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Managing Water-Ecosystem-Food Nexus using participatory approaches: insights from an innovative methodological approach developed in two Mediterranean areas

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The formulation of effective policies to address both the present allocation and future conservation of natural resources in an integrated way remains an essential and challenging task. In this regard, managing the Nexus is increasingly seen as a priority in resource governance. Nature-based Solutions (NbS) are gradually being advocated to enhance sustainable and resilient Nexus management efforts. Designing and planning NbS tailored to local contexts requires a thorough understanding of the specific challenges and perspectives, as well as the divergent perspectives among stakeholders. This paper presents and analyses an effective stakeholder engagement strategy, based on the Learning & Action Alliances (LAA) scheme and aimed at identifying Water-Ecosystems-Food (WEF) Nexus challenges and selecting NbS in two case studies in the Mediterranean area (Greece and Italy). In total, 60 stakeholders were engaged in more than 40 events (workshops, seminars, open days, field trips etc.), while 25 individual interviews were also conducted. By fostering collaboration and stakeholder ownership, the methodology provided actionable insights and promoted context-specific solutions. The stakeholders proposed 24 NbSs in the Italian case study, most of which were related to agricultural landscape management, while in the Greek case study, 2 of the 4 top-ranked measures were NbSs. The findings underline the importance of participatory approaches and transdisciplinary tools in addressing Nexus challenges, offering a replicable framework for sustainable resource management in resource-stressed regions.

KEYWORDS

stakeholder engagement, Causal Loop Diagrams, serious game, SWOT analysis, Mediterranean area, sustainability

1 Introduction

Under a rapid global socio-economic development and population growth that threaten the stability of Earth's systems (Rockström et al., 2009; Persson et al., 2022), water and food stand as crucial resources for human well-being and pivotal elements for socio-economic progress, that heavily rely on mutual interconnections (Chen and Chen, 2021). The world population is projected to increase by approximately 53% by 2050 (FAO, 2014), which will significantly elevate the demand for natural resources, leading to their reduced utility rates (Ahmad et al., 2021). Agriculture accounts for about 70% of global freshwater withdrawals, yet more than a billion people still lack access to drinking water, and a staggering one-third of all food produced annually is wasted or lost (Aldaya et al., 2022). Additionally, land use changes have impacted almost a third of the global land area over the last six decades (Winkler et al., 2021). Effectively managing natural resources is a high priority to guarantee sustainability, as emphasized by Sustainable Development Goals (United Nations (UN), 2015).

While increased and diversified uses of natural resources can lead to conflicts, they also offer opportunities for development and economic diversification, thereby strengthening regional economies (Bof et al., 2021). In this context, natural resource managers should strive to balance various resource uses to promote effective regional economic development models. Concurrently, they must endeavor to prevent conflicts and alleviate environmental impacts associated with productive activities, pursuing an integrated management of resources. In this direction, "Nexus thinking" was first conceived by the World Economic Forum in 2011 to emphasize the interconnectedness of natural resources use in ensuring fundamental and universal rights to water and food security, safeguarding ecosystems' sustainability (Choi et al., 2022). Although various organizations and researchers have proposed different definitions of the Nexus across different sectors and contexts (Hoff, 2011), the primary objective of implementing a Nexus approach is the identification of potential synergies and trade-offs among these sectors.

Nexus security is a multifaceted concept shaped not only by the intrinsic characteristics of natural resources but also by diverse external factors, including economic and societal objectives, and stakeholder interests (Hoolohan et al., 2018; Karutz et al., 2022). It is part of a broader framework and represents a structured way to address cross-cutting issues related to inputs (water-energy) and food production according to ecosystem management and impacts, starting with the identification of existing interlinkages among them (Fabiani et al., 2020). Developing management models that integrate multiple objectives is inherently complex and challenging. One of the main challenges in achieving WEF Nexus sustainability is the integrated resource planning and implementation processes involving various stakeholders, such as regulatory public agencies, civil society, and the private sector, each with distinct interests (Melloni et al., 2020). Typically, decision-making in management tends to prioritize the interests of a single stakeholder, which can lead to conflicts among different groups (White et al., 2017). Implementing an integrated stakeholder engagement strategy for a multi-level assessment of WEF security addresses the limitations of focusing on individual Nexus sectors, thereby providing a more comprehensive evaluation (Cansino-Loeza and Ponce-Ortega, 2024).

Achieving Nexus security requires the identification of effective measures that can provide multiple joint benefits for all the Nexus sectors. The European Commission delineates NbSs as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to simultaneously provide economic, social, and environmental benefits" (European Commission, 2015). Expanding upon this definition, NbSs can be targeted at resolving multiple distinct problems or concerns in both urban and rural settings, facilitating the implementation of a Nexus approach. NbSs tackle societal challenges while facilitating resource recuperation, addressing climate mitigation and adaptation objectives, enhancing human well-being, restoring ecosystems, and promoting biodiversity (Langergraber et al., 2020). NbSs are anticipated to assume a significant role in the EU Green Deal Strategy (European Commission, 2019), and the EU Biodiversity Strategy to 2030 (European Commission, 2020a), to execute the Farm to Fork Strategy (European Commission, 2020b) which is intricately associated with the WEF Nexus challenges (Carvalho et al., 2022).

Nexus modelling requires the adoption of suitable approaches that can help understanding critical interconnections is complex systems. System Dynamics Modelling (SDM) is a well-established methodology grounded in system concepts and theory, designed to quantify system behaviors with complex feedback mechanisms for more accurate projections (Forrester, 1961; Forrester, 1968). Several researchers have demonstrated the potential of SDM in Nexus management (Wang et al., 2023; Barati et al., 2023; Francisco et al., 2023), as it provides models for the analysis of interconnected and interdependent cause-and-effect chains within complex systems, as well as for the active participation of stakeholders. In this regard, a pivotal works from Stave (2010) and Voinov et al. (2018) identified the key elements that characterize different participatory approaches that can be used to analyze complex environmental systems, highlighting also the main advantages (and potential limitations) of SDM. The relevance of SDM for Nexus studies has also been recently explored in several works (see among the others Sušnik, 2018; Laspidou et al., 2020; Sušnik et al., 2021, Gao et al., 2024).

Among the available participatory methodologies aimed at understanding, discussing and analyzing the intricacies of complex systems, ultimately facilitating social learning, the "serious gaming" is gaining attention (Tschakert and Dietrich, 2010). Serious games, defined as games designed for purposes beyond mere entertainment, exert significant influence, particularly in the realm of natural resources education (Gerber et al., 2021). Serious games are increasingly recognized as a potentially effective intervention tool (Rodela et al., 2019) for exploring stakeholder perspectives and concerns. Utilizing a game-based approach, participants are prompted to examine system behaviors through scenario assessment and to aid

negotiations in localized settings (Speelman et al., 2014; van Noordwijk et al., 2020). Serious games serve as powerful and persuasive tools for facilitating participation, generation of ideas, and stakeholder dialogue (Bontchev et al., 2021). Spanning diverse formats and platforms, serious games can play a pivotal role in facilitating participatory design (Flood et al., 2018), catalyzing decision-making processes and driving behavioral shifts (Gao et al., 2021).

In this context, this paper presents the stakeholders' engagement strategy formulated for selected pilot areas in Greece and Italy within the framework of the PRIMA-funded LENSES project. The adopted strategy places stakeholders at the core of the WEF Nexus approach, aiming to collaboratively explore, understand, and address trade-offs, related conflicts, and management challenges, with the objective of co-designing, assessing, adopting and implementing solutions for Nexus management. The adopted approach is deeply rooted in the Learning and Action Alliances (i.e., collaborative environments for stakeholders that have been developed in both presented case studies) (O'Donnell et al., 2018; Maskrey et al., 2020) and based—among others—on Participatory SDM techniques and serious gaming for an improved understanding of WEF Nexus and of the potential impacts NbSs may have on a sustainable Nexus management. After introducing the two pilot areas and the applied methodologies in Section 2, and presenting the corresponding results in Section 3, Section 4 discusses these results by addressing three key research questions: (i) How can participatory approaches and transdisciplinary tools effectively support the Water-Ecosystem-Food (WEF) Nexus management in resource-stressed Mediterranean areas? (ii) What are the main WEF Nexus challenges and potential solutions identified by stakeholders in the pilot areas, and how do Nature-Based Solutions (NbS) contribute to these challenges? (iii) How do local contexts and stakeholder dynamics influence the identification, prioritization, and implementation of WEF Nexus solutions?

2 Materials and methods

2.1 Methodological framework

The proposed stakeholder engagement strategy encompasses both individual and group activities supporting an iterative process, adhering to key principles designed to optimize outcomes. Creating a positive environment is paramount to ensure all participants feel included and motivated to engage, thereby mitigating the risk of exclusion. Transparency is also essential to prevent perceptions of bias, and to respect and value participants' viewpoints. The role of facilitators is central, as they need to maintain neutrality. Accordingly, the process of merely providing data must be clearly distinguished from genuine stakeholder engagement, ensuring that stakeholders never feel they are being approached or utilized solely as data sources.

The formulated methodological framework encompasses six principal elements: (1) NEXUS pillars analysis; (2) stakeholders' identification and engagement; (3) SDM: Causal Loop Diagrams; (4) LENSES Serious Game; (5) measures' identification and selection; and (6) Political Economy Analysis (Figure 1).

It is pertinent to note that the implementation of these elements may vary depending on the unique capacities and needs of each area. Notably, not all elements need to be employed universally, nor must they be implemented uniformly across all regions. The following sub-sections provide detailed discussions on the proposed approach and essential considerations for the application of the methodology.

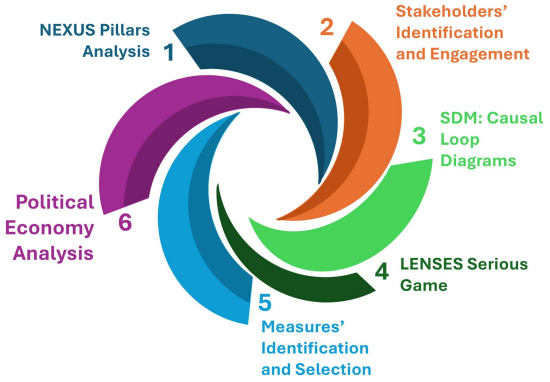

FIGURE 1
Stakeholder engagement strategy as part of the LENSES LAA development process.

2.2 NEXUS pillars analysis

2.2.1 Study areas

Two pilot areas were selected within the Mediterranean basin, located in Greece and in Italy. Despite their differences (e.g., spatial extent, land and water use patterns), the selected regions exemplify typical Mediterranean conditions and are facing similar challenges, including the climate patterns and climate change impacts, the surface water and groundwater interactions, the competitive resource usage for productive activities, the dominance of agricultural activities as well as of tourism for economic development, the increasing impacts of such activities on the state of natural resources and local ecosystems.

Greece: Agia watershed and Pinios River Delta (PRD) pilot areas are situated within the Pinios River Basin (PRB) in the Thessaly region, Central Greece. The Agia watershed spreads at approximately 53 km^2 and is characterized by a complex geological and geomorphological environment, with steep terrain ranging from 94 to 1,520 m a.s.l. along its northern part and quasi flat plain at its southern extent (Figure 2A). This watershed includes the Pinios Hydrologic Observatory (PHO), one of nine Greek observatories that form the Hellenic Long-Term Ecological Research Network (LTER Greece), which is integrated into the European and International LTER networks. Land use in the Agia watershed is predominantly forest and semi-natural areas (56%), followed by agricultural areas (41%), and artificial surfaces (3%). Spatially, mixed forests dominate the northern mountainous part, while orchards, primarily apples and cherries, are prevalent in the southern Agia plain.

The Pinios River Delta covers approximately 74 km^2 and forms the plain where the Pinios River discharges into the Thermaikos Gulf (Figure 2A). The PRD is characterized by significant biodiversity, featuring a variety of plant and animal life, including riparian forests, estuarine landscapes with riparian woodlands, marshlands, small freshwater lakes, sandy dunes, and coastal areas. According to the Corine Land Cover 2018 (CLC2018) dataset, agricultural areas are dominant in the PRD, constituting 74% of the total area, followed by

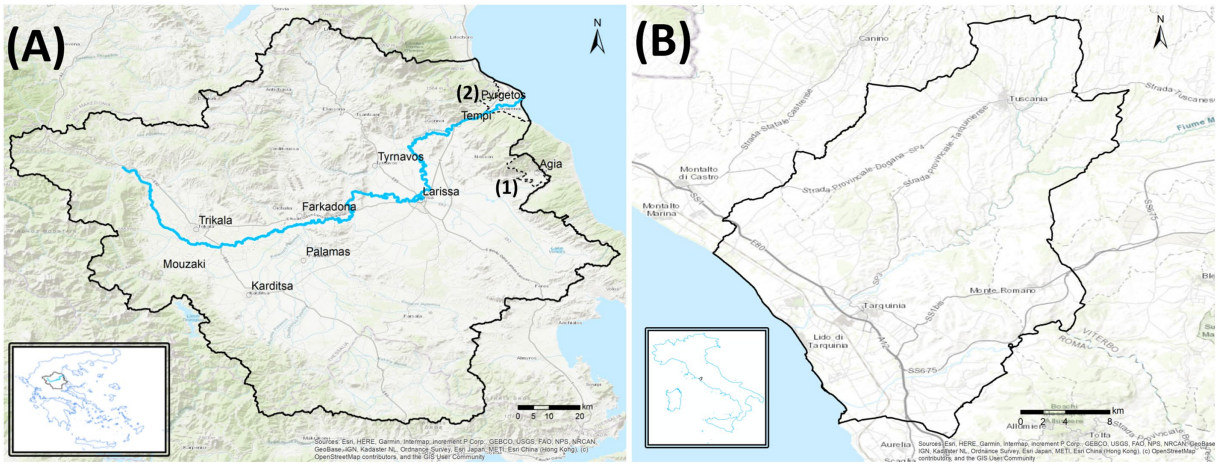

FIGURE 2
Pilot areas of **(A)** Agia watershed (1) and Pinios River Delta (2) located in Pinios River Basin, central Greece and **(B)** Tarquinia pilot area situated in central Italy.

wetlands (10%), artificial surfaces (10%), forest and semi-natural areas (4%), and water bodies (3%).

Italy: Tarquinia plain area is located in Central Italy—Lazio Region, around 90 km north of Rome (Figure 2B). The area mainly includes the watershed of the Marta River that has a spatial extent of approximately 1,047 km^2, including Bolsena Lake which covers 114 km^2, through which Marta River originates with a length of 49 km. The climate is typical Mediterranean (Koppen classification: Csa) (Kottek et al., 2006), characterized by warm dry summers, mild winters, and an average annual rainfall of approximately 600 mm, mainly occurring in autumn and spring. The mean daily temperature is 15.3°C, ranging from 7.7°C in January to 23.7°C in July.

According to the CLC2018 dataset, agricultural areas dominate the Marta River basin, covering 82% of the total area. This is followed by forest and semi-natural areas (16.5%), artificial surfaces (1%), salinized areas (0.2%) and water bodies (0.02%). In Tarquinia plain, the Utilized Agricultural Area (UAA) represents 9.37% of the total area, with cereals, horticulture and fodder being the most grown crops.

2.2.2 Water sector

Agriculture constitutes the major water consumer for both Greek pilot areas. The significant intensification of agricultural operations coupled with unsustainable irrigation methods have generated a pressing demand for increased irrigation water which is mainly covered by groundwater. In Agia watershed, agricultural use accounts for about 90% of total water consumption, followed by industrial (8%), and domestic (2%) uses. Almost all irrigation water is abstracted from groundwater through private wells, while a limited number of public wells exist which are connected to collective pressurized networks. Surface water reservoirs also serve as sources of irrigation water mainly for orchards located at the north mountainous region of PHO. As for the Pinios River Delta, agricultural activities represent 92% of overall water usage, followed by industrial (4%), and domestic (4%) water uses. Irrigation water is sourced through existing and old Pinios river course and groundwater. Moreover, the whole PHO and a third (76%) of PRD areas are officially designated as vulnerable areas to nitrate pollution of agricultural origin.

On the contrary, in Tarquinia plain water supply relies primarily on surface water from the rivers Marta and Mignone to cover demands the distribution of which is more balanced between domestic and irrigation (47% of total water consumption including tourism, and 53%, respectively). The Marta River is the only outlet of the Bolsena lake, and its estuary is located on the coast near the plain of Tarquinia, after having flown about 49 km crossing the province of Viterbo. Also, the Mignone River estuary is in the Tarquinia coast area, and it originates from the confluence of small streams from the northern area of the Viterbo province. The irrigation water is primarily drawn from the Marta River and overseen by the Water Users Association (WUA) known as the "Consorzio di Bonifica Litorale Nord." In 2017, approximately 10,000 ha of irrigable land was managed by the WUA in Tarquinia, of which 2,600 ha were irrigated mainly by micro-irrigation. The agriculture water consumption, managed by WUA, is around 5.51 hm^3 yearly. Due to intensive agriculture, 85% of the agricultural area has been designated as a Nitrate Vulnerable Zone (NVZ). The main challenges in this area are closely linked to the quantity and quality of water in agricultural areas. During the summer there is a high demand for water (both for agriculture and tourism) and the distribution of this water is complex due to structural and management problems of the WUA. This problem is also linked to the high energy costs of pumping water in the irrigation networks. In addition, the quality of groundwater is not very good due to nitrate pollution from fertilizers.

2.2.3 Ecosystem sector

PRB constitutes an area of both high ecological value and environmental vulnerability. It includes a wide range of ecosystems that face numerous pressures, including altered hydrological regimes and pollution mainly from agricultural runoff. Significant hydro-morphological alterations due to irrigation practices have modified the natural flow regime, thus stressing the riverine ecosystems (Stefanidis et al., 2016). Other studies highlight the impact of high levels of pesticide residues found in water bodies across the basin that stress aquatic organisms and degrade the ecological status of the river (Tsaboula et al., 2019) and the impact of extensive use of fertilizers and

pollution from domestic and industrial sources in water quality and ecosystems health (Bellos et al., 2004; Chatzinikolaou and Lazaridou, 2007).

The PHO and PRD are considered some of the most important hydro-ecosystems in Pinios River Basin. More than 43% of PRD area is part of the NATURA2000 network and is recognized internationally as an Important Bird Area. Groundwater salinization constitutes one of the major issues that potentially affects the ecosystems (Pisinaras et al., 2021), while maintaining the ecological flow in Pinios River constitutes a challenge during summer because of direct river water abstraction for irrigation. Regarding PHO, about 30% of its area is included in the NATURA2000 network, while locally elevated nitrate concentrations (up to 86.5 mg/L) indicate the impact of agricultural activities in groundwater quality (Pisinaras et al., 2018).

Tarquinia pilot hosts a biodiversity hotspot within a saline environment, notably embodied by the "Saline di Tarquinia" Natural Park. One of the main environmental challenges in the Tarquinia area is habitat degradation due to the abandonment of salterns and changes in land use. Coastal wetlands like the Tarquinia Salterns are sensitive to changes in water management and are affected by both land-based pollution and sea-level rise, highlighting the need for ongoing restoration and monitoring to protect their biodiversity and ecological functions (Cimmaruta et al., 2011).

2.2.4 Food/agriculture sector

Agriculture is the dominant economic activity in both pilot areas located in Greece and crucial for their socio-economic stability. In the PHO area, apple trees are the primary crop, covering nearly half of the agricultural area, followed by significant cultivation of stone fruits and cereals. Other crops include nuts, forage and olives. In the PRD area, forage crops are predominant, followed by energy crops, and corn, with wheat and other cereals also contributing substantially. Although not the dominant, the most dynamic crop in PRD is the kiwi fruit, the area of which is continuously increasing during the last two decades.

In Tarquinia, the main economic activities are tourism (Tarquinia has been on the UNESCO World Heritage list since 2004) and agriculture, which are closely linked to the WEF Nexus. The agricultural area is characterized by intensive farming: arable areas dominate (about 80%), followed by permanent grassland and pasture, and fruit trees. In detail, the main crops are fodder, winter wheat, horticulture, barley, peas and field beans, and olive trees, according to data of 2020 from Italian Statistical Data.[1] The city of Tarquinia, together with the nearby Montalto di Castro, records the highest per capita income in the province of Viterbo, connected to agriculture, seaside, and archeological tourism.

2.3 Stakeholders' identification and engagement

A systematic and flexible methodology has been developed within the context of the PRIMA LENSES[2] (Baratella et al., 2023) and H2020 REXUS (Malamataris et al., 2023) projects to map key stakeholders in each pilot area through a series of steps: (i) drafting an initial list of stakeholders and utilizing a snowballing technique to expand the number of relevant institutions and individuals; (ii) analyzing diversity to ensure a well-balanced representation of all types of actors, genders and sectors; and (iii) conducting a suitability assessment of the identified stakeholders by mapping them against two criteria: influence (i.e., the capacity or power of an actor to resolve or alleviate the identified problems) and interest (i.e., the extent to which the problem matters to the actors, such as whether it is in their interest to address it or if the problem is a major issue for their business).

Stakeholders with a high level of both interest and influence were prioritized and directly involved in project activities. However, engagement efforts also targeted stakeholders with high influence but low interest to facilitate their gradual involvement in the process. Other groups were invited to participate in certain activities and kept well-informed about the LAA progress.

2.4 SDM: Causal Loop Diagrams

System Dynamics Modelling (SDM) comprises a set of methods that support System Thinking also ensuring a direct engagement of stakeholders (reference is often made to Participatory System Dynamics Modelling—PSDM), ultimately helping to better understand complex socio-environmental systems through the analysis of the complex web of interactions among variables (Sterman, 2000). Causal Loop Diagrams (CLDs), which belong to the class of qualitative PSDM tools, help building a conceptual model of a complex system, capturing linkages among variables and feedback loops.

The core building blocks of CLD are variables and their direct causal relationships, which can be either positive or negative (if they increase in the same direction or in the opposite direction, respectively) (Sterman, 2000). Another key element of CLDs is represented by feedback loops, i.e., cyclical connections among variables. A positive (or reinforcing) feedback loop generates exponentially escalating behavior, while a negative (or balancing) feedback loop generates balancing or goal-seeking behavior.

The use of CLDs is particularly relevant to: (i) describe a problem situation and its possible causes and solutions; (ii) help people externalize and share their mental models and perceptions; (iii) show people the dynamic system they are part of and propose solutions, also using scenario analysis (e.g., Pruyt, 2013). A relevant potential related to the use of CLDs in Nexus-related problems has been recently acknowledged in the scientific literature (Sušnik et al., 2018; de Vito et al., 2019; Purwanto et al., 2019; Laspidou et al., 2020; Wu et al., 2021), particularly as they can help building a shared view of the system under investigation, and find consensus on the main problems/challenges and potential solutions for the study area. The involvement of stakeholders in CLD building and analysis can occur in several ways (i.e., directly or through either the analysts or the experts involved in the projects).

2.5 LENSES serious game

The LENSES Nexus-SDG Serious Game has been developed in the context of the PRIMA funded LENSES European research project. The

1 https://www.istat.it/it/agricoltura

2 https://www.lenses-prima.eu/

Serious Game promotes active management of the WEF Nexus, in pursuit of achieving Sustainable Development Goals (SDGs) targets. This is achieved by generating a list of suitable NbS along with their associated ecosystem services, allowing participants to select the most appropriate solutions and visualize their scores in a user-friendly form.

Once participants select the area of interest and the stakeholder group they primarily represent (such as farmers, land use planners etc.), the Serious Game evolves through the five distinct steps it consists. In the first step, maps of climate-related indicators and land use suitability maps for specific crops for the future period 2040–2070 are presented. Interactive Causal Loop Diagrams are used to explore relationships between the pilot area's system elements. In the second and third steps, participants identify and select the challenges and the affected systems, respectively. Subsequently, a list of suitable NbSs and their associated ecosystem services is provided, enabling participants to select those NbSs that maximize contribution to SDGs, supplied ecosystem services, co-benefits and trade-offs within the WEF systems. The primary objective is to identify the most appropriate options and earn SDG coins based on the number of SDGs addressed by each NbS. Finally, a report is generated, summarizing the participants' choices and the associated outcomes, allowing players to gain insights from the collaborative decision-making process and to prioritize the selected NbS.

The Game simulates the governance context in which NbSs are discussed and negotiated among stakeholders with diverse interests and perspectives. Role-playing enables participants to experience scenarios where opposing views and goals are often represented. This participatory process involves a group of participants collectively exploring complex realities and challenges, allowing individuals within teams to make informed decisions for Nexus management. This approach challenges conventional thinking and fosters collaboration, teamwork, and engagement.

An overview of the software and applications used to design and develop the Nexus-SDG as a Serious Game is presented in Table 1.

Bubble is the main platform used to develop the Serious game and incorporate the interactive web maps built with Leaflet and interactive diagrams built with Kumu application. Bubble.io is a visual web development platform that allowed the creation of the web application without the need of programming languages and provides a user-friendly interface for designing and building web applications through visual elements and workflows. Key features of Bubble.io includes the visual development for the design of the user interface of the web application, the built-in databases that stores and manages data and finally the visual editor for defining the workflows and logic of the web application. Additionally, for the development of the interactive web maps the programming language of JavaScript has been used, through the Leaflet open-source library. It is a lightweight and versatile mapping library that provides developers with the tools to integrate maps into web applications. Finally, Figma has been used on the design process of the Serious game to create mockups and the first prototypes before the development of the technical infrastructure of the game.

TABLE 1 Software used for the design and development of the serious game.

Software	Description
Bubble	Develop the whole serious game front-end and back-end.
Leaflet	Develop the user-interface of the web-maps.
Kumu	User-interface to build and analyze the causal loops diagrams.
Figma	Design the mock-ups of the serious game.

2.6 Measures' identification and selection

As part of the stakeholders' workshops, the participants discussed existing challenges and objectives, and were requested to propose regionalized measures to tackle these challenges and meet WEF goals. Stakeholders examined each goal separately and proposed various measures to secure them.

The proposed measures were then assessed and prioritized. For this purpose, stakeholders determined weighting factors for a series of evaluation criteria which were selected following intensive discussions with scientific partners and stakeholders. The considered criteria were as follows: (a) *urgency and efficiency time*, i.e., the necessity or priority of a measure's adoption/implementation for the immediate fulfillment of defined goals; (b) *effectiveness*, i.e., the degree of a goal satisfaction for which a measure is designed, adopted and implemented; (c) *co-benefits and intersectionality*, i.e., the positive side effects on third sectors that a measure can cause to natural and artificial environment, and fulfillment of a wide range of goals and targets by the implementation of a single measure, particularly in case of goals and targets referring to different Nexus sectors; (d) *negative side effects*, i.e., the negative side effects that a measure can cause to natural and artificial environments; (e) *maturity and enabling environment*, i.e., the administrative and techno-economic readiness to implement a measure, and the time required for a measure' implementation to initiate; (f) *acceptance*, i.e., the level of socio-economic acceptance of a measure by the locals and generally affected groups of citizens and their economic activities; (g) *sustainability*, i.e., the level of equal distribution of generated benefits among the various stakeholder groups, without causing damage to any of these groups; and (h) *cost*, i.e., the direct cost of a measure's adoption/implementation. The process for prioritizing the proposed measures is illustrated in Figure 3.

2.7 Political economy analysis

A Political and Economy Analysis (PEA) is a tool used to understand the complex political and economic context within which organizations work. A PEA is concerned with the distribution of power and wealth within a society, and in particular with the processes that create, sustain and transform these relationships over time (Batchelor et al., 2016). The rationale behind performing a PEA within LENSES was to unravel the connections between actors, institutions, and formal and informal norms with the aim of deepening the understanding of the evolution and dynamics of interactions between the political and economic spheres. The preliminary PEA undertaken within LENSES provided valuable insights to set roadmaps toward more efficient and accelerated implementation of identified WEF Nexus measures that are informed by stakeholders' values and by the underlying context in which policy and economy operate in each area.

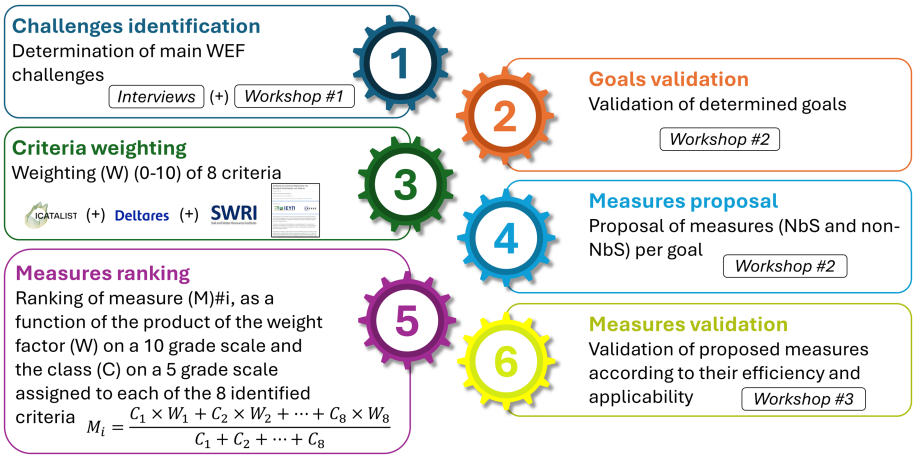

FIGURE 3
Measures prioritization process and the environment at which each step is developed (e.g., Workshop #2).

3 Results

3.1 Stakeholders' mapping

A unique code was assigned to each different stakeholder based on their main related Nexus sector (the prefixes W, E, and F refer to the water, ecosystem, and food sectors, respectively). The group of engaged stakeholders in the Greek pilot area comprised 19 members. Overall, the water, ecosystem, and food sectors were represented by 5, 4, and 10 stakeholders, respectively. In addition, stakeholders were categorized according to their type; i.e., there were 9 decision and policy-makers (POL) (i.e., W1, W2, W3, W5, E1, E2, E3, F4, and F10), 5 representatives of end users (USER) (i.e., F1, F2, F3, F6, and F8), 1 representative of a private company (COM), such as financial institution (i.e., F7), and 4 research and academia representatives (RES) (i.e., W4, E5, F5, and F9). Levels of influence and interest were also assigned to each stakeholder and are detailed in Figure 4A. A high diversity and a well-balanced representation of all WEF Nexus sectors and institutional/governance levels were achieved, supporting the efforts toward a sustainable Nexus approach.

In the Italian pilot area of Tarquinia, the stakeholder panel included 41 actors from different backgrounds and sectors: 9 from public entities and policy makers, 20 farmers and their associations, 1 from private sector, 3 NGOs and local associations, and 10 advisors and researchers. Based on stakeholder roles and main interests, 21 functional clusters were identified, with 6 categories based on stakeholder type (POL = policy makers, USER = farmers and associations, CIT = citizens and NGOs, EXP = individual experts, COM = private companies, RES = academia). Stakeholders' mapping is depicted in Figure 4B (for more detail, see Baratella et al., 2023).

3.2 Stakeholders' involvement activities

The LAA framework was fully implemented during the LENSES project in PHO and PRD pilot areas, and included a series of personal structured interviews with 19 stakeholders; the organization of 3 workshops, 2 open days, 3 stakeholders' cafe meetings, 4 new-farmers seminars, 2 partners' field trips, and 1 students' trip, and participation in 1 local cherry fair.

In the Italian area the LAA was implemented using stakeholder functional role mapping as a basic information base. A wide range of participatory activities were carried out with multi-stakeholders groups, involving increasingly larger groups of participants, from individual interviews (13) workshops (5), visioning exercises to co-develop pathways for Nexus management (3), an educational seminar for students, teachers and consultants, the participation in 1 field trip, participation and to the local agricultural fair and exhibition "MoMeMa." Particular attention was paid to the local media, where news and updates of the activities were reported from time to time (local and national newspapers, online or printed).

3.3 Identification of Nexus challenges

The primary sectoral Nexus challenges, identified through LAA participatory activities, have been systematically validated and agreed upon with local and regional stakeholders. This consensus was achieved through a series of participatory workshops, which facilitated comprehensive stakeholder engagement. The challenges were formulated very broadly, in the form of strategic objectives for the area, resulting consistent across both the Greek (Panagopoulos et al., 2023) and Italian (Vanino et al., 2024) pilot areas, as follows:

- Challenge 1: Achieving and maintaining good quality and sufficient quantity of water resources
- Challenge 2: Sustainability of the agricultural sector
- Challenge 3: Protection and restoration of ecosystems

During the first stakeholders' workshop, a specific exercise was conducted to better detail each challenge, through the identification of: (i) obstacles and inhibitors; (ii) risks and impacts; (iii) strengths and opportunities; and (iv) indicators to monitor how each challenge can be addressed. The stakeholders were asked to use color-coded posters, with each color representing a different Nexus sector: blue for "water," green for "ecosystem," and brown for "food." The SWOT

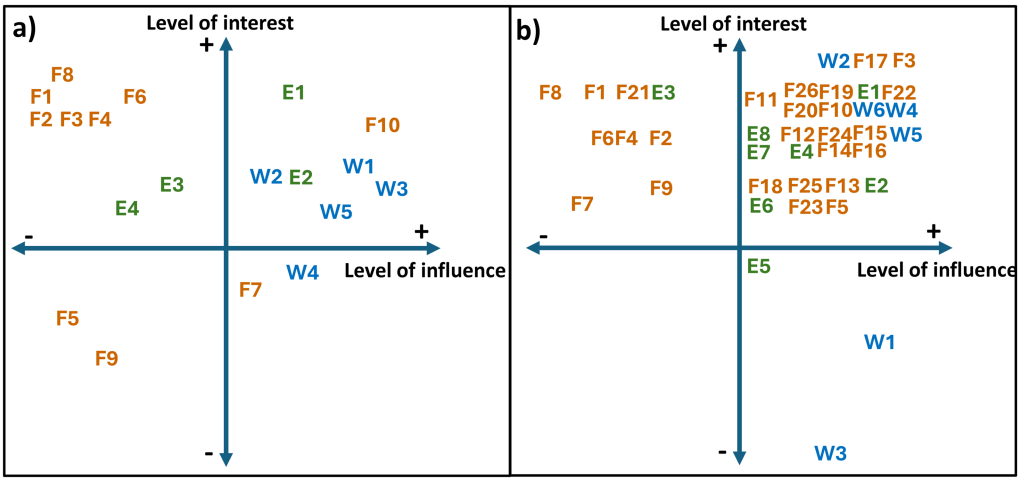

FIGURE 4
Stakeholders' mapping **(A)** at the Greek pilot areas and **(B)** at Tarquinia pilot area based on their related Nexus sector.

analysis was structured into four quadrants: the upper two quadrants encompass internal factors, i.e., strengths and weaknesses, while the lower two quadrants comprise external factors, i.e., opportunities and threats. The most prevalent responses from stakeholders, organized per sector, are summarized in Figure 5 for the Greek pilot areas. This figure encapsulates the aggregated feedback and priority concerns expressed by stakeholders, providing a nuanced understanding of sector-specific challenges and opportunities.

Going into details, high water consumption (for both PHO and PRD) and groundwater over-abstraction (for PHO) for irrigation is the core challenge. Water resources are, in general, considered sufficient but issues can arise during the peak irrigation demand in dry years, which is expected to be worsened by climate change. From the environmental perspective, the partial conversion of the natural landscape to agricultural land has adversely impacted ecosystems mainly in PRD. In fact, there is evidence of salinization phenomena in PRD, and high nitrate concentrations are observed locally in both PRD and PHO. Current climatic conditions and anticipated climate change can also exert significant pressure on the sustainability of agriculture, a crucial economic activity in both areas. Over the past decade, kiwi fruit cultivation in PRD has increased substantially, with the cultivation area nearly doubling. Kiwi fruit cultivation requires low-salinity irrigation water, which is primarily sourced from surface water abstracted from the main course of Pinios River since the groundwater salinity levels in PRD are unsuitable for this purpose. Thus, the irrigation demands of the most rapidly expanding crop in PRD depend on water from Pinios River, the availability of which can fluctuate significantly during drought periods. In contrast, irrigation needs in the Agia watershed are predominantly met through groundwater. However, there is typically a local decrease in groundwater availability for irrigation toward the end of the irrigation season, particularly during dry spells.

More in detail, the Nexus challenges for the Greek pilot area pertain to: (a) agricultural productivity and sustainability, particularly concerning irrigated agriculture, to ensure the availability of surface water and groundwater for irrigation, while considering the effectiveness of water allocation criteria; (b) optimization of agrochemicals use in agriculture to achieve and maintain appropriate water quality standards; and (c) conservation of flora and fauna, alongside maintaining ecological flow in rivers and streams. To address these challenges, the sectoral objectives have been defined as follows: (a) *Water*: enhance efficiency in water use for irrigation; (b) *Ecosystem*: increase the implementation of NbSs and maintain or improve the conservation status of ecosystems; and (c) *Food:* improve crop management to increase resilience to extreme events, and secure farmers' income against fluctuations in agricultural input costs.

The most prevalent responses from stakeholders concerning Tarquinia pilot area are presented in Figure 6. The main challenge for the Tarquinia area is related to the quality and, secondarily, to the quantity of water mainly concerning agricultural uses. A key role is played by regulating surface water (SW) and groundwater (GW) conditions, as water quality has significantly deteriorated over the area. The quantity is not currently an issue but there is an increasing threat due to the potential effect of climate change coupled with the growing demand for irrigation water (even during winter) which is not currently distributed and managed efficiently, and the constraints imposed by the tourist sector during the summer months. Water provisioning for the ecosystem and soil quality is also currently a key challenge, as soil fertility directly affects agricultural productivity and cultivated plants, and increasing erosion rates characterize some areas of the basin. Interestingly, there are not yet explicit conflicts in the water sector, primarily because, under current conditions, water is still generally available for irrigated agriculture. However, there are increasing concerns related to resource management. The demand is rising due to an increase in both intensively cultivated areas and tourist influx into the redion. Additionally, there are growing quality issues, which can be partly attributed to agricultural practices and partly to insufficient modernization and expansion of sewage treatment plans in the upstream of Tarquinia. More generally, there is a perceived lack of effectiveness in land use management, and new challenges need to be considered, such as the withdrawal of some highly productive areas from cultivation and their use for the installation of solar panels, causing social regret and fierce competition for land use with current national energy policies on agrivoltaic

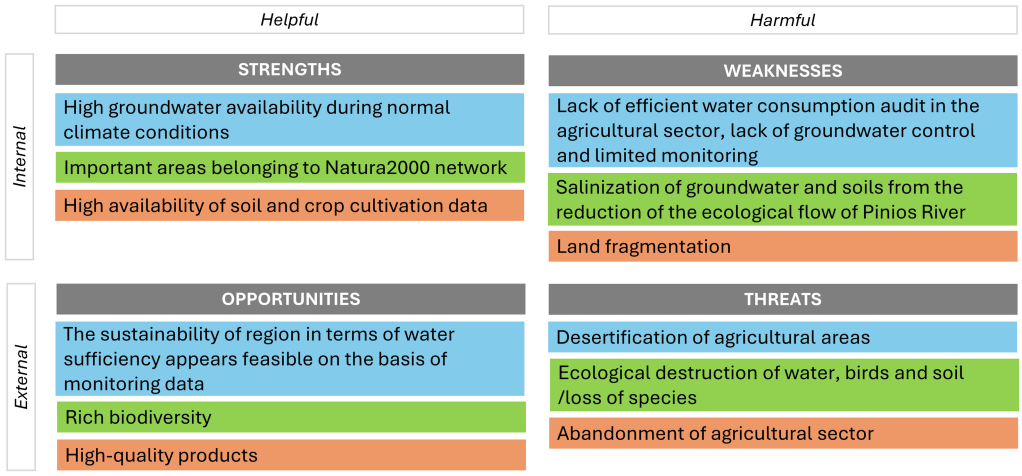

FIGURE 5
SWOT analysis results derived from LAA activities in Greek pilot areas.

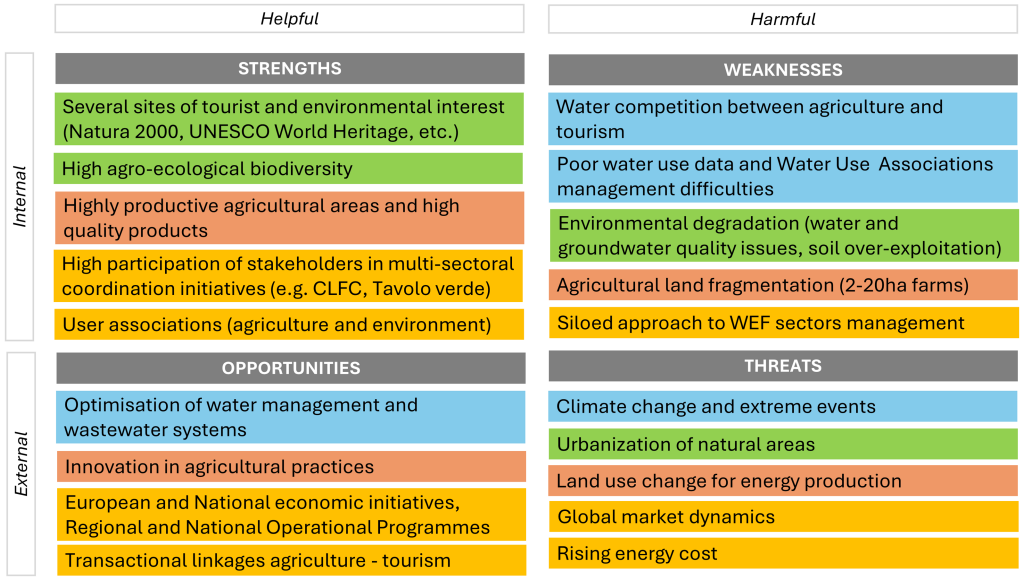

FIGURE 6
SWOT analysis results for Italian pilot area.

systems. Furthermore, at a lower scale, the need for farmers to sustain their business following the market requirements does not allow rational and sustainable planning of crops and agricultural practices. The social capital within the farmers' community is decreasing, leading them to assume a rather competitive behavior. The competitive behavior and the low price of the agricultural products in the market push farmers to increase the quantity of the production, with an ever-increasing pressure on the ecological resources due to the excessive use of fertilizers (Figure 6).

The results of the SWOT analysis show fairly clear strengths and opportunities in the Tarquinia plain. A highly productive and biodiverse environment allows for a fruitful and productive agriculture, in a place where farmers, politicians and stakeholders are keen to participate in multi-sectoral planning initiatives to discuss, share and find common solutions for their area. The potential for innovative agricultural practices to preserve soil and the ecosystem in the long term is a commonly perceived opportunity, as is the urgent need for a close link and synergy with the tourism sector. The growing interest, availability and confidence in cross-sectoral approaches, such as the WEF Nexus, was recognized as a key step in addressing emerging local and global challenges.

3.4 Causal Loop Diagrams development

A preliminary version of the Causal Loop Diagram (CLD) has been prepared for the Greek pilot areas from the 'baseline' information available in the study area. A revised version of the model was then

prepared, based on the results of a set of interviews that have been conducted with local stakeholders. The CLD, presented in Supplementary Figure 1, has been directly built by the stakeholders, starting from a comprehensive list of the key variables. This required a basic training for the facilitators (pilot leaders) and an explanation of CLD basics to stakeholders.

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

A shift is needed in the water sector, which should also include new water infrastructures as crucial assets for the development of a productive and sustainable agricultural sector (i.e., to increase the 'Agricultural productivity' and 'Economic sustainability of agriculture'), and more in general for the economic and 'Community well-being' over the area.

Regarding specifically the 'food/land sector', intensive and irrational agricultural practices in 'Irrigated areas' are heavily impacting the area (e.g., in terms of 'Nitrate pollution' due to the 'Use of chemicals and fertilizers'). In this direction, innovation is needed although there is a limited political will to shift toward more sustainable practices mainly to avoid conflicts with farmers, which would require additional 'Training on good practices' and 'Awareness on sustainable water management and water conservation'. One of the key issues emerged in the stakeholder consultation phase is the lack of 'Coordination among farmers—Consortia'. Several stakeholders highlighted that the very limited capacity of farmers to collaborate within an established structure, coupled with other issues such as the high level of 'Land fragmentation' over the area, is having manifold impacts on the agricultural sector, including, e.g., the limited innovation capacity of the system and the low profitability of agriculture. In general there is a low level of 'Awareness on sustainable water management and water conservation' for farmers, who do not have proper incentives to innovate (e.g., 'Subsidies' and 'Training on good practices').

Referring to the 'ecosystem' sector, one of the issues that emerged from the interviews on the environmental condition is related to the problem of poor 'soil quality', which depends, e.g., on the increase of 'soil pollution' and 'soil erosion' and on the loss of 'soil fertility'. Huge impacts are related to agricultural activities and 'livestock grazing', but many stakeholders mentioned the increasing lack of 'Effective waste management, which is also worsened by the 'tourism' activities and by the 'urbanization'. In this sector the role of NbSs could be particularly relevant, but with cascading benefits on the system as a whole.

The impacts of 'Climate change' are also increasingly evident, in terms of frequency and intensity of extremes ('Floods frequency and severity', 'Drought frequency and severity'). Despite a low awareness (due also to the very limited exchange of knowledge and information) characterizing some groups of stakeholders such as farmers, the severe impacts of recent extremes contributed to raise awareness.

As for the Tarquinia pilot area, a preliminary version of the CLD has been prepared based on the 'baseline' information available on the study area, and then revised, based on the results of a set of interviews that have been conducted with local stakeholders. In the Tarquinia case study, the CLD, presented in Supplementary Figure 2, has been modified with the stakeholders, following a specific mapping exercise (see also Baratella et al., 2023), which allowed a mapping of the main cause-effect connections among variables.

Starting from the 'water' sector, a key natural element for the area is the Marta River which is the main water source for satisfying both drinking and agricultural water demand. Although the area is traditionally characterized by a relative abundance of water, there are increasing concerns related to the potential impacts of prolonged and more frequent droughts, as well as to the increasing demand of water for other purposes (mainly due to the population that significantly increases during the summer period). However, so far, the main challenge is related to 'nutrient pollution', mainly due on the one hand to the 'use of chemicals and fertilizers' in agriculture, and on the other hand to the limited 'wastewater treatment efficiency' during summer population peak. The whole area is, indeed, designated as a NVZ (Nitrate Vulnerable Zone).

Regarding the 'food/land' sector, intensive agriculture is being practiced particularly in the downstream area of the plain, which is fertile, with an increase in 'irrigated areas'. However, the sustainability and profitability of agricultural activities are being conditioned by 'land fragmentation' (the average farm size is below 20 ha), by the 'market conditions' (mainly related to the presence of large retailers and big companies) and by the very limited effectiveness of subsidies such as the Common Agricultural Policy ('CAP') that are more frequently accessed by big farms which therefore have an increasing profit and potential for further investing in agriculture. The agricultural practices adopted are significantly threatening the 'soil quality' and creating issues to the 'soil erosion regulation'. A strong coordination among different actors, mainly farmers' associations and cooperatives is being supported with several initiatives (e.g., the Tavolo Verde and the Biodistretto) to promote a transition in the agricultural sector. Nevertheless, some resistance to change is still perceived within the community of farmers, mainly due to the low 'farmer awareness' and the limited economic/financial support.

Focusing on the 'ecosystem' sector, there are some relevant 'Natural areas' in the basin, which include the 'Saline di Tarquinia' and several ZPS (Special Protection Zones), as well as other areas subjected to archeological restrictions. In this regard, some stakeholders highlighted that a limited availability of water for environmental purposes is increasingly recorded, and this definitely affects the quality of the landscape. With the aim of proposing a sustainable development model for the area as a whole, there is an ongoing initiative ('River–Lake-Coast contract'), i.e., a planning and management document that involves approximately 12 municipalities along with several local associations, to pursue integrated sustainable management of the whole hydrological system from upstream (Lago di Bolsena) to downstream (coastal area).

3.5 Serious game implementation

During the third stakeholders' workshop in the Greek pilot area, the implementation of the Serious Game revealed a diverse array of NbS aimed at addressing the challenges identified for the PHO and PRD pilot areas. A total of 23 water-related, 16 ecosystem-related, and 14 food-related NbSs were proposed, accompanied by a notable accumulation of SDG coins, underscoring the holistic nature of the selected NbSs. Main water-related NbSs include the soil water holding capacity increase to reduce irrigation needs, organic land cover utilization to combat surface water loss and soil desertification, and biochar incorporation to enhance soil health and water retention. Additionally, deep-rooted plants promotion and aggressive tillage avoidance could help conserve soil moisture and prevent water loss. River reconnection to their floodplains could provide natural water storage, wetlands restoration in high groundwater recharge areas could improve water quality, and river meandering could enhance the drainage capacity of the pilot areas. Concerning the ecosystem-related NbSs, planting restoration and maintenance could mitigate pollutant transport, biodiversity restoration could enrich species richness, and slope revegetation could enhance soil structure. Regarding the food-related NbSs, mulching could improve soil structure and water holding capacity, biochar incorporation could minimize the need for fertilizers, and using cover crops and deep-rooted plants could maintain soil health and reduce water pollution risk. Additionally, conservative low tillage combined with deep-rooted plants could enhance soil homogeneity and structure.

In Tarquinia, the serious game was used for the training of agricultural students and teachers, agrotechnicians and consultants to support learning through an interactive capacity building tool. An educational seminar was organized and held at the local agricultural college, where the audience was divided into small groups according to their expertise, i.e., students of the same age, teachers and consultants/technicians, each group being facilitated in playing by a researcher. In each group, the players sat in a circle and used their own mobile phones to play, constantly interacting with each other as they would when playing with mobile apps. A large screen in the room projected a real-time play of the Serious Game to familiarize first-time players with the game's options and rules, and make it easier to use.

Under a range of future scenarios, players, acting as decision-makers, farmers and other stakeholders, explored the impacts of management strategies and policy options, and carried out an assessment of different policy interventions. 39 NbSs were proposed in total, i.e., 12 water-related, 13 food-related and 14 ecosystem-related. Crop rotation, organic fertilization or integration with crop residues and bio-compost to increase soil carbon stocks, phytoremediation and organic pest control were the main issues identified for food systems. Other measures concerned forest regeneration, soil conservation with cover crops, agroforestry actions, erosion control systems, ecological restoration of coastal ecosystems: in fact, ecosystem and water dimensions are closely linked in the Tarquinia plain and are characterized by strategies focused on habitat protection in wetlands and coastal areas, in need of actions to reconnect the river and surrounding plans to obtain a better management of surface and groundwater (recharge of aquifers, revegetation of riverbanks, promotion of flows).

Overall, there was a high appreciation of the 'digital game' medium for conveying information about NBSs, especially in relation to the fact that each player could explore the different options using their mobile phone in a collective gaming context, making the approach to new concepts more 'personal' and fun, and facilitating the internalization of different points of view.

The main pitfalls of the methodology recorded in Tarquinia were two contrasting ones: firstly, the older players among the teachers and consultants were vulnerable to the digital divide and needed support to play the game. This points to the need to accurately analyze the sub-audience among the Nexus stakeholders who should be the recipients of the Serious Game methodology, since the digital divide affects with different magnitude all WEFE actors, policymakers and farmers as well. Secondly, the game often crashed due to an overload of players connecting at the same time, making it a bit cumbersome to use, especially for young people with high digital competence.

3.6 Measures' prioritization

The evaluation of the importance of each criterion was performed by the stakeholders through an online questionnaire on a 10-grade scale, so each one of the eight criteria was assigned a weight in the form of an integer from 1 up to 10. A total of 25 PRIMA LENSES and H2020 REXUS partners and stakeholders responded to the questionnaire. Criteria scores were calculated as median values of the individually assigned marks, as follows in descending order: urgency and efficiency time: 8.5; sustainability: 8.4; co-benefits and intersectionality: 8.3; acceptance: 8.0; effectiveness: 7.9; maturity and enabling environment/cost: 7.3; and negative side effects: 6.3.

In parallel, the final list of proposed measures was processed for homogenization and uniformity and sent to the stakeholders in an online questionnaire. The evaluation of the measures was based on the assignment of a class to each of the eight aforementioned criteria on a five-grade scale, from 1 to 5, depending on the importance attributed to each criterion and each measure (see Figure 3). The final score assigned to each measure was calculated as the weighted average of all the received responses. The multiplicity of each measure in other goals and challenges was also considered, meaning that a specific measure was referenced in more than one goals and/or challenges.

The four top-ranked measures for the Greek pilot areas, in descending order are: (a) efficient soil water management through irrigation scheduling (NbS); (b) improvement of advisory and support structures (governance solution); (c) construction of water-saving projects, i.e., small dams and reservoirs, mountain hydrology, and rainwater harvesting systems (gray solution); and (d) agroecological practices for weed and biomass management, i.e., mulching (NbS).

A list of 24 NbSs was selected by stakeholders in the Italian pilot area to address the specific issues of their territory (Vanino et al., 2024). 46% of the identified NbSs are related to subtype "Agricultural landscape management," 16% to "Ecological restoration to degraded terrestrial ecosystems" and 16% to "protection and conservation strategies in terrestrial, marine and coastal areas ecosystems."

The most effective and practical measures proposed by stakeholders were found to be similar to those proposed by the Serious Game. This finding underscores the realistic and applicable nature of the Serious Game approach within the Greek and Italian pilot areas and potentially throughout the wider Mediterranean region.

3.7 Political economy analysis and synthesis of results

The Political Economy Analysis was solely performed in the Greek pilot areas where stakeholders were tasked with identifying the actors involved and their incentives concerning the implementation of each priority measure. Then, additional information was collated concerning each actor's behavior, including power and resources to implement the solutions. A series of questions were posed to stakeholders focused on characterizing the key actors capable of implementing key Nexus solutions. To streamline the process and ensure active participation during the final workshop, the four top-ranked measures were divided into two different categories: technical and governance solutions, each represented on separate posters. Stakeholders reviewed each poster separately. Ministries, agricultural cooperatives, individual farmers, and research institutions were identified as the primary key actors for both categories of solutions. The main incentives for accelerating technical solutions include the enforcement of environmental legislation, and the need to ensure the security of natural resources. For governance solutions, incentives include reduction of production costs, and profit generation. The power and resources of the key actors are primarily related to the strong institutional role and social acceptance for technical solutions, and the robust connections between research institutions and policymakers for governance solutions.

Stakeholders across the Greek and Italian pilot areas identified three major challenges (water over-abstraction, ecosystem degradation, and agricultural sustainability) through iterative workshops and relevant exercises. Tools like Causal Loop Diagrams (CLDs) and the Serious Game effectively captured stakeholder inputs and visualized trade-offs, enabling consensus on measures to address these challenges. The measures prioritized in each pilot area reflected region-specific needs. In Greece, the emphasis was on irrigation scheduling and nitrate pollution control, addressing over-abstraction and groundwater quality issues. In Italy, measures like agroforestry and wetland restoration tackled soil erosion and nutrient runoff. Across both areas, Nature-Based Solutions (NbSs) represented a significant portion of the proposed interventions, highlighting their critical role in sustainable Nexus management. The participatory process revealed that local socio-economic conditions strongly influence the prioritization and feasibility of solutions. For example, Greek stakeholders favored technical measures with immediate benefits, while Italian stakeholders emphasized long-term ecosystem restoration.

4 Discussion

4.1 How can participatory approaches and transdisciplinary tools effectively support the Water-Ecosystem-Food (WEF) Nexus management in resource-stressed Mediterranean areas?

The participatory approach implemented in the 2 pilot areas and built around stakeholder engagement strategies such as LAAs, SDM, and Serious Games, proved effective in enhancing mutual understanding of complex interconnections within the WEF Nexus. The use of CLDs allowed stakeholders to visualize and internalize the complex interaction mechanisms between water, ecosystem, and agricultural activities, ultimately facilitating dialogue (Sušnik et al., 2018; de Vito et al., 2019). Nevertheless, the complexity of the CLDs was difficult to be managed by some of the stakeholders and therefore careful facilitation, providing more time and information was needed to maintain the active participation of these stakeholders.

The Serious Game proved to be useful in simulating and exploring the complexities of managing WEF Nexus interactions and enabled stakeholders to experiment with different scenarios (climate change and NbS). This outcome agrees to the study of Scholz et al. (2024), in which the contribution of transdisciplinary tools in facilitating knowledge integration across diverse stakeholders to effectively tackle complex environmental issues was identified. Lang et al. (2012) indicated that transdisciplinary research constitutes a critical element to address complex societal issues through knowledge co-production and shared learning experiences. Our experience highlighted the potential of using Serious Games for implementing structured processes to integrate different types of knowledge. However, the digital divide, observed mainly in the Italian case study, is a potential limitation in using such advanced digital tools for engagement.

Because the applied participatory approaches were adapted to the local contexts, the stakeholders felt their contributions had meaningful impacts on the outcomes. This result agrees with Maskrey et al. (2020), who found that localized participatory approaches often lead to higher stakeholder ownership of outcomes. However, especially during the technical workshops conducted, it was challenging to motivate certain stakeholders' groups, mainly from the agricultural sector, to effectively participate in such activities. This was mainly due to the fact that the agricultural sector, which was already affected by the energy crisis happened during the engagement period and rising production costs, found it difficult to see immediate, practical benefits from engaging in a research-based participatory process. Voinov and Bousquet (2010) indicated that groups of economically stressed stakeholders are more difficult to be engaged in participatory research. These challenges underscore the importance of carefully designed incentive mechanisms to make participation attractive for these groups. Moreover, maintaining neutrality from the beginning of the stakeholder engagement process constituted a key factor for building trust among stakeholders and ensuring inclusive participation. This is in line with the study of Lang et al. (2012), according to which neutral facilitation can enable diverse stakeholders to share their perspectives without the fear of bias or exclusion.

4.2 What are the main WEF Nexus challenges and potential solutions identified by stakeholders in the pilot areas, and how do Nature-Based Solutions (NbS) contribute to these challenges?

The study identified several interconnected challenges across water, ecosystem, and food sectors, influenced by local resource stress and socio-economic activities. In the Greek pilot areas, the primary concerns centered on water over-abstraction for agriculture and the need to improve irrigation practices to ensure sustainability under increasing climate pressures. In the Italian region, the main challenges

are related to water quality deterioration and soil erosion, mainly driven by intensive agricultural practices.

Stakeholders proposed a range of Nature-Based Solutions to address these issues. In the Greek pilot areas, two NbSs were prioritized in the top four ranked measures, including efficient soil water management through irrigation scheduling and agroecological practices for weed and biomass management. These solutions directly mitigate key WEF challenges. Irrigation scheduling improves water efficiency by optimizing water usage and reducing over-abstraction, while agroecological practices like mulching enhance soil moisture retention and reduce erosion, making agricultural systems more resilient to climate pressures (Wen et al., 2017). In the Italian pilot area, stakeholders promoted NbSs that address agricultural landscape management and conservation/restoration of degraded ecosystems. This aligns with the challenges of water quality deterioration and soil erosion, where NbS such as restoring landscape connectivity and improving soil health help to reduce runoff and nutrient loss, thus protecting water bodies from agricultural pollutants (Keesstra et al., 2018).

Insights from the workshops revealed that some stakeholders struggled to fully understand the concept of NbS, highlighting the need for enhanced pre-workshop preparation and clearer communication during workshops, particularly for those less familiar with technical terms. This observation aligns with findings from Seddon et al. (2021), who noted that NbS require comprehensive communication to ensure stakeholders grasp both the concept and its potential applications. Moreover, the reluctance of agricultural stakeholders to see the immediate benefits of participating presents a barrier, as Lafortezza et al. (2018) noted that NbS often focus heavily on long-term gains, which may not align with the short-term priorities of economically constrained stakeholders. While NbS offer substantial environmental, social, and economic co-benefits in the long run, their delayed return on investment can deter stakeholders seeking more immediate outcomes. This reinforces the need to effectively communicate both the short-and long-term benefits of NbS, ensuring that solutions resonate with the short-term motivations of different sectors while still promoting long-term sustainability.

The Political Economy Analysis of the Greek pilot areas provides crucial insights into the dynamics of actor involvement in implementing Nexus solutions. The findings reveal distinct incentives and power distributions among key stakeholders, including ministries, agricultural cooperatives, farmers, and research institutions. These stakeholders hold different motivations depending on the type of solutions—technical or governance—which has significant implications for the success of implementation. For technical measures, stakeholders, particularly those in institutional roles, are motivated by environmental legislation enforcement and natural resource security, suggesting that regulatory frameworks are pivotal in driving change. Similar findings have been reported by Stein and Jaspersen (2019), who highlight the importance of regulatory compliance in mobilizing resources for environmental interventions.

In contrast, the incentives for governance solutions primarily revolve around economic benefits such as reducing production costs and generating profit, which reflects the economic-oriented focus of both agricultural cooperatives and individual farmers. This is consistent with findings in Greece that governance strategies often align with economic incentives, particularly in agriculture (Papadopoulou et al., 2020). The analysis also highlights the differing forms of power that stakeholders wield. For technical solutions, ministries benefit from their formal institutional authority and broad social acceptance, enabling them to steer implementation effectively. On the other hand, governance solutions are influenced significantly by the robust linkages between research institutions and policymakers, emphasizing the role of knowledge exchange and collaboration in policy development (Malamataris et al., 2023). These findings underscore the need for tailored engagement strategies that align with the distinct incentives and power structures of key actors to ensure the effective realization of Nexus solutions. Future efforts should aim to bridge economic incentives with regulatory measures to create a synergistic pathway for the adoption of both technical and governance interventions.

4.3 How do local contexts and stakeholder dynamics influence the identification, prioritization, and implementation of WEF Nexus solutions?

Local socio-economic and environmental contexts significantly shaped both the identification and prioritization of solutions in each study area. In Greece, stakeholder dynamics, particularly those from the agricultural sector, and the specific challenges led to a focus on more immediate technical interventions, including both Nature-Based Solutions and traditional "gray" measures like water-saving infrastructure. This focus on context-specific and immediate interventions aligns with findings by Melloni et al. (2020), who noted that effective WEF Nexus solutions must account for the unique socio-environmental conditions of each region. Moreover, stakeholders representing the food sector are currently prioritizing their everyday engagements over long-term sustainability planning, due to the ongoing significant increase in cultivation costs and the energy crisis. Wang et al. (2020) indicate that socio-economic pressures can significantly limit the willingness of stakeholders to invest in sustainability initiatives that do not yield immediate financial benefits. Addressing these concerns through practical incentives and clearer value demonstration will be essential in achieving broad stakeholder participation.

Italian stakeholders emphasized long-term sustainable practices, which aligned with the region's concerns about soil quality and biodiversity. The influence of local context in shaping stakeholder priorities also aligns with Schmidt et al. (2020), who emphasized the importance of transdisciplinary approaches and continuous stakeholder interaction to address complex sustainability challenges. Furthermore, the value of incorporating local stakeholder perspectives in sustainable development strategies is supported by Fujitani et al. (2017), who demonstrated that participatory management can significantly enhance local ecological knowledge and foster more effective and context-specific environmental solutions.

Through the performed systematic stakeholders' engagement, an insightful lesson was that amongst economically stressed and limited knowledge stakeholders, hybrid approaches that entailed a synthesis of gray and green (NbS) solutions would be easier to conceive and accept. In fact, such solutions offer the comfort and reassurance of known anticipated results through the gray solutions, which may

address the identified challenges quicker, whilst building up the environment for long-term outcomes through the systematic and widespread implementation of NbS. However, because of the distrust to NbS owed to lack of information and reluctance to wait for their outcome, it is imperative that a well-organized and systematically conducted evidence-based information campaign is employed.

5 Conclusion

This study highlights the effectiveness of participatory approaches and transdisciplinary tools in addressing the complex Water-Ecosystem-Food (WEF) Nexus challenges in resource-stressed Mediterranean regions. By engaging over 60 stakeholders across two pilot areas—Greece and Italy—the study identified critical Nexus challenges, such as water over-abstraction, ecosystem degradation, and agricultural sustainability. Through the well-structured participatory framework, the stakeholders collaboratively developed and prioritized case specific measures, with NbSs representing a significant portion of them. From a practical perspective, the study highlights the importance of creating inclusive, stakeholder-driven processes that account for local socio-economic dynamics and specific WEF Nexus challenges. The Greek case study focused more on technical and governance measures whereas the Italian case study emphasized more on long-term sustainable practices and cross-sectoral synergies. The identified measures, including NbS, were prioritized to address challenges within sectors while minimizing tradeoffs. The use of Serious Game effectively aligned stakeholder proposed measures with solutions that could be implemented. Furthermore, our findings highlight the complexity of Nexus challenges, which can potentially be exacerbated by climate change, reduced water availability and unsustainable land management practices. A whole system approach, advocating for integrated analysis and understanding sectoral interdependencies, is indispensable for identifying balanced resource management.

Future efforts could involve further research on the NbSs proposed by the engaged stakeholders in order to have deeper insights into how these solutions evolve and their sustained effectiveness over time. Since agriculture is crucial for the study areas from the socio-economic point of view, investigating the potential application of innovative agricultural practices that align with Nexus management would contribute considerably to enhancing the sustainability of the two case study areas. Furthermore, transitioning from qualitative to quantitative PSDM tools through the development of stock and flow models, will enable better prediction and understanding of system responses to interventions, leading to more informed decision-making. Moreover, future research should explore the scalability of the proposed methodology to other regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

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Conflict of interest

PK, CP, and DT were employed by DRAXIS Environmental S.A.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1469762/full#supplementary-material

References

Ahmad, F., Ahmad, S., Zaindin, M., and Adhami, A. Y. (2021). A robust neutrosophic modeling and optimization approach for integrated energy-food-water security nexus management under uncertainty. *Water* 13:121. doi: 10.3390/w13020121

Aldaya, M. M., Sesma-Martín, D., and Schyns, J. F. (2022). Advances and challenges in the water footprint assessment research field: towards a more integrated understanding of the water–energy–food–land Nexus in a changing climate. *Water* 14:1488. doi: 10.3390/w14091488

Baratella, V., Pirelli, T., Giordano, R., Pagano, A., Portoghese, I., Bea, M., et al. (2023). Stakeholders analysis and engagement to address water-ecosystems-food Nexus challenges in Mediterranean environments: a case study in Italy. *Ital. J. Agron.* 18:2200. doi: 10.4081/ija.2023.2200

Barati, A. A., Pour, M. D., and Sardooei, M. A. (2023). Water crisis in Iran: a system dynamics approach on water, energy, food, land and climate (WEFLC) nexus. *Sci. Total Environ.* 882:163549. doi: 10.1016/j.scitotenv.2023.163549

Batchelor, C., Hoogeveen, J., Faurès, J. M., and Peiser, L. (2016). Water accounting & auditing guidelines: a sourcebook, Water reports 43. Rome, Italy: Food and Agriculture Organisation of the United Nations (FAO).

Bellos, D., Sawidis, T., and Tsekos, I. (2004). Nutrient chemistry of river pinios (Thessalia, Greece). *Environ. Int.* 30, 105–115. doi: 10.1016/S0160-4120(03)00153-3

Bof, P. H., Marques, G. F., Tilmant, A., Dalcin, A. P., and Olivares, M. (2021). Water–food–energy nexus tradeoffs in the São Marcos river basin. *Water* 13:817. doi: 10.3390/w13060817

Bontchev, B., Antonova, A., Terzieva, V., and Dankov, Y. (2021). "Let us save Venice"—an educational online maze game for climate resilience. *Sustain. For.* 14:7. doi: 10.3390/su14010007

Cansino-Loeza, B., and Ponce-Ortega, J. M. (2024). "Sustainable assessment of water–energy–food nexus through a multistakeholder optimization approach" in Developments in environmental modelling, Elsevier, vol. 32, 261–332.

Carvalho, P. N., Finger, D. C., Masi, F., Cipolletta, G., Oral, H. V., Tóth, A., et al. (2022). Nature-based solutions addressing the water-energy-food nexus: review of theoretical concepts and urban case studies. *J. Cleaner Prod.* 338:130652. doi: 10.1016/j.jclepro.2022.130652

Chatzinikolaou, Y., and Lazaridou, M. (2007). Identification of the self-purification stretches of the Pinios River, Central Greece. *Mediterr. Mar. Sci.* 8, 19–32. doi: 10.12681/mms.151

Chen, W., and Chen, Y. (2021). Pre-warning measurement of water resources security in the Yangtze river basin from the perspective of water-energy-food symbiosis. *Water* 13:475. doi: 10.3390/w13040475

Choi, S. H., Shin, B., and Shin, E. (2022). Managing apparent loss and real loss from the nexus perspective using system dynamics. *Water* 14:231. doi: 10.3390/w14020231

Cimmaruta, R., Blasi, S., Angeletti, D., and Nascetti, G. (2011). The recent history of the Tarquinia Salterns offers the opportunity to investigate parallel changes at the habitat and biodiversity levels. *Trans. Waters Bull.* 4, 53–59. doi: 10.1285/i1825229Xv4n1p53

de Vito, R., Pagano, A., Portoghese, I., Giordano, R., Vurro, M., and Fratino, U. (2019). Integrated approach for supporting sustainable water resources management of irrigation based on the WEFN framework. *Water Resour. Manag.* 33, 1281–1295. doi: 10.1007/s11269-019-2196-5

European Commission (2015). "Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities" in Final report of the Horizon 2020 Expert Group on nature-based solutions & re-naturing cities. Luxembourg: Publications Office of the European Union.

European Commission. (2019). Communication from the commission to the European Parliament, the European council, the council, the European economic and social committee and the Committee of the Regions. The European Green Deal. Brussels: European Commission.

European Commission. (2020a). Communication from the commission to the European Parliament, the council, the European economic and social committee and the Committee of the Regions. EU biodiversity strategy for 2030. Bringing nature back into our lives. Brussels: European Commission.

European Commission. (2020b). Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. A farm to fork strategy for a fair, healthy and environmentally-friendly food system. Brussels: European Commission.

Fabiani, S., Vanino, S., Napoli, R., and Nino, P. (2020). Water energy food nexus approach for sustainability assessment at farm level: an experience from an intensive agricultural area in Central Italy. *Environ. Sci. Policy* 104, 1–12. doi: 10.1016/j.envsci.2019.10.008

FAO (2014). The water-energy-food Nexus: a new approach in support of food security and sustainable agriculture. FAO: Rome, Italy, 28.

Flood, S., Cradock-Henry, N. A., Blackett, P., and Edwards, P. (2018). Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. *Environ. Res. Lett.* 13:063005. doi: 10.1088/1748-9326/aac1c6

Forrester, J. W. (1961). Industrial dynamics. Cambridge, MA, USA: Massachussets Institute of Technology John Wiley and Sons: Hoboken, NJ, USA.

Forrester, J. W. (1968). Principles of systems. Cambridge, MA, USA: Wright Allen Press.

Francisco, É. C., de Arruda Ignácio, P. S., Piolli, A. L., and Dal Poz, M. E. S. (2023). Food-energy-water (FEW) nexus: sustainable food production governance through system dynamics modeling. *J. Cleaner Prod.* 386:135825. doi: 10.1016/j.jclepro.2022.135825

Fujitani, M., McFall, A., Randler, C., and Arlinghaus, R. (2017). Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science. *Sci. Adv.* 3:e1602516. doi: 10.1126/sciadv.1602516

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

Gao, W., Guo, Y., and Jiang, F. (2021). Playing for a resilient future: a serious game designed to explore and understand the complexity of the interaction among climate change, disaster risk, and urban development. *Int. J. Environ. Res. Public Health* 18:8949. doi: 10.3390/ijerph18178949

Gerber, A., Ulrich, M., Wäger, F. X., Roca-Puigròs, M., Gonçalves, J. S., and Wäger, P. (2021). Games on climate change: identifying development potentials through advanced classification and game characteristics mapping. *Sustain. For.* 13:1997. doi: 10.3390/su13041997

Hoff, H. (2011). Understanding the Nexus: background paper for the Bonn2011 Nexus conference. Stockholm, Sweden: Stockholm Environment Institute (SEI).

Hoolohan, C., Larkin, A., McLachlan, C., Falconer, R., Soutar, I., Suckling, J., et al. (2018). Engaging stakeholders in research to address water–energy–food (WEF) nexus challenges. *Sustain. Sci.* 13, 1415–1426. doi: 10.1007/s11625-018-0552-7

Karutz, R., Omann, I., Gorelick, S. M., Klassert, C. J., Zozmann, H., Zhu, Y., et al. (2022). Capturing stakeholders' challenges of the food–water–energy nexus - a participatory approach for Pune and the Bhima Basin, India. *Sustainability* 14:5323. doi: 10.3390/su14095323

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., et al. (2018). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* 610-611, 997–1009. doi: 10.1016/j.scitotenv.2017.08.077

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15, 259–263. doi: 10.1127/0941-2948/2006/0130

Lafortezza, R., Chen, J., Van Den Bosch, C. K., and Randrup, T. B. (2018). Nature-based solutions for resilient landscapes and cities. *Environ. Res.* 165, 431–441. doi: 10.1016/j.envres.2017.11.038

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., et al. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustain. Sci.* 7, 25–43. doi: 10.1007/s11625-011-0149-x

Langergraber, G., Pucher, B., Simperler, L., Kisser, J., Katsou, E., Buehler, D., et al. (2020). Implementing nature-based solutions for creating a resourceful circular city. *Blue-Green Syst.* 2, 173–185. doi: 10.2166/bgs.2020.933

Laspidou, C. S., Mellios, N. K., Spyropoulou, A. E., Kofinas, D. T., and Papadopoulou, M. 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.* 717:137264. doi: 10.1016/j.scitotenv.2020.137264

Malamataris, D., Chatzi, A., Babakos, K., Pisinaras, V., Hatzigiannakis, E., Willaarts, B. A., et al. (2023). A participatory approach to exploring Nexus challenges: a case study on the Pinios River basin, Greece. *Water* 15:3949. doi: 10.3390/w15223949

Maskrey, S., Vilcan, T., O'Donnell, E., and Lamond, J. (2020). Using learning and action alliances to build capacity for local flood risk management. *Environ. Sci. Pol.* 107, 198–205. doi: 10.1016/j.envsci.2020.02.012

Melloni, G., Turetta, A. P. D., Bonatti, M., and Sieber, S. (2020). A stakeholder analysis for a water-energy-food nexus evaluation in an Atlantic forest area: implications for an integrated assessment and a participatory approach. *Water* 12:1977. doi: 10.3390/w12071977

O'Donnell, E. C., Lamond, J. E., and Thorne, C. R. (2018). Learning and action alliance framework to facilitate stakeholder collaboration and social learning in urban flood risk management. *Environ. Sci. Pol.* 80, 1–8. doi: 10.1016/j.envsci.2017.10.013

Panagopoulos, A., Malamataris, D., Chatzi, A., Babakos, K., Hatzigiannakis, E., and Pisinaras, V. (2023). Stakeholders' perceptions on water-ecosystem-food nexus challenges in a Mediterranean rural agricultural region. In Proceedings of the 12th world congress on water resources and environment (EWRA 2023), 27 June – 1 July 2023, Thessaloniki, Greece.

Papadopoulou, C. A., Papadopoulou, M. P., Laspidou, C., Munaretto, S., and Brouwer, F. (2020). Towards a low-carbon economy: a nexus-oriented policy coherence analysis in Greece. *Sustain. For.* 12:373. doi: 10.3390/su12010373

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., De Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56, 1510–1521. doi: 10.1021/acs.est.1c04158

Pisinaras, V., Panagopoulos, A., Herrmann, F., Bogena, H. R., Doulgeris, C., Ilias, A., et al. (2018). Hydrologic and geochemical research at Pinios hydrologic observatory: initial results. *Vadose Zone J.* 17, 1–16. doi: 10.2136/vzj2018.05.0102

Pisinaras, V., Paraskevas, C., and Panagopoulos, A. (2021). Investigating the effects of agricultural water management in a Mediterranean coastal aquifer under current and projected climate conditions. *Water* 13:108. doi: 10.3390/w13010108

Pruyt, E. (2013). Small system dynamics models for big issues: triple jump towards real-world complexity. Delft: TU Delft Library.

Purwanto, A., Sušnik, J., Suryadi, F. X., and de Fraiture, C. (2019). Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang regency, Indonesia. *J. Cleaner Prod.* 240:118170. doi: 10.1016/j.jclepro.2019.118170

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. III, Lambin, E., et al. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecol. Soc.* 14. doi: 10.5751/ES-03180-140232

Rodela, R., Ligtenberg, A., and Bosma, R. (2019). Conceptualizing serious games as a learning-based intervention in the context of natural resources and environmental governance. *Water* 11:245. doi: 10.3390/w11020245

Schmidt, L., Falk, T., Siegmund-Schultze, M., and Spangenberg, J. H. (2020). The objectives of stakeholder involvement in transdisciplinary research. A conceptual framework for a reflective and reflexive practise. *Ecol. Econ.* 176:106751. doi: 10.1016/j.ecolecon.2020.106751

Scholz, R. W., Zscheischler, J., Köckler, H., Czichos, R., Hofmann, K. M., and Sindermann, C. (2024). Transdisciplinary knowledge integration–PART I: theoretical foundations and an organizational structure. *Technol. Forecast. Soc. Chang.* 202:123281. doi: 10.1016/j.techfore.2024.123281

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., et al. (2021). Getting the message right on nature-based solutions to climate change. *Glob. Chang. Biol.* 27, 1518–1546. doi: 10.1111/gcb.15513

Speelman, E. N., García-Barrios, L. E., Groot, J. C. J., and Tittonell, P. (2014). Gaming for smallholder participation in the design of more sustainable agricultural landscapes. *Agric. Syst.* 126, 62–75. doi: 10.1016/j.agsy.2013.09.002

Stave, K. (2010). Participatory system dynamics modeling for sustainable environmental management: observations from four cases. *Sustain. For.* 2, 2762–2784. doi: 10.3390/su2092762

Stefanidis, K., Panagopoulos, Y., Psomas, A., and Mimikou, M. (2016). Assessment of the natural flow regime in a Mediterranean river impacted from irrigated agriculture. *Sci. Total Environ.* 573, 1492–1502. doi: 10.1016/j.scitotenv.2016.08.046

Stein, C., and Jaspersen, L. J. (2019). A relational framework for investigating nexus governance. *Geogr. J.* 185, 377–390. doi: 10.1111/geoj.12284

Sterman, J. (2000). Business dynamics: systems thinking and modelling for a complex world. McGraw-Hill.

Sušnik, J. (2018). Data-driven quantification of the global water-energy-food system. *Resour. Conserv. Recycl.* 133, 179–190. doi: 10.1016/j.resconrec.2018.02.023

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., et al. (2018). Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: the SIM4NEXUS approach. *Water* 10:139. doi: 10.3390/w10020139

Sušnik, J., Masia, S., Indriksone, D., Brēmere, I., and Vamvakeridou-Lydroudia, L. (2021). System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. *Sci. Total Environ.* 775:145827. doi: 10.1016/j.scitotenv.2021.145827

Tsaboula, A., Papadakis, E. N., Vryzas, Z., Kotopoulou, A., Kintzikoglou, K., and Papadopoulou-Mourkidou, E. (2019). Assessment and management of pesticide pollution at a river basin level part I: aquatic ecotoxicological quality indices. *Sci. Total Environ.* 653, 1597–1611. doi: 10.1016/j.scitotenv.2018.08.240

Tschakert, P., and Dietrich, K. A. (2010). Anticipatory learning for climate change adaptation and resilience. *Ecol. Soc.* 15. doi: 10.5751/ES-03335-150211

United Nations (UN) (2015). Transforming our world: the 2030 agenda for sustainable development. New York, USA: United Nations.

van Noordwijk, M., Speelman, E., Hofstede, G. J., Farida, A., Abdurrahim, A. Y., Miccolis, A., et al. (2020). Sustainable agroforestry landscape management: changing the game. *Land* 9:243. doi: 10.3390/land9080243

Vanino, S., Baratella, V., Pirelli, T., Ferrari, D., Di Fonzo, A., Pucci, F., et al. (2024). Nature-based solutions for optimizing the water–ecosystem–food Nexus in Mediterranean countries. *Sustain. For.* 16:4064. doi: 10.3390/su16104064

Voinov, A., and Bousquet, F. (2010). Modelling with stakeholders. *Environ. Modell. Software* 25, 1268–1281. doi: 10.1016/j.envsoft.2010.03.007

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., et al. (2018). Tools and methods in participatory modeling: selecting the right tool for the job. *Environ. Model Softw.* 109, 232–255. doi: 10.1016/j.envsoft.2018.08.028

Wang, X., Dong, Z., and Sušnik, J. (2023). System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. *Sci. Total Environ.* 863:160993. doi: 10.1016/j.scitotenv.2022.160993

Wang, L., Li, W., and Qi, L. (2020). Stakeholder pressures and corporate environmental strategies: a meta-analysis. *Sustain. For.* 12:1172. doi: 10.3390/su12031172

Wen, Y., Shang, S., and Yang, J. (2017). Optimization of irrigation scheduling for spring wheat with mulching and limited irrigation water in an arid climate. *Agric. Water Manag.* 192, 33–44. doi: 10.1016/j.agwat.2017.06.023

White, D. D., Jones, J. L., Maciejewski, R., Aggarwal, R., and Mascaro, G. (2017). Stakeholder analysis for the food-energy-water nexus in Phoenix, Arizona: implications for nexus governance. *Sustain. For.* 9:2204. doi: 10.3390/su9122204

Winkler, K., Fuchs, R., Rounsevell, M., and Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nat. Commun.* 12:2501. doi: 10.1038/s41467-021-22702-2

Wu, L., Elshorbagy, A., Pande, S., and Zhuo, L. (2021). Trade-offs and synergies in the water-energy-food nexus: the case of Saskatchewan, Canada. *Resour. Conserv. Recycl.* 164:105192. doi: 10.1016/j.resconrec.2020.105192