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On the use of Participatory System Dynamics Modelling for WEF Nexus management: Hints from two case studies in the Mediterranean region

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ABSTRACT

The security of natural resources is increasingly threatened by multiple pressures that range from climate change impacts to socio-economic conditions, and requires a coordinated action by several practitioners and policy-makers. The concept of Nexus has therefore gained increasing attention in recent scientific literature, as it aims to achieve natural resources security in a holistic and integrated way; however, it has still been limitedly put into practice. Different sectors can be included in Nexus studies, and in the present work reference is made to a rather innovative combination which includes Water, Food and Ecosystems. The present paper proposes the use of Participatory System Dynamics Modelling (PSDM) techniques for an improved Nexus understanding, analysis and management to support policy- and decision-makers. More specifically, we argue that Stock and Flow Diagrams (SFDs), besides providing an improved understanding of the complex interactions and interdependencies in Nexus systems, can also help evaluate multiple policies and solutions for Nexus management based on the use of Sensitivity Analysis and on a what-if Scenario Analysis. In this process, the involvement of stakeholders throughout the modelling phases (from model structure building to scenario selection and analysis) guarantees the inclusion of local knowledge as well as the relevance and ownership of results. Reference is made to the experience in a couple of case studies, namely the Pinios River Basin and the Greater Chania Area (both in Greece but characterized by socio-environmental conditions typical of the whole Mediterranean Area), where Nexus management is central to guaranteeing a sustainable future.

1. Introduction

The demand for natural resources at a global scale is increasing and their management is growing in complexity, as they are characterized by several critical and intense ‘hyperconnections’ (Sušnik and Staddon, 2022), while being also threatened by external stresses, such as climate change and socio-economic dynamics (Kellner, 2023; Wu et al., 2022; de Amorim et al., 2018). The concept of Nexus, which was first proposed by Hoff (2011), has gained increasing interest in responding to resource management challenges: the essence of ‘Nexus thinking’ is about identifying interconnections across sectors (which often include but are not limited to water, energy, food, ecosystems, climate, society) and scales, highlighting their dynamic interactions, which are often poorly understood (Wu et al., 2021). Achieving ‘Nexus security’ means reducing trade-offs, promoting synergies, increasing system resilience, and seeking strategies and policies for sustainable development (Albrecht et al., 2018; Sušnik and Staddon, 2022). Therefore, addressing security challenges requires a comprehensive Nexus understanding, which often integrates human systems (e.g., socio-economic dynamics) and natural systems (e.g., hydrological or biological processes) in the same analysis (Wu et al., 2021).

The interest towards Nexus has also grown considerably in recent years along with the need to identify approaches for quantifying cross-sectoral interactions (Wei Li et al., 2025; Rhouma et al., 2024). As discussed by Sušnik and Staddon (2022), the “one-size-fits-all” approach is not an objective of Nexus studies. However, some common approaches

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are often used for Nexus assessments, which include: System Dynamics Modelling (SDM), (multi-region) Input-Output Modelling (MRIO), Agent-Based Modelling (ABM), Life-Cycle Assessment (LCA) and Integrated Assessment Modelling (IAMs). An increasing number of Nexus studies has been conducted using SDM, which facilitates the integration of different sources of knowledge, and highlights the complex interactions within socio-environmental systems and how these might be influenced by policies and actions (de Vito et al., 2017, de Vito et al., 2019; Sušnik, 2018; Bakhshianlamouki et al., 2019; Purwanto et al., 2019; Laspidou et al., 2020; Sušnik et al., 2021; Zhang et al., 2021; Barhagh et al., 2021; González-Rosell et al., 2020; Terzi et al., 2021; Ioannou and Laspidou, 2022; Huang et al., 2024; Gao et al., 2024; Li et al., 2024; Dang et al., 2024; Mirindi et al., 2024; Yu et al., 2025; Giordano et al., 2025). Among the others, Gallagher et al. (2020) described an experience in the Mekong River basin, highlighting the relevance of participatory and systems-thinking informed approaches to anticipating and responding to risks that emerge from Nexus relations. Stakeholders were directly involved in policy analysis using SDM at national level (Sušnik et al., 2021), ultimately aiming at identifying the cross-sectoral implications and potential trade-offs of different actions and strategies. Samadi-Foroushani et al. (2022) proposed an integrated framework based on SDM to analyze the water governance political structure, while considering relevant impacts in other sectors, including food. SDM is used to simulate system evolution over a 20-year horizon, and to identify the most appropriate systemic solutions for fair and sustainable resources management. Yu et al. (2025) recently used the potential of SDM for running Scenario Analysis, to support decision-makers identifying the multi-dimensional impacts of policies mainly related to agricultural systems, but with a focus on cross-sectoral trade-offs and synergies.

Despite increasing relevance in the scientific community, a few gaps in Nexus studies have been recently discussed (Sušnik and Staddon, 2022), which include: i) the need to explicitly include ecosystems and ecosystem services, as changes in ecosystems affect resources security and anthropogenic activities impact ecosystems; ii) the opportunity of integrating qualitative and quantitative approaches and information, enhancing the potential of qualitative approaches to help understand Nexus interactions and increasing the awareness on Nexus interconnectedness; iii) the need to involve stakeholders from the design phase throughout the project activities, to guarantee the policy relevance of Nexus studies and facilitate Nexus implementation.

Starting from these premises, the main objective of the present work is to develop and test an innovative methodological approach – based on Participatory SDM (PSDM) - to help practitioners, policy and decision-makers achieve a twofold goal: i) improving ‘Nexus thinking’, based on a deeper understanding and visualization of inter- and cross-sectoral interconnections; ii) facilitating ‘Nexus doing’, through an improved modelling of the potential future trajectories of the investigated system, accounting for both external drivers (such as climate change) and policy actions. The proposed approach relies specifically on the use of Stock and Flow Diagrams (SFDs) to build a shared picture of the Nexus system under investigation, and uses the potential of Sensitivity Analysis and Scenario Analysis to identify key variables and comparatively highlight their potential impact on system state and evolution under a wide range of conditions. Stakeholders have been directly engaged in multiple steps of the modelling procedure, and their knowledge used in all stages of SFD building, analysis and validation. Differently from most of the recent literature, the ‘E' in WEF identifies the Ecosystem dimension, which is therefore explicitly included in the analysis. This choice reflects the fundamental role that ecological processes and services play in mediating the dynamics of Water (W) and Food (F), especially under the pressure of global change. In the present work reference is made to the implementation of the methodology in the Pinios River Basin and in the Greater Chania Area (Greece) case studies, but the proposed approach can be replicated in different contexts.

2. Materials and methods

2.1. An overview of Participatory System Dynamics Modelling

SDM comprises different tools and methods to analyze causal interactions and explain the evolution of system behavior over time, and is used for a wide range of purposes, which mainly include strategic analysis and policy design (Pruyt, 2013; Elsawah et al., 2017; Liu et al., 2022). Either qualitative (Causal Loop Diagrams, CLDs) or quantitative (Stock and Flow Diagrams, SFDs) approaches can be used, depending on several issues which include the purpose of the analysis, the variables that need to be used (‘hard’ or ‘soft’) and the users' needs and interests (Brychkov et al., 2022; Sterman, 2000). In summary, while CLDs only provide conceptual system mapping, SFDs require equations to quantify the state and evolution of variables (Coletta et al., 2024a; Coletta et al., 2024b). The discussion about the opportunities and advantages (and limitations) of both qualitative and quantitative SDM, particularly for policy analysis, is still alive in literature, without a unique response.

SFDs are particularly useful in decision-making contexts (Malbon and Parkhurst, 2023). In fact, SFDs allow testing assumptions and assessing impacts of policies/strategies in multiple scenarios by answering ‘what if’ and/or ‘which is best’ questions, ultimately supporting strategic decision- and policy-making under uncertainty (Engelbertink, 2019). Despite its limited capacity as a ‘predictive' tool, a SFD can be used to inform scenario planning and support preliminary analyses about the future.

SDM has been identified as a valuable tool in the field of Participatory Modelling (Voinov et al., 2016, 2018), and Participatory System Dynamics Modelling (PSDM) explicitly refers in the literature to the use of SDM with direct engagement of stakeholders in different modelling stages, from problem definition and system description to policy analysis (Stave, 2010; Coletta et al., 2021; Pluchinotta et al., 2024). PSDM is the basis of Group Model Building (GMB) and centered on the idea that decision- and policy-makers need to actively contribute to model development to guarantee its usability and relevance (Sterman, 2000; Voinov et al., 2018; Brychkov et al., 2022; Teng et al., 2025). PSDM facilitates a participatory process mainly oriented to develop – based on system thinking principles – a shared understanding of the system or problem under investigation. Besides improving system understanding, it also contributes to creating a sense of confidence and a common ownership of results and, ultimately, commitment towards the proposed strategies and solutions (Pruyt, 2013; Forrester, 1990; Scrieciu et al., 2021).

SFDs have several features and capabilities that facilitate interaction with stakeholders, such as: the capacity to describe temporal dynamics, the capacity to integrate different types of variables and therefore to perform both qualitative and quantitative forecasting, the capacity to handle complexity (also based on feedback loops modelling) and uncertainty. SFDs also have good transparency and ease to communicate results (see e.g., Voinov et al., 2018; Pluchinotta et al., 2024).

2.2. Overview of the methodological approach

The methodological approach proposed in the present work is based on the development, analysis and use of SFDs for understanding WEF Nexus systems and modelling the impacts of a wide range of drivers and policies. It is graphically summarized in the following Fig. 1.

First, the SFD helps ‘map' the Nexus, i.e., can be used for describing the complexity of system structure, identifying cross-sectoral interdependencies and highlighting the key elements and most influential dynamics that can affect the state and evolution of the system. The SFD is also populated with equations and data, often relying on the evidence of sectoral models (e.g., hydrological models), field data but also expert judgement and local knowledge. For this purpose, stakeholders are involved through: i) semi-structured interviews for building sectoral perspectives and identifying cross-sectoral interdependencies; ii)

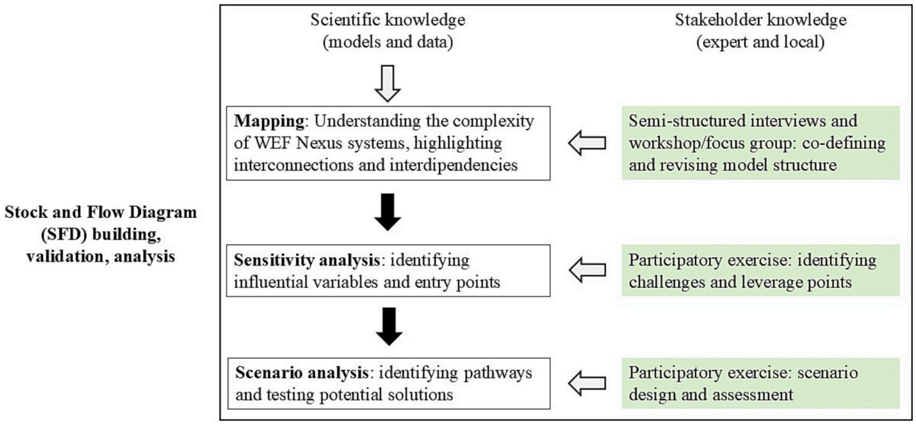

Fig. 1. Conceptual overview of the methodological approach.

participatory exercises (during a workshop or a focus group) for revising model structure, focusing on selected dynamics that are particularly relevant to discuss, ultimately trying to reach consensus on system structure. The contribution of stakeholders is also highly valuable to identify relevant variables and/or indicators that can be used to characterize the state of each sector.

Second, a Sensitivity Analysis (SA) is used to preliminarily test the influence that key input variables may exert on the state of target variables (Pruyt, 2013). This is based on the results of the participatory activities detailed in the previous step, specifically oriented to identify key variables affecting system state and potential evolution. This information helps analysts and pilot leaders select relevant drivers and potential leverage points, thus preliminarily identifying how system dynamics might change. In this regard we argue that SA, besides being a well-established method for testing the coherence of a model, can be profitably used for a preliminary screening of the input variables that might influence the evolution of the system more. For the purpose of the present work, the model is tested using a univariate SA, i.e., changing only one variable at a time and observing the impacts on model outputs. This analysis might help understand which variables potentially have a higher influence on the state of target variables.

Lastly, the what-if Scenario Analysis helps identify potential pathways of the system, under multiple conditions (Pruyt, 2013; Sterman, 2000). It is particularly relevant to comparatively test the impacts of a multiplicity of policy actions on key variables, ultimately supporting decision- and policy-makers understanding the implications of multiple strategies (Pluchinotta et al., 2021). During a dedicated stakeholder workshop, a group exercise is performed to build a shared 'vision' for each area over the next 30 years. This exercise helps with brainstorming on the expected and/or desired system evolution, but also on other potential 'futures' that might occur as a consequence of selected drivers/pressures or following the implementation of specific actions. A relevant part of the exercise is devoted to the identification of potential actions, strategies and policies to implement for achieving that vision. During the workshop, the purposes of the analysis – which can help visualize (and compare) scenarios without being a 'predictive' tool – is clarified. Scenarios are run by the analysts and then discussed with stakeholders, focusing on system trajectories and potential tipping points, but also trying to understand the effectiveness of selected measures.

Stakeholder engagement is therefore guaranteed in all phases of SFD development and use. Specific activities (either individual or group-based) are tailored to support SFD building, validation and analysis.

The SFDs are built and analyzed using Vensim, a well-known SD software, which also has routines for Sensitivity Analysis and scenario testing.

3. Description of the case studies

The proposed approach has been developed and tested in two case studies in the Mediterranean region, which share some similarities in terms of socio-economic and environmental conditions. However, it could be easily replicated elsewhere, even in significantly different contexts.

3.1. Pinios River Basin

The Pinios River Basin (hereafter PRB) is a pilot area for the Water Framework Directive implementation, located in central Greece. The basin is mainly devoted to agriculture, and therefore irrigation water demand is exerting increasing impacts on both groundwater (GW) and surface water (SW) (Malamataris et al., 2023). The focus of the present work is on two sub-areas within the PRB, namely the Agia and Delta, both shown in Fig. 2.

The Agia watershed, in particular, hosts the Pinios Hydrologic Observatory (Pisinaras et al., 2018), which is part of the LTER-Greece network (Skoulikidis et al., 2021). Given the relevance of agriculture in the region, the activities of the Observatory primarily focus on understanding water balance and sustainable use, hydrodynamic processes, agro-hydrological dynamics, and are driven by a long-lasting and robust connection with local and regional stakeholders. The development of irrigation in the Agia area started in the 1970s and, historically,

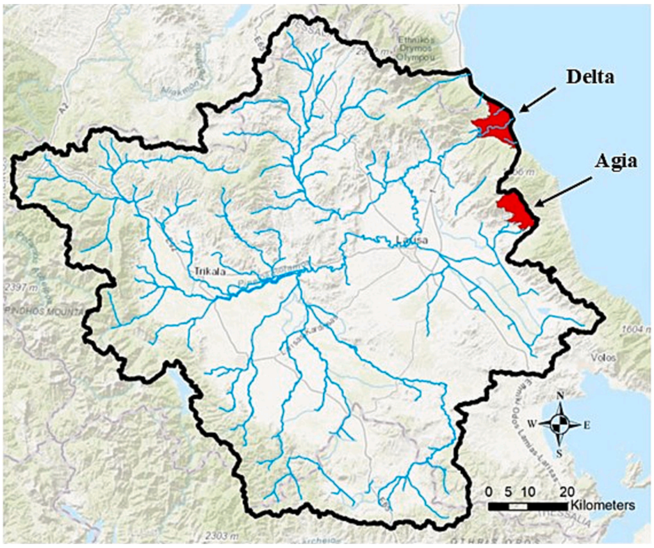

Fig. 2. Map of the Pinios River Basin, with a focus on the Agia and Delta areas.

water quantity has not been considered an issue. However, increasing concerns are rising on irrigation demand in hydrologically poor years, also considering the expansion of chestnuts and (to a lesser extent) of apple trees. As a response, small, private reservoirs are increasingly being constructed in the upper part of the catchment. Besides affecting water resources quantity, agriculture is also impacting GW quality since locally high NO_3 concentrations are observed in the plain part of the watershed. Furthermore, increased GW salinization is observed locally and attributed to irrigation water return flow caused by irrational irrigation practices and fertilization malpractices (Pisinaras et al., 2018).

In the Delta area, instead, water for irrigation mainly comes from the Pinios River, through temporary diversion dams. A relevant contribution has also been attributed to GW capillary rise from the phreatic aquifer (Pisinaras et al., 2021). The main crops (in terms of area) are alfalfa, wheat and sunflower, while kiwi fruit has been rapidly expanding in the last years. The expansion of agriculture and related land demand, along with the growth of the touristic sector, are exerting pressures on the environment. In terms of water quality, GW salinization processes are being observed, along with locally high NO_3^- and NH_4^+ concentrations in the phreatic aquifer (Pisinaras et al., 2021).

Stakeholder identification and selection for the entire engagement process, including the PSDM, followed a systematic and replicable methodology as detailed by Malamataris et al. (2025). The process began with the development of an initial list of stakeholders, informed by insights gained from the establishment and operation of the Pinios Hydrologic Observatory, as well as previous projects, and the specific relevance of each actor to the WEF context. This list was then expanded using a snowballing technique, which facilitated the identification of additional relevant stakeholders through referrals and networks. To ensure balanced representation, the stakeholder pool was analyzed for diversity across actor types and sectors. Finally, a suitability assessment was carried out for each stakeholder, evaluating their influence—defined as their capacity to address or resolve key issues—and their interest, meaning the extent to which they were affected by or concerned with WEF interactions. A total of nineteen stakeholders were engaged, with five, four, and ten representing the Water, Ecosystem, and Food sectors, respectively. Further details on the stakeholders involved in the PRB are available in the Supplementary Materials (Table S1).

3.2. Greater Chania area

The study area is a wide region around Chania (Crete), that includes the Koiliaris River Basin and the Keritis River Basin, as well as the Akrotiri peninsula and the city of Chania, since there are significant inter-basin water transfers. The Koiliaris watershed is, in particular, a Critical Zone Observatory (CZO, established in 2004) belonging to the European LTER (Long-Term Ecological Research) Network and to the LTER-Greece Network. The region has been increasingly impacted by intensive agriculture and overgrazing, which cause severe soil degradation, further exacerbated by climate change and inefficient water resources management. Grazed shrublands and pastures account for more than two-thirds of the total area, while agricultural land is mainly covered by olive groves, citrus orchards, vineyards and vegetable farms. For a more comprehensive analysis, an interested reader could refer to the work by Lilli et al. (2020).

Since its establishment, the observatory has engaged a diverse range of key stakeholders through various public consultations. These have included regional and local government bodies, academic institutions, public water authorities, environmental organizations, as well as local farmers and agricultural associations. As part of the LENSES project, we organized several stakeholder engagement activities, with a particular emphasis on understanding farmers' behavior and perspectives. One public meeting was held with members of the local avocado growers' association, attracting approximately forty farmers focused on water and food sector issues. In addition, two representatives from research institutions and two from the regional government also participated. Furthermore, a webinar was conducted with thirty-nine participants, including thirty-seven legislators from the Region of Crete and two representatives from academic institutions. Finally, a focus group discussion was held with ten unaffiliated farmers (i.e., not members of any formal farmer association), providing additional insights into individual farmer perspectives.Fig. 3 presents a topographic map with the areal extend of the greater Chania study area. Further details on the stakeholders involved in the Greater Chania Area are available in the Supplementary Materials (Table S2).

4. Results

The present section provides an overview of the SFDs developed for both study areas, highlighting the key elements included and the main dynamics considered. An interested reader is invited to refer to the Supplementary Material for the whole set of equations behind the SFDs. Furthermore, some insights that can be provided by the Sensitivity Analysis are also introduced and critically discussed. Lastly, the use of the SFDs for running a Scenario Analysis is detailed.

Many elements of the SFDs are common, as they describe well established bio-physical dynamics and very basic dependencies among variables (e.g., the dynamics related to water demand for drinking or irrigation purposes). However, several parts of the SFD have been tailored to pilot specificities and adapted to the local context (e.g., water demand for irrigation is calculated in the same way, but crop water needs depend on the most relevant crops of the areas) mainly thanks to the information provided by local stakeholders. In particular, stakeholders were involved (both through interviews and participatory exercises) in finalizing the SFD structure, and in the identification of the main dynamics to include in the model. Specific questions were oriented to facilitate the building of equations regulating those dynamics. Some stakeholders also provided information on data sources for selected input variables.

The SFDs currently simulate 30 years with a monthly time step. Using a monthly average approach allows the model to focus on long-term trends rather than short-term fluctuations, which aligns with its strategic planning purpose. The time step is also coherent with the main phenomena being described (e.g., monthly variation of water demand) and the resolution of other models (e.g., hydrological models).

Without any loss of complexity and interconnectedness, the SFDs have been organized as sub-models. On the one hand, this helps simplify the visual structure of the models. On the other hand, this also helps focus, if needed, on sectors in isolation ('water', 'food' and 'ecosystems')

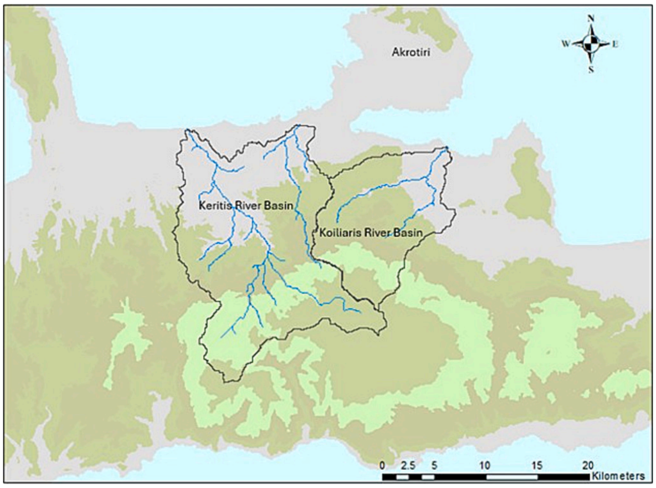

Fig. 3. Topographic map depicting the areal extent of the Greater Chania study area, including the Koiliaris River Basin, Keritis River Basin, Chania and Akrotiri Peninsula. The map highlights key hydrological features, elevation variations, and the spatial distribution of the study sites.

while keeping the interdependencies.

Although SFDs are not inherently spatial, spatial information has been included through 'subscripts', which allow a single variable to represent many different spatial units or categories. We basically divided the two study areas into a subset of Areas of Interest (AoI, 'Delta' and 'Agia' for the Pinios; 'Keritis', 'Koiliaris River', 'Akrotiri', 'Chania' for the Chania Greater Area). Following some literature on the topic (Elsawah et al., 2017; Voinov et al., 2018), the SFD can be easily replicated (i.e., model instances are created) for each AoI, provided that interconnections and interdependencies among AoI (e.g., fluxes of water) are adequately represented.

4.1. Stock and Flow Diagram for the Pinios case study

4.1.1. Overview

The following Fig. 4 provides an overview of the water sub-model for the Pinios. On the left-hand side of the Figure, the main dynamics related to the water quantity are simulated. In particular, reference is made to both SW (mainly the Pinios River in Delta area) and GW. The drinking water demand is also simulated, including the monthly variation which is particularly relevant during the summer due to the fluctuations in the number of tourists (particularly in the Delta area). The water demand for irrigation is computed in the 'Food' sub-model and used here. One of the key specificities of this model is the explicit modelling of capillary rise contribution to the crop/plant growth in the Delta area (Pisinaras et al., 2021).

All variables related to water quantity are calculated in a fully quantitative form, as they come from either hydrological models and/or field observations. Just to make an example, the 'SW availability' is computed based on the average monthly river flow recorded in the Pinios upstream of the Delta area, whereas variables related to GW state are derived from hydrological models (the Soil and Water Assessment Tool, SWAT) applied for the area (Pisinaras et al., 2021). The construction of new reservoirs emerged during stakeholder consultation activities as one of the four top-ranked measures (Malamataris et al., 2025). Based on the current plans for the area, the potential availability of additional volumes of water for irrigation (3.5 Mm^3 and 5 Mm^3 for the Delta and Agia, respectively) has been considered.

On the right-hand side of the Fig. 4, the dynamics related to SW and GW quality are represented. As water quality depends on multiple variables/parameters that would be challenging to consider in a fully quantitative form, we decided to use a dimensionless variable ranging between 0 and 1.

The variables with an orange background can be used to easily activate/de-activate scenarios.

The following Fig. 5 provides an overview of the 'Food' sub-model for the Pinios. The left part of the model mainly focuses on the simulation of irrigation water demand (upper part) and on fertilizers use (lower part). It mainly aims at quantitatively modelling the impact of irrigation practices on water quantity and quality.

The right part of the model provides, instead, a simplified assessment of the 'Average agricultural sustainability', which relates to the productivity, profitability and long-term viability of agricultural practices. The relevant variables are estimated in a qualitative form. This can be activated in specific scenarios.

Fig. 6 provides an overview of the 'Ecosystems' sub-model. Particular attention is given to the analysis of three key phenomena for the area, i.e., the levels of 'Soil erosion', 'Soil quality' and 'State of natural areas', which is also more specifically related to the 'State of riparian habitat and forest conservation'. Considering the complexity of the dynamics included in this sub-model, most of the variables are represented in qualitative form (i.e., ranging between [0–1]).

A 'Baseline' version of the model, representing current system conditions, was calibrated and validated with the support of the pilot leaders, either by referring to measured/modelled quantities (e.g., hydrological variables) or based on expert knowledge. Several rounds of internal revision were performed before the model was shared and discussed with stakeholders.

4.1.2. Sensitivity Analysis

The following Table 1 details the sensitivity tests for the Pinios case, highlighting the variables involved and the range of variation, compared to the baseline value. The selection of variables is based on the results of a participatory exercise, specifically oriented to the identification of relevant drivers and challenges (e.g., Climate Change, Irrigation efficiency, etc.), and on the identification of potential leverage points and sustainability measures (e.g., Mulching, Irrigation scheduling, etc.). Each test is based on 200 simulations performed with a uniform variation of the selected variable within the selected range.

Table 2 provides an overview of the results of the tests, highlighting

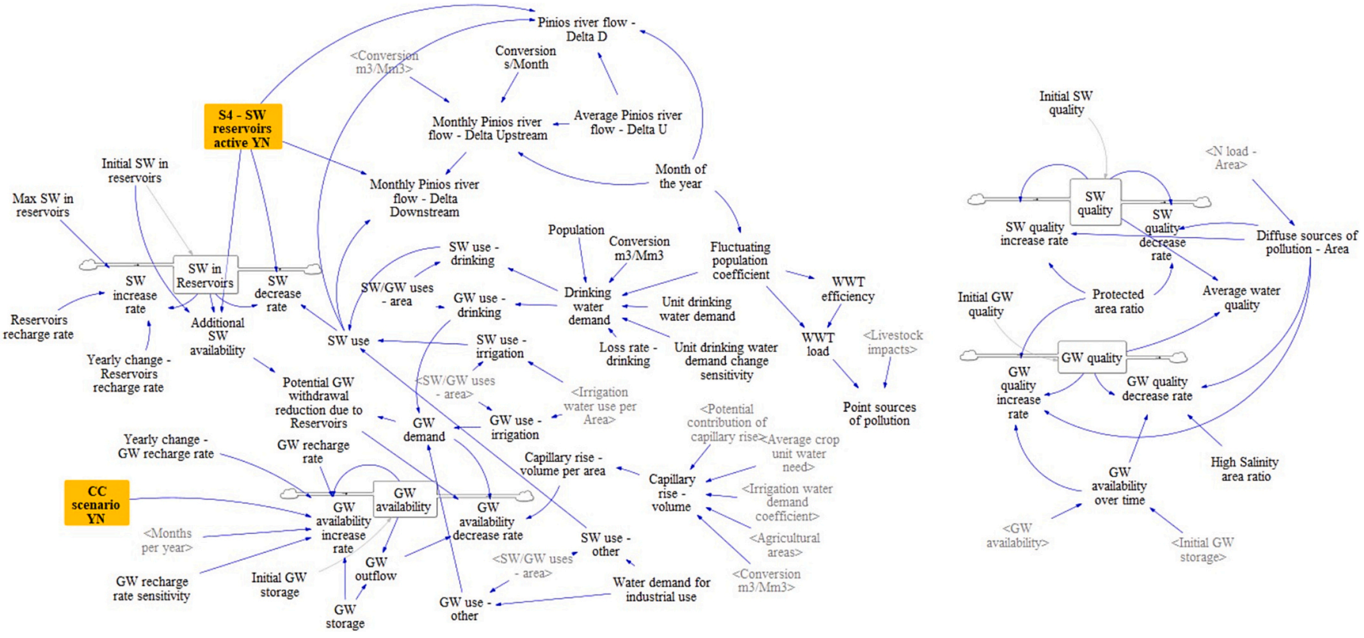

Fig. 4. View of the 'Water' sub-model for the Pinios Stock and Flow Diagram.

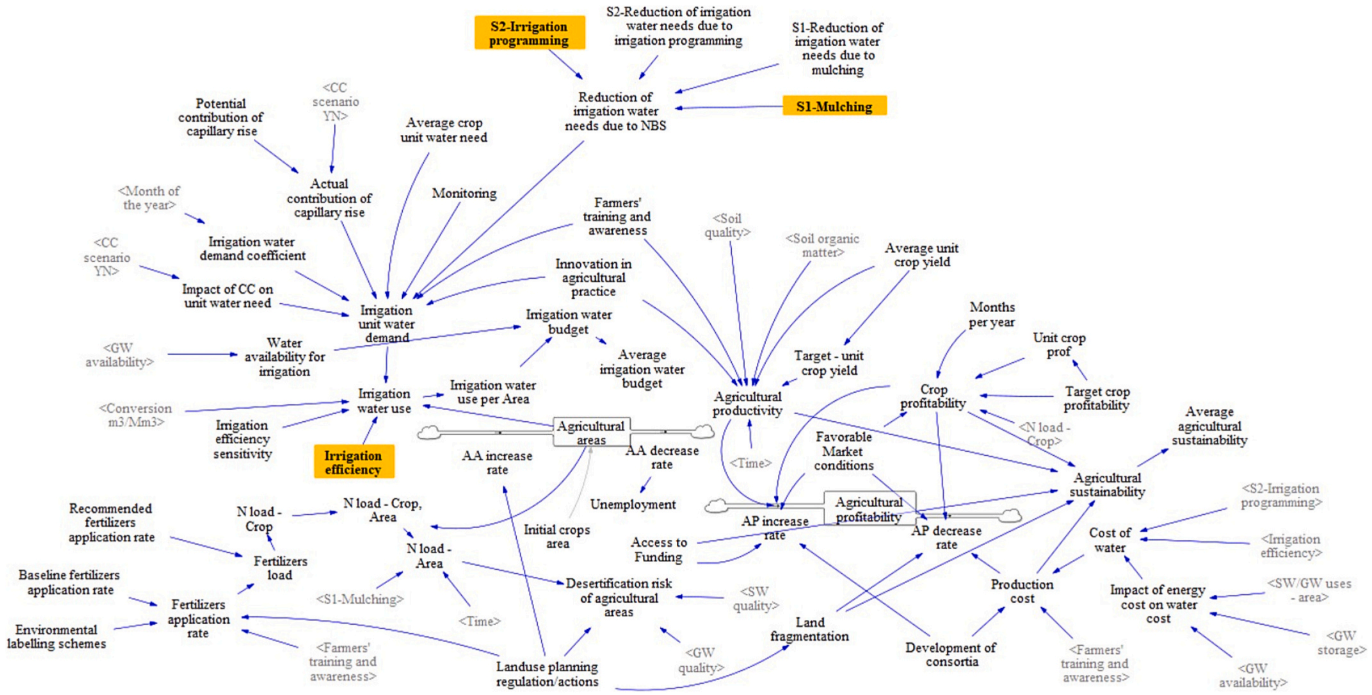

Fig. 5. View of the 'Food' sub-model for the Pinios Stock and Flow Diagram.

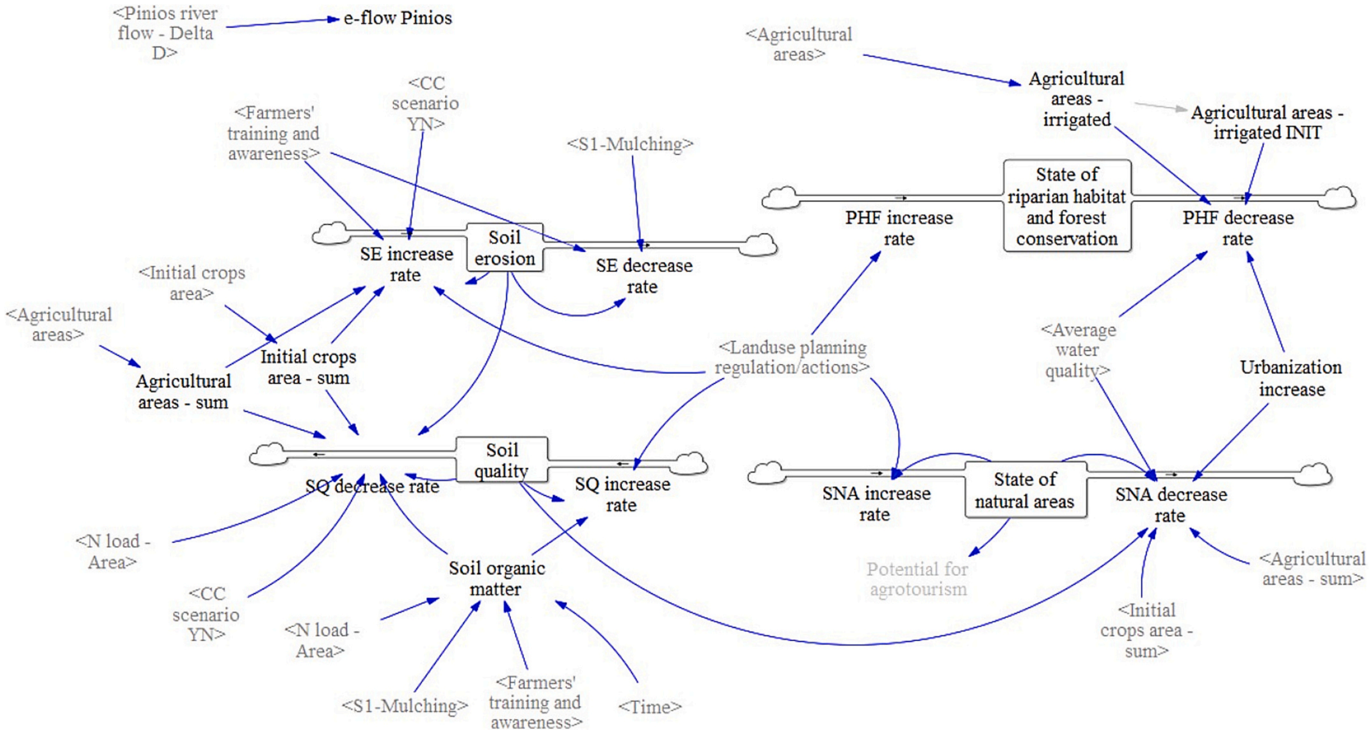

Fig. 6. View of the 'Ecosystems' sub-model for the Pinios Stock and Flow Diagram.

the magnitude of impacts (if any) on a subset of relevant output variables across all sectors (Water – W, Ecosystems – E, Food, F). A qualitative assessment (High - H, Medium - M, Low – L) is assigned in Table 2 by the analyst, based on the detailed analysis of the sensitivity of output variables to changes in the selected inputs. For the sake of simplicity, the results are aggregated for both sub-areas.

The detailed results of the Sensitivity Analysis are displayed in the following as confidence bounds, which are computed at each point in time by ranking and sampling all the simulation runs. Thus, for example, in a 50 % confidence bound, 1/4 (25 %) of the runs will have values higher than the upper bound, and 1/4 (25 %) will have values lower than the lower bound.

As an example, the results of Test C - which explores the sensitivity to 'Average GW recharge rate' - are shown. The most sensitive variable is clearly the 'GW availability' (Fig. 7), in particular in the Agia area.

Table 1
Summary of the Sensitivity Analysis (SA) tests for the Pinios Stock and Flow Diagram. CC stands for Climate Change, while GW stands for Groundwater.

Test	Variable	Baseline	Range for SA
A	CC Scenario	1	0–1
B	Unit drinking water demand change_sensitivity	1	0.5–1.5
C	GW recharge rate_sensitivity	1	0.5–1.5
D	S2-Irrigation scheduling	0	0–1
E	S1-Mulching	0	0–1
F	Farmers' training and awareness	0	0–1
G	Irrigation efficiency_sensitivity	1	0.5–1.5
H	Landuse planning and regulation actions	0.5	0–1

Table 2
Overview of the results of the Sensitivity Analysis tests for the Pinios. SW stands for Surface Water, while GW stands for Groundwater. H refers to High, M to Medium and L to Low.

Output variables	Sector	Test							
		A	B	C	D	E	F	G	H
Drinking water demand	W	–	H	–	–	–	–	–	–
GW availability	W	L	H	H	H	–	L	H	–
SW quality	W	–	–	–	–	–	L	–	L
GW quality	W	–	–	M	–	L	H	–	L
Irrigation water use per area	F	–	–	–	L	L	L	H	–
Average agriculture sustainability	F	M	–	–	M	M	H	L	H
Soil erosion	E	H	–	–	–	M	H	–	H
Soil quality	E	H	–	–	–	M	M	–	H

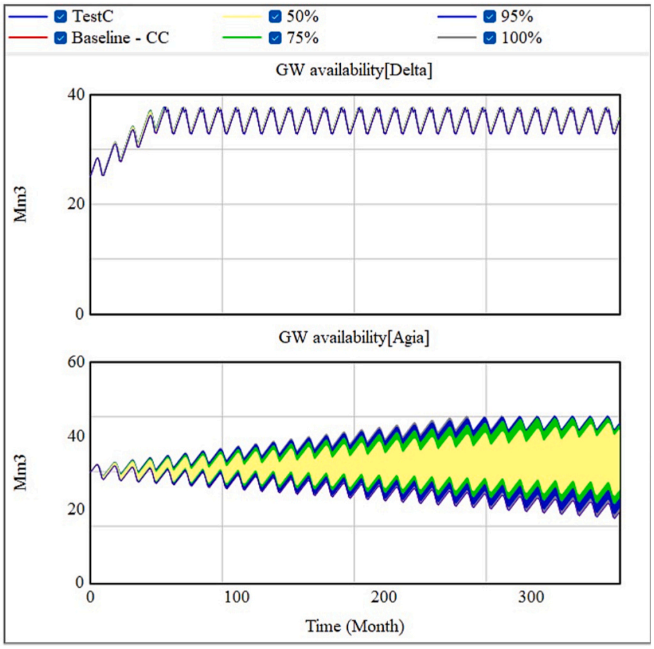

Fig. 7. Results of the sensitivity run 'C' for the Pinios Stock and Flow Diagram: 'GW availability'

4.1.3. *Scenario Analysis*

Based also on the results of the Sensitivity Analysis, a targeted Scenario Analysis has been performed. For the purpose of the present work, a subset of variables has been identified by the stakeholders as central for analyzing sectoral challenges in the Pinios case study, namely:

i) GW availability (water sector);
ii) Average agricultural sustainability (agriculture/food sector);
iii) Soil quality (ecosystems sector).

The following scenarios were modelled coherently with the outcomes of the 'visioning' exercise performed during the stakeholder workshop:

- o **BAU** (Business-As Usual): current conditions are just projected in the future, assuming that no major changes occur, to facilitate comparison with other scenarios.
- o **Scenario 0** (**S0**): it takes into consideration the impacts of climate change only. In the model, reference is made to the results obtained in one of the climate projections used, i.e., the RCP 8.5.
- o **Scenario 1** (**S1**): it takes into account the activation of one of the selected Nature-Based Solution (NBS), i.e., the mulching. The assumption here is that the measure is implemented on 100 % of apple orchards area (769 ha) in the Agia area and to 100 % of kiwi fruit orchards area (596 ha) in the Delta area.
- o **Scenario 2** (**S2**): it considers another NBS that was selected by the stakeholders, i.e., effective soil water management through irrigation scheduling. The assumption here is that the measure is implemented in 100 % of apple orchards area (769 ha) in the Agia area and to 100 % of kiwi fruit orchards area (596 ha) in the Delta area.
- o **Scenario 3** (**S3**): it takes into account the activation of socio-institutional strategies, modelling specifically i) the improvement of 'farmer training and awareness' level, ii) an increase in the development of farmers' consortia, iii) the activation of 'landuse planning/regulation actions'.
- o **Scenario 4** (**S4**): it is explicitly focused on the activation of new reservoirs for storing surface water.
- o **Scenario 5** (**S5**): it takes into account the benefits associated with the improvement of irrigation systems efficiency.

In summary, the selected scenarios show the role of climate change and related implications for the area (S0), the impact of key NBS selected by stakeholders (S1, S2), the potential benefits of socio-institutional measures (S3) as well as the opportunity of activating infrastructural measures (S4 and S5). For the sake of simplicity, we considered the activation of measures individually, but the impact of several actions at the same time could be easily modelled. All scenarios have been precompiled and discussed with the pilot leaders and with stakeholders to feed the discussion on the potential future trajectories of the system. The discussion was mainly based on the analysis of different scenarios, summarized in the form of a presentation, without direct interaction with the SFD which would be particularly challenging for stakeholders. Discussing all the results obtained is beyond the scope of the present work. In the following, a couple of them are presented, mainly to show the methodological approach and to explain how they were used in the discussion during the stakeholder workshop.

Scenario S1 (Fig. 8) shows that the impacts of Climate Change (CC) could be (to some extent) mitigated through the activation of mitigation measures. In this case, reference is made to one of the main selected NBS, i.e., mulching. Clearly the mulching has a rather limited impact on the state of GW (only a very limited reduction of GW used takes place, based on the evidence of hydrological models) but can definitely contribute to the increase of Agricultural sustainability, and to an improvement of Soil quality.

Scenario S3 (Fig. 9) shows that the contribution of the selected socio-institutional measures might be potentially relevant for the sustainable development of the area. Although the decrease in GW availability due to CC can only be partially mitigated, such measures could be particularly useful to guarantee that the soil quality is (at least) preserved and that the agriculture is sustainable and profitable over the long term.

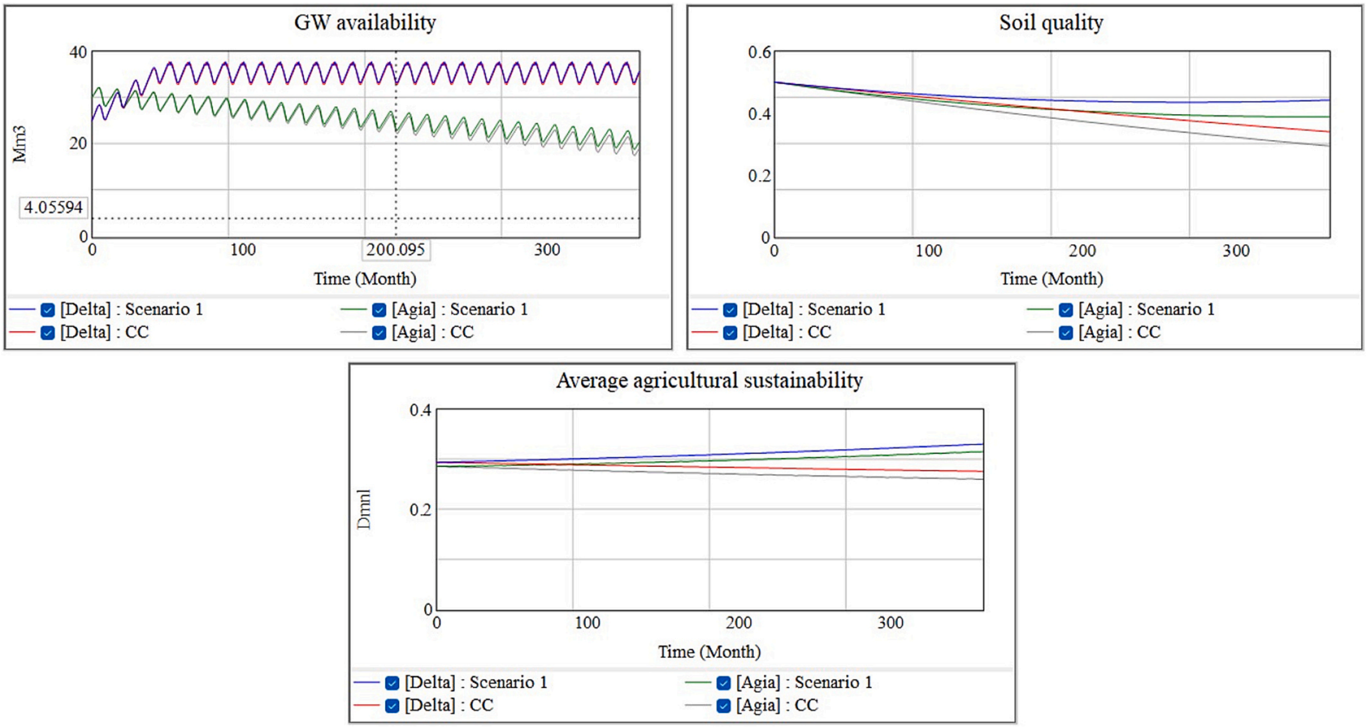

Fig. 8. View of the results of the Scenario Analysis (Scenario S1) for the Pinios pilot Stock and Flow Diagram.

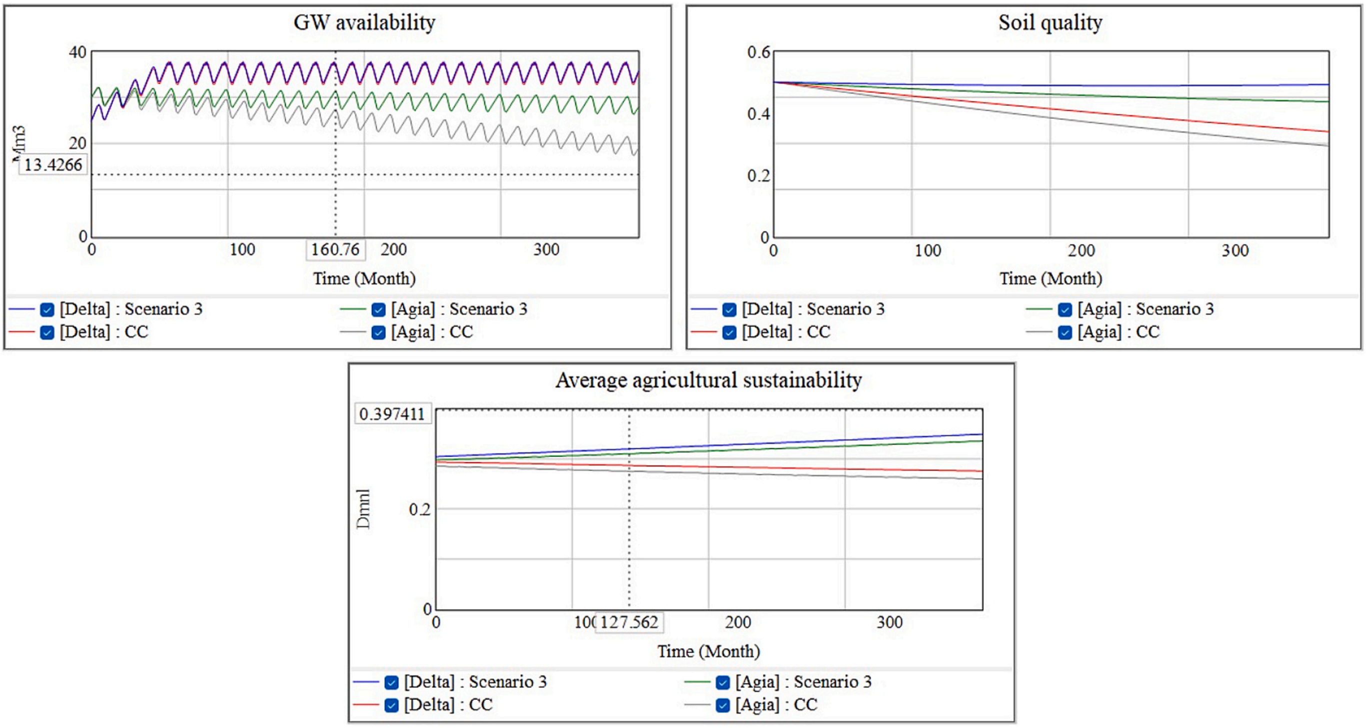

Fig. 9. View of the results of the Scenario Analysis (Scenario S3) for the Pinios Stock and Flow Diagram.

4.2. Stock and Flow Diagram for the Greater Chania case study

4.2.1. Overview

The following Fig. 10 provides an overview of the water sub-model. On the left-hand side of the Figure, the main dynamics related to the water quantity are simulated. Reference is made to both SW (upper-left part) and GW (lower-left part). Regarding the main hydrological quantities (inflows to SW bodies, GW recharge rate, etc.) direct reference is made to average-year conditions provided by WEAP (Water Evaluation and Planning) model, calibrated and validated for the area. The drinking water demand is simulated, including the monthly variation which is particularly relevant during the summer due to the fluctuations of tourists (particularly in some areas, such as the Keritis area), starting from observed data for the area. The water demand for

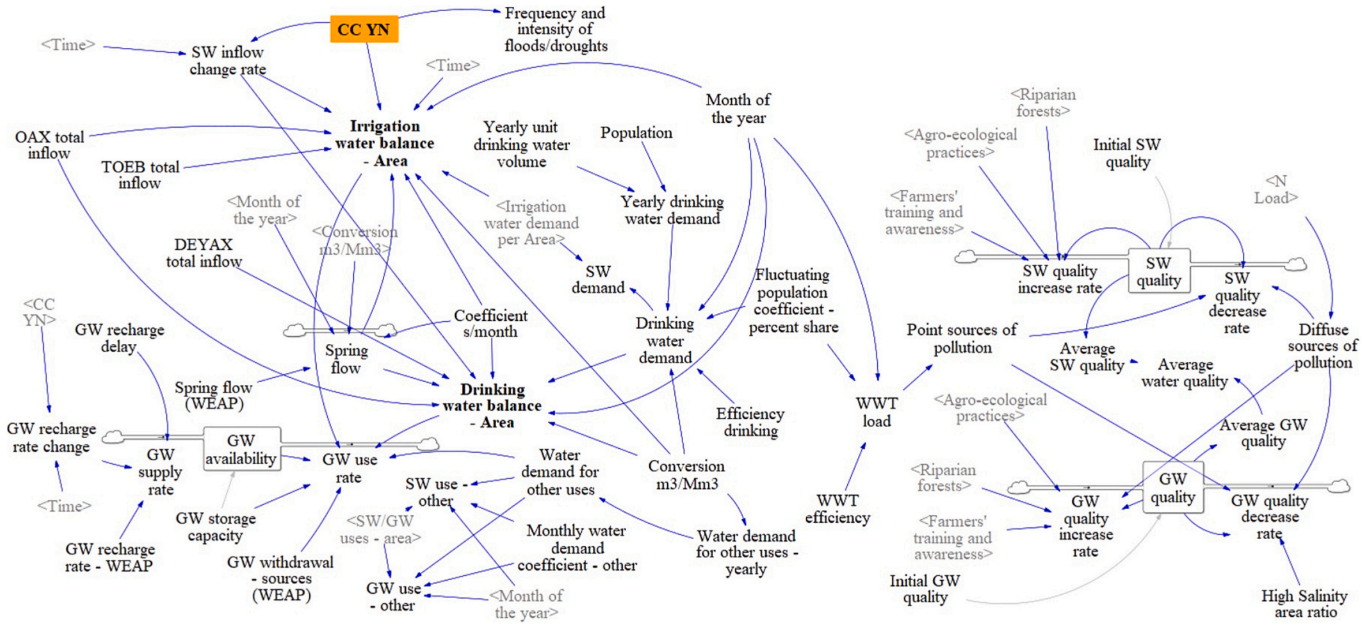

Fig. 10. View of the ‘Water’ sub-model for the Greater Chania Stock and Flow Diagram.

irrigation is computed in the ‘Agriculture' sub-model and used to perform a simple monthly water balance model. Reference is made to an average value of irrigation water demand (4000 m^3/ha) for the whole area. A peculiarity is that there is a very limited water storage in the area, as most of the water comes from springs and is limitedly collected just before the distribution.

The dynamics related to ‘SW quality’ and ‘GW quality’ are instead represented on the right-hand side of the Fig. 10. A semi-quantitative assessment is proposed in this model as well, and the variation of those variables occurs within the range [0–1]. Besides the role of agriculture, previous research highlighted the relevant impacts of livestock practices on the state of the area and on the quality of GW. This aspect has been explicitly taken into account, and the effect of an excessive presence of livestock on Nitrogen (N) is modelled in a semi-quantitative form.

The following Fig. 11 provides an overview of the ‘Agriculture'/ ’Food’ sub-model. The left part of the model is mainly focused on the simulation of irrigation water demand (upper part) and of the load of fertilizers (lower part). As already mentioned, an average irrigation unit water need equal to 4000 m3/ha (and a variable monthly irrigation water demand coefficient) is considered, following the hypotheses used for the WEAP model. For the impact of livestock and pasture areas, based on the available information on the study area, the current capacity of the Koiliaris River Area in terms of animals/ha is much higher than a ‘sustainable' threshold (14 animals/ha, compared to 1–2 animals/ ha), with severe impacts on water and soil quality.

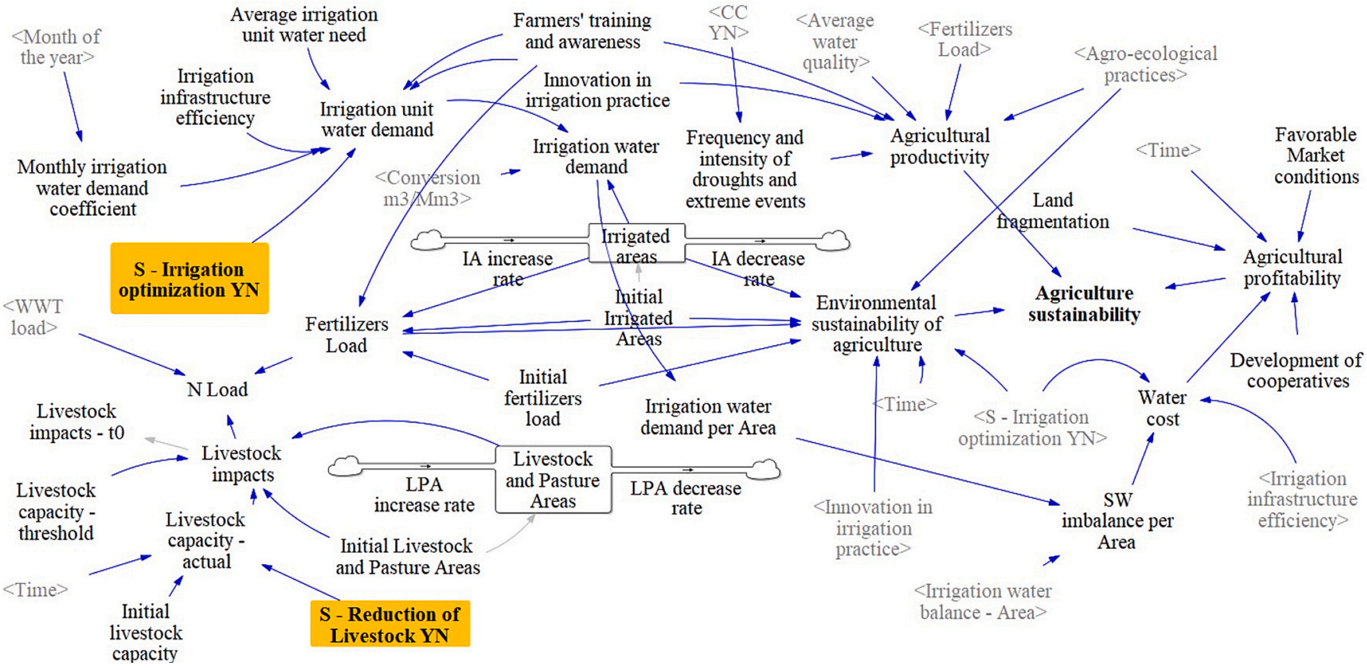

Fig. 11. View of the ‘Agriculture' sub-model for the Greater Chania Stock and Flow Diagram.

The right part of the model provides, instead, a simplified assessment of the ‘sustainability’ of agricultural practices. In this model, the concept of ‘sustainability’ of agricultural practices mainly considers three different components, namely: i) the profitability and viability on the long term of agricultural activities for the farmers, also given the increasing land fragmentation; ii) the environmental sustainability, considering the quality of adopted practices; iii) the productivity of agriculture. The variables here are estimated in a qualitative form in the range [0–1]. Particular attention is given to the potential impact of the variable cost of water (depending e.g., on its availability) and to the role of socio-institutional conditions (e.g., the level of training of farmers and growth of consortia).

The Fig. 12 provides an overview of the ‘Ecosystems’ sub-model. Particular attention is given to the analysis of two key phenomena for the area, i.e., the level of ‘Soil erosion’ and the ‘Soil Degradation. Considering the complexity of the dynamics included in this sub-model, and the need to cover spatial scale, which would require a detailed modelling approach which cannot be fully guaranteed by the stock and flow model, most of the variables are represented in qualitative form (i.e., ranging between [0–1] as previously explained for the other variables).

4.2.2. *Sensitivity Analysis*

The following Table 3 details all the simulations that were carried out for the Sensitivity Analysis in the Greater Chania Area case study, highlighting the range for each variable. The selection of variables is based on the results of a participatory exercise, specifically oriented to the identification of relevant drivers and challenges (e.g., Climate Change, Average unit irrigation water need, etc.), and on the identification of potential leverage points and sustainability measures (e.g., Agro-ecological practices, Innovation in irrigation practice, etc.). For the present work, each test included 200 simulations, with a uniform variation of the selected variable within its specified range.

The Table 4, then, provides an overview of the results of the tests for key sectoral variables and a qualitative assessment (High - H, Medium - M, Low - L) is used to express how sensitive the output variable is to changes in the selected inputs. A couple of detailed examples follow.

Following the same approach detailed in Subsection 4.1.2, the results of the Test K - which explores potential variations in the ‘Agro-ecological practices’ – are proposed in the following. A strong influence exists on ‘SW quality’ (Fig. 13), but many other variables can be affected as well.

Table 3
Summary of the Sensitivity Analysis tests for the Greater Chania case study. CC stands for Climate Change, while YN stands for Yes or Not.

Test	Variable	Baseline - CC	Range
A	CC YN	1	0–1
B	Yearly unit drinking water volume	73	58–88 (±20 %)
C	Average unit irrigation water need	4000	3000–5000
D	Irrigation infrastructure efficiency	0.5	0–1
E	S - Irrigation optimization YN	0	0–1
F	Farmers' training and awareness	0	0–1
G	Innovation in irrigation practice	0	0–1
H	Development of cooperatives	0.2	0–1
I	Terraces	0	0–1
J	Riparian forests	0	0–1
K	Agro-ecological practices	0	0–1

4.2.3. *Scenario Analysis*

Based also on the results of the Sensitivity Analysis, a targeted Scenario Analysis has been performed. For the purpose of the present work, reference was made to a subset of variables that have been identified by the stakeholders as central for analyzing sectoral challenges in the Greater Chania study area, namely:

- Drinking water balance and Irrigation Water balance (Water sector);
- Agricultural sustainability (Food sector);
- SW quality, GW quality, Soil degradation and Soil erosion (Water and Ecosystems sector).

The following scenarios were modelled according to the results of the ‘visioning’ exercise performed during the stakeholder workshop:

- o **BAU** (Business-As Usual): current conditions are just projected in the future, assuming that no major changes occur, to facilitate comparison with other scenarios.
- o **Scenario 0** (**S0**): it takes into consideration the impacts of climate change only. For the sake of simplicity, we modelled a gradual reduction of water inflow/availability (up to −20 % in 30 years).
- o **Scenario 1** (**S1**): it takes into account the optimization of irrigation scheduling for all crops in the area.

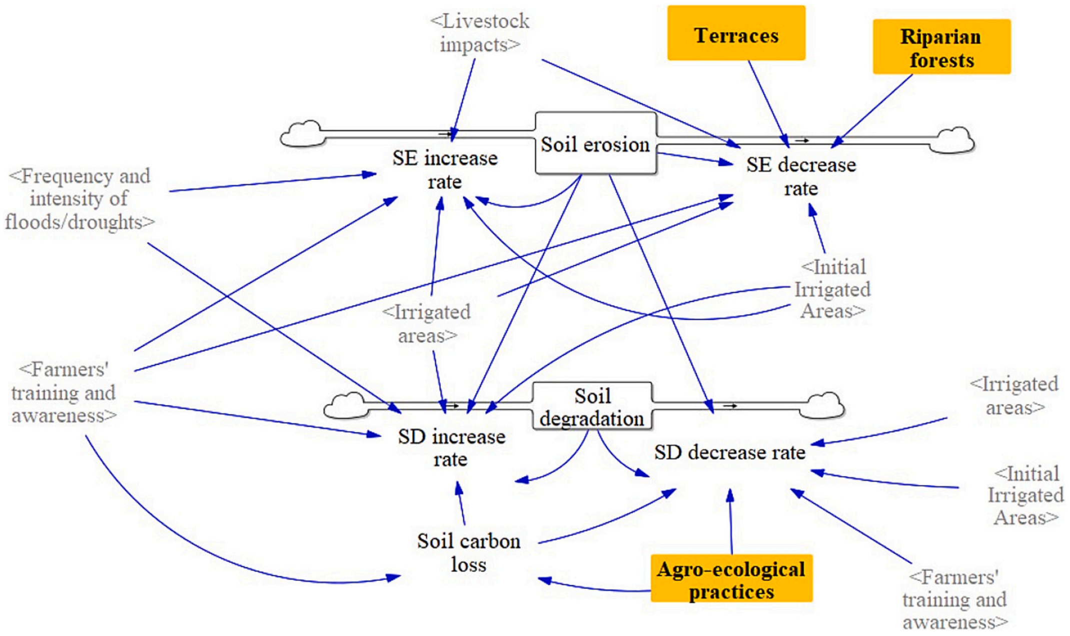

Fig. 12. View of the ‘Ecosystems’ sub-model for the Greater Chania Stock and Flow Diagram.

Table 4
Overview of the results of the Sensitivity Analysis tests for the Greater Chania case study. SW stands for Surface Water, while GW stands for Groundwater. H refers to High, M to Medium and L to Low.

Output variables	Sector	Test										
		A	B	C	D	E	F	G	H	I	J	K
Drinking water demand	W	–	H	–	–	–	–	–	–	–	–	–
GW availability	W	L	L	H	H	L	–	–	–	–	–	–
SW quality	W	–	–	–	–	–	M	–	–	–	M	M
GW quality	W	–	–	–	–	–	M	–	–	–	–	M
Irrigation water demand	F	–	–	H	H	M	L	–	–	–	–	–
Agricultural productivity	F	M	–	–	–	–	M	M	–	–	–	L
Agricultural profitability	F	–	–	–	–	H	–	–	H	–	–	–
Environmental sustainability of agriculture	F	–	–	–	–	M	L	M	–	–	–	M
Soil erosion	E	H	–	–	–	–	H	–	–	M	H	H
Soil degradation	E	M	–	–	–	–	M	–	–	–	–	H

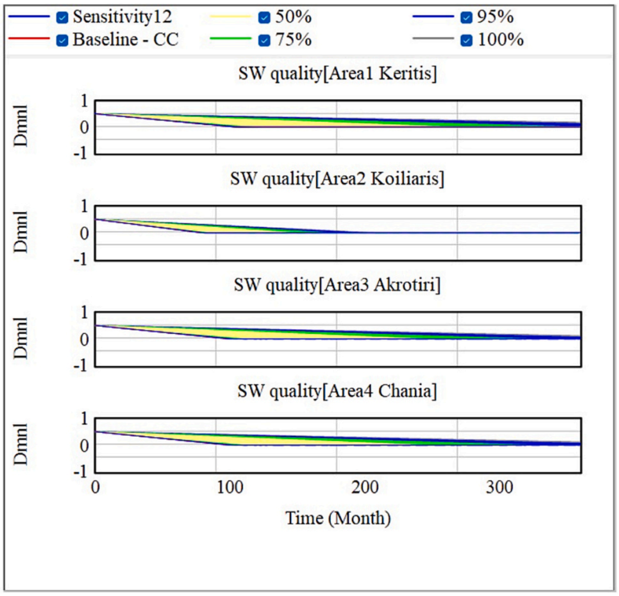

Fig. 13. Results of the sensitivity run 'K' for the Greater Chania Stock and Flow Diagram: 'SW quality'.

- **Scenario 2** (**S2**): it considers the reduction of pressures due to livestock activities. The scenario shows the impact of the reduction of the pressure due to livestock (−2 animal/ha/year), until a threshold of 2 animals/ha/year is reached.
- **Scenario 3** (**S3**): it describes qualitatively the effects of the activation of the main NBS selected in the study area, namely the development of terraces and of riparian forests, showing the impacts on key variables.
- **Scenario 4** (**S4**): it is focused on the activation of agroecological practices in the area, showing its impacts mainly on the reduction of soil degradation.

As explained in the section on the Pinios case, the Scenario Analysis mainly aims to make explicit the role of climate change and to show the potential implications for the area, along with selected measures (including NBS) that were identified in the process of stakeholder consultation (Lilli et al., 2020; Maragkaki et al., 2024; Lilli et al., 2024).

All scenarios have been pre-compiled and discussed in detail with the pilot leaders before the WS, to verify the relevance and consistency of results. They were shown to stakeholders to feed the discussion on the potential future trajectories of the system. As in Section 4.1.3 only a couple of those are presented in the following, to show the methodological approach and to explain how they can be used.

The following Fig. 14 provides a summary of Scenario S1, focused on the optimization of irrigation practices. This scenario builds on the Climate Change (CC) scenario (S0). It shows that the Irrigation water balance can be kept positive (i.e., the system should be able to absorb the stress due to CC), ensuring that lower volumes of water are used for the purpose. An additional benefit relates to agricultural sustainability, which increases over time mainly considering the increased environmental sustainability of agricultural practices. Compared to the BAU environmental processes are just accelerated due to the impacts of CC.

The following Fig. 15 provides a summary of the Scenario S4, which shows the impacts of the adoption of agro-ecological practices. This scenario builds on the CC scenario (S0). It shows that despite the fact that these measures are not expected to have a deep impact in terms of water quantity, they can positively impact water quality (both SW and GW). The situation in the Koiliaris sub-area is significantly different (and worse), mainly considering the impacts of livestock practices. The main effect, however, is a significant contribution to the reduction of soil degradation, mainly due to the contribution to the reduction of soil carbon loss.

5. Discussion

The present work stems from a growing interest worldwide in Nexus systems, also fed by growing concerns on resource exploitation and sustainability, and in the identification of effective methods to facilitate their understanding and the identification of potential system trajectories. The analysis of global Nexus systems has been recently the focus of several pieces of research (Sušnik, 2018; Sušnik et al., 2021; D'Odorico et al., 2018; McGrane et al., 2019) which highlighted the need for integrated approaches capable of working across different scales, supporting the quantification of interdependencies among sectors and facilitating cross-sectoral collaboration.

The present work proposes a holistic approach to Nexus, based on the use of PSDM techniques. In particular, we argue that the use of quantitative PSDM (i.e., SFDs) can help stakeholders navigate the whole process from an improved Nexus understanding to Nexus management, also through the use of sensitivity tests and scenario analyses to explore the evolution pathways of the investigated system and the potential impact of actions and policies.

First, it is worth highlighting that the structure of SFDs can facilitate the understanding of the key interdependencies and boundaries of the Nexus system under investigation. Building a shared holistic system picture is central to facilitating the transition from Nexus 'thinking' to Nexus 'doing'. This requires, also according to relevant literature (Sušnik and Staddon, 2022), broadening the boundaries of the analysis, including sectors (such as e.g., the Ecosystems), that have often been neglected despite their centrality in achieving resources security. The capacity to deal with complex systems and uncertainty, while guaranteeing transparency and a straightforward communication of results (Voinov et al., 2018) makes SFDs particularly suitable for Nexus studies, and for interacting with stakeholders.

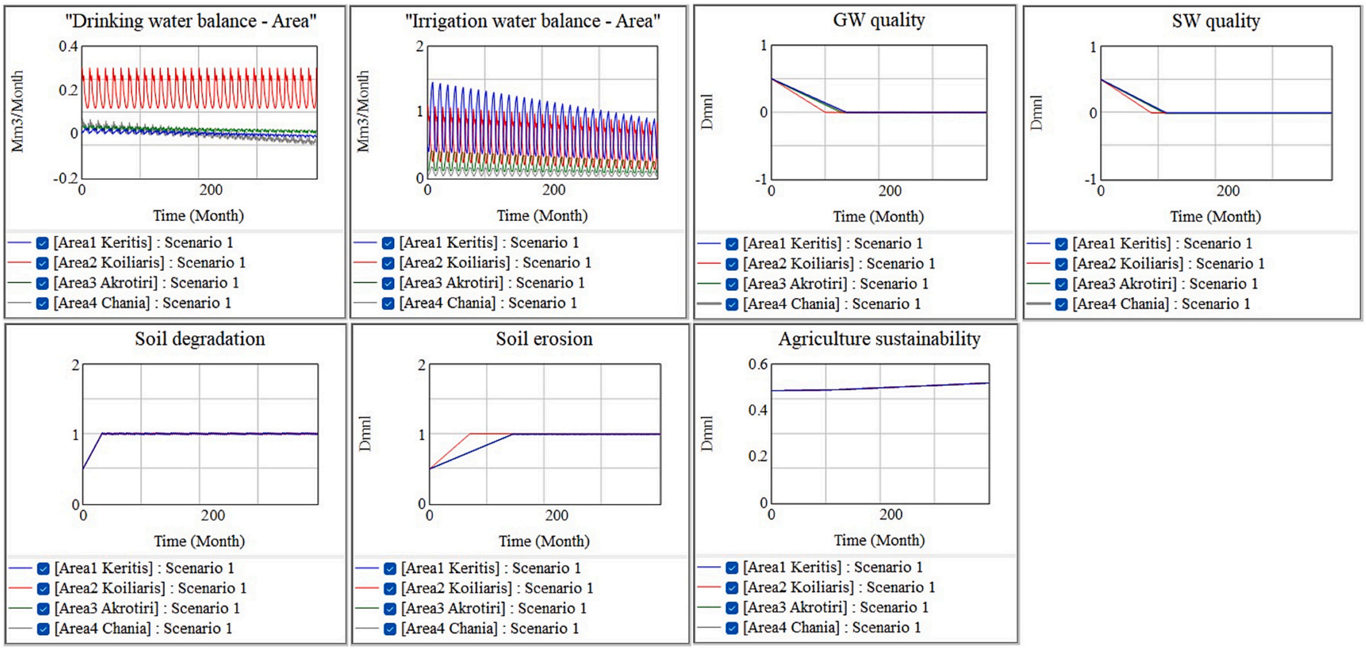

Fig. 14. Results of Scenario S1 for the Greater Chania Stock and Flow Diagram.

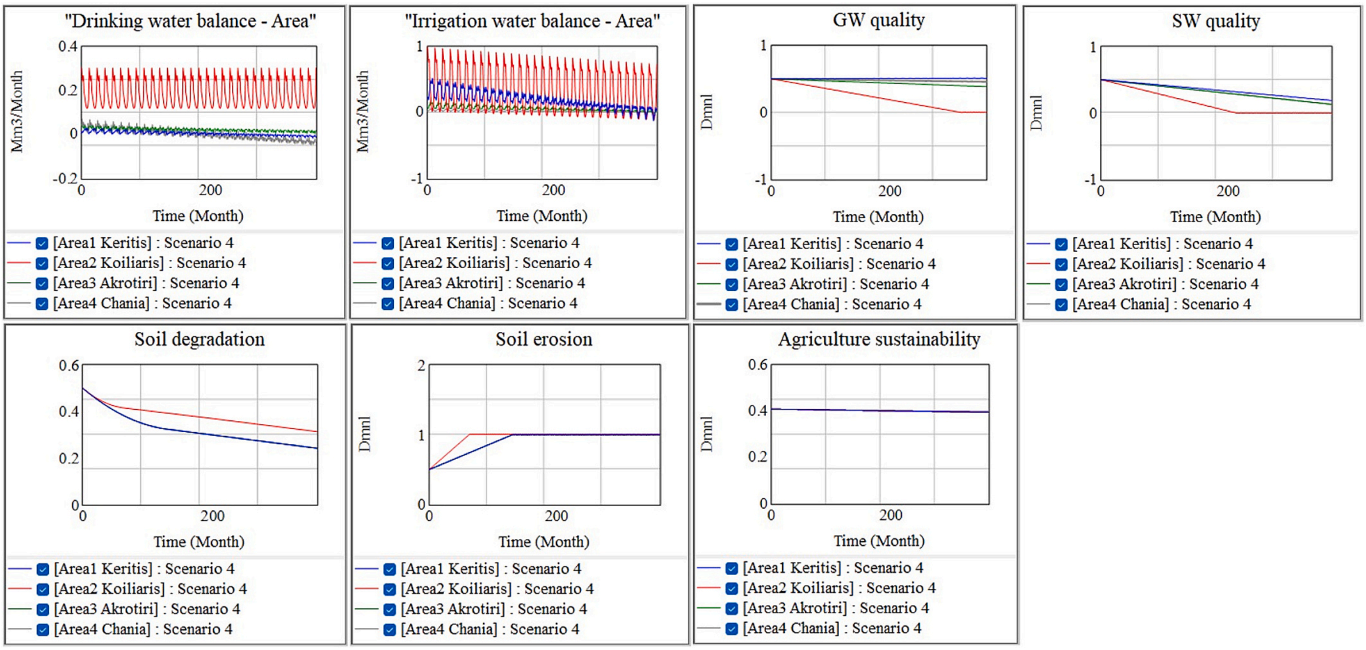

Fig. 15. Results of the Scenario S4 for the Greater Chania Stock and Flow Diagram.

Second, SFDs can easily integrate both qualitative and quantitative modelling in a robust and scientifically sound architecture - a frontier for Nexus research (Sušnik and Staddon, 2022) - allowing the integration of different types of variables and sources of knowledge (Voinov et al., 2018). The quantitative variables (e.g., those describing physical processes such as water supply/demand, agricultural production, etc.) are based either on observed data or on the results of sectoral models (e.g., hydrological models); the semi-quantitative or qualitative variables (expressed in dimensionless form in the range between 0 and 1) often rely on expert judgement to describe dynamics that are complex to model but useful to correctly describe system state and evolution. Qualitative and quantitative approaches are increasingly blended in Nexus studies (Sušnik and Staddon, 2022), and this guarantees robustness in modelling, especially if the qualitative description is developed with stakeholders. Despite the undoubted advantages, it should be carefully considered that SFDs can be used both for qualitative and quantitative forecast and the quality of information conveyed through the SFD significantly varies depending on the quality of baseline information.

Third, the proposed approach relies on a deep and active engagement of stakeholders throughout the modelling process, which has been identified as a frontier in Nexus studies (Sušnik and Staddon, 2022). Both model structure and equations are built relying on the integration of scientific and expert knowledge, and stakeholders are actively involved in all key phases of model building, revision, validation and use for Scenario Analysis. Decision- and policy-makers benefit from a deeper (and broader) understanding of the complexity of Nexus and of the impacts and implications of actions, which would be significant yet inevitably limited using sectoral models. Their participation throughout modelling activities thus helps produce "policy-relevant messages". This is particularly true for the Scenario Analysis, which allows exploring system response to external drivers and policy actions. In this regard, we argue that it is crucial to highlight that SFDs should not be considered as predictive tools, rather as tools to explore and compare the evolution of the Nexus system under investigation over time, with a focus on the cross-sectoral implications and impacts. The outcomes should therefore better inform decision- and policy-makers about the implications of any strategy, highlighting potential trade-offs and synergies. However, it should be considered that the complexity of a SFD structure and of the underlying mathematics might significantly limit the direct interaction with stakeholders (even those with a technical background). For this reason, the adopted strategy was mainly oriented to an 'indirect' interaction. In particular, both interviews and participatory exercises were tailored to build, clarify and revise SFD structure, with questions oriented to understand the cause-effect connections among variables, as well as the quantitative dependencies. Simple exercises facilitated by pilot leaders were used to identify the most important sectoral variables, and to co-design scenarios based on a 'visioning' exercise. The latter aimed at identifying the desired and/or most likely future, along with potential relevant future pathways occurring as a consequence of the implementation of measures and actions. Scenarios were then run by the analysts and presented to stakeholders focusing on the graphs describing the main variables, without a direct interaction with the SFD. One of the potential future developments of the activity relates to the definition of a user-friendly interface that could help with running, visualizing, comparing and discussing scenarios in a more interactive way.

It is also worth remarking that the experience in the case studies highlighted that the 'dialogue' itself is at least as important as the outcome of the analysis. The activities helped co-define a picture of the study area and identifying potential pathways for the system under investigation. The Scenario Analysis contributed to defining a vision for the study areas, and therefore helped stakeholders find consensus on how to drive the system towards sustainability. Nature-based Solutions were described and promoted as a potential response to the challenges of the study area, but space was given to all the options suggested by stakeholders. In our view, this was a crucial element to support the dialogue and to help represent all points of view without any limitation or restriction.

Although the present work contributes to filling some gaps in current Nexus research, some questions are still open to future research. In particular, the SFDs in the current form, may neglect some relevant behaviors that should be considered to better describe the potential evolution of the system, such as the potential for adaptation. An example can help easily clarify the issue. Both models show a reduction in either SW or GW availability as an effect of climate change. Nevertheless, the model assumes that the behavior of water users (e.g., the farmers) does not adapt to such variable conditions and that no changes occur (e.g., no variation in crop types and crop water needs). This is clearly not realistic, as the adaptation to evolving conditions is a key component of 'real-world' systems. Additional efforts would also be needed for improving the quality of Scenario Analysis. This would particularly require: i) an improved capacity to account for adaptation actions in SFDs, activating specific behavior or responses under specific conditions (e.g., when a tipping point is reached); ii) a stronger mathematical formulation for helping decision- and policy-makers comparing and selecting effective solutions such e.g., multi-objective optimization algorithms (MOO); iii) an almost automatic integration and dialogue between SFDs and sectoral models (e.g., hydrological tools), to facilitate the creation and update of scenarios; iv) an explicit treatment of uncertainty, through an explicit integration of stochastic elements into the SFDs; v) the integration with Agent-Based Modelling (ABM) to better describe the impact that individual or collective behaviors might have on the evolution of Nexus systems; vi) the development of a user-friendly interface to facilitate the interaction of stakeholders with SFDs.

6. Conclusions

The present work proposes an innovative approach based on the use of PSDM techniques (specifically, SFDs) for WEF Nexus analysis and management. Reference is made to two case studies located in the Mediterranean Area (namely, the Pinios River Basin and the Greater Chania Area) that share similar challenges and pressures, but can be replicated in principle to the analysis of any Nexus system. The main objective of the work is to develop and test a methodological approach that can support decision- and policy-makers both improving Nexus understanding and facilitating Nexus implementation. SFDs can support the former as they provide an effective visualization and analysis of cross-sectoral interdependencies, and facilitate the latter through specific tools, such as the Sensitivity Analysis and the Scenario Analysis, that can be used to clarify potential pathways for system evolution. A key element of innovation of the proposed approach lies in the active engagement of stakeholders throughout project activities, from model building to model validation and use. SFDs showed significant advantages, such as the capacity to deal with qualitative and quantitative information, the transparency and the potential for treating uncertainty. Some limitations, such as the potential oversimplification of 'real' dynamics and processes over time and space, or the challenges related to the use of SFDs in the interaction with stakeholders are also discussed and will be the focus of future research. Emphasis is given, in the present work, to the use of SFDs to perform a 'what-if' Scenario Analysis that can help draw potential future system trajectories, accounting for both external drivers and selected policy actions. In our view, this is a value added of the proposed approach and an invaluable opportunity to feed the discussion on Nexus systems and on the potential related to a multiplicity of measures that might facilitate sustainability transitions.

CRediT authorship contribution statement

Alessandro Pagano: Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Virginia Rosa Coletta:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Ivan Portoghese:** Validation, Writing – review & editing. **Andreas Panagopoulos:** Methodology, Validation, Writing – review & editing. **Vassilios Pisinaras:** Methodology, Validation, Writing – review & editing. **Anna Chatzi:** Methodology, Validation, Writing – review & editing. **Dimitrios Malamataris:** Methodology, Validation, Writing – review & editing. **Konstantinos Babakos:** Methodology, Validation, Writing – review & editing. **Maria A. Lilli:** Methodology, Validation, Writing – review & editing. **Nikolaos P. Nikolaidis:** Methodology, Validation, Writing – review & editing. **Raffaele Giordano:** Conceptualization, Methodology, Validation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: (Alessandro Pagano reports financial support was provided by PRIMA Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108012.

Data availability

Data will be made available on request.

References

Albrecht, Tamee R., Crootof, Arica, Scott, Christopher A., 2018. The water-energy-food Nexus: a systematic review of methods for Nexus assessment. Environ. Res. Lett. 13 (4). https://doi.org/10.1088/1748-9326/aaa9c6.

Bakhshianlamouki, Elham, Masia, Sara, Karimi, Poolad, van der Zaag, Pieter, Sušnik, Janez, 2019. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food Nexus in the Urmia Lake Basin, Iran. Sci. Total Environ. 708, 134874. https://doi.org/10.1016/j.scitotenv.2019.134874.

Barhagh, Seyed Ershad, Zarghami, Mahdi, Ghale, Yusuf Alizade Govarchin, Shahbazbegian, Mohammad Reza, 2021. System dynamics to assess the effectiveness of restoration scenarios for the Urmia Lake: a prey-predator approach for the human-environment uncertain interactions. J. Hydrol. 593 (February). https://doi.org/10.1016/j.jhydrol.2020.125891.

Brychkov, Dmitry, Domegan, Christine, McHugh, Patricia, 2022. Coming and going in loops: participatory modelling of a system with all its complexity. J. Macromark. 42 (1), 12–29. https://doi.org/10.1177/02761467211062504.

Coletta, Virginia Rosa, Pagano, Alessandro, Pluchinotta, Irene, Fratino, Umberto, Scrieciu, Albert, Nanu, Florentina, Giordano, Raffaele, 2021. Causal loop diagrams for supporting nature based solutions participatory design and performance assessment. J. Environ. Manag. 280 (xxxx), 111668. https://doi.org/10.1016/j.jenvman.2020.111668.

Coletta, Virginia R., Pagano, Alessandro, Pluchinotta, Irene, Zimmermann, Nici, Davies, Michael, Butler, Adrian, Fratino, Umberto, Giordano, Raffaele, 2024a. Participatory causal loop diagrams building for supporting decision-makers integrating flood risk Management in an Urban Regeneration Process. Earth's Future 12 (1), 1–18. https://doi.org/10.1029/2023EF003659.

Coletta, Virginia Rosa, Pagano, Alessandro, Zimmermann, Nici, Davies, Michael, Butler, Adrian, Fratino, Umberto, Giordano, Raffaele, Pluchinotta, Irene, 2024b. Socio-hydrological modelling using participatory system dynamics modelling for enhancing urban flood resilience through blue-green infrastructure. J. Hydrol. 636 (June). https://doi.org/10.1016/j.jhydrol.2024.131248.

Dang, Chiheng, Zhang, Hongbo, Singh, Vijay P., Zhang, Shuqi, Dengrui, Mu, Yao, Congcong, Yu, Zhang, Lyu, Fengguang, Liu, Shangdong, 2024. Tracking and managing the water-food-environment-ecosystem (WFEE) Nexus in groundwater irrigation districts using system dynamics modelling. Sci. Total Environ. 947 (October). https://doi.org/10.1016/j.scitotenv.2024.174705.

de Amorim, Wellyngton Silva, Valduga, Isabela Blasi, Ribeiro, João Marcelo Pereira, Williamson, Victoria Guazzelli, Krauser, Grace Ellen, Magtoto, Mica Katrina, de Andrade Guerra, José Baltazar Salgueirinho Osório, 2018. The Nexus between water, energy, and food in the context of the global risks: an analysis of the interactions between food, water, and energy security. Environ. Impact Assess. Rev. 72 (September), 1–11. https://doi.org/10.1016/j.eiar.2018.05.002.

de Vito, R., Portoghese, I., Pagano, A., Fratino, U., Vurro, M., 2017. An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food Nexus framework. Adv. Water Resour. 110. https://doi.org/10.1016/j.advwatres.2017.10.027.

de Vito, Rossella, Pagano, Alessandro, Portoghese, Ivan, Giordano, Raffaele, Vurro, Michele, Fratino, Umberto, 2019. Integrated approach for supporting sustainable water resources Management of Irrigation Based on the WEFN framework. Water Resour. Manag. 33 (4), 1281–1295. https://doi.org/10.1007/s11269-019-2196-5.

D'Odorico, Paolo, Davis, Kyle Frankel, Rosa, Lorenzo, Carr, Joel A., Chiarelli, Davide, Dell'Angelo, Jampel, Gephart, Jessica, et al., 2018. The global food-energy-water Nexus. Rev. Geophys. 56 (3), 456–531. https://doi.org/10.1029/2017RG000591.

Elsawah, Sondoss, Pierce, Suzanne A., Hamilton, Serena H., van Delden, Hedwig, Haase, Dagmar, Elmahdi, Amgad, Jakeman, Anthony J., 2017. An overview of the system dynamics process for integrated modelling of socio-ecological systems: lessons on good modelling practice from five case studies. Environ. Model. Softw. 93, 127–145. https://doi.org/10.1016/j.envsoft.2017.03.001.

Engelbertink, Dion, 2019. System Dynamics-Based Scenario Planning.

Forrester, J.W., 1990. Principles of Systems. Portland: Productivity.

Gallagher, Louise, Kopainsky, Birgit, Bassi, Andrea M., Betancourt, Andrea, Buth, Chanmeta, Chan, Puthearath, Costanzo, Simon, et al., 2020. Supporting stakeholders to anticipate and respond to risks in a Mekong River water-energy-food Nexus. Ecol. Soc. 25 (4), 1–16. https://doi.org/10.5751/ES-11919-250429.

Gao, Danyang, Chen, Albert S., Memon, Fayyaz Ali, 2024. A systematic review of methods for investigating climate change impacts on water-energy-food Nexus. Water Resour. Manag. 38 (1), 1–43. https://doi.org/10.1007/s11269-023-03659-x.

Giordano, Raffaele, Osann, Anna, Henao, Esteban, López, Maria Llanos, Piqueras, José González, Nikolaidis, Nikolaos P., Lilli, Maria, Coletta, Virginia Rosa, Pagano, Alessandro, 2025. Causal loop diagrams for bridging the gap between water-energy-food-ecosystem Nexus thinking and Nexus doing: evidence from two case studies. J. Hydrol. 650 (April). https://doi.org/10.1016/j.jhydrol.2024.132571.

González-Rosell, Adrián, Blanco, Maria, Arfa, Imen, 2020. Integrating stakeholder views and system dynamics to assess the water–energy–food Nexus in Andalusia. Water (Switzerland) 12 (11), 1–19. https://doi.org/10.3390/w12113172.

Hoff, Holger, 2011. Background Paper for the Bonn 2011 Nexus Conference: The Water, Energy and Food Security Nexus.

Huang, An, Tian, Li, Li, Yongfu, Xiong, Binyu, Yu, Jianghao, Gao, Yuan, Li, Qing, et al., 2024. Regional complex system simulation optimization through linking governance and environment performance: a case study of water environmental carrying capacity based on the SDES model. Environ. Impact Assess. Rev. 104 (January). https://doi.org/10.1016/j.eiar.2023.107356.

Ioannou, Alexandra E., Laspidou, Chrysi S., 2022. Resilience analysis framework for a water–energy–food Nexus system under climate change. Front. Environ. Sci. 10 (May). https://doi.org/10.3389/fenvs.2022.820125.

Kellner, Elke, 2023. Identifying leverage points for shifting water-energy-food Nexus cases towards sustainability through the networks of action situations approach combined with systems thinking. Sustain. Sci. 18 (1), 135–152. https://doi.org/10.1007/s11625-022-01170-7.

Laspidou, Chrysi S., Mellios, Nikolaos K., Spyropoulou, Alexandra E., Kofinas, Dimitrios Th., Papadopoulou, Maria P., 2020. Systems thinking on the resource Nexus: modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. Sci. Total Environ. 717 (May), 137264. https://doi.org/10.1016/J.SCITOTENV.2020.137264.

Li, Wenbin, Liang, Youjia, Liu, Lijun, He, Qingqing, Huang, Jiejun, Yin, Zhangcai, 2024. Spatio-temporal impacts of land use change on water-energy-food Nexus carbon emissions in China, 2011–2020. Environ. Impact Assess. Rev. 105 (March). https://doi.org/10.1016/j.eiar.2024.107436.

Li, Wei, Ward, Philip J., van Wesenbeeck, Lia, 2025. A critical review of quantifying water-energy-food Nexus interactions. In: Renewable and Sustainable Energy Reviews. Elsevier Ltd. https://doi.org/10.1016/j.rser.2024.115280.

Lilli, Maria A., Nerantzaki, Sofia D., Riziotis, Christos, Kotronakis, Manolis, Efstathiou, Dionissis, Kontakos, Dimitris, Lymberakis, Petros, et al., 2020. Vision-based decision-making methodology for riparian Forest restoration and flood protection using nature-based solutions. Sustainability 12 (8), 3305. https://doi.org/10.3390/su12083305.

Lilli, Maria A., Efstathiou, Dionissis, Koukianaki, Evangelia A., Paranychianakis, Nikolaos, Nikolaidis, Nikolaos P., 2024. Optimizing the water-ecosystem-food Nexus of avocado plantations. Front. Water 6 (June). https://doi.org/10.3389/frwa.2024.1412146.

Liu, Huimin, Wang, Shanshan, He, Hui, Tan, Linghui, Chan, Albert P.C., 2022. Nip risk in the bud: a system dynamic model to govern NIMBY conflict. Environ. Impact Assess. Rev. 97 (November). https://doi.org/10.1016/j.eiar.2022.106916.

Malamataris, Dimitrios, Chatzi, Anna, Babakos, Konstantinos, Pisinaras, Vassilios, Hatzigiannakis, Evangelos, Willaarts, Barbara A., Bea, Manuel, Pagano, Alessandro, Panagopoulos, Andreas, 2023. A participatory approach to exploring nexus challenges: a case study on the Pinios River Basin, Greece. Water (Switzerland) 15 (22). https://doi.org/10.3390/w15223949.

Malamataris, Dimitrios, Pisinaras, Vassilios, Pagano, Alessandro, Baratella, Valentina, Vanino, Silvia, Bea, Manuel, Babakos, Konstantinos, et al., 2025. Managing water-ecosystem-food Nexus using participatory approaches: insights from an innovative methodological approach developed in two Mediterranean areas. Front. Water 7 (January). https://doi.org/10.3389/frwa.2025.1469762.

Malbon, Eleanor, Parkhurst, Justin, 2023. System dynamics modelling and the use of evidence to inform policymaking. Policy Stud. 44 (4), 454–472. https://doi.org/10.1080/01442872.2022.2080814.

Maragkaki, Antonia, Koukianaki, Evangelia A., Lilli, Maria A., Efstathiou, Dionissis, Nikolaidis, Nikolaos P., 2024. Optimizing the water-ecosystem-food Nexus using nature-based solutions at the basin scale. Front. Water 6 (June). https://doi.org/10.3389/frwa.2024.1386925.

McGrane, Scott J., Acuto, Michele, Artioli, Francesca, Chen, Po Yu, Comber, Robert, Cottee, Julian, Farr-Wharton, Geremy, et al., 2019. Scaling the Nexus: towards integrated frameworks for Analysing water, energy and food. Geogr. J. 185 (4), 419–431. https://doi.org/10.1111/geoj.12256.

Mirindi, Derrick, Sušnik, Janez, Masia, Sara, Jewitt, Graham, 2024. A system dynamics modelling assessment of water-energy-food resource demand futures at the City scale: Goma, Democratic Republic of Congo. World Dev. Sustain. 5 (December). https://doi.org/10.1016/j.wds.2024.100159.

Pisinaras, Vassilios, Panagopoulos, Andreas, Herrmann, Frank, Bogena, Heye R., Doulgeris, Charalampos, Ilias, Andreas, Tziritis, Evangelos, Wendland, Frank, 2018. Hydrologic and geochemical research at Pinios hydrologic observatory: initial results. Vadose Zone J. 17 (1), 1–16. https://doi.org/10.2136/vzj2018.05.0102.

Pisinaras, Vassilios, Paraskevas, Charalampos, Panagopoulos, Andreas, 2021. Investigating the effects of agricultural water management in a mediterranean coastal aquifer under current and projected climate conditions. Water 13 (1), 108. https://doi.org/10.3390/w13010108.

Pluchinotta, Irene, Pagano, Alessandro, Vilcan, Tudorel, Ahilan, Sangaralingam, Kapetas, Leon, Maskrey, Shaun, Krivtsov, Vladimir, Thorne, Colin, O'Donnell, Emily, 2021. A participatory system dynamics model to investigate sustainable urban water management in Ebbsfleet garden city. Sustain. Cities Soc. 67 (April). https://doi.org/10.1016/j.scs.2021.102709.

Pluchinotta, Irene, Zhou, Ke, Zimmermann, Nici, 2024. Dealing with soft variables and data scarcity: lessons learnt from quantification in a participatory system dynamics modelling process. Syst. Dyn. Rev. 40 (4). https://doi.org/10.1002/sdr.1770.

Pruyt, Erik, 2013. System dynamics. In: Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Complexity. TU Delft Library, Delft, The Netherlands. https://doi.org/10.1007/978-1-84882-809-4_2.

Purwanto, Aries, Janez Sušnik, F.X., Suryadi, de Fraiture, Charlotte, 2019. Using group model building to develop a causal loop mapping of the water-energy-food security Nexus in Karawang regency, Indonesia. J. Clean. Prod. 240. https://doi.org/10.1016/j.jclepro.2019.118170.

Rhouma, Ali, El Jeitany, Jerome, Mohtar, Rabi, Gil, José Maria, 2024. Trends in the water–energy–food Nexus research. Sustainability (Switzerland). https://doi.org/10.3390/su16031162. Multidisciplinary Digital Publishing Institute (MDPI).

Samadi-Foroushani, Marzieh, Keyhanpour, Mohammad Javad, Musavi-Jahromi, Seyed Habib, Ebrahimi, Hossein, 2022. Integrated water resources management based on water governance and water-food-energy Nexus through system dynamics and social network analyzing approaches. Water Resour. Manag. 36 (15), 6093–6113. https://doi.org/10.1007/s11269-022-03343-6.

Scrieciu, Albert, Pagano, Alessandro, Coletta, Virginia Rosa, Fratino, Umberto, Giordano, Raffaele, 2021. Bayesian belief networks for integrating scientific and stakeholders' knowledge to support nature-based solution implementation. Front. Earth Sci. 9 (July), 1–18. https://doi.org/10.3389/feart.2021.674618.

Skoulikidis, Nikolaos Theodor, Nikolaidis, Nikolaos Pavlos, Panagopoulos, Andreas, Fischer-Kowalski, Marina, Zogaris, Stamatis, Petridis, Panos, Pisinaras, Vassilis, et al., 2021. The LTER-Greece environmental observatory network: design and initial achievements. Water 13 (21), 2971. https://doi.org/10.3390/w13212971.

Stave, Krystyna, 2010. Participatory system dynamics modeling for sustainable environmental management: observations from four cases. Sustainability 2 (9), 2762–2784. https://doi.org/10.3390/su2092762.

Sterman, J., 2000. Business Dynamics: Systems Thinking and Modelling for a Complex World. McGraw-Hill Higher Education.

Sušnik, Janez, 2018. Data-driven quantification of the global water-energy-food system. Resour. Conserv. Recycl. 133 (June), 179–190. https://doi.org/10.1016/J.RESCONREC.2018.02.023.

Sušnik, Janez, Staddon, Chad, 2022. Evaluation of water-energy-food (WEF) Nexus research: perspectives, challenges, and directions for future research. J. Am. Water Resour. Assoc. 58 (6), 1189–1198. https://doi.org/10.1111/1752-1688.12977.

Sušnik, Janez, Masia, Sara, Indriksone, Daina, Brēmere, Ingrīda, Vamvakeridou-Lydroudia, Lydia, 2021. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate Nexus in Latvia. Sci. Total Environ. 775. https://doi.org/10.1016/j.scitotenv.2021.145827.

Teng, Yue, Bao, Yinghui, Wang, Yushi, Liu, Sha, Li, Zhongfu, Tiong, Robert L.K., 2025. Recognizing and reconciling dynamic stakeholder conflicts for sustainability in old residential community renovation project strategies. Environ. Impact Assess. Rev. 110 (January). https://doi.org/10.1016/j.eiar.2024.107693.

Terzi, Stefano, Sušnik, Janez, Schneiderbauer, Stefan, Torresan, Silvia, Critto, Andrea, 2021. Stochastic system dynamics modelling for climate change water scarcity assessment of a reservoir in the Italian Alps. Nat. Hazards Earth Syst. Sci. 21 (11), 3519–3537. https://doi.org/10.5194/nhess-21-3519-2021.

Voinov, Alexey, Kolagani, Nagesh, McCall, Michael K., Glynn, Pierre D., Kragt, Marit E., Ostermann, Frank O., Pierce, Suzanne A., Ramu, Palaniappan, 2016. Modelling with stakeholders - next generation. Environ. Model. Softw. 77, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016.

Voinov, Alexey, Jenni, Karen, Gray, Steven, Kolagani, Nagesh, Glynn, Pierre D., Bommel, Pierre, Prell, Christina, et al., 2018. Tools and methods in participatory modeling: selecting the right tool for the job. Environ. Model Softw. 109 (November), 232–255. https://doi.org/10.1016/j.envsoft.2018.08.028.

Wu, Lina, Elshorbagy, Amin, Pande, Saket, Zhuo, La, 2021. Trade-offs and synergies in the water-energy-food nexus: the case of Saskatchewan, Canada. Resour. Conserv. Recycl. 164 (January). https://doi.org/10.1016/j.resconrec.2020.105192.

Wu, Lina, Elshorbagy, Amin, Alam, Md Shahabul, 2022. Dynamics of water-energy-food nexus interactions with climate change and policy options. Environ. Res. Commun. 4 (1). https://doi.org/10.1088/2515-7620/ac4bab.

Yu, Bo, Liu, Xueqing, Bi, Xuehao, Sun, Hua, Buysse, Jeroen, 2025. Agricultural resource management strategies for greenhouse gas mitigation: the land-energy-food-waste Nexus based on system dynamics model. Environ. Impact Assess. Rev. 110 (January). https://doi.org/10.1016/j.eiar.2024.107647.

Zhang, Tong, Tan, Qian, Zhang, Shan, Zhang, Tianyuan, Zhang, Weijia, 2021. A participatory methodology for characterizing and prescribing water-energy-food nexus based on improved casual loop diagrams. Resour. Conserv. Recycl. 164 (August 2020), 105124. https://doi.org/10.1016/j.resconrec.2020.105124.