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An integrated methodology for systematic stakeholder engagement in environmental decision-making under the Water-Energy-Food-Ecosystems nexus framework

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A R T I C L E I N F O

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A B S T R A C T

The 'nexus' approach is a promising exemplar underpinning systemic thinking and advancing integrated resource use. In this context, stakeholder engagement comprises a significant challenge as stakeholders are affecting and affected by resource availability and exploitation. This paper focuses on the operationalisation/systematisation of abstract concepts expressed during participatory workshops and its contribution to the efficient management of the Water-Energy-Food-Ecosystems (WEFE) nexus by supporting the design of future policies and integrated solutions. A novel methodological framework is presented combining the Analytic Hierarchy Process (AHP) and the Multicriteria Analysis of Policies method (MULTIPOL) in order to seek solutions and build innovative policy options. AHP and MULTIPOL complement each other as the first indicates *which* solutions are most effective while the latter indicates *how* such solutions may be implemented by adopting relevant policies. The application of the proposed methodology is demonstrated in the environmental management of a transboundary river basin. Results show that the suggested methodological framework is robust, applicable to wider contexts and spatial scales, and coherent. The construction of (new) green-gray infrastructures (irrigation infrastructures, Nature-based Solutions (NbS), fish corridor, reclamation works, energy infrastructures) was classified as the most effective solution while protection of water quality, minimisation of water losses, limitation of flood risks, ecosystems preservation and the adoption of eco-friendly/multi-functional patterns of spatial development constitute important priorities for (transboundary) river basins. The analysis adds to the current literature addressing qualitative research on the WEFE nexus and the systematisation of stakeholder input by employing qualitative/quantitative methods.

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1. Introduction

More than 70 % of the world's freshwater resources are exploited for food production (agriculture), energy generation, domestic and industrial use (FAO, 2017). According to the 6th IPCC assessment report (IPCC et al., 2023), climate change is projected to have an increasing impact on global water cycle. It may affect precipitation and temperature patterns throughout the globe (Bayazit, 2015; Papadopoulou et al., 2016; Chattopadhyay et al., 2017; Arnell et al., 2019; Tabari, 2020; Kourtis and Tsihrintzis, 2021; NASA, 2023), while pressures on natural resources may be exacerbated due to population growth and economic development. Intensive use of energy sources has increased (e.g., Pérez-Lombard et al., 2008; Ellabban et al., 2014; Sharma et al., 2021) and it will further continue to rise (Papadis and Tsatsaronis, 2020; Umar et al., 2021; Rahman et al., 2022; Danish et al., 2023), amplifying the over-exploitation of resources and inducing the escalation of greenhouse gas (GHG) emissions. Besides, proliferating food demand entails high pressures on land uses, soil and the atmosphere (Verburg et al., 2006; Smith and Gregory, 2013; Benke and Tomkins, 2017; Shaheb et al., 2021; Moodley et al., 2023), emanating from intensive agricultural practices that affect water and soil quality, contribute to GHG emissions, place at risk ecosystems balance and, in many cases, result in extensive deforestations. On the other side, cropland is often threatened by drought events and uncontrollable expansion of drylands (Potamianou et al., 2019), limited availability of irrigation water, land use conflicts due to unrestrained urban expansion as well as harsh rainfalls and floods.

Therefore, the effective management of resources under climate change conditions constitutes a prevailing challenge at both scientific and decision-making levels, as it affects physical and human-made environment, calling thus for the exploration of integrated solutions, encompassing multiple sectors and complex relationships among interacting elements.

During the last decades, the 'nexus' approach has gained ground among scientists and policy makers as it encourages systemic thinking across multiple interlinked sectors (Hoff, 2011; Howarth and Monasterolo, 2016; Al-Saidi and Elagib, 2017; Albrecht et al., 2018; Shannak et al., 2018; Pahl-Wostl, 2019; Laspidou et al., 2020; Papadopoulou et al., 2020; Hogeboom et al., 2021; Estoque, 2023). Its holistic rationale considers complicated interrelationships in order to strengthen nexus understanding, identify synergies, analyse conflicts and investigate trade-offs so that adverse impacts are limited. It is also tied to the critical challenge of decoupling resource use from economic growth.

In this framework, the Water-Energy-Food-Ecosystems (WEFE) nexus represents a promising exemplar, contributing to: (i) the sustainable use of resources; and (ii) the design of environmentally sound policy decisions at multiple spatial scales. Flood protection, preservation of water quality, maintenance of ecological flow regime, availability of irrigation water, decarbonisation and sustainable exploitation of energy resources, production of high quality nutrition products, conservation of biodiversity are among the most critical matters, strongly dependent on and simultaneously affecting WEFE nexus management.

The WEFE nexus approach supports the progress of multifaceted social, environmental and economic objectives by delving into critical interactions influencing resource availability. It integrates fragmented and sectorial knowledge setting the ground for interdisciplinary research at both scientific and policy-making levels. Hence, it is evident that effective nexus governance and policy integration are fundamental prerequisites in order to secure environmental protection and foster social welfare and economic prosperity.

Within this context, stakeholders (e.g., local authorities, civil society, NGOs, agricultural associations, etc.) should be able to identify mutually beneficial solutions that decisively contribute to ecosystems health, water resources sustainability, food/agricultural sector viability and energy sources rational exploitation, via understanding synergies, trade-offs, conflicts and inter-dependencies among the WEFE sectors. Cooperation of key stakeholders, resulting in the transfer of knowledge created through research into practice, is at the heart of the WEFE nexus approach (Avellán et al., 2025). Research outcomes need to be a result of co-creation processes, so that they are owned and understood by academics, practitioners, decision makers and citizens alike (Greenhalgh et al., 2016). A co-creation process is the type of qualitative research that takes into account stakeholder input and analyses it by identifying and organising the produced knowledge in a way that is received well by all engaged actors.

Stakeholder/public engagement is a well-established participatory planning practice (Arnstein, 1969; Webler et al., 2001; Barnes et al., 2003; Fung, 2015; Papadopoulou and Hatzichristos, 2020), acknowledged for its potential to balance conflicting interests, create coalitions and support the democratic aspect of decision-making. It boosts empowerment, legitimacy and learning (Bobbio, 2019) by stimulating mutual understanding, knowledge sharing, trust building and the establishment of collaborative networks working towards the achievement of common ends. Especially in the case of environmental management, the intricate and dynamic nature of respective problems implies the need to adopt more transparent decision-making practices that incorporate diverse knowledge and cultural backgrounds (Reed, 2008). Having studied a plethora of relevant case studies, Beirle (2002) claims that "*public participation has not only improved environmental policy but it has also played an important educational role and has helped resolve the conflict and mistrust that often plague environmental issues*". In addition, stakeholder engagement helps planners to deepen into means of power and 'activate' marginalized stakeholders, i.e., less powerful stakeholders but still interested to get involved in the decision-making processes. In the case of problems addressed under a 'nexus rationale', the role of stakeholders is prominent in order to fill the gaps between theoretical concepts and practical implementations of the 'nexus' (Naidoo et al., 2021) as stakeholder engagement processes constitute incubators of knowledge and contribute to the broad dissemination and extensive application of research outcomes. Representatives of different nexus sectors shed light on hidden dimensions of a study problem, reflect on existing pressures, elaborate on nexus interlinkages and illustrate troubles arising when implementing nexus-related policies; thus, offering valuable input at the local scale and supporting knowledge proliferation. Consequently, active stakeholder participation has the potential to stimulate the design of improved policies (Reed et al., 2018; Cronan et al., 2022; MacDonald et al., 2022; Avellán et al., 2025) that efficiently address sustainable resource use in practice.

At this point, the critical matter of operationalising the Stakeholder Engagement (SHE) process, i.e., analysing stakeholder perceptions and converting abstract and intangible concepts into tangible data and outputs (Nogeste and Walker, 2005; Balane et al., 2020; Real and Schmittinger, 2022), and systematising stakeholder input comes to light. Which is the most effective way to incorporate stakeholder opinions and perspectives into future policies, and transform/translate them into meaningful and explicit responses to current problems? A considerable number of researchers have put their efforts on exploring and testing a number of methods and techniques that support the operationalisation and systematisation of the SHE processes. Coleman et al. (2017) proposed a combination of Delphi method and crowdsourcing for investigating solutions to climate change and identifying adaptive interventions to mitigate water pollution in the Lake Champlain Basin. A Stakeholder-Based Life Cycle Assessment (SBLCA) has been tested by Thabrew et al. (2009) to support development planning implementation. Scolobig and Lilliestam (2016) analysed the pros and cons of combining multi-criteria analysis, plural rationality and scenario-based approaches in knowledge co-production, integration of stakeholder suggestions and translation of their inputs into options for solving environmental problems. Another indicative example comes from Germany where a SHE process was applied as an instrument for designing measures and initiate implementations targeting at the reduction of micro-pollutants (Development of the Trace Substance Strategy in Germany, 2016–2022; Hillenbrand et al., 2023); possible recommendations were proposed during stakeholder workshops while their implementation was discussed during a stakeholder forum. A pilot phase concerning the implementation of the selected measures/actions as well as the evaluation of the overall process followed (Hillenbrand et al., 2023). Results of the abovementioned studies indicated that the SHE processes contribute significantly to the design of well-informed environmental policies and socially-accepted solutions through knowledge sharing and compromise of conflicting interests.

Nevertheless, the complexity that surrounds stakeholder-driven environmental/WEFE nexus management necessitates the adoption of rigorous and methodical techniques that provide valuable results, as there is little information available to instruct researchers on how to conduct such an analysis within the WEFE nexus theory.

In this context, this work builds on the current literature and seeks to make a step forward in the research focusing on the operationalisation of the SHE process in problems involving the management of the WEFE nexus through the combination of qualitative and quantitative techniques. It is an attempt to contribute to the available methodological tools addressing the SHE processes, and places emphasis on how stakeholder input can be systematised, modelled and translated into realistic policies and integrated solutions. Its aim is to present a methodological framework that operationalises and streamlines stakeholder input for improving WEFE management under climate change conditions.

The basic research questions are: (i) How abstract concepts/opinions expressed by stakeholders during a SHE process (e.g., workshop) can be systematised and incorporated into the decision-making process? (ii) How these abstract concepts/opinions can be exploited while designing future policies and integrated solutions? and (iii) How important is the operationalisation of stakeholder feedback acquired through SHE processes to the efficient management of the WEFE nexus? A combined framework of two methodologies, i.e., the Analytic Hierarchy Process (AHP) and Multicriteria Analysis of Policies (MULTIPOL – sub-tool of the LIPSOR model), is proposed as a way to integrate the perspectives of stakeholders and as a process to systematically understand and analyse their input. The AHP supports the prioritisation of evaluation criteria, the assessment and classification of alternative solutions (practical implementations) while MULTIPOL builds on strategic policy options and policy measures (specifications of strategic policy options) underpinning the application of suggested solutions. We should clarify that a solution is the intervention that takes place in practice, e.g., a new infrastructure, the adoption of new agricultural practices, the establishment of new administrative processes. A policy measure is the mean that governs the implementation of a solution, the provision that informs implementers on how the solution will be implemented and achieved, under which framework it will take place and which steps should be followed towards its implementation. The AHP represents a theory of measurement suitable for handling both tangible and intangible factors (Wedley, 1990; Saaty, 1994) through the quantification of qualitative data based on a numerical scale (Saaty, 2008). It has been applied focusing on the WEF nexus analysis for developing composite indices (Nhamo et al., 2020) and criteria weighting (Mansour et al., 2022). MULTIPOL incorporates both measurable (quantitative) and non-measurable (qualitative) data and applies the weighted sum model as a systematic tool supporting evaluation of policies and decision-making (Godet, 2007); it is tested for the first time together with the AHP for assessing policy recommendations as to the WEFE nexus management. The two methods are applied complementarily as AHP indicates *which* solution(s) to implement while MULTIPOL indicates *how* the selected solution(s) may be implemented. The transboundary Nestos/Mesta river basin shared between Greece and Bulgaria is the test-bed for the suggested framework.

2. Materials and methods

The inclusion of local communities, municipal/regional authorities, research/academic institutes and the business sector in the decision-making process, by integrating their preferences and aspirations into policies governing the sustainable management of the WEFE nexus at river basin scale, constitutes one of the core priorities of the EU NEXOGENESIS (H2020) project (https://nexogenesis.eu/). In this context, the Nestos/Mesta (GR/BG) case study (one of the five case studies of the NEXOGENESIS project) focuses on the exploration of efficient WEFE management solutions by mobilising and involving stakeholders (SH) affecting and affected by relevant decisions and policies. The main goal is to set up a co-creation framework that facilitates knowledge sharing, trust building, as well as the establishment of collaborations and the design of innovative solutions supporting the sustainability of the river basin. Apart from the SHE process, the accomplishment of such a goal presupposes the explicit interpretation of stakeholder input and its conversion into sound policy decisions and socially-accepted solutions. Consequently, robust methodological tools are needed in order to operationalise/systematise stakeholder feedback and transform it into realistic options.

The methodological framework applied, consists of three main stages (Fig. 1): (i) the SHE process supporting stakeholder participation and the acquisition of feedback from different interested parties; (ii) the systematisation of the feedback gained (1st

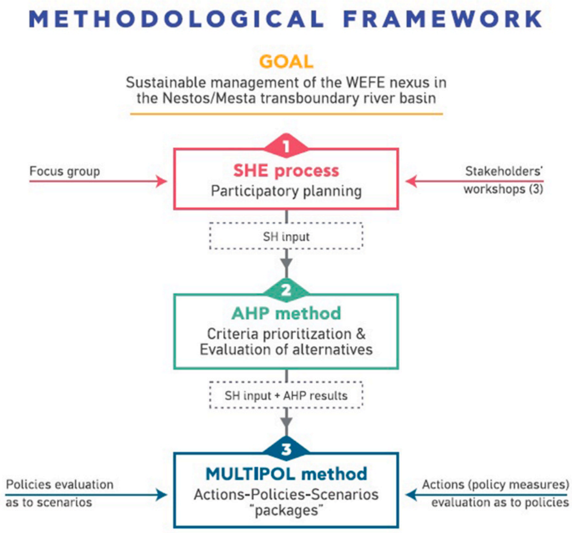

Fig. 1. Methodological framework.

level), i.e., its transformation into objectives, solutions and implementation criteria, and the classification of solutions from the most to the least preferable one by utilizing the AHP; (iii) the systematisation of the feedback gained (2nd level), i.e., its translation into future policy options and specific policy measures, and the design of integrated actions (policy measures)-policies (policy options)-scenarios (solutions) 'packages' by employing the MULTIPOL method.

It should be mentioned that the suggested methodological framework is replicable to any river basin, or other geographical scale, without any limitation as it is general enough to incorporate context-specific requirements. It represents a general framework supporting the sustainable management of the available resources allowing for stakeholder input systematisation and translation into socially-accepted solutions and meaningful policies guiding the unhindered implementation of the respective solutions.

2.1. The stakeholder engagement process

The SHE process included the organisation of three workshops and one Focus group (Fig. 2). The WEFE nexus approach was adopted in order to streamline current and future challenges as to resource use under a holistic rationale. The structure of the workshops and the Focus group was based on the following scheme.

- 1st Workshop: Brainstorming on existing pressures and critical WEFE nexus interlinkages.
- 2nd Workshop: Brainstorming on possible solutions and policies governing the WEFE nexus – Preliminary list of solutions and policies.
- 3rd Workshop: Validation of solutions and policies.
- Focus group: Assessment of policy coherence – Divergences and synergies.

Officials/Designated representatives of the WEFE nexus sectors, i.e., local and regional governmental authorities, farmer associations, water management and environmental protection authorities, the business sector and academic/research institutes were invited by project partners and gave their feedback through open discussions and constitutive dialogue. Specific questions as to (i) existing pressures put on the WEFE nexus, (ii) possible future solutions, and (iii) policies governing the relevant sectors triggered the discussions between stakeholders and researchers. Minutes were kept and analysed to create and validate explicit lists of solutions and policies. It should be mentioned that no content analysis methods/softwares were used as a structured approach based on specific questions and targeted responses guided the dialogues that took place during the workshops and the Focus group.

2.2. Analytic Hierarchy Process (AHP)

The first stage towards systematising stakeholders' input involved the AHP and the 'translation' of abstract concepts/opinions into objectives, criteria and alternative solutions. It was applied to: i) assign weights to selected criteria; ii) assess performances of the alternative solutions; and iii) establish robust numerical relationships among the different WEFE sectors. Assessments were conducted by the research team after a number of iterations in order to reach consensus. The AHP constitutes one of the most common and widely used Multiple-Criteria Decision Analysis (MCDA) methods in various research fields (e.g., Russo and Camanho, 2015; Kourtis et al., 2020, 2021). It supports the analysis of complex decisions (Darko et al., 2019) by structuring a decision problem as a multi-level hierarchy (Saaty, 1980) and by involving a number of multiple, usually contradictory and subjective criteria (Ishizaka and Labib,

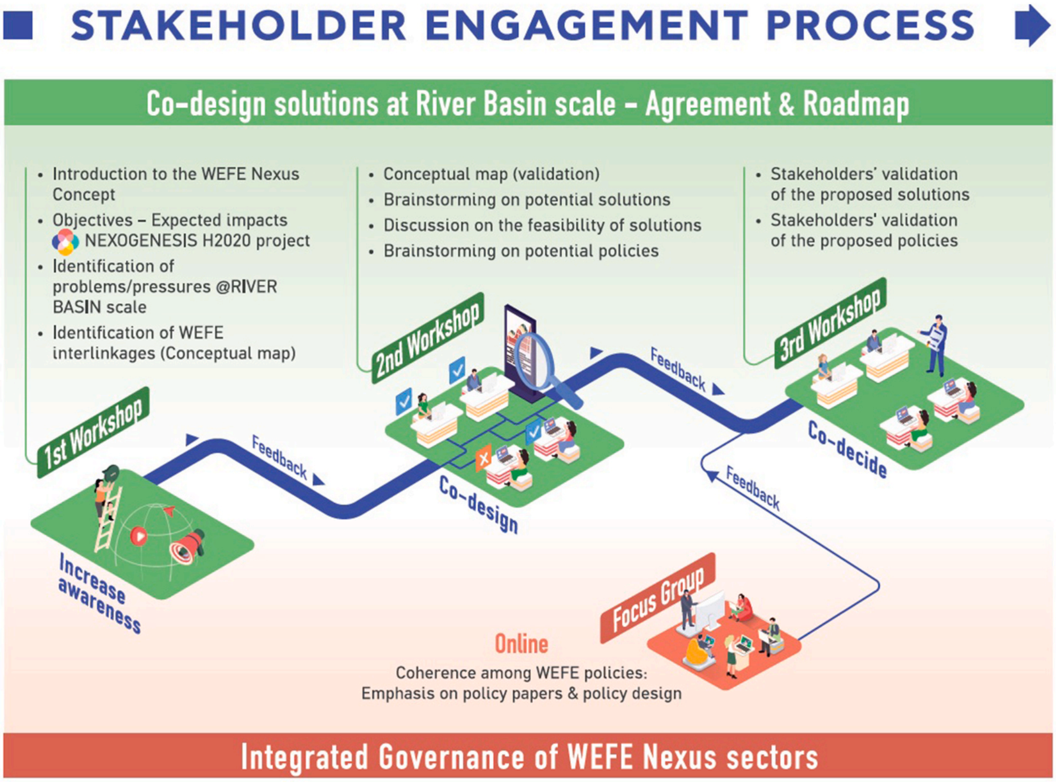

Fig. 2. The stakeholder engagement (SHE) process.

2011). It is essentially based on three principles: decomposition, comparisons, and setting priorities (Saaty, 1986), and constitutes a "*measurement theory*" based on pairwise comparisons and judgments for assigning priorities/weights to its elements (Saaty, 1994, 2008; Podvezko, 2009). The decision problem is decomposed into three basic elements, i.e., goal, criteria and alternative solutions; if necessary, sub-criteria, illustrating particular aspects of the main criteria, may also be defined. Prioritisation must be adequately complex to include all the relevant data but also 'agile' so that changes can be made if necessary (Saaty, 1987).

The process is applied through six distinct stages (Saaty, 2008): (i) representation of the problem as a hierarchy; (ii) formulation of judgments via pairwise comparisons; (iii) quantification of judgments into meaningful numbers; (iv) assignment of priorities/weights to the hierarchy elements; (v) synthesis of the individual results; and (vi) implementation of sensitivity analysis. Comparison matrices are developed for all elements belonging to the same hierarchy level. Such elements are pair-wised compared with respect to each element belonging to the direct superior hierarchy level, based on a qualitative scale (Saaty scale) ranging from 1 to 9, i.e., 1: equal importance, 3: moderate importance, 5: strong importance, 7: very strong importance, 9: extreme importance. Reciprocal values, i.e., 1/3, 1/5, 1/7 and 1/9, indicate the level to which the first compared element is less important than the second one. Intermediate values (2, 4, 6, 8) can be used for expressing a compromising judgment between two basic values. The total number of comparisons can be calculated as follows:

$$n(n-1)/2 \tag{1}$$

where n is the number of elements.

The comparison matrix, $n \times n$ dimensions, for each level of the hierarchy is developed denoting the influence of the criteria/alternative in relation to all other criteria/alternatives. Ideally, if judgments are fully consistent, the following holds, illustrating the importance of the index i versus index j (Saaty, 1987):

$$I_{ij=}w_i/w_j \tag{2}$$

The weights of each index and for each indicator are estimated as follows:

$$w_i = \frac{\left(\prod_{1}^{n} I_{ij}\right)^{1/n}}{\sum_{1}^{n}\left(\prod_{1}^{n} I_{ij}\right)^{1/n}} \tag{3}$$

where: w_i is the weight of the *i*th index/indicator, and I_{ij} is the priority of the i_{th} index/indicator in the *j*th column of the pair-wise comparison matrix.

In order to verify the consistency of weights, the Consistency Ratio (CR) can be estimated (Saaty, 1987):

$$CR = CI/RI \tag{4}$$

where: *CI* is the consistency index, *RI* is a random index which depends on the order of the matrix developed (Saaty, 1977). The Consistency Index (*CI*) can be calculated as follows:

$$CI = k - \left(n/_{n-1} \right) \tag{5}$$

where: *k* is the principal eigenvalue, and *n* has been already defined.

2.3. Multicriteria Analysis of Policies (MULTIPOL)

MULTIPOL is a MCDA method that performs two separate assessments: a finite number of actions (policy measures) are evaluated as to a finite number of policies (general strategic policy options) (1st assessment) and policies are evaluated as to selected scenarios (integrated solutions) (2nd assessment). In the first case, the goal is to explore which actions suit well to each of the policies involved in the decision problem. In the second case, policies are classified according to their possibility to enable the implementation of each scenario. Thus, a number of actions, policies, scenarios and evaluation criteria form the decision space and MULTIPOL streamlines the decision-making process by considering different and multiple aspects of the planning process (Godet, 2007). Integrated 'packages' of actions-policies-scenarios are generated, indicating the most efficient pathways for the development of the study system (Stratigea and Papadopoulou, 2013; Papadopoulou and Giaoutzi, 2024).

Achieving a desirable future situation that goes beyond current trends lies at the heart of MULTIPOL. Although decision-makers take into account existing pressures and forecasts, they formulate desirable scenarios (solutions), usually by involving stakeholders, and explore policies facilitating their implementation; availability of resources (e.g., financial resources) is the only limitation of this challenge. Under this rationale, the outcome of MULTIPOL is a synthesis of plausible future directions resulting from the classification of actions as to policies and the classification of policies as to scenarios.

The method is applied by developing: (i) the Actions-Criteria impact matrix where actions are evaluated as to criteria based on a 0–20 scale; (ii) the Policies-Criteria weighted matrix; (iii) the Scenarios-Criteria weighted matrix. Weights, in both weighted matrices, add up to 100. MULTIPOL is based on a matrix multiplication process and calculations are executed by utilizing the Weighted Sum Model:

$$A_i^{WSM-score} = \sum_{j=1}^{n} w_j a_{ij}, \textit{where } i = 1, 2, 3, \ldots, m \tag{6}$$

where: A_i is a matrix which includes the weighted scores of actions *i* as to policies, w_j the weight of each criterion within the context of each policy, a_{ij} the score of the *i*th action as to the *j*th criterion. The model is adapted accordingly in the case of policies-scenarios evaluation where the Policies-Criteria matrix is utilized as an impact matrix.

Outcomes include: (i) the assessment of actions performance and their classification as to policies (1st evaluation); (ii) the assessment of policies and their classification as to scenarios (2nd evaluation). For each action, its performance as to each policy, its total performance (Average) and the variation of its scores [Standard Deviation (SD)] are estimated. Respective values are calculated in the case of policies evaluation as to scenarios.

MULTIPOL has been used by several researchers for exploring future pathways supporting rural development and land use management (Stratigea and Papadopoulou, 2013), sustainable tourism development (Ariyani and Fauzi, 2023; Rustini et al., 2023), sustainable mobility (Cieśla and Macioszek, 2022), and urban railway services sustainability (Wijayanto et al., 2022), among others. Within the current analysis, the MULTIPOL method is applied for the first time focusing on the sustainable management of the WEFE nexus at river basin scale; it is based on stakeholder input regarding possible policies and solutions that will contribute to efficient resource use under climate change conditions.

3. Test-bed methodology application

Nestos/Mesta (GR/BG) river basin is one of the 71 transboundary river basins of Europe located in the Balkan area (Fig. 3) and in eco-region 7 (Eastern Balkans; Water Framework Directive, 2000/60/EC-Annex XIA). The river route is approximately 250 km long and the catchment surface area is about 5500 km^2. Its greater part is mountainous with the only exception in the deltaic area (estuaries) (Fig. 3) (Boskidis et al., 2011, 2012a, 2012b). Fig. 4 presents the main land use-land cover types (e.g., forests, semi-natural areas and agricultural areas) in the basin (Corine Land Cover, 2018). Nestos/Mesta forms a significant ecosystem (NATURA, 2000 site) throughout its course and its delta is protected by the Ramsar Convention. According to Tsihrintzis et al. (2007), nine coastal lagoons (choked, shallow and elongated) are located in the western part of the basin operating as buffer zones for the transfer of agricultural residues from the adjacent plain to the coastal zone.

In the early 1990s, two dams, Thissavros and Platanovrisi (170 m and 95 m high), were constructed in the Greek territory at

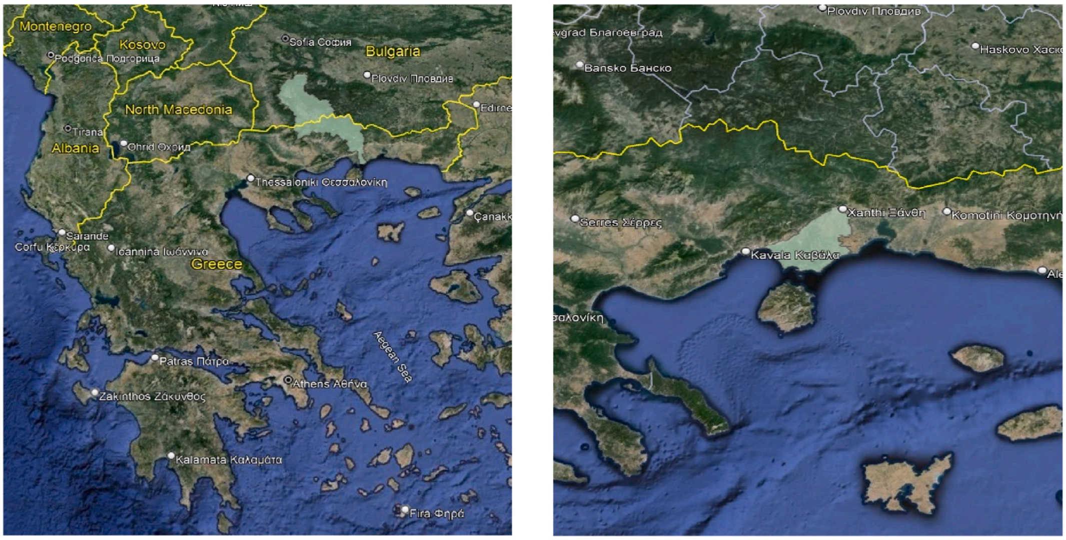

Fig. 3. Nestos/Mesta transboundary river basin (left); Nestos delta (right).Background source: Google Earth.

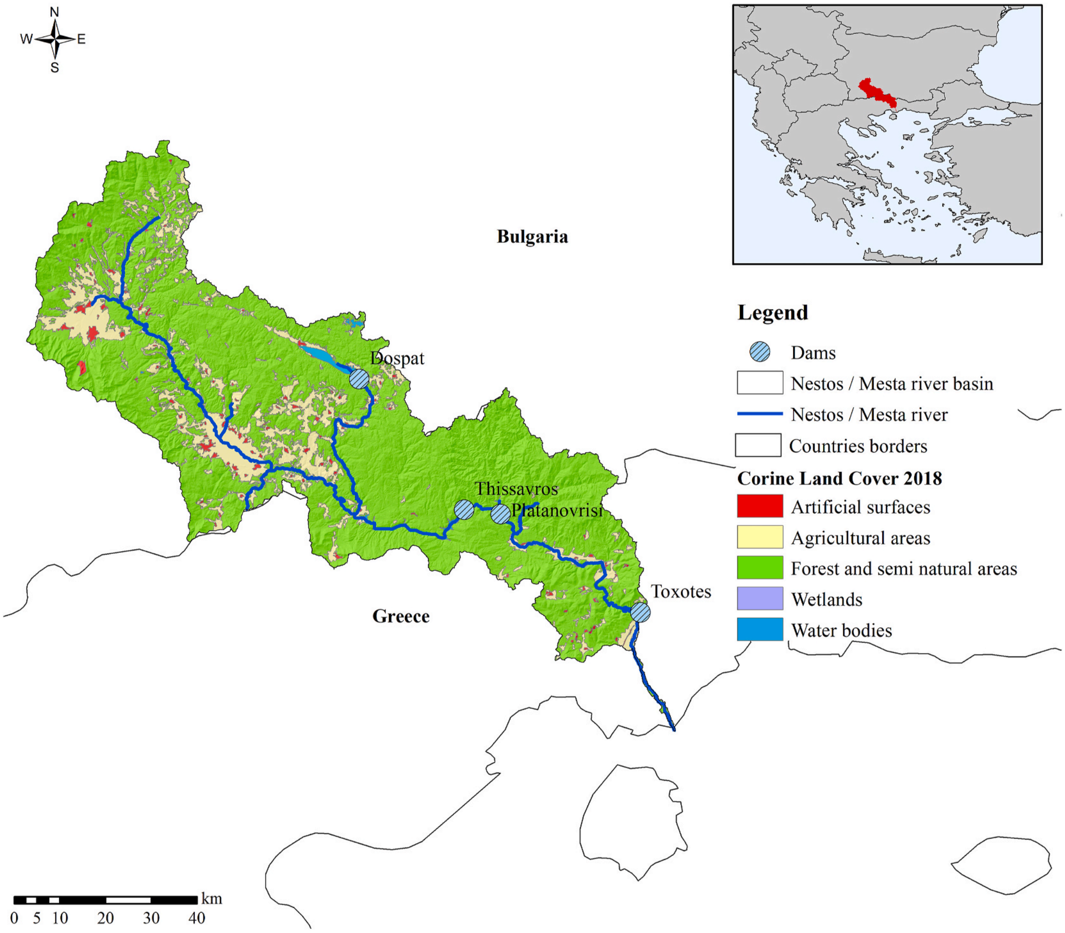

Fig. 4. Nestos/Mesta river basin and land uses.

distances of 30 km and 45 km, respectively, from the Greek-Bulgarian border, mainly for electricity production purposes. The dams, besides energy production, cover irrigation needs of the cultivated areas downstream and regulate the ecological flow throughout the year. Moreover, a smaller dam exists further downstream, near Toxotes village, and is used to divert river water to the irrigation network of the delta plain. A minimum environmental flow of 6 m^3/s is required to be maintained for the conservation needs of the deltaic ecosystems, supporting at the same time the high value agricultural, livestock, and aquacultural products that are intensively cultivated. Seasonal water resources management downstream is a major issue that needs to be addressed in order to overcome conflicting water uses between electricity production, irrigation needs and aquatic ecosystems conservation. Therefore, fair allocation of water resources to the several users and integrated governance of the water, energy, food/agriculture and ecosystems sectors at transboundary level represent crucial priorities and main institutional goals for the Nestos/Mesta river basin. However, it should be mentioned that there is no major water issues between the two countries since there is an agreement for a minimum water discharge entering Greece at the Greek-Bulgarian border.

3.1. Participatory planning workshops

The participatory planning exercise took place firstly in order to elicit feedback from stakeholders related to local needs and peculiarities, existing problems, comparative advantages and future challenges, conflicts and synergies among the WEFE nexus sectors, possible future solutions, current policy gaps and design of improved policies. Three workshops and one Focus group were organised based on the Grant Agreement of the NEXOGENESIS (H2020) project that also prescribed the content of each workshop and of the Focus group. During the first workshop, the targets of the project and the WEFE nexus concept were presented, while participants were asked to elaborate on existing pressures regarding the WEFE nexus system. Their input was incorporated in a draft conceptual map, graphically representing interlinkages and interdependencies among the WEFE sectors. The second workshop focused on the validation of the final conceptual map (Laspidou et al., 2023) and the analysis of feasible policies and solutions to current problems. Policies and solutions discussed align with the legislation governing the WEFE nexus sectors and the dialogue with the stakeholders was based on a detailed presentation of policy goals and policy instruments included in national policy documents and having been previously analysed by the research team. Suggested solutions and policies were included in a preliminary list. During the third workshop, stakeholders were asked to validate them, and a final list of solutions and policies was created. Finally, a Focus group concerning the assessment of policy coherence at both theoretical and practical level was organised in order to explore possible divergences and synergies (Mooren et al., 2024).

Policy makers at local level, agricultural associations, water management and environmental protection authorities, representatives of the business sector and academic/research institutes from Greece and Bulgaria participated and provided their feedback (Tables 1 and 2). The first two workshops were conducted in the languages of the two countries (i.e., Greek and Bulgarian), while the third one was an international workshop supported by translation services. The Focus group was conducted in English and participants comprised a sub-group of stakeholders having also joined the workshops.

3.2. AHP application

The systematisation of stakeholder input guided the implementation of the AHP. The hierarchy was structured by decomposing the problem under study into sub-components, i.e., the overarching goal, the evaluation criteria and the alternative solutions. The goal refers to the sustainable management of the WEFE nexus in the Nestos/Mesta transboundary river basin. The evaluation criteria emanated from the priorities identified during the 1st stakeholder workshop as to the efficient WEFE nexus management, while alternative solutions represented the requirements expressed and validated by stakeholders during the 2nd and 3rd workshops. The hierarchy is delineated in Fig. 5 and the analytical description of its various components is presented in Table 3.

Table 1
Workshop participants.

	1st Workshop (no. of participants)	2nd Workshop (no. of participants)	3rd Workshop (no. of participants)	Focus Group (no. of participants)
Civil society	–	–	1	–
Policy makers at local level	18	12	18	2
Agricultural authorities and representatives	2	1	8	–
Energy authorities and representatives	–	1	–	1
Water management authorities and representatives	5	2	2	2
River basin authorities and representatives	1	2	–	–
Environmental protection authorities and representatives	7	3	2	2
Business/private or public enterprises	1	1	2	–
Media/science communicators	2	3	2	–
Academic/research institutes	2	2	2	–
	Total:38	Total:27	Total:37	Total:7

Table 2
Stakeholder engagement process – Results.

Activity	No. of Stakeholders	Issues at stake	Feedback (stakeholders)	Feedback systematisation (NXG experts team)
1st Stakeholder Workshop (March–April 2022)	38	– Presentation of the NXG project – Existing pressures related to the WEFE nexus – Critical WEFE nexus interlinkages	– Increased flood risk – Sediments in the river – Conflicting water uses (energy-food/ agricultural sectors) – River pollution – Limited wastewater treatment – Endangered species – Ecosystems maintenance / Minimum ecological flow	– Identification of hotspots and critical WEFE nexus interlinkages – List of existing WEFE nexus management priorities – Future goals
2nd Stakeholder Workshop (November 2022)	27	– Validation of WEFE critical interlinkages – Design of improved policies governing the WEFE nexus – Solutions to existing problems	– Well-informed policies are needed – Policies and solutions should focus on: flood risk mitigation, agricultural income and sustainable development of agriculture, exploitation of renewables, removal of sediments and mitigation of coastal erosion, preservation of ecosystems and biodiversity, wastewater treatment, elimination of land use conflicts, monitoring water quality and mitigation of pollution, management of competitive water uses – Interventions should consider climate change impacts	– List of policies targeting at the integrated management of the WEFE nexus – List of solutions targeting at the sustainable development of the study area
3rd Stakeholder Workshop (March 2023)	37	– Validation of policies and solutions for the future development of the study area and the integrated management of the WEFE nexus	– Emphasis should be placed on infrastructures – Need for better communication between decision-making authorities and more efficient administration – Need for increasing awareness on WEFE nexus management and adoption of bottom-up administrative practices – Collaboration between local communities and national level decision-makers should be strengthened	– Final list of policies – Final list of alternative solutions (scenarios)
Focus Group (May 2023)	7	– Level of coherence among policy papers governing the WEFE nexus sectors – Conflicts/synergies in practice	– Satisfying level of coherence but higher level of integration is needed between policies governing the WEFE nexus sectors – Conflicts and lower level of coherence at policy implementation stage	– Identification of gaps and suggestions for managing such gaps – Feedback to policies and solutions

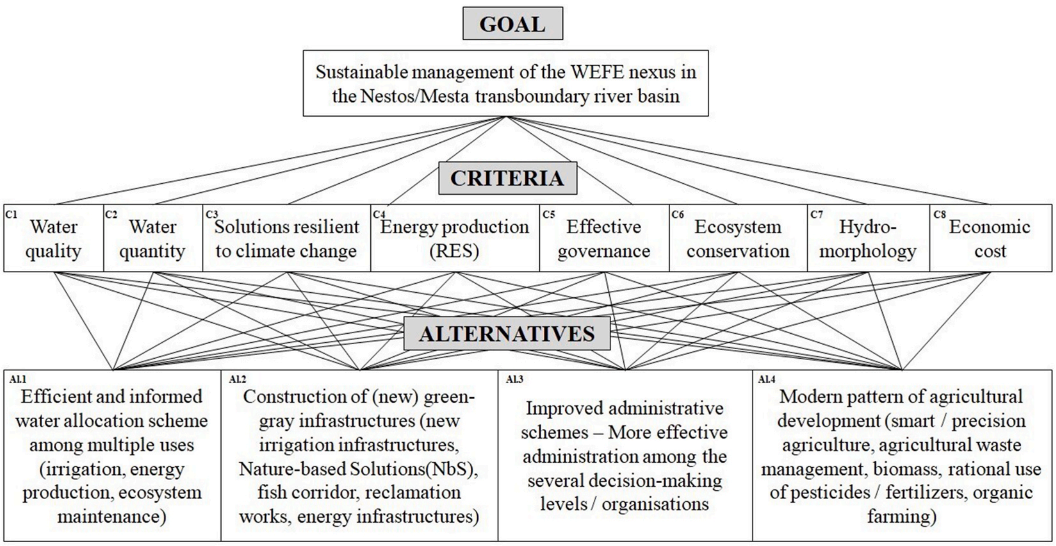

Fig. 5. AHP hierarchy.

Table 3
AHP hierarchy–description of components.

AHP element	Label	Analytical description
Goal (Hierarchy level: 1)	Sustainable management of the WEFE nexus in the Nestos/Mesta river basin	The goal focuses on the efficient management and rational use of the available resources in the Nestos/Mesta transboundary river basin. Local needs, characteristics and peculiarities are considered.
Criteria (Hierarchy level: 2)	**C1**: Water quality	This criterion places emphasis on monitoring sources of pollution, restoration of sensitive water reservoirs and ecosystems, reduction of pollution emanating from several sources (e.g., agricultural waste, industrial activities, etc.) in line with the Water Framework Directive (WFD, 2000/60/EC).
	C2: Water quantity	This criterion focuses on the sustainable management of water in the river basin in terms of quantity and in line with the Floods Directive (Floods Directive, 2007/60/EC).
	C3: Solutions resilient to climate change	This criterion refers to initiatives, measures and activities supporting the confrontation of climate change impacts through proactive planning, infrastructures and increased awareness.
	C4: Energy production (available energy potential)	This criterion concerns the exploitation of all available energy resources (water, geothermy, biomass, energy crops, photovoltaics, wind turbines) in order to increase the share of energy produced by RES at local scale.
	C5: Effective governance	This criterion focuses on the effectiveness of administrative organisations, the design of well-informed decisions, the improvement of communication between the several decision-making levels and the acceleration of policy implementation when it comes to the sustainable management of resources.
	C6: Ecosystems conservation (ecosystem services)	This criterion prioritises the well-functioning of ecosystems and the unhindered provision of ecosystem services (provisioning, regulating, cultural and supporting).
	C7: Hydro-morphology	This criterion builds on the protection of geomorphology, landscape and water reservoirs. It includes water flow, biodiversity and habitats, embankments, etc. and places emphasis on the elimination/confrontation of existing or future pressures.
	C8: Economic cost	This criterion focuses on the economic aspect of the suggested solutions, reflecting on the relevant costs that each solution entails.
Alternatives (Hierarchy level: 3)	**Al.1**: Efficient and informed water allocation scheme among multiple uses (irrigation, energy production, ecosystem maintenance)	This alternative suggests that emphasis should be placed on the improved management of the dams so that water use conflicts are eliminated. Dams provide water for electricity production, irrigation and ecological flow. A fair and balanced allocation of water is of significant importance in order to achieve ecosystem well-functioning, improved agricultural production and sufficient electricity production.
	Al.2: Construction of (new) green-gray infrastructures (new irrigation infrastructures, Nature-based Solutions (NbS), fish corridor, reclamation works, energy infrastructures)	This alternative focuses on infrastructures, i.e., construction of new infrastructures, maintenance/modernisation of existing infrastructures. Specific infrastructures are proposed based on: the problems reported by local stakeholders, the structure of local economy, the physical environment, the existing needs and shortcomings as well as on the comparative advantages of the area that could be exploited in order current problems to be mitigated/ resolved.
	Al.3: Improved administrative schemes – More effective administration among the several decision-making levels/ organisations	This alternative promotes improved administrative schemes, better coordination among the several decision-making bodies, acceleration of processes at a managerial level and effective policy implementation.
	Al.4: Modern pattern of agricultural development (smart/ precision agriculture, agricultural waste management, exploitation of biomass for energy production-recycling and reuse, rational use of pesticides/fertilizers, organic farming)	This alternative places emphasis on the development of agricultural sector and upgrades its role in order to become a 'key driver' of change and innovation. It suggests the adoption of a modern pattern of agricultural development through the use of technologies that regulate irrigation, reduce waste, exploit biomass for energy production and monitor the use of pesticides. This entails the efficient use of resources, the elimination of pollution emanating from agricultural waste, the protection of ecosystems, the saving of irrigation water and the significant contribution of the sector to the local income.

All AHP computations were undertaken using the Expert Choice software (Expert Choice, 2023). Starting from the lowest hierarchy level, eight matrices including pairwise comparisons among alternatives (alternative in row over alternative in column) as to each criterion were structured. Assessments were based on the Saaty scale. The second stage of pairwise comparisons concerned assessments among the eight evaluation criteria as to the main goal; the importance of a criterion in row over a criterion in column was assessed by using the same scale, and criteria weights were elicited. AHP results included: i) criteria weights, reflecting the importance of each criterion in the context of the problem under study and the goal initially set (Table 4); and ii) ranking of alternatives as to the main goal

Table 4
Classification of criteria as to their weights.

Criterion (short label)	Criterion (long label)	Criterion weight
C3	Solutions resilient to climate change	0.277
C6	Ecosystems conservation (ecosystem services)	0.245
C2	Water quantity	0.183
C7	Hydro-morphology	0.122
C4	Energy production (available energy potential)	0.058
C5	Effective governance	0.052
C1	Water quality	0.041
C8	Economic cost	0.022

Table 5
Ranking of alternative solutions.

Alternative (short label)	Alternative (long label)	Score (performance)
Al.2	Construction of (new) green-gray infrastructures (new irrigation infrastructures, Nature-based Solutions (NbS), fish corridor, reclamation works, energy infrastructures).	0.437
Al.4	Modern pattern of agricultural development (smart/precision agriculture, agricultural waste management, exploitation of biomass for energy production-recycling and reuse, rational use of pesticides/fertilizers, organic farming).	0.311
Al.1	Efficient and informed water allocation scheme among multiple uses (irrigation, energy production, ecosystem maintenance).	0.173
Al.3	Improved administrative schemes – More effective administration among the several decision-making levels/ organisations.	0.079

based on their performance with respect to the weighted criteria (Table 5).

Evaluation criteria incorporate core dimensions of the main goal. Criterion C3: 'Solutions resilient to climate change' picks the highest importance rate, followed by criterion C6: 'Ecosystems conservation (ecosystem services)'. Adaptation to climate change and mitigation of its impacts constitute substantial prerequisites for the future development of the Nestos/Mesta river basin as flood risk assessment, viability of agriculture and efficient water allocation are regulatory factors affecting standards of living and local income. Moreover, the region accommodates one of the most significant ecosystems of Greece, whose services contribute decisively to environmental protection, preservation of the local flora and fauna, maintenance of the agricultural sector and sustainance of the local cultural identity.

Alternatives incorporate future challenges reported by stakeholders and related to ecosystems maintenance, protection of biodiversity, sustainable management of agriculture, development of infrastructures supporting climate change mitigation, renewable energy generation, improved administrative practices and balanced allocation of water resources among the several users. According to the overall ranking of alternatives the best alternative is Al.2, followed by alternative Al.4; alternative Al.1 comes third while alternative Al.3 is the least preferred one.

3.3. *MULTIPOL application*

The stage of evaluating and selecting the most efficient solution(s) that correspond to current requirements and address reported deficiencies is followed by the stage of implementation. This stage is guided by policies and explicit measures, setting the framework within which the relevant solutions will take place, and specifying how such solutions will 'pass' from theory to practice. Hence, the third and final stage of the proposed methodological scheme focused on the assessment of policies (general policy options)/actions (policy measures)/scenarios (solutions), and the design of integrated 'policies-scenarios packages' indicating pathways through which the considered solutions may be realised. The MULTIPOL method was applied and two separate evaluations, i.e., actions-policies and policies-scenarios, were executed.

As already mentioned, MULTIPOL employs a matrix multiplication process involving three matrices: the actions-criteria impact matrix, the policies-criteria weighted matrix and the scenarios-criteria weighted matrix. Consequently, the data processed by MULTIPOL included: (i) the evaluation criteria (same criteria as in the case of the AHP); (ii) a list of actions; (iii) a list of policies; (iv) two scenarios; and (v) the three matrices referred above. The scenarios considered were identical to the alternative solutions that received the two highest scores from the AHP evaluation (Scenario S1 identical to Al.2, Scenario S2 identical to Al.4). Policies and actions were elicited from stakeholder feedback (2nd and 3rd workshops) while policy gaps identified by stakeholders participated in the Focus group, was a complementary material considered when defining policy options. The lists of actions and policies include.

Actions (policy measures)

– A1: Modernisation of irrigation systems – Minimisation of water losses

– A2: Monitoring the quantity of pesticides/toxic substances discharged in the river
– A3: Limitation of flood risks / Construction of flood preventing infrastructures
– A4: Establishment of general rules regulating agricultural water pricing
– A5: Wastewater treatment plants – Use of treated effluents for irrigation
– A6: Monitoring water volumes coming from upstream (Bulgaria)
– A7: Assessment of and public awareness on the ecosystem services of the river system
– A8: Protection of wetlands and grasslands
– A9: Elimination of land use conflicts between forest and crop land/pastures
– A10: Securing the minimum environmental flow
– A11: Limitation of coastal erosion
– A12: Protection of biodiversity from intensive agriculture
– A13: Creation of an inventory including biodiversity threats
– A14: Cultivation of dynamic crops with export possibilities
– A15: Stimuli for enhancing aquaculture production
– A16: Energy production from RES (geothermy, forest and agricultural biomass, P/Vs, wind turbines)

Policies (general policy options)

– P1: Emphasis on the protection and sustainable management of surface water and groundwater resources; adaptation of energy, agricultural/food and ecosystems sectors accordingly
– P2: Multi-functionality of agricultural sector – Efficient exploitation of the available resources
– P3: Eco-friendly pattern of development – Minimum level of (human) interventions

Results from the evaluations are graphically depicted in Fig. 6.

Such diagrams represent classifications of actions as to policies and classifications of policies as to scenarios, allowing decision-makers to define groups of actions-policies and groups of policies-scenarios, whose synthesis results in integrated actions-policies-scenarios packages, i.e., strategic directions for future development. Regarding the combinations between actions and policies, it is evident that some actions are closer to some specific policies while some others fit to more than one policy. Coming to combinations between scenarios and policies, it is clear that policy P2 (multi-functionality of agricultural sector) is closer to scenario S2 (modern pattern of agricultural development) while policy P3 (eco-friendly pattern of development) is closer to scenario S1 (construction of green-gray infrastructures). Policy P1 (emphasis on the protection of water resources and adaptation) is rather neutral supporting the implementation of both scenarios S1 and S2. The horizontal and vertical axes are dimensionless as the scope of these diagrams is to depict: (i) the dispersion of actions with respect to policies and the level of integration between actions and policies; and (ii) the dispersion of policies with respect to scenarios and the level of integration between policies and scenarios. This is based on the calculation of eigenvalues and inertia indicating the level of coherence and consistency of the results as well as the level of stability of the system. Therefore, explicit groups of actions-policies and policies-scenarios indicate strong coherence and consistency; otherwise, the multi-criteria process should be revised. Integrated packages of actions-policies-scenarios resulted from the two MULTIPOL evaluations are summarized in Table 6.

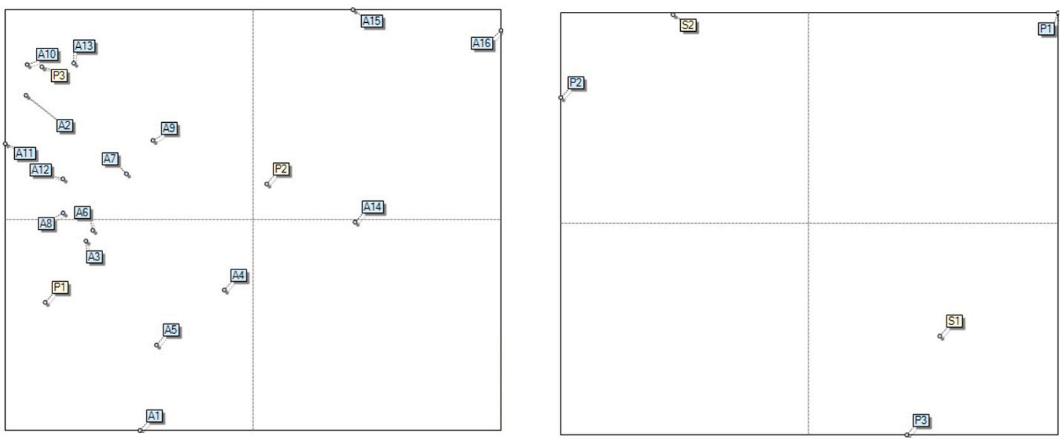

Fig. 6. (a) Actions-policies closeness map: dispersion of actions with respect to policies - Level of integration between actions and policies (b): Policies-scenarios closeness map: dispersion of policies with respect to scenarios–level of integration between policies and scenarios. The horizontal and vertical axes are dimensionless.

Table 6
MULTIPOL results–actions-policies-scenarios packages.

Scenarios	Policies	Actions
S1: Construction of (new) green-gray infrastructures (new irrigation infrastructures, NbS, fish corridor, reclamation works, energy infrastructures)	P3: Eco-friendly pattern of development – Minimum level of (human) interventions	– A2: Monitoring the quantity of pesticides/toxic substances discharged in the river – A7: Assessment of ecosystem status and evaluation of ecosystem services – A8: Protection of wetlands and grasslands – A9: Elimination of land use conflicts between forest and crop land/pastures – A10: Securing the minimum environmental flow – A11: Limitation of coastal erosion – A12: Protection of biodiversity from intensive agriculture – A13: Creation of an inventory including biodiversity threats
	P1: Emphasis on the protection and sustainable management of surface water and groundwater resources and adaptation of energy, agricultural/food and ecosystems sectors accordingly	– A1: Modernisation of irrigation systems – Minimisation of water losses – A3: Limitation of flood risks/ Construction of flood preventing infrastructures – A4: Establishment of general rules regulating agricultural water pricing – A5: Wastewater treatment plants – Use of treated effluents for irrigation – A6: Monitoring water volumes coming from upstream (Bulgaria) – A7: Assessment of ecosystem status and evaluation of ecosystem services – A8: Protection of wetlands and grasslands – A12: Protection of biodiversity from intensive agriculture
S2: Modern pattern of agricultural development (smart/ precision agriculture, agricultural waste management, biomass, rational use of pesticides/ fertilizers, organic farming)	P2: Multi-functionality of agricultural sector – Efficient exploitation of the available resources	– A4: Establishment of general rules regulating agricultural water pricing – A5: Wastewater treatment plants – Use of treated effluents for irrigation – A14: Cultivation of dynamic crops with export possibilities – A15: Stimuli for enhancing aquaculture production – A16: Energy production from RES (geothermy, forest and agricultural biomass P/Vs, wind turbines)
	P1: Emphasis on the protection and sustainable management of surface water and groundwater resources and adaptation of energy, agricultural/food and ecosystems sectors accordingly	– A1: Modernisation of irrigation systems – Minimisation of water losses – A3: Limitation of flood risks/ Construction of flood preventing infrastructures – A4: Establishment of general rules regulating agricultural water pricing – A5: Wastewater treatment plants – Use of treated effluents for irrigation – A6: Monitoring water volumes coming from upstream (Bulgaria) – A7: Assessment of ecosystem status and evaluation of ecosystem services – A8: Protection of wetlands and grasslands – A12: Protection of biodiversity from intensive agriculture

4. Discussion

The sustainable management and integrated governance of the WEFE nexus at different spatial scales, cultural and social contexts, comprises a critical dimension of environmental planning. Howells and Rogner (2014) stated that the development and implementation of sectoral plans and policies must take into account the different linkages among sectors while in the literature, different variations of the WEFE nexus approach receive much attention over the last years (e.g., Valdez et al., 2016; Carmona-Moreno et al., 2019; Cristiano et al., 2021; Jain et al., 2023; Guo et al., 2024; Probst et al., 2024; Tocados-Franco et al., 2024). By utilizing the nexus approach, researchers aim to assess the interplay of different sectors, to propose changes in the decision-making process and to assess policies. Lucca et al. (2023) reviewed the WEFE nexus research in the Mediterranean aiming to support the operationalisation of the approach; they concluded that the current research remains insufficient in delivering comprehensive and cohesive evaluations. In addition, the management of the WEFE nexus, especially in transboundary river basins, constitutes a complex challenge. For instance, De Strasser et al. (2016) developed a framework for assessing the WEFE nexus in transboundary river basins; the proposed framework aimed to identify the different sectorial impacts and trade-offs, and to suggest potential policy measures and technical actions. Probst et al. (2024) employed the WEFE Nexus approach in the Danube river basin, in order to assess the implications of maize irrigation through comprehensive scenario exploration. Their analysis provided a robust foundation for understanding the complex nexus dynamics which are critical for the sustainable management of the WEFE resources in the region. The methodological framework presented in this paper, adds to the abovementioned literature findings by suggesting an integrated evaluation framework that encompasses the sustainable governance of the WEFE nexus system. Although it is general enough, so that it is replicable to any case study, it was tested in a Mediterranean transboundary river basin and showcased that it provides rigorous and valid results supporting the sustainable development of the entire basin by simultaneously considering four interlinked sectors and offering the potential to compromise trade-offs, so that adverse impacts are limited.

Moreover, there is an increased interest in stakeholder engagement for addressing environmental problems and supporting environmental decision making (Luyet et al., 2012; Glucker et al., 2013; McKinley et al., 2017; Whitmarsh and Corner, 2017; Reed et al., 2018; Ferreira et al., 2020; Han et al., 2024). Different researchers (e.g., Hoolohan et al., 2018; Melloni et al., 2020; Jalonen et al., 2022; Malamataris et al., 2023) have explored the role of stakeholder engagement in promoting effective WEFE nexus governance. At river basin scale, their findings underscore the significance of participatory decision-making processes and flexible management approaches for navigating the complexities of (transboundary) water resources management. Among the issues explored is the integrated and sustainable management of water resources by seeking socially-accepted solutions (e.g., Alamanos et al., 2021) as well as the implementation of the designed solutions (e.g., Megdal et al., 2017). Other researchers focused on the involvement of stakeholders in: monitoring the effects of interventions taking place in rivers/river basins (e.g., dams; Verbrugge et al., 2017), water quality modelling (e.g., Hassanzadeh et al., 2019), efficient water planning (e.g., Rojas et al., 2020), and in projects related to the integrated management of watersheds (e.g., Luyet et al., 2012). As a result, the development of collaborative governance frameworks is essential for addressing the multifaceted challenges posed in transboundary river basins (Yasuda and Demydenko, 2024) in conjunction with urban sprawl, population growth and climate change. The integration of these approaches in the decision-making process can ensure the sustainable provision of water, energy and food, while safeguarding ecosystems and fostering regional cooperation. In the context of the current analysis, this has been achieved by conducting three stakeholder workshops and a Focus group targeting at collecting, systematising and incorporating local/context-specific knowledge into policies governing the WEFE nexus and into solutions ensuring its sustainable management. Stakeholder input was intertwined with scientific knowledge towards designing socially-accepted solutions and policies while a key group of stakeholders (local coalitions) has been created wishing to further promote their implementation.

Operationalising the SHE process constitutes a significant challenge and an essential dimension of environmental problems; especially in cases involving the management of complex interactions, conflicts and trade-offs. Several research attempts emphasise the need to consolidate and incorporate the feedback of stakeholders into scientific knowledge in order to better interpret local particularities and to design targeted interventions. This article adds to the existing literature by suggesting and testing a methodological framework that employs participatory planning, AHP and MULTIPOL. The aim is to operationalise the abstract concepts and opinions expressed by stakeholders with respect to the sustainable management of the WEFE nexus and to systematise them into feasible solutions and effective policies. The AHP and the MULTIPOL method are applied complementarily as the first gives input to the latter. Both methods systematise stakeholder opinions and aspirations; the AHP transforms them into meaningful evaluation criteria and alternative solutions while MULTIPOL translates them into realistic and well-informed policies. Hence, the AHP indicates *which* alternative solution(s) to apply while MULTIPOL indicates *how* the selected alternative(s) may be applied. The proposed framework is novel, robust, specific and considers various factors, i.e., environmental, economic and social aspects of the study problem, while it combines both qualitative and quantitative analysis (AHP/MULTIPOL).

The ideal number of workshops/Focus groups needed to be organised to validate relevant solutions and policies, depends on past experience and cultural background of both researchers and stakeholders, and can be adapted accordingly. However, stakeholder sustainment is a critical challenge that requires capturing stakeholders' interest and keeping it alive. Biases on their responses can be limited through trust building, compromise of conflicting interests, common understanding and empowerment of marginalized stakeholders. In the case of the Nestos/Mesta river basin, this was achieved by involving stakeholders with different professional backgrounds and educational levels while, open discussion and dialogue among the participants was the most suitable participatory technique to be used in our case. However, depending on the specificities of each case and the level that stakeholders are familiar with co-creation activities, the adopted participatory technique(s) can be adapted accordingly.

AHP results showed that the most important criteria (C3 and C6) are related to climate change adaptation and ecosystems maintenance, comprising core priorities highlighted by local stakeholders. The ranking of alternatives is also in alignment with stakeholder ambitions and expectations. Ideally, stakeholders would like all alternative solutions to be implemented. During the workshops, they agreed that there is an urgent need for upgrading existing infrastructures and invest on new ones that will enhance resilience to floods, safeguard unhindered irrigation demand, support renewable energy production, protect local biodiversity and preserve ecosystems. They also mentioned the necessity for re-structuring the agricultural sector by adopting new patterns of agricultural development that will place emphasis on the use of innovative technologies and on the adoption of environmentally friendly practices, i.e., reduction of water losses, elimination of water pollution, monitoring the use of fertilizers/pesticides, cultivation of high-quality products and smart exploitation of agricultural waste. A fairer and more effective allocation of water in dams is another essential prerequisite. Apart from electricity production, water should be available when required by farmers for irrigation, especially during the dry summer season, while a minimum threshold of ecological flow should be obtained for the sake of ecosystem viability. Lastly, stakeholders insisted that administration should be drastically reformed so that administrative processes are accelerated, communication among the several decision-making levels is improved and available economic resources are effectively absorbed. However, the modernisation of infrastructures and the structure of new ones supporting resilience to climate change have been referred to as the most prominent priorities, something that is in line with the results of AHP. It should be mentioned that this alternative attained the highest performance in four criteria, C2: Water quantity, C3: Solutions resilient to climate change, C4: Energy production and C7: Hydro-morphology. This is more or less expected as the aforementioned criteria require the well-functioning of modern infrastructures that will safeguard the effective allocation of water to several users by simultaneously reducing losses, protect both the physical and human-made environment from flood events, support renewable energy generation and preserve landscape against natural disasters.

Regarding MULTIPOL, outcomes indicated that if emphasis is given to infrastructures, the modernisation of existing infrastructures or the structure of new ones should follow an eco-friendly pattern of development with minimum interventions to the physical environment and ecosystems, e.g., adoption of Nature-based Solutions aligned with the sustainable assessment and exploitation of ecosystem services, limitation of coastal erosion, extensive use of equipment monitoring water pollution, environmental flow and biodiversity threats as well as application of agricultural practices contributing to the limitation of water losses. In the case of scenario S2 that prioritises agricultural development (smart agriculture, agricultural waste management, rational use of pesticides/fertilizers, organic farming), the most effective policy options supporting its implementation highlight the multi-functional role that agriculture can play in the development of the entire basin and the efficient use of all available resources; irrigation water pricing and limitation of excessive water consumption, production of high-quality agricultural products and reinforcement of exports, modernisation of aquaculture, energy production from agricultural waste as well as land use regulations reducing conflicts between food and energy sectors and living space for the further development of renewables are representative policy measures suggested by stakeholders and corresponding to current needs. Policy P1, referring to the protection and balanced use of surface water and groundwater, is complementary and fits well to both scenarios as it includes policy measures targeting at: the modernisation of irrigation systems so that water losses are minimised, the construction of flood preventing infrastructures, the increased use of treated water, the protection of biodiversity from intensive agricultural practices and the maintenance of grasslands and wetlands. The application of MULTIPOL facilitated the systematisation of stakeholder input as to desired solutions and policies by integrating them into concrete ‘policies-scenarios’ packages that represent strategic pathways and recommendations towards the implementation of the scenarios considered.

Overall, the suggested methodological framework combines methods and tools having been tested and validated with regards to the quality, credibility and reliability of the results they produce. AHP and MULTIPOL provided realistic outcomes corresponding to the priorities set by stakeholders as to the confrontation of existing problems and future challenges while there were no unexpected results indicating inconsistencies. Moreover, the adopted methodology provided integrated solutions and policies building on the interlinkages between the WEFE sectors considered. Its application is not limited to the WEFE management at river basin scale but it can be applied in any similar case independently of the spatial scale and the nexus sectors taken into account. It can also be applied in problems with different contexts such as integrated spatial planning, transportation planning, agricultural development, sustainable management of the tourist sector and integrated water resources management. The main issues it addresses include the coordination of the SHE process, the systematic review of stakeholder input, the investigation of widely-accepted and effective solutions and the implementation of efficient and well-informed policies. All these are key dimensions of problems related to nexus management and integrated environmental-social-economic development.

5. Conclusions

The methodological framework presented and tested in this paper supports holistic WEFE nexus management under climate change conditions by considering stakeholders’ feedback along with scientific evidence emanating from literature, research outcomes, and past experience from completed projects. Three stakeholder workshops and one Focus group were organised in order to share visions and expectations, build trust and obtain a valuable knowledge background as to pressures exerted to the WEFE nexus and possible solutions/policies expected to mitigate climate change impacts. Two MCDA methods, AHP and MULTIPOL, were introduced and tested as to their suitability to systematise and effectively address the co-produced knowledge. The main advantage of their combined application is that all factors influencing a decision-making process are taken into consideration while it is the first time that MULTIPOL is applied for the holistic management of the WEFE nexus.

Regarding AHP, it embodies multiple stakeholders’ priorities (criteria) and preferences as to possible solutions in order to tackle existing problems; consequently, subjectivity that is an inherent characteristic of MCDA is limited. It is a user friendly method that facilitates the explicit analysis of complex problems through their decomposition into sub-components. Moreover, it combines qualitative and quantitative analysis allowing thus to take into consideration intangible qualitative data and abstract concepts. Finally, it allows decision-makers to check inconsistencies, run sensitivity analysis and revise the decision problem accordingly.

Concerning MULTIPOL, it is a robust decision-making tool that enables the design of integrated future pathways through the quantification of qualitative data by employing a simple weighted average model. It guides decision-makers by delving into critical dimensions of a decision problem, i.e., analysis of policies, specific policy measures and future scenarios, and by producing policy recommendations that will lead to the implementation of realistic scenarios. Therefore, integrated strategic directions are formulated and a step-by-step guidance towards the achievement of developmental goals is provided.

The application of the combined AHP-MULTIPOL methodology showed that the proposed framework facilitates the operationalisation of the SHE process by systematising opinions and desires into realistic solutions and policies. It allows moving from abstract concepts to tangible recommendations by conducting dialogues on current pressures and possible future options, analyzing minutes kept during participatory workshops and Focus groups, and 'translating' them into criteria, solutions and policies validated by the interested stakeholders, 'feeding' thus the decision-making process. AHP and MULTIPOL exploit such type of qualitative information by employing quantitative models that support prioritisation of solutions and formulation of integrated 'scenarios (solutions)-policies' packages, consisting roadmaps towards the achievement of solutions through policy implementation. Consequently, the proposed methodological framework responds to the research questions initially set, placing emphasis on: (i) the systematisation of abstract concepts expressed during the SHE processes; (ii) the exploitation of such concepts to design integrated solutions and policies; and (iii) the operationalisation of the SHE input so that efficient management of the WEFE nexus is achieved. Key findings indicate the need for adopting holistic approaches enabling the balanced management and fair allocation of the available resources, the incorporation of local experience and stakeholders' opinions into the decision-making process so that targeted and socially-accepted solutions and policies are designed, and the use of models integrating qualitative information so that important factors affecting a problem are not overlooked. Additionally, the Nestos/Mesta case study showcased that protection of water quality from agricultural waste, minimisation of water losses, limitation of flood risks and monitoring water volumes coming from the upstream areas, preservation of ecosystems and adoption of eco-friendly/multi-functional patterns of spatial development constitute important priorities for (transboundary) river basins. A further development of this systematic process could test the involvement of stakeholders in the MCDA process per se and let them assign judgments as to the scores (performances) of alternatives, policies and actions with respect to the evaluation criteria. Such an attempt would of course require the revision and adaptation of the SHE process as well as the availability of extra resources in terms of time, stakeholders training and guidance, hands-on exercises and MCDA expert(s) contribution. Content analysis combined with the use of tools like the DPSIR framework, the Atlas ti software or other tools supported by generative AI algorithms could also add to the proposed methodology.

CRediT authorship contribution statement

Chrysaida-Aliki Papadopoulou: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ioannis M. Kourtis:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis. **Chrysi Laspidou:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Vassilios A. Tsihrintzis:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Maria P. Papadopoulou:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization, Funding acquisition.

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Declaration of competing interest

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

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Data availability

The data that has been used is confidential.

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