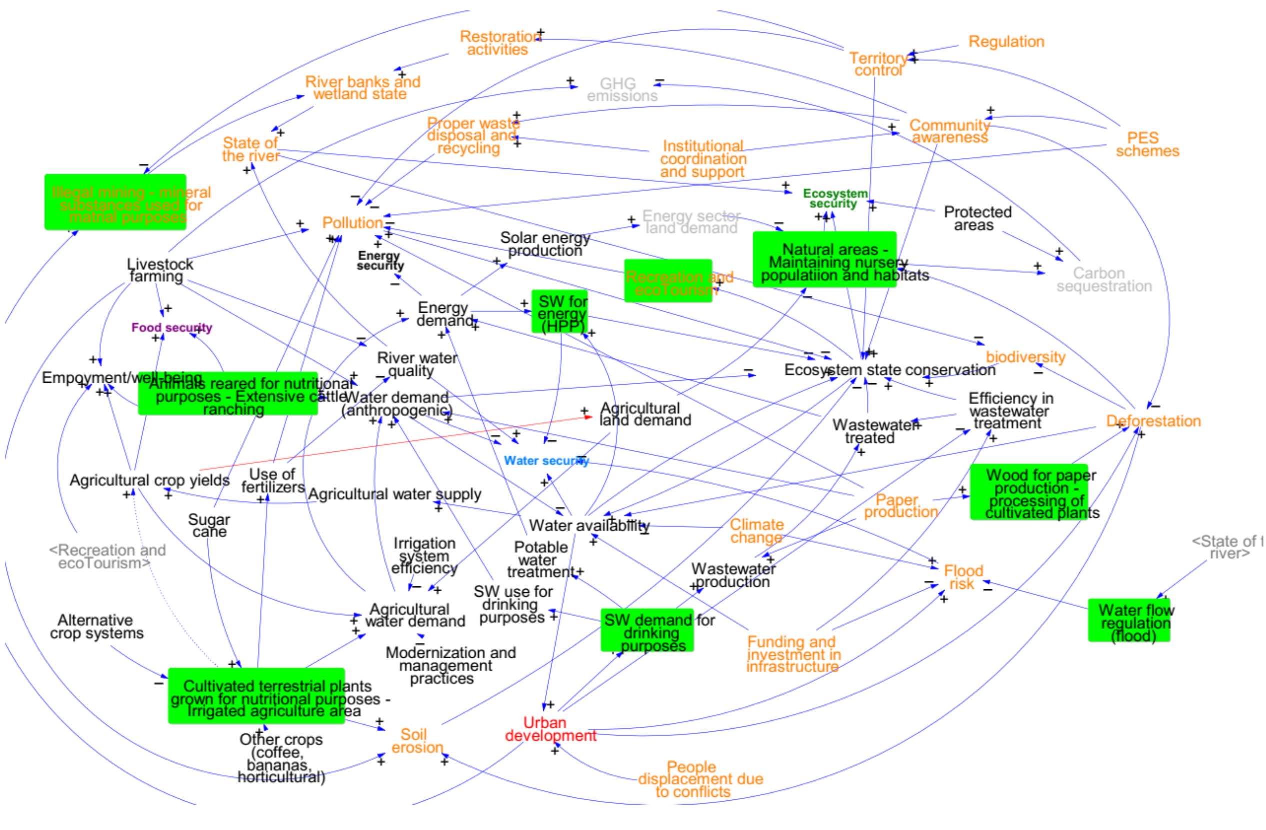

Figure 10: Preliminary CLD developed for the Nima-Cauca pilot

The CLD highlights the central role played by the Nima-Amaime-Cauca river on the state of the area, with a significant geographical distinction: the upstream area of the catchment (which is mainly natural) is fundamental for the state of the river, which is heavily exploited mainly for drinking purposes (e.g. the municipality of Palmira is supplied by the river), hydropower production and agricultural activities. Starting from the latter issue, it should be remarked that agricultural activities are highly relevant for the well-being of local communities, although some practices are not considered as sustainable over the long term. This is the case of sugarcane production, which is essential for the development of the area since colonial times, but associated with a high water demand and to significant impacts, which include a relevant pollution over the area (which causes increasing concerns for the health of local population). Basically, this also causes a limited availability of drinking water in dry periods, and a very low quality of service (significantly conditioned by the low efficiency of the local aqueduct). In this direction, the stakeholders highlighted the need for additional investments on the infrastructural systems by the government, also in view of potential effects of climate change. The role of the municipalities, which should ensure the safety of water supply, is crucial in this direction. Investing in the improvement of sewerage systems, along with an improved territorial planning, is also perceived as crucial for the safety of the area as the impacts of flooding events as a consequence of heavy rainfalls are increasing. Other measures that might be implemented to support a transition of the system are related to the use of alternative/innovative crops and agricultural practices which may have a reduced impact on water resources use and on the whole environment.

As already mentioned, the issue of water security is tightly connected with the water quality issues, which are increasingly relevant over the area. The causes of water pollution are manifold, and include the productive activities (as e.g. local companies sometimes do not put in place effective treatments and procedures), livestock farming (mainly pig and chicken farms) and inefficient/absent wastewater treatment plants. Additionally, chemicals and fertilizers used in agriculture are affecting the state of water and soil. The impacts on population, in terms of water availability, as well as in terms of illness, are relevant. Furthermore, there is a very limited environmental awareness particularly from very poor rural communities, which do not properly recycle and dispose waste. The impacts of surface water pollution are also significant, and particularly detrimental for the environment, as both local flora and fauna (e.g. fish population) are affected. One of the key mentioned barriers is the lack of government investment and commitment in the improvement of infrastructural systems. A lack of regulation is also perceived, as it should help 'reconciling' big companies with local authorities, ultimately limiting illegal or unsustainable behaviors.

Another key challenge/issue for the pilot area is related to the state of the environment, as the watershed includes very specific and sensitive ecosystems such as the Páramo area and the native forest in the Andean mountainous area. A relevant conflict is perceived here, as there is on the one hand an increasing urbanization, with an associated demand for land (which is provoking deforestation and increasing water demand), and on the other hand there are productive activities (including the paper production and processing) negatively impacting the environment. Concerning the former point, the spatial planning is very limited, and many new settlements are being located close to the river, and associated with dangerous practices such as illegal extraction of sand and stones. This is also occurring as a consequence of socio-economic dynamics (such as the migration of foreigners and displacement of people as a consequence of conflicts). Concerning the latter point, many activities (e.g. paper production, livestock grazing, intensive agricultural practices) yet relevant for the area, increase deforestation (native plants, pine and eucalyptus plantations) and cause erosion issues. A technical measure in place is related to the reforestation of high areas of the basin. From the socio-institutional point of view, local stakeholders perceive a conflict between local communities (which take care of the forest and are also promoting processes of restoration of riverine areas) and big companies (which pursue economic profit, but are involved in programs for restoring the environment and promoting ecotourism). In this direction, the lack of presence and control by public authorities is perceived as a significant barrier, although an opportunity already exists, represented by the presence of PES schemes (Payment for Ecosystem Services) which are currently implemented in the livestock sector. Ultimately, the lack of institutional presence and control over the territory is also seen as contributing to the low level of community awareness on environmental conservation, which has an influence on the capacity of local communities to protect the natural resources of the area. Furthermore, a stronger institutional control over the area is also needed in view of safer and more sustainable and controlled operations of local companies. A key role is attributed by the interviewees to the municipalities and to the C.V.C. (Corporación Autónoma Regional del Valle del Cauca, which has surveillance and monitoring tasks over the watershed), as the impact of illegal mining (sand and stones extraction close to the river) is significantly growing.

A 'transversal' issue, which is totally in line with the Nexus approach, is the need for incentive mechanisms to align land use/management decisions in the watershed to shared environmental and socio-economic goals of actors in this watershed. One of the main goals is to secure future water supply for the human population and ensure water availability for agriculture and industry (including the hydropower generation industry).

Main findings

The main findings of the modeling activities highlight the main issues affecting the Nexus security and resilience, both in terms of (inter-)sectoral policies and ecological resources availability and use. Basically, efforts are needed at multiple levels for optimizing the water quantity and quality for the different users/uses, as well as for protecting vulnerable and unique ecosystems (the Andean forests, Páramo areas, Guadua forests). Policies are needed for coherently activate the three main filters for the ESs production and mobilization, i.e. Infrastructures, Institutions and Perceptions, as summarized in the following Table 16.

Table 16: List of infrastructures, institutions and perception (Nima Cauca).

Filter	Description
Institution	Coordination among the institutions and mutual support Innovative regulation and PES schemes Improved control of the territory Improved spatial planning (urbanization)
Infrastructures	Drinking water supply infrastructures Improved waste disposal and wastewater treatment systems Infrastructure related to productive activities
Perception	Community awareness on the relevance of ecosystems Ambiguity in ESs perception and 'conflicts'

The findings above could be considered as a preliminary identification of the key challenges to the Nexus security and resilience. Such results will be discussed during the workshops and through additional targeted interviews and updated throughout project duration.

3.3.3 Identification of indicators

As described in the methodological section, interviews have been oriented to identify relevant indicators for assessing the current state and potential evolution of the area under different scenarios. Particular attention has been given to the selection of Domain Objectives (DOs) and Nexus Indicators (NIs). The identification of Nexus Resilience Qualities (NRQs) is preliminary performed as well, although the analysis of scenarios based on more detailed modelling is required to better understand which variables may help controlling and, ultimately, enhancing system resilience over time. It is worth to remark that the following Table 17 includes a tentative list of indicators that have been suggested by the stakeholders during the interviews (bottom-up phase of the process). Additional activities, to be performed mainly during the workshops, will be oriented to refine the list and provide also information on the most relevant indicators to be used. In the Table, indicators are explicitly related to the main problem/challenge to which they have been related and to the basic processes they refer to (this is needed to directly connect the indicators to the PSDM). Cells are in light blue for indicators that are replicated with reference to different problems/challenges.

Table 17: List of indicators identified with the stakeholders in the Nima-Cauca pilot

PROBLEM/CHALLENGE	DESCRIPTION - PROCESS	VARIABLES/INDICATORS (SH)	SECTOR(S)	CLASSIFICATION		
Ecosystem state	Deforestation	Pine cultivation area	Ec	*state indicator*		
	Deforestation	Protected areas	Land-Ec	*state indicator*	DO-availability (Max)	NI: F-Ec
	Deforestation Soil Erosion	Forested area	Land-Ec	*state indicator*	DO-availability (Max)	NI: F-Ec
	Biodiversity	Presence of wild animals	Ec	*state indicator*	DO-availability (Max)	
	Biodiversity	Presence of fish species	Ec	*state indicator*	DO-availability (Max)	
	Deforestation Environmental degradation	Urbanization	Land-Ec	*state indicator*		
	Environmental degradation	Settlements close to the river	Land-Ec	*state indicator*	DO-availability/accessibility (Min)	
	Deforestation Environmental degradation	Level of community awareness			DO (Max)	
	Environmental degradation	Illegal mining activities	Land-Ec		DO (Min)	
	Environmental degradation	Pig and chicken farms (#)	Land-Ec		DO (Max-Min)	
	Environmental degradation	Water quality parameters	W-F-Ec	*state indicator*	DO (Max)	
	Soil erosion	Soil water saturation	W-Land	*state indicator*		
	Environmental degradation	Use of agrochemicals	F-Ec		DO (Min)	
Water quantity	Water use	Water demand (increasing)	W		DO-availability/accessibility (Min)	NI: W-F-Ec
	Water availability	Clean water availability (volume)	W		DO-availability (Max)	
	Water accessibility	Water accessibility (limited)	W		DO-accessibility (Max)	NI: W-F-Ec
	Water accessibility	Capacity of pumping systems	W		DO-accessibility (Max)	
	Water use	Water use for agriculture (sugar cane)	W-F		DO-accessibility (Min)	NI: W-F
	Water accessibility	Regular water service	W		DO-accessibility (Max)	
	Water use	Number of users	W	*state indicator*		
	Water use	Level of water metering	W		DO-availability/accessibility (Max)	
	Water availability	Presence of water intakes	W	*state indicator*		

Water quality	Water contamination River quality	Water quality parameters	W-Ec	*state indicator*	DO-availability/accessibility (Max)	
	Water contamination River quality	Population illness			DO (Min)	
	River quality	Presence of fish species	W-Ec	*state indicator*	DO-availability (Max)	
	River quality	Pig and chicken farms (#)	F		DO (Max-Min)	
	River quality	Wastewater treatment plants	W-Ec		DO-availability (Max)	
Governance issues	Lack of institutional support Lack of community environmental awareness	PES schemes	Ec		DO (Max)	
	Lack of community environmental awareness	Recycling and proper waste disposal	Ec		DO (Max)	
CC and extreme events	Water-related risks	Flood frequency	W-Land	*state indicator*		
	Water-related risks	Infrastructure performance	W-Land		DO (Max)	

As mentioned in the methodological description, a Nexus system could be considered resilient if, under internal and external stressors the security dimensions (i.e. Water Security, Food Security and Energy security) are guaranteed by a healthy ecosystem, which is capable to produce the needed services. Preliminarily, following the evidence of the activities performed, NRQs can be mainly related to: i) the availability of increased volumes of water with sufficient quality for the specific needs/uses, along with its increased accessibility through improved infrastructural systems and management structures; ii) the extension and state of upstream forests and local ecosystems, as they exert multiple functions that are crucial to balance hydrological, biophysical, and socioeconomic asymmetries that need to be addressed for a sustainable development of the watershed.

4 Conclusions and further developments

This deliverable describes the activities carried out in several REXUS pilots and the results concerning the stakeholders' engagement in the identification of the key elements and relationships characterizing the Nexus structure. A system-thinking based approach was adopted to map the complex and non-linear connections among the different elements - i.e. ecological resources, ecological processes, human processes and activities, and infrastructures - affecting the production and mobilization of ESs for the Nexus security.

Different methodological approaches were adopted to analyse the knowledge collected during the stakeholders' engagement activities. Specifically, the Participatory Social Mapping and Social Network Analysis allowed us to build the socio-ecological-technological network and to detect potential barriers hampering the production and use of ESs due to ineffective interactions. The results of the analysis in some of the REXUS pilots show the key role that the social capital could play in influencing the actors' behaviour and, thus the Nexus security. Lack of effective interactions hampers the flow of information and knowledge, reducing the effectiveness of innovation processes - e.g. in agricultural practices. In several cases, a very limited social capital within the farmers' community was detected, resulting in a limited access to resources - e.g. water for irrigation. Moreover, the lack of effective interactions influences the cooperation among the different actors in carrying out important tasks for the Nexus management, worsening the institutional fragmentation.

The detected collaborative barriers will be used to facilitate the debate with stakeholders to identify potential networking interventions, i.e. actions aiming at overcoming those barriers and facilitating the Nexus collaborative management.

The use of PSDM supports advancing the integration of sectoral models, and guarantees an improved understanding of the transformation from resource to service (e.g. water for irrigation). The Participatory System Dynamic Modelling exercises allowed us to identify the key elements of the Nexus and to map their cause-effects interconnections. Qualitative CLD were developed in several REXUS pilots, allowing us to detect potential trade-offs among the different sectorial security dimensions. The analysis of the CLD showed that the optimization of the management and distributions of the ecological resources is not enough to guantee the Nexus security. Policies are needed to coherently activate the three main filters for the ESs production and mobilization, i.e. Infrastructures, Institutions and Perceptions.

The identification and selection of relevant indicators, with a direct participation of local stakeholders, helps modelling and describing the current state and the expected evolution of key variables over time and under different conditions (ranging from climate change to policy actions). The next steps will be mainly oriented to explicitly include key indicators within PSDM, thus modelling (and showing to stakeholders for discussion) their state in different scenarios.

The results of the analysis described in this deliverable will be used to support the different phases of the interaction with the stakeholders, aiming at co-designing the Nexus solutions.

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