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ORIGINAL ARTICLE

Introducing GoNEXUS SEF: a solutions evaluation framework for the joint governance of water, energy, and food resources

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Abstract
To enhance water, energy, and food security and promote ecosystems conservation, it is necessary to design policies or solutions capable of addressing cross-sectoral challenges. In this paper, GoNEXUS SEF, an evaluation framework for co-designing and evaluating nexus solutions, is presented. This framework provides guidelines for conducting a nexus-coherence assessment to improve the governance of the water-energy-food-ecosystems nexus. The assessment involves a participatory process that integrates qualitative and quantitative methodologies through systemic approaches. The crucial aspects necessary in the development of methodologies that address the nexus have been identified and considered. The framework was applied to a practical case study, an increase in the irrigation water price in Andalusia—Spain for the horizon of 2030. Case study results revealed that the measure can generate synergies since it favours water savings, irrigation water efficiency and ecosystems conservation. However, trade-offs are observed, mainly undermining the economic development of agriculture in the region. GoNEXUS SEF has proven capable of evaluating nexus solutions by measuring cross-sectoral synergies and trade-offs. It highlights hidden properties and identifies leverage points and key aspects of a complex cross-sectoral system to apply nexus solutions more effectively to promote sustainable development. In addition, the framework can be adapted to fit different case studies, considering their own challenges and their spatial and temporal scales, which gives it a competitive advantage over other methodologies focused on analysing the nexus.

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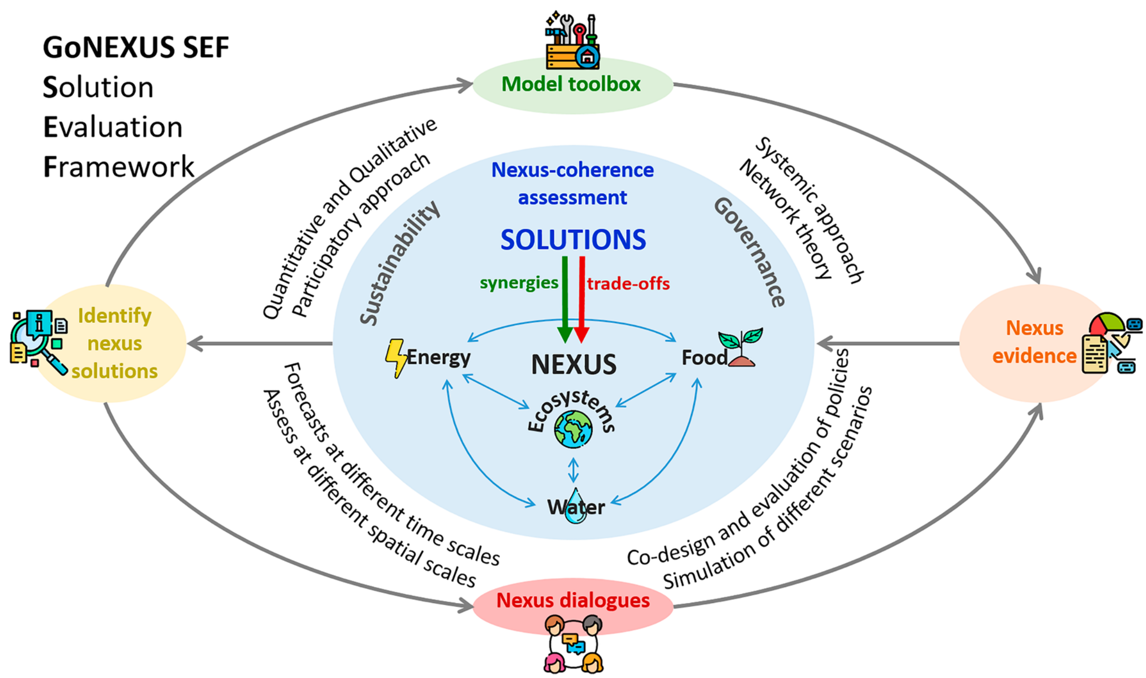

Keywords Water-energy-food-ecosystems · Participatory approach · Nexus coherence assessment · Nexus governance · Systemic approach · Network theory

Introduction

Currently, achieving food, energy, and water security and the conservation of ecosystems are some of the main sustainability challenges (EC 2021; Axworthy and Adeel 2014). Traditionally, in these sectors, the policy measures and decisions have been taken separately; however, it is becoming increasingly evident that these sectors are "hyperconnected" (Susnik and Stadon 2021; Khan et al. 2022), and that the actions taken in one affect the rest in a chain reaction.

The water-energy-food-ecosystems nexus (WEFE nexus, or simply nexus) approach analyses the interactions between the different sectors and the effects generated by human socioeconomic activities on the production, consumption, and availability of water, energy, food, and their impact on ecosystems (Wiegleb and Bruns 2018). In this sense, the nexus approach can enhance water, energy, and food security and promote the conservation of ecosystems by increasing efficiency, reducing trade-offs, building synergies, and improving governance across sectors (Hoff 2011).

To drive the transition to sustainable growth, it is also necessary to design solutions that address the challenges generated by socioeconomic, environmental, and cross-sectoral system interactions. Precisely because of its capabilities, the nexus approach is proficient in underpinning policy recommendations (Hoff 2011). Therefore, the nexus approach has gained considerable attention and has been widely used to design policies that contribute to sustainable development and integrated resource management (Orimoloye 2022; Purwanto et al. 2021; Wiegleb and Bruns 2018; Wichelns 2017). Various methodologies and tools have been developed to analyse and evaluate the WEFE nexus (Meng et al. 2023; Taguta et al. 2022; Stylianopoulou et al. 2020; Aboelnga et al. 2018; Albrecht et al. 2018). Few integrated tools exist to assess the nexus and, while these tools have brought fundamental advances to nexus study, many of these methodologies are too theoretical, conceptual, or are complex to put into practice. In the literature, some of the crucial criteria of nexus methodologies have been identified: (1) tools that integrate quantitative and qualitative information; (2) tools capable of analysing cross-sectoral policies; (3) tools capable of assessing at different spatial scales; and (4) tools capable of simulating future scenarios at different temporal scales. Nonetheless, to the best of our knowledge, methodologies or tools that consider all these criteria have not been identified. Therefore, to address this research gap, further investigation is required. According to Orimoloye (2022), the confluence of academic ideas and actual execution is essential for addressing the management, governance, and policy difficulties of the nexus.

The overarching objective of this study is to contribute to the joint governance of water, energy, and food resources by developing a solution evaluation framework (GoNEXUS SEF) to co-design and evaluate nexus solutions. For this, the specific objectives are:

- Propose a novel methodological framework (GoNEXUS SEF) to co-design and evaluate nexus solutions.
- Demonstrate the utility and the functionality of this framework as a guide to support evidence-based decision-making, through the application to a practical case study.

The GoNEXUS SEF is a novel framework that allows the identification and evaluation of nexus solutions by integrating various qualitative and quantitative methodologies through systemic approaches. For the evaluation, we also present nexus cross-impact analysis (N-CIA), a methodology that allows performing a nexus-coherence assessment to identify nexus solutions suitable to address cross-sectoral challenges. As a practical example, an irrigation water pricing solution scenario and its influence on water, energy, food security, and ecosystems conservation in the region of Andalusia, Spain is presented. Besides, this methodological framework can be easily replicated to other case studies, at different temporal and spatial scales. The framework includes stakeholder engagement to identify challenges, understand nexus interactions, co-design solutions, and generate results derived from dialogues. It also includes a modelling approach to simulate the solution scenario and obtain quantitative results. Finally, the framework integrates these dialogues and model results to analyse them with N-CIA, a systemic approach that allows for a cross-nexus impact analysis. The combination of all of these makes GoNEXUS SEF a novel evaluation framework in the study of the WEFE nexus.

The remainder of the paper is organised as follows: Sect. "State-of-the-art and need to develop a suitable methodological framework to operationalise the WEFE nexus" delves into the state-of-the-art nexus studies. "Development of a Solution Evaluation Framework for the WEFE nexus" explains the framework and the methodological approach. "Framework application through a practical case study" presents a practical case study and its results. "Discussion of findings" discusses the framework, methodology, and results of the practical case study. Finally, in "Concluding remarks", relevant points are outlined, and conclusions are drawn.

State-of-the-art and need to develop a suitable methodological framework to operationalise the WEFE nexus

Methods and tools review

Since the first mentions of the water-energy-food nexus approach at the World Economic Forum annual meeting in 2008 (World Economic Forum 2011a), the Global Risks 2011 (World Economic Forum 2011b) and the 2011 Bonn Conference (Hoff 2011), the nexus perspective has gained thrust in policy and science arenas (Orimoloye 2022; Purwanto et al. 2021). The WEFE nexus approach analyses the interactions between the different sectors and has the potential to reduce trade-offs, build synergies, and improve nexus governance (Hoff 2011).

To analyse the WEFE nexus and determine the synergies and trade-offs across sectors, several tools have been developed in recent years. For example, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is a multi-model tool used to assess the water, energy, and food nexus at the national or sub-national level (Giampietro et al. 2013, 2022). CLEWs (Climate, Land-use, Energy, and Water strategies) focuses on assessing nexus interlinkages using complex sectoral models for water, energy, and land use (Howells et al. 2013; Muñoz-Castillo et al. 2019). The WEF Nexus Tool 2.0 is a multi-stakeholder water, energy, and food resource allocation strategy assessment tool that identifies potential current and future nexus interlinkage bottlenecks to overcome resource stress challenges (Daher and Mohtar 2015; Lee et al. 2020). There are multiple other nexus tools such as WEF Nexus Index (Simpson et al. 2020); PRIMA (Kraucunas et al. 2015); WEF Nexus Assessment 1.0 (Flammini et al. 2014); Foreseer (Allwood et al. 2016; Price et al. 2018); Q-Nexus model (Karnib 2017; Karnib and Alameh 2020); EWF Nexus Tool (Al-Ansari et al. 2015); Pardee RAND WEF Security Index (Willis et al. 2016); and many others (Taguta et al. 2022; Sušnik and Staddon 2021; Stylianopoulou et al. 2020; Albrecht et al. 2018).

These tools have brought advances and fundamental insights to nexus study; however, these tools still have various shortcomings. For instance, the nexus is typically analysed through sectoral models as separate resource systems with distinct flows between them, rather than as a holistic system (Stylianopoulou et al. 2020; Cairns and Krzywoszynska 2016). Stylianopoulou et al. (2020) reported that "regardless of the continuing global interest in the nexus, the interpretation of the interconnections of these elements remains limited, and this has been proven by the number of studies that still focus on only one element among water, energy or food to explore the Nexus, instead of finding new methods and tools to interrelate all the WEF elements". While most of these tools only address the water-energy-food nexus, they often neglect the environmental or ecosystem resources, which are transversal to the nexus and play a fundamental role in resource management (Fernandes Torres et al. 2019). Furthermore, these tools usually analyse the variation of flows among nexus sectors for different scenarios without considering the temporal scale, which is a key variable for policymaking and nexus governance (Pahl-Wostl et al. 2021).

Overall, these tools have a high degree of complexity. On the one hand, simpler tools tend to have less analytical capacity because of their lower granularity, which limits their applicability. On the other hand, more complex tools generally allow for more detailed analysis, such as scenario analysis, but also require a higher skill set to operate or apply (Dargin et al. 2019), and policymakers often see the WEFE nexus as a black box (Xu and Yao 2022), making it difficult to govern the nexus puzzle. Overall, most of these tools have limitations that can result in shortcomings when analysing the nexus.

Based on the nexus literature review, we have identified the aspects that we consider relevant in WEFE nexus tools and methodologies:

- The holistic assessment of the nexus and its sectors (Stylianopoulou et al. 2020; Cairns and Krzywoszynska 2016).
- Application of robust systemic approaches to achieve a more comprehensive analysis of nexus interlinkages (Purwanto et al. 2021; Sušnik and Staddon 2021; Wu et al. 2021; Sušnik et al. 2021; González-Rosell et al. 2020).
- The use of multiple methods to identify innovative ways to tackle the nexus, emphasising the integration of quantitative and qualitative approaches (Sušnik and Staddon 2021; González-Rosell et al. 2020; Albrecht et al. 2018).
- Participatory approaches engaging multisectoral stakeholders (Sušnik and Staddon 2021; Zhang et al. 2021; de Andrade Guerra et al. 2021; González-Rosell et al. 2020; Martinez et al. 2018; Hoolohan et al. 2018; Mohtar and Daher 2016).
- Assessing nexus interlinkages across sectors considering temporal scales through projections (Sušnik et al. 2022; Lawford 2019; McGrane et al. 2019; Pahl-Wostl et al. 2021).
- Adaptable methodologies to assess different spatial scales according to the scope of governance: local, regional, river basin, national, continental, or even global (Taguta et al. 2022; Pahl-Wostl et al. 2021; Purwanto et al. 2021; Lawford 2019; McGrane et al. 2019).
- Clear methodologies that can be used to understand nexus interlinkages, synergies, and trade-offs in nexus policy assessments (Xu and Yao 2022; de Andrade Guerra et al. 2021).
- The application of the nexus approach to real and practical studies (Simpson and Jewitt 2019; Purwanto et al. 2021).
- Adequate data and information to address nexus knowledge needs (Meng et al. 2023; Orimoloye 2022; Purwanto et al. 2021; Lawford 2019).
- Tools capable of simulating future scenarios and assessing interactions between policy objectives (Lee et al. 2020; González-Rosell et al. 2020; Muñoz-Castillo et al. 2019; Price et al. 2018; Al-Ansari et al. 2015; Willis et al. 2016).
- Incorporating nexus transversal components related to climate, environment or ecosystems (Kellner 2022; Khan et al. 2022; Dagar et al. 2021; Udias et al. 2018; Sušnik et al. 2018; De Strasser et al. 2016).

Gaps identification

From the aspects identified above and based on our previous experience, we selected four criteria that are crucial to operationalize the nexus: (1) tools that integrate quantitative and qualitative information; (2) tools capable of analysing cross-sectoral policies; (3) tools capable of assessment at different spatial scales; and (4) tools capable of simulating future scenarios at different temporal scales. Figure 1 shows the different tools and methods (from Sect. 2.1), and whether they comply with these aspects. The figures show a gap in the centre, where the four aspects converge, we do not find tools that meet all these crucial aspects.

In this sense, shortcomings still exist when operationalising the WEFE nexus. According to Simpson and Jewitt (2019), no nexus method fits all situations and scenarios. However, more than a methodology or tool, in this study, a methodological framework is proposed. Most of the analysed methods and tools have their own methodological framework and there are also other frameworks in the nexus studies (e.g. Daher et al. 2017; Papadopoulou et al. 2020). Unlike these other frameworks, our framework focuses on achieving policy objectives and allows researchers and policymakers to design and evaluate solutions capable of addressing nexus challenges. That is, to the greatest extent possible, it is a framework that integrates different methods and considers the crucial aspects identified in nexus studies. Accordingly, Taguta et al. (2022) mentioned that researchers and developers should consider utility, transferability, and scalability across uses and users when improving existing and developing new nexus tools so that the approach can be adapted to tailor each situation. Furthermore, Stylianopoulou et al. (2020) reported that it is necessary to establish new holistic frameworks of approach that can interlink WEFE nexus resources and be useful for all current and

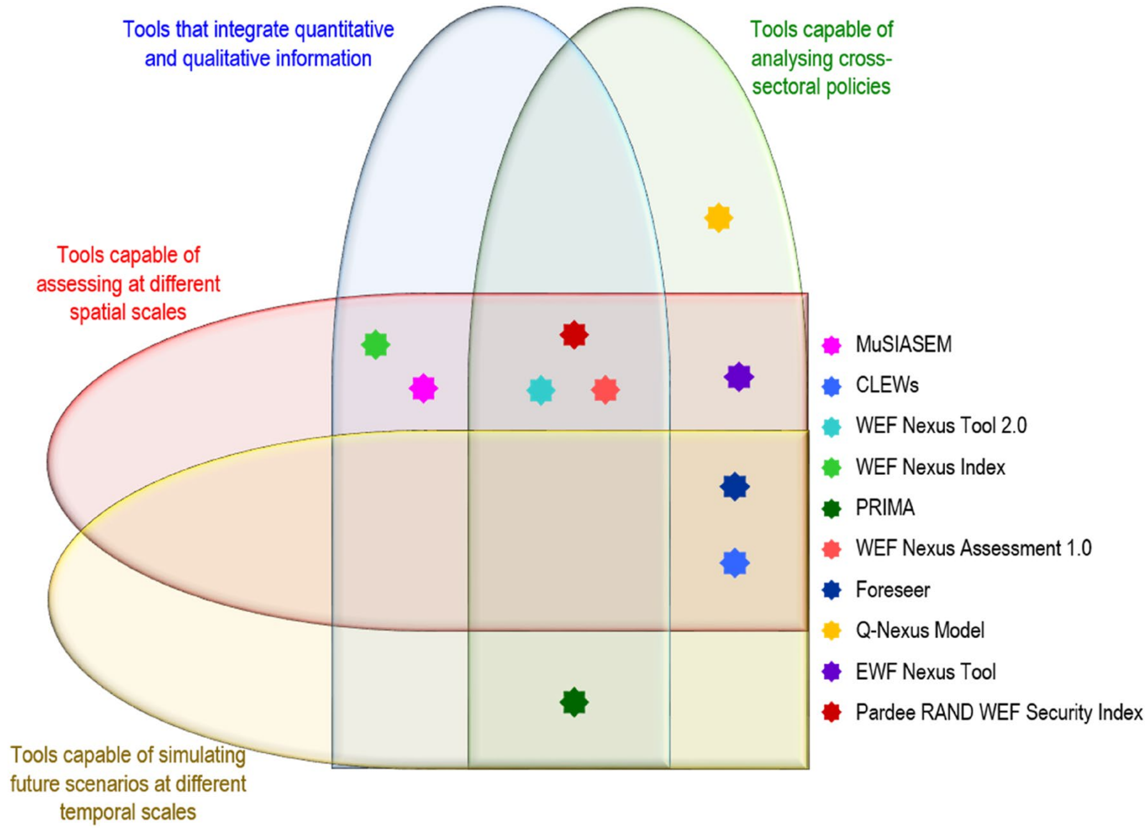

Fig. 1 Identifying the gaps in WEFE nexus tools and methods. Source: Own elaboration

future research. The development of this methodology is a major contribution for researchers and policymakers, as it will enable the design, evaluation, and subsequent coordination of policies to govern the WEFE nexus in a more holistic manner and drive the transition to sustainability.

Development of a Solution Evaluation Framework for the WEFE nexus

Solution Evaluation Framework (GoNEXUS SEF)

Taking these aspects into account, we present the GoNEXUS Solution Evaluation Framework (GoNEXUS SEF) which aims to co-design and evaluate nexus solutions to perform comprehensive analyses and improve the governance of the WEFE nexus. The GoNEXUS SEF is a framework with a participatory process capable of integrating different qualitative and quantitative methods according to the requirements of each case study. In the context of the WEFE nexus approach, we define a nexus solution as a policy, measure, or instrument of a technical, operational, and/or institutional nature, which aims to address challenges within one or more sectors of the nexus, analysing those challenges as a holistic system.

This methodological framework was designed by the authors from scratch and has 5 phases and 12 steps (Fig. 2). Although there is a logical sequence, these steps are not necessarily in sequential order. The process is dynamic and iterative; it has several interconnected phases and feedback loops, some steps are part of different phases, and others occur in parallel or are repeated several times throughout the entire process. The phases of the process are as follows:

A. Identify nexus solutions: Identify and prioritise solutions capable of addressing relevant nexus challenges and achieving policy objectives, considering the socioeconomic, political, climatic, territorial, land use, and technological factors, and governance context. This phase is performed jointly between stakeholders and researchers; in this sense, the process follows the bottom-up and top-down approaches.
B. Nexus dialogues: Engage cross-sectoral dialogues with stakeholders to promote collective understanding of the nexus interconnections, validate, and generate new evidence for the case study and solution.

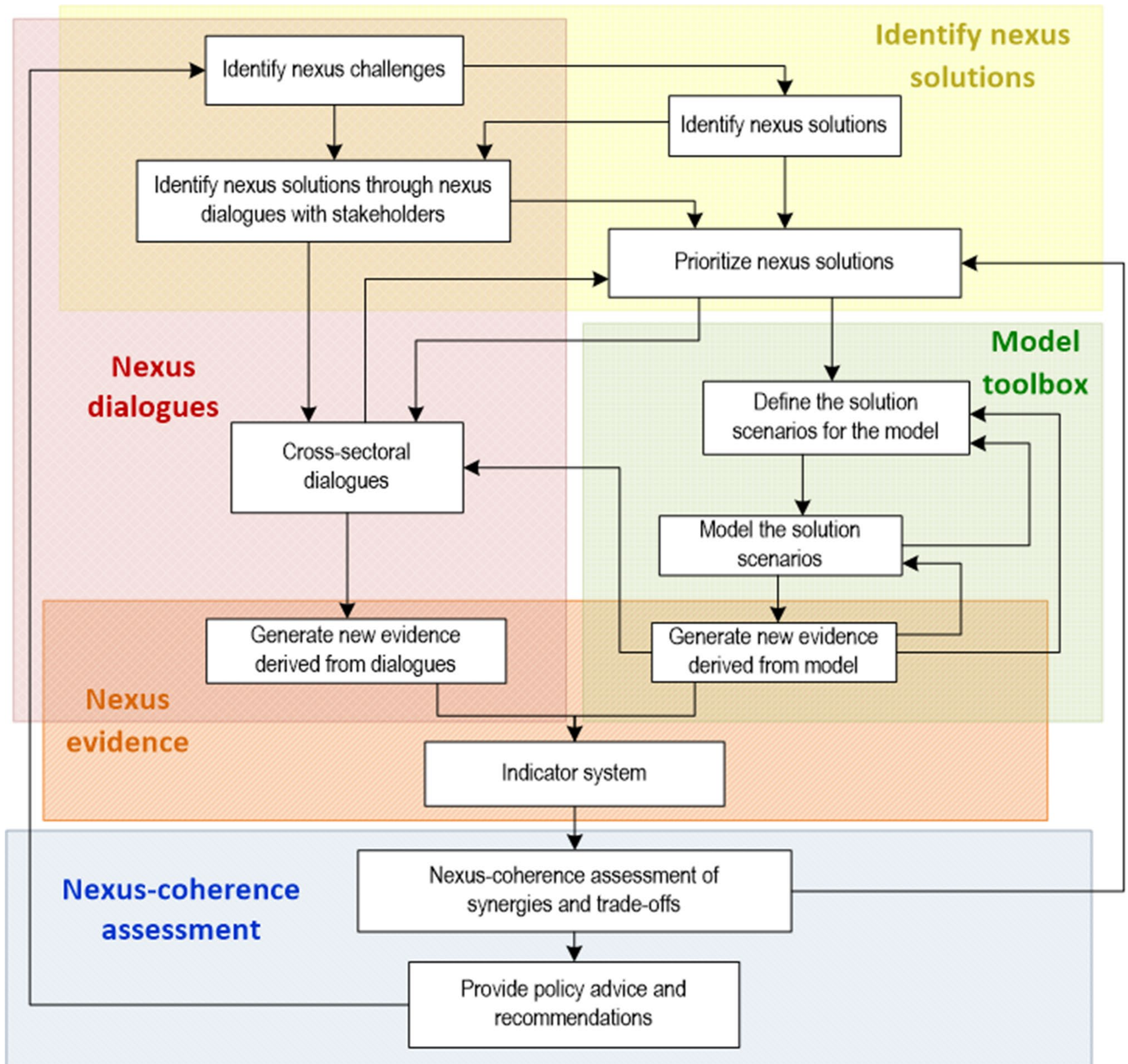

Fig. 2 GoNEXUS Solution Evaluation Framework. Source: Own elaboration

C. Model toolbox: Use a powerful model toolbox (one or various models) to generate new quantitative evidence for the solution scenario(s) in the case study.
D. Nexus evidence: Compile the new qualitative and quantitative nexus evidence generated from the dialogues and model toolbox through an indicator system for the case study and solution(s).
E. Nexus-coherence assessment: Perform a nexus-coherence assessment to identify nexus synergies and trade-offs to provide policy recommendations for case studies and solution(s).

In more detail, the process is divided into 12 steps as follows:

1. Identify nexus challenges (phases A and B): Diagnosing nexus challenges allows us to understand the main nexus issues and provide first clues of potential solutions.
2. Identify nexus solutions (phase A): Identify solutions based on a literature review, past and current policy measures, and objectives to address the previously identified nexus challenges.

3. Identify nexus solutions through nexus dialogues with stakeholders (phases A and B): This step complements the "identify nexus solutions" step and covers potential solutions identified by stakeholders that have not been previously identified by researchers. Additionally, if stakeholders identify a solution that has previously been identified by researchers, it validates the relevance of that solution.
4. Prioritise nexus solutions (phase A): This step condenses the previous identification steps by selecting the most relevant solution(s) for the case study.
5. Define the solution scenarios for the models (phase C): The solutions selected must be defined in terms of the models, which implies defining the input and output variables, solution boundaries, data sources, implementation period, and solution analysis period, among other considerations.
6. Model the solution scenarios (phase C): The solution scenario is translated into a programming language where the model of the case study is written and can be simulated.
7. Generate new evidence derived from models (phases C and D): The evidence derived from the model is generated by simulating the solution scenarios and obtaining projections of the different WEFE nexus indicators.
8. Cross-sectoral dialogues (phase B): The cross-sectoral dialogue is a complex and iterative process in which selected solutions are validated, the data generated from solutions are analysed, and how the solutions affect and interact with the different parts of the nexus are discussed. This process occurs through a series of interviews and workshops with stakeholders from different nexus sectors.
9. Generate new evidence derived from dialogues (phases B and D): New qualitative and quantitative information for the case study is generated from the dialogues.
10. Indicator system (phase D): The information that comes from the dialogues and models is collected and unified through a system of indicators.
11. Nexus-coherence assessment of synergies and trade-offs (phase E): The impacts of the solution on water, food, and energy security, and the conservation of ecosystems are evaluated.
12. Provide policy advice and recommendations (phase E): In this last step, the results obtained from the evaluation of the different solutions are collected to provide coherent policy advice and recommendations for the case study.

From the five phases presented in the evaluation framework, we focus on detailing the nexus coherence assessment phase methodology. The remaining phases are described in more detail in "Framework application through a practical case study".

Nexus-coherence assessment

Highlights of Nexus cross-impact analysis

To perform a nexus coherence assessment, we propose applying a cross-impact analysis (CIA) methodology adapted to analyse the WEFE nexus. Weitz et al. (2018) already used CIA to analyse Sustainable Development Goals (SDGs). Zelinka and Amadei (2019a, b) also used CIA combined with system thinking to study SDGs and reported that hard systemic approaches are required to extract a deeper understanding of complex systems. In our case, to be able to study the WEFE nexus and the impacts that a nexus solution has on a multi-sectoral nexus system, we modified and adapted CIA into nexus cross-impact analysis (N-CIA) methodology.

The N-CIA is a quantitative methodology that evaluates how the implementation of one or several solutions impacts a WEFE nexus system by measuring the impacts on a series of WEFE nexus objectives in terms of synergies (reinforcement) and trade-offs (counteraction) relationships. This methodology is an analytical method that combines the results from nexus dialogues (stakeholder engagement) and a model toolbox (one or several models) to integrate qualitative and quantitative information. It is a systemic approach that can be applied to different case studies, considering their own given context with their specific geography (spatial scale), time period (temporal scale), governance arrangements, and technological options.

This makes it very useful for conducting a cross-sectoral assessment of nexus solutions and analysing the WEFE nexus as a holistic system. N-CIA uses a seven-point typology (adapted from Nilsson et al. 2016a) to develop a cross-impact matrix that describes the influences of a network system comprising the solutions and an indicator system. Based on the matrix, network theory (Newman 2003) is applied to analyse the network system and calculate second-order influence to next determine the impacts on the nexus. This methodology seeks to evaluate to what extent a solution contributes to achieve policy objectives in the water, energy, food and ecosystems domains.

Cross-impact matrix

The core of N-CIA is a cross-impact matrix, a system typically presented by an $(n \times n)$ matrix (Gordon and Stover 2003). The components (n) of the matrix are indicators from the indicator system (Step 10 of the framework) and the identified nexus solutions. The matrix is filled based on the seven-point typology (adapted from Nilsson et al. 2016a,

b) and the scoring is guided by analysing how the indicator or solution found in the row influences that in the column. The typology ranges from − 3 to + 3 (− 3 influence substantially reduces the amount of other indicators; a − 2 influence reduces the amount of another indicator; a − 1 influence slightly reduces the amount of another indicator; 0 has no positive or negative influence; a 1 influence slightly increases the amount of another indicator; a 2 influence increases the amount of another indicator; and a 3 influence substantially increases the amount of other indicators). This stage of the process is key, and correctly identifying the interactions between the different indicators is essential for successful analysis. The assigned score between the indicators is based on the evidence generated from the dialogues through interviews and workshops with stakeholders and experts. The assigned score for the influence of a nexus solution on an indicator is based on the result obtained from the scenario of a solution modelled in the model toolbox. Thus, in the N-CIA methodology, soft and hard approaches are combined to feed the cross-impact matrix.

The influences of each indicator or solution can be added by row and column to obtain the descriptive information of the matrix. The column-sum adds the net influence of an indicator over all other indicators, and the row-sum adds the extent to which the indicator is influenced by all other indicators (for a methodological example, see Fig. 4). The matrix provides the first analytical scope of how the indicators interact; however, more powerful tools are required to analyse the information in depth.

Network theory analysis to assess the impacts on the WEFE nexus

Once the cross-impact matrix is elaborated, network theory tools and techniques (Newman 2003) are used to identify systemic and statistical properties and characterise the structure and behaviour of a networked system. In GoNEXUS SEF, the impacts of a solution on the WEFE nexus are measured in three stages.

In the first stage, using network graph models and network theory analysis, we can elucidate the meaning of network properties, how they came to be as they are, and the interactions between different elements. In the network graph applied to analyse a nexus solution, each node represents an indicator or solution and is connected to another node through an edge or arrow according to the corresponding influence (seven-point typology) of the cross-impact matrix. The network graph allows visual analysis of the interrelationships throughout the entire network (for a methodological example see Fig. 6a); however, it is necessary to quantify the influences of a solution on the different sectors of the WEFE nexus.

In the second stage, we quantify the influences of the solution on the indicator system, up to the second order. The total influence at the second order, or simply the total influence, is calculated by adding the first-order influences to the second-order influences of the solution over the network system of indicators. First-order influences are easier to calculate because they are the influences placed directly in the matrix. Second-order influences are the indirect influences of the solution at the second degree; they consider the influences of the indicators that the solution previously influences. The tree network graph (for a methodological example, see Fig. 4b) allows visualisation of the paths of first and second influences in an orderly manner. The solution is placed at the beginning, followed by a series of indicators corresponding to the first order and next to the second order, in such a way that it is possible to identify how the influences propagate through the network. The influence of one node on another is represented by an arrow, for example $S \rightarrow V_i$ represents that the solution influences the indicator V_i. Notably, first-order indicators can be the same as second-order indicators, only at different levels of influence.

Total influence (I^{Total}) is calculated according to Eq. (1):

$$I^{\text{Total}} = \underbrace{\sum_i I_i^{S \rightarrow V_i}}_{\text{First order}} + \underbrace{\frac{1}{2} \sum_{i,j} \left(I_i^{S \rightarrow V_i} \times I_{i,j}^{V_i \rightarrow V_{j}\_2} \right)}_{\text{Second order}}, \tag{1}$$

where i is the edge of the solution S node and the indicator V_i node; therefore, $I_i^{S \rightarrow V_i}$ is the influence of the solution on the indicator at the first order. Similarly, j is the edge of the indicator V_i node and the indicator V_j_2 node; therefore, $I_{i,j}^{V_i \rightarrow V_j\_2}$ is the influence of the first indicator on the second. Conceptually, the V_i indicators are the same as the V_j_2 indicators but at different orders of influence. An indicator cannot influence itself; therefore, in all cases, $i \neq j$.

In certain cases, the solution has no direct connecting path to an indicator and the connection passes through another indicator. In network theory, the geodesic path is the shortest path through a network from one node to another (Newman 2003). Because we are calculating the influences in the second order, it is important to determine the geodesic paths of the solution in such a way that there are no geodesic paths > 2, or that these are as small a percentage as possible according to each case, to adequately evaluate the solution with the N-CIA methodology. Additionally, the mean geodesic path is the average of the geodesic paths of a node. The lower the mean geodesic path of a solution, the more direct the influence on the indicator system; in general, the lines indicate that the mean geodesic path of the solution must be between 1 and 2.

In the third stage, by applying nexus weights to each indicator, we measure the impacts (synergies and trade-offs) of a solution on the WEFE nexus (i.e., food, energy, and water security, and ecosystems conservation). Thus far, we have calculated the degree of influence of a solution on a series of indicators. The aim of this analysis is to determine the synergies and trade-offs that a solution (or solutions) has on the WEFE nexus. Moreover, we simulate the behaviour of the nexus system based on structural properties and local rules. To measure the impacts on food, energy, and water security, and ecosystems conservation, or over a series of policies and nexus objectives, first, the nexus weights of the selected indicators must be identified. To make this identification, a detailed analysis of each indicator must be conducted, and the effect that each indicator has on each related nexus objective must be weighted in a range from 0 to 1 in such a way that the total sum of the effects of an indicator on all nexus objectives must sum up to 1. It is also important to determine whether the effect is positive or negative; therefore, a positive or negative sign to the weighted effect must be added (for a methodological example, see Fig. 7). This weighting can be achieved through dialogue with stakeholder experts and/or researchers.

Subsequently, these weights are applied to calculate the influences on the nexus sectors (I_{n}) according to Eq. (2):

$$I_{\mathrm{n}} = \sum_{i} (I_i^{S\rightarrow V_i} \times W_{i,n}^{V_i}) + \frac{1}{2} \sum_{i,j} \left(I_i^{S\rightarrow V_i} \times I_{i,j}^{V_i\rightarrow V_{j}\_2} \times W_{j,n}^{V_{j}\_2} \right) \ldots \forall n, \quad (2)$$

where n represents the different nexus sectors (i.e., water, energy, food, and ecosystems) or policy objectives. $W_{i,n}^{V_i}$ and $W_{j,n}^{V_{j}\_2}$ are the nexus weights of sector n of indicators V_i and V_j_2, respectively.

For a deeper analysis, positive influences can be identified and added to determine the synergies. Likewise, negative influences can be identified and added to determine the trade-offs of the solution in different nexus sectors.

The unit of measurement is the network's own impact index, which measures the intensity of the impact on the different sectors of the nexus (policy and nexus objectives) to identify synergies and trade-offs from one or several solutions. To analyse the results, it must be considered that, in the reference scenario (in which no solution is applied), all influences, both first and second order, are null.

Framework application through a practical case study

The solution presented as a practical example of the methodological framework is the water pricing (WP) increase in the region of Andalusia, Spain. An increase of €0.02/m^3 (point zero two euros per cubic meter) in the price of irrigation water is applied, and the impacts on nexus policy objectives, and therefore on the water, energy, food security, and conservation of ecosystems are measured in the medium term, the year 2030. We chose 2030 because it is a middle term that is aligned with the fulfilment of various policy objectives, such as the SDGs.

The case study results for the GoNEXUS SEF phases of identifying solutions, nexus dialogues, and the model toolbox were collected in a series of previous studies. Martinez et al. (2017) developed parts of the phases of identifying solutions and nexus dialogues, emphasising the identification of challenges. Alternatively, Martinez et al. (2018) complemented the phases of identifying solutions and nexus dialogues through interviews and workshops with stakeholders, applying Fuzzy Cognitive Mapping (FCM) methodology, which represents the behaviour of nexus systems based on stakeholders' perceptions. González-Rosell et al. (2020) developed a toolbox phase using a participatory system dynamics model (SDM) for Andalusia and analysed the WP solution scenario.

We combined the results of these studies and analysed them using N-CIA for nexus coherence assessment. FCM is a soft systems approach, while SDM is a hard systems approach, therefore, N-CIA harnesses the benefits of both approaches by combining the results into a mixed-approach analysis. The framework process and nexus coherence assessment results for the practical case study are presented below, according to the GoNEXUS SEF and N-CIA methodology.

Challenges, policy objectives, and nexus solution identification

The first steps within the methodological framework are the identification of challenges, policy objectives and nexus solutions for the case study. Agriculture plays an important socioeconomic role in Andalusia; the region is one of the main global producers of olives and one of the main European suppliers of fruit and vegetables. Andalusia has approximately one million hectares of irrigated agricultural area, and although 84% of the total irrigated area uses modernised irrigation systems, the agricultural sector consumes > 80% of the regional water withdrawals (INE 2020). The high levels of water demand and increasing effects of climate change have added pressure on water resources, generating high levels of water stress, soil erosion, and desertification in all Andalusian River basins (Blanco et al. 2017; Paneque et al. 2018). In addition, the high degree of modern irrigation systems entails higher energy consumption, and therefore a considerable dependence on the energy sector (García et al. 2014). In turn, higher energy consumption leads to higher greenhouse gas (GHG) emissions, thereby aggravating the effects of climate change.

We, together with a panel of 14 stakeholders and experts from the water, energy, food, and ecosystems conservation sectors in Andalusia, identified six general nexus challenges in the region through nexus dialogues (Martinez et al. 2017). The challenges are as follows:

- Sustainable management of water resources
- Mitigation and adaptation to climate change
- Energy efficiency and promotion of renewable energies
- Combating soil erosion and desertification
- Food production efficiency in the use of resources
- Sustainable socio-economic development

Likewise, we identified and listed the different policy objectives in Andalusia (Brouwer et al. 2020). From this list, we have selected the most relevant policy objectives for this study. These selected objectives are shown in Table 1, and we analyse the WEFE nexus objectives that each policy objective addresses.

The analysis of the challenges and objectives in Andalusia highlights the need to analyse policies that deal mainly with pressures on water, but also on energy and ecosystems while promoting its sustainable use and economic development of the food and agricultural sectors. In this sense, stakeholders have identified water-pricing measures as one of the main solutions for achieving water security in the region. In addition, the Water Framework Directive of the European Union (EU) considers that cost recovery of water services through economic instruments such as water pricing can improve the management of water resources and boost

Table 1 Policy and nexus objectives in Andalusia

Policy objectives in Andalusia			Nexus objectives*
Code	Name	Description	
O1	Conservation of water bodies	Good ecological status of all water bodies Introduce measures to reduce diffuse pollution, both for ground and surface water, caused by inadequate use of fertilisers and pesticides	*Water quality* *Water availability* *Reduce water consumption* **Water ecosystems**
O2	Rational water use	Rational water use to ensure long term water supply Achieve an effective and efficient use of water for irrigation through improving water saving Reduce irrigation water use through improving irrigation infrastructure and monitoring systems	*Reduce water consumption* *Water efficiency*
O3	Promote regenerated and desalinated water use	Improve water availability in irrigated areas in particular through regenerated and desalinated water	*Water availability*
O4	Promote energy saving	Obtain 25% of energy saving	***Energy efficiency*** ***Reduce energy consumption***
O5	Promote renewable energy	Provide 25% of energy consumption from renewable sources Decarbonise 30% of the energy consumption with respect to the value of 2007 Obtain 5% self-consumption of electricity generated from renewable sources	***Renewable energy***
O6	Reduce greenhouse gas emissions	Reduce the greenhouse gas emissions by 18% in 2030 compared to the 2005 level, which equals approximately 4.28 tons of carbon dioxide (CO_2) per inhabitant and year	**Reduce emissions**
O7	Improve sustainable competitiveness of the agricultural sector	Improve the sustainable competitiveness of the agricultural and agro-industrial sectors Improve social and economic conditions to generate stable agrarian employment	<u>Food productivity</u> <u>Food supply</u> <u>Resilient agricultural sector</u>
O8	Ecological and territorial land use planning	Increase afforestation of agrarian lands Restoring, preserving, and enhancing ecosystems related to agriculture and forestry Closer coordination of urban and land use policies and instruments Prevent soil erosion and desertification	<u>Resilient agricultural sector</u> **Land ecosystems**

*For the nexus objective, water security in italics is divided into water efficiency, water availability, reduce water consumption, and water quality. Energy security in bolditalics is divided into energy efficiency, reduce energy consumption, and renewable energy. Food security in the underline is divided into food productivity, food supply, and the resilient agricultural sector. Ecosystems in bold are divided into reduced emissions, water, and land ecosystems. Source: Own elaboration economic efficiency and water sustainability (EU 2000; Berbel and Expósito 2020).

Indicator system

The indicator system is a list of 16 indicators selected from a series of nexus indicators identified by stakeholders in the dialogues and combined with a set of indicators available in the model toolbox (SDM). These are relevant and specific nexus indicators with their respective units of measurement. The indicator system and analysed nexus solution are shown in Table 2.

Model Toolbox: evidence derived from models

Explicit quantification of water-energy-food-ecosystems relations is imperative for the proper assessment of nexus solutions. In this study, we used a participatory SDM developed by González-Rosell et al. (2020), which is based on historical data and projections from different WEFE sectors in Andalusia. We focused on a WP scenario simulated up to 2030. The quantification of the scenario impacts was carried out by measuring the percentage variation between the WP and the baseline scenarios for the selected indicators (Fig. 3).

To properly assess the impacts of the solution on the nexus, it is essential to integrate qualitative aspects into the quantitative results. The following steps will show quantitative and qualitative integration using N-CIA.

Cross impact matrix

The cross-impact matrix is a 17 × 17 matrix (Fig. 4) comprising 16 indicators and the solution to be analysed. In this case, a single solution is shown; however, the methodology allows the analysis of several solutions within the matrix. The matrix was filled out taking into account the interrelationships between the indicators according to the stakeholders and measuring the impacts of the solution on the indicators using the results of the model toolbox. The seven-point typology was used to characterise the influence of the indicators according to the results of the FCM (Martinez et al. 2018). The results of the FCM are presented in ranges from − 1 to + 1, for which the respective conversion

Table 2 Water pricing solution and indicator system for the Andalusian case study. Source: Own elaboration

Code	Name	Description
WP	Water price increase (€0.02/m^3)	The solution presented is a €0.02/m^3 water price increase in irrigation water. Unit: euros per cubic meter
V01	Primary energy production (ktoe)	The total production of primary energy in the region. Andalusia does not produce fossil fuels, therefore primary production is renewable energy. Unit: kiloton of oil equivalent
V02	Water availability (hm^3)	The total water availability from conventional and non-conventional water sources in all the Andalusian river basins. Unit: cubic hectometre
V03	Irrigation water use (hm^3)	Total water use for agricultural irrigation. Unit: cubic hectometre
V04	Crops income (M€)	Total regional income from the cultivation of irrigation and rainfed crops. Unit: million euros
V05	GHG emissions ($ktCO_2eq$)	Total greenhouse gas emissions from industry, transport, services, residential, agriculture, and fishing sectors in the region. Unit: kiloton of carbon dioxide equivalent
V06	Utilised agricultural area (1000 ha)	The total area comprising arable land, permanent grassland, permanent crops, and kitchen gardens used by the holding. Unit: thousand hectares
V07	Irrigated area (1000 ha)	The total area of crops which are irrigated at least once in the annual agricultural cycle. Unit: thousand hectares
V08	Ecological focus area (1000 ha)	The area comprising forest and natural land, set aside and fallow land, and pulses crops. Unit: thousand hectares
V09	Percentage of renewable energy (%)	Percentage of energy that comes from renewable sources in the region. Unit: percentage
V10	Final energy consumption (ktoe)	Total final energy consumption in industry, transport, services, residential, agriculture, and fishing sectors in the region. Unit: kiloton of oil equivalent
V11	Energy efficiency (%)	Energy efficiency measures the amount of gross inland energy consumed from the total energy available for final consumption. Unit: percentage
V12	Crops average income (€/ha)	The average economic yield produced per hectare. Unit: euros per hectare
V13	Livestock income (M€)	Total regional income from livestock activities. Unit: million euros
V14	Irrigation water productivity (€/m^3)	The economic yield produced per unit of irrigation water use. Unit: euros per cubic meter
V15	Wastewater and desalinised water use (hm^3)	Water use from wastewater and desalinised non-conventional water sources. Unit: cubic hectometre
V16	Rainfed area (1000 ha)	The total area of crops which are not irrigated. Unit: thousand hectares

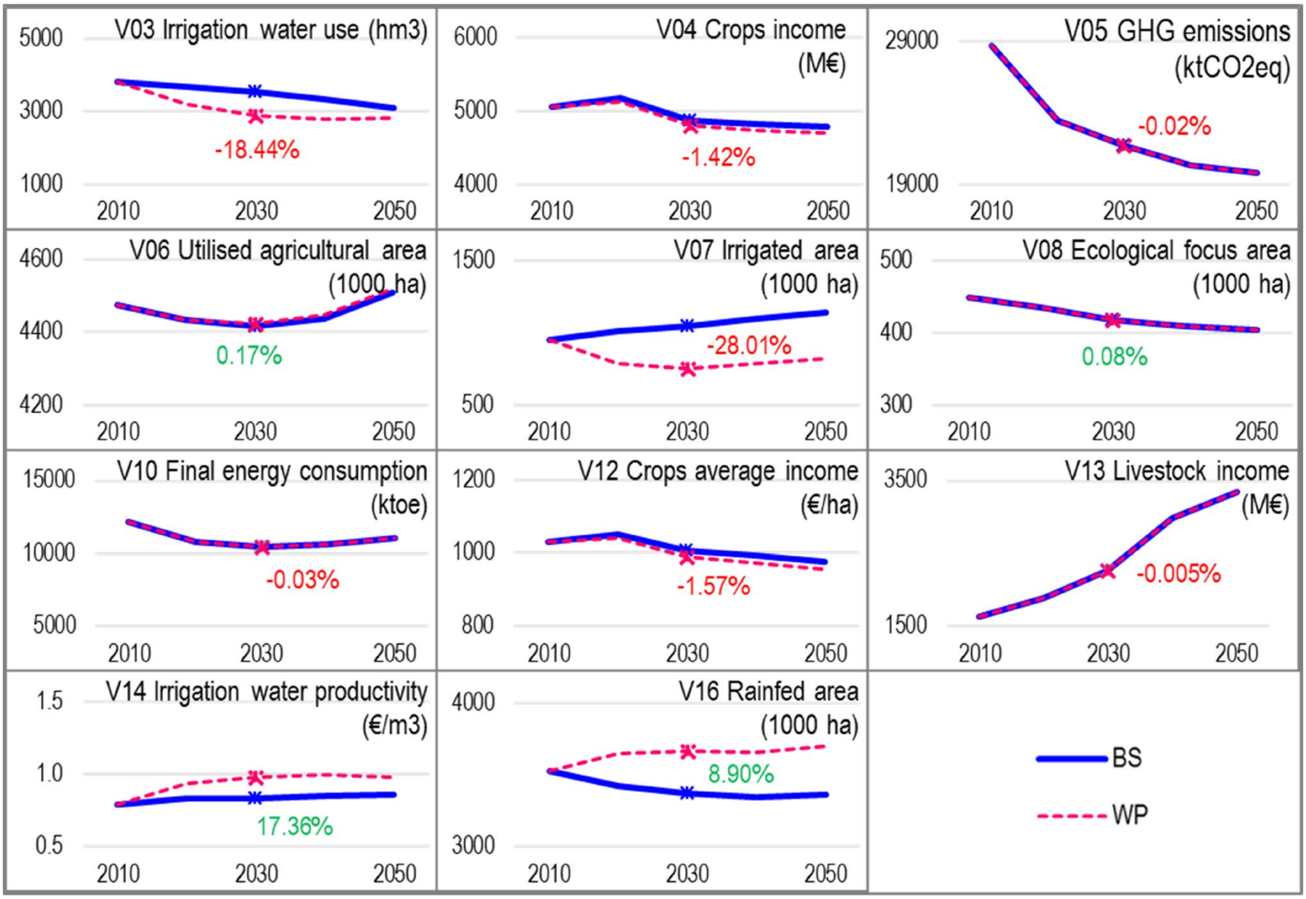

Fig. 3 Generation of new quantitative evidence: percentage of variation of indicators between the water price scenario (WP) and baseline scenario (BS) for the year 2030. Source: Own elaboration based on the participatory SDM results (González-Rosell et al. 2020)

to the seven-point typology was performed. Likewise, the seven-point typology was used to characterise the influence of the WP solution on the indicators according to the results obtained from participatory SDM (González-Rosell et al. 2020). In this case, the percentage of change in the indicators (see "Model Toolbox: evidence derived from models") was adapted to the seven-point typology.

As an indicator cannot influence itself, the diagonal of the matrix always has a null value. By counting the number of influences, we can determine that the matrix is populated by 27.2% without considering the diagonal. Likewise, it is possible to observe that the most positive influence (+03) is from indicator V02 on V03 and the most negative influence (−3) is from the WP solution on indicator V07.

Network theory analysis

According to the methodology, with network theory analysis, the structure and behaviour of the networked indicator system are characterised to analyse how the solution affects the nexus system. Some elements can be exploited in the cross-impact matrix (Fig. 4). In the column sum, we can identify the most influential indicators of the system: indicator V02 is the most positively influential (7), and indicator V01 is the most negatively influential (−5). Likewise, in the row-sum, we can identify the most influenced indicators: V12 is the most positively influenced indicator (5), and V2 is the most negatively influenced indicator of the system (−3). The net influence column is the sum of the column-sum and row-sum and allows the analysis of the balance of influences of each indicator. The sum of influences in the absolute values (SIAV) column adds the row and column influences in the absolute value, which allows the analysis of how much an indicator affects the system in general terms.

Figure 5 represents these elements to analyse the degree distribution of each node of the system and determine the number of connections that each node has. The abscissa axis represents the row sum (influence), and the ordinate represents the column sum (influenced). Each circle is an indicator; the size of the circle is the SIAV, and the colour is the net influence (green positive and red negative). In the first quadrant, indicators V04 and V12 stand out with

Code	WP	V01	V02	V03	V04	V05	V06	V07	V08	V09	V10	V11	V12	V13	V14	V15	V16	SUM	Net influence	SIAV
WP		0	0	-2	-1	-1	1	-3	1	0	-1	0	-1	-1	2	0	1	-5	-5	15
V01	0		-1	-1	0	0	-1	-1	0	0	0	0	0	0	0	-1	0	-5	-1	9
V02	0	1		3	1	0	0	2	0	0	0	0	0	0	0	0	0	7	4	12
V03	0	1	-2		1	0	0	1	-1	0	0	0	1	0	-1	0	0	0	-1	15
V04	0	1	0	0		1	0	1	0	0	0	0	2	0	1	0	0	6	10	12
V05	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	-2	4
V06	0	0	0	-1	1	0		1	0	0	0	0	1	0	0	0	0	2	0	8
V07	0	0	-1	0	1	0	-1		0	0	1	0	1	0	0	0	0	1	2	18
V08	0	0	0	0	0	0	-1	-1		0	0	0	0	0	0	0	0	-2	-2	4
V09	0	1	0	0	0	-1	0	-1	0		0	1	1	0	0	0	0	1	2	6
V10	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	4
V11	0	0	0	0	0	-1	0	0	0	0	-1		0	0	0	0	0	-2	0	4
V12	0	0	0	0	0	0	0	1	0	1	0	1		0	0	0	0	3	8	10
V13	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	-1	1
V14	0	0	0	0	0	0	0	1	0	0	0	0	0	0		0	0	1	3	5
V15	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0		0	2	1	3
V16	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0		1	2	2
SUM	0	4	-3	-1	4	-2	-2	1	0	1	0	2	5	-1	2	-1	1			

Fig. 4 Cross-impact matrix of the indicator system and solution from Table 2 for the water pricing in the Andalusia case study. Source: Own elaboration

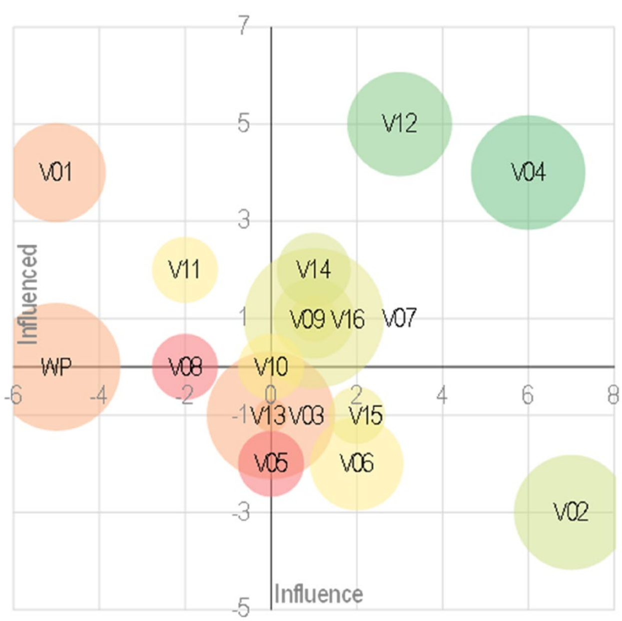

Fig. 5 Analysis of the degree of distribution of the network system based on the cross-impact matrix in Fig. 4. Source: Own elaboration

a more intense green colour according to the 10 and 8 net influences, respectively. In the first quadrant, indicator V07 had the largest SIAV, with a total of 18. The indicators with the lowest net influence were V08 and V05 with −2 in both cases.

The WP solution is located on the abscissa axis, and the influence of the indicators on the solution has not been determined because it was not a determining analysis for this case study. Alternatively, the WP solution has a net negative influence (−5) on the network system; however, we still have to determine its impact on the nexus system. To determine its impact on the nexus system, the N-CIA methodology must be applied. However, we first visualised the network system using a network graph model.

Figure 6a shows the network graph that represents the cross-impact matrix. It has 17 nodes, corresponding to 16 indicators and the WP solution. The size and colour of the edges represent the degree of influence according to the seven-point typology, and the size of the node is determined by the net influence. The solution is at the centre, and we see how it positively and negatively influences the other indicators. In addition, we can see how node V07 concentrates on the largest number of edges, and how nodes V04 and V12 concentrate on the input and output of

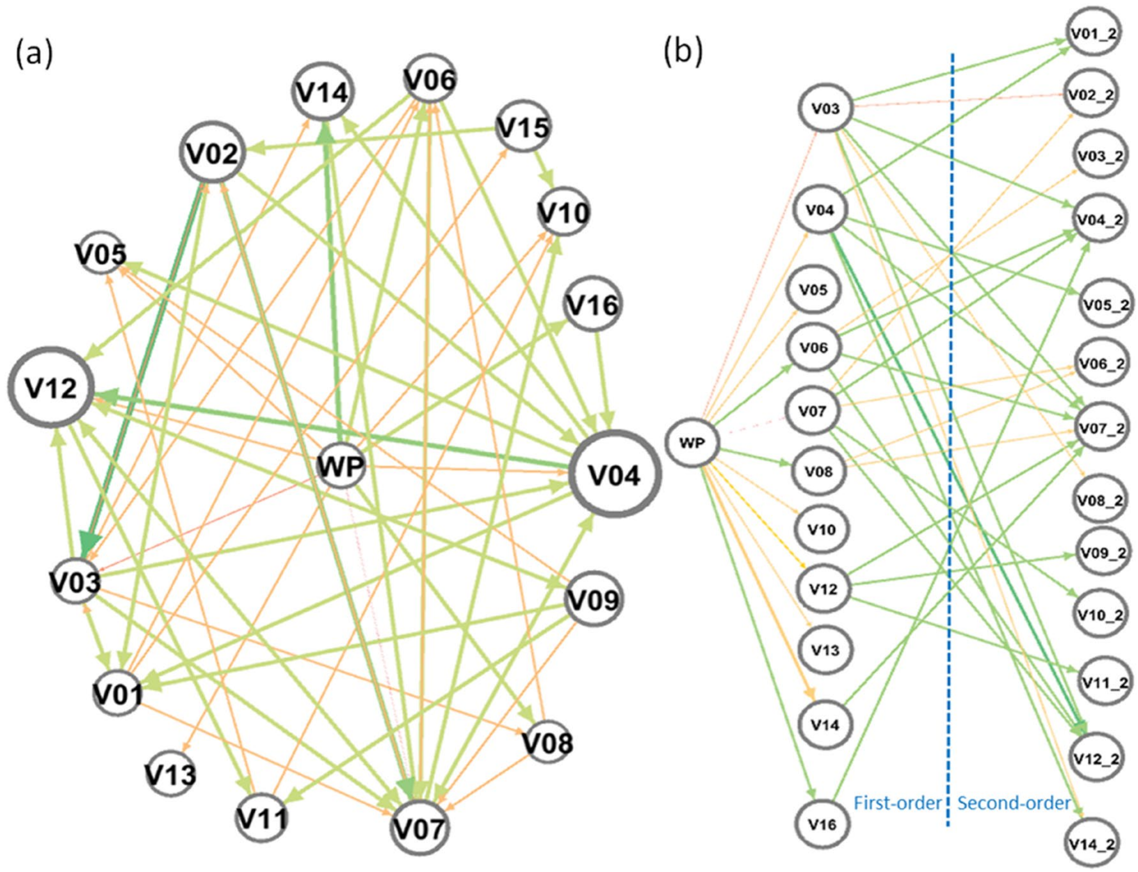

Fig. 6 **a** Full network graph: links between 16 indicators and WP solution based on the cross-impact matrix. **b** Tree network graph of the total influence of the WP solution in the first and second order based on the cross-impact matrix. Colour scale as in Fig. 4. Source: Own elaboration

several green (positive) edges. In contrast, node V13 had the lowest incidence of edges.

Before calculating the impact on the nexus, the tree network graph (Fig. 6b) provides the first visual inside of the paths of influences on the network in the first and second order and also allows visual evaluation of the geodesic paths of the WP node. At the first order of influence, we can see that the solution has a direct influence on 11 of the 16 indicators, and in the second order, it influences 13 indicators. In this case, there is only one geodesic path > 2 (V15), and the mean geodesic path is 1.31; therefore, the solution can be correctly analysed using the N-CIA methodology.

Impacts on the WEFE nexus results

The cross-impact matrix represents the interrelations between the indicators and the solution. Next step will be to analyse the synergies and trade-offs between nexus objectives. According to the N-CIA methodology, the effects of each indicator on Andalusian policy objectives and nexus objectives must be determined. In this case, the weighting of these effects was performed by the researchers based on information gathered from stakeholders in the nexus dialogues. Figure 7 shows these weights, where the first and second columns show the policy objectives and nexus objectives, as shown in Table 1, and the successive columns show how the weight of each indicator is distributed over nexus objectives. The effects of an indicator on the different nexus objectives can be positive or negative; however, if we add the column effects of each indicator in absolute values, we will see that they are distributed in such a way that the total weights add up to 1.

Applying Eq. (2) and considering the effects of each indicator shown in Figs. 7 and 8 shows the synergies and trade-offs of the WP solution on policy objectives in Andalusia. In addition, a heat map allowed us to identify the total tendency, green positives, and red negatives. We can observe that the positively influenced policy objectives are the conservation of water bodies (O1), rational water use (O2), promotion of energy saving (O4), reduction in greenhouse gas emissions (O6), and ecological and territorial land use planning (O8), while those negatively influenced are promotion of regenerated and desalinated water use (O3), promotion of renewable energy (O5), and

Policy objective	Nexus objectives	V01	V02	V03	V04	V05	V06	V07	V08	V09	V10	V11	V12	V13	V14	V15	V16
O1	Water quality		0.10	-0.05		-0.07	-0.03	-0.05	0.03					-0.05			
	Water availability		0.55	-0.10	-0.07	-0.08	-0.03	-0.05	0.10				-0.04		0.08		0.04
	Reduce water consumption	-0.05		-0.16	-0.04		-0.03	-0.05		-0.03			-0.02		0.03	0.10	0.02
	Water ecosystems	-0.05	0.10	-0.10		-0.10	-0.03	-0.05	0.05					-0.05	0.08		0.03
O2	Reduce water consumption			-0.11	-0.04		-0.03	-0.05					-0.03		0.12		0.03
	Water efficiency			0.12				0.07			0.06		0.05		0.40	0.10	
O3	Water availability										0.05					0.48	
O4	Energy efficiency									-0.10		0.40					
	Reduce energy consumption			-0.11	-0.05		-0.05	-0.07	-0.02		-0.58	0.30	-0.05		-0.20	-0.10	-0.02
O5	Renewable energy	0.70	0.10							0.52							
O6	Reduce emissions	-0.15		-0.05	-0.05	-0.55	-0.03	-0.05	0.06	0.30	-0.25	0.20	-0.02	-0.20	-0.01	-0.10	-0.02
O7	Food productivity		0.05	0.10	0.30	-0.05	0.10	0.20			0.03	0.10	0.30	0.25	0.04	0.03	0.10
	Food supply		0.05	0.10	0.30	-0.05	0.32	0.15	-0.09		0.03		0.22	0.23	0.04	0.04	0.20
	Resilient agricultural sector				0.15		0.10	0.05					0.21	0.20		0.03	0.20
O8	Resilient agricultural sector		0.05			-0.05	0.10	-0.10	0.05								0.20
	Land ecosystems	-0.05				-0.05	-0.15	-0.06	0.60	-0.05			-0.06	-0.02		-0.02	0.14

Fig. 7 Effect of each indicator on water, energy, food security, and ecosystems conservation for the Andalusia case study. Source: Own elaboration

improving sustainable competitiveness of the agricultural sector (O7).

Below, we describe how each policy objective is influenced by the WP solution by analysing the synergies and trade-offs according to the paths of influence between the indicators represented in Fig. 6b. For illustration purposes, we explain hereafter the results for the policy objectives (see Fig. 8). The conservation of water bodies (O1) has the greatest total influence; synergies (7.13) are observed mainly through paths WP→V03 and WP→V03→V02 mainly related to the decrease of the irrigation water use (hm3) (V03), and trade-offs (−0.84) are related to various small influences. Objective O2 (rational water use) has synergies (2.56) mainly through the path WP→V14 related to the increase of Irrigation water productivity (€/m3) (V14) and also has trade-offs (−1.53) related to various small influences. Objective O3 is the one with the smallest influence, with a total negative of −0.13, mainly through the path WP→V07→V10 related to the reduction of Irrigated area (1000 ha) (V07) and Final energy consumption (ktoe) (V10). Objective O4 has synergies (2.69), mainly through pathways WP→V07 and WP→V07→V10, and trade-offs (−1.32) through pathways WP→V14 and WP→V03→V14 related to the increase of Irrigation water productivity (€/m3) (V14). The objective of promoting renewable energy (O5) also has a small influence; the synergies (0.35) are due to the WP→V04→V01 pathway and are related to the indicator V06. O5 also had trade-offs (-1.31), mainly due to the WP→V03→V01 pathway. Objective O6 has a mostly positive influence (2.68) owing to the WP→V05 and WP→V07→V10 pathways. O6 also has some trade-offs (-0.51) related to various small influences. Objective O7 has the greatest negative influence; trade-offs predominate (-9.97) mainly from the WP→V03, WP→V07, and WP→V07→V04 pathways, related to the decrease of Irrigation water use (hm3) (V03), Irrigated area (1000 ha) (V07) and Crops Income (M€) (V04); however, synergies are also considerable (4.26), mainly from the WP→V06, WP→V16 pathways, related to increase of utilized agricultural area (1000 ha) (V06), mainly Rainfed area (1000 ha) (V16) and other small influences. Finally, O8 has mostly positive influences (3.56), mainly through the WP→V08 and WP→V16 pathways, related to increase of Ecological focus area (1000 ha) (V08) and Rainfed area (1000 ha) (V16). It also has a negative influence (−0.70) related to various small influences.

Similarly, in Fig. 8 we can see the influences on the nexus objectives. The heat map shows the general positive influences, except in the food sector and part of the energy sector. Overall, water security has a positive impact. Water availability and reduced water consumption have synergies (3.49 and 2.35, respectively) mainly through the paths WP→V03, WP→V07, and WP→V14, and both have trade-offs (−0.41 and −0.48, respectively) with various small influences. Water efficiency has synergies (1.33), mainly through paths WP→V03→V14 and WP→V14, and trade-offs (−1.26), mainly through path WP→V07. Water quality is the water security objective with the shortest influence, synergies (0.98) mainly between paths WP→V03 and WP→V07, and trade-offs (−0.15) between paths WP→V06.

Objectives		1st-Order (synergy)	1st-Order (trade-off)	2nd-Order (synergy)	2nd-Order (trade-off)	Total (synergy)	Total (trade-off)
Policy objectives	O1	2.59	-0.12	4.54	-0.72	7.13	-0.84
	O2	1.51	-0.59	1.05	-0.94	2.56	-1.53
	O3	0	-0.05	0	-0.08	0	-0.13
	O4	1.11	-0.49	1.58	-0.83	2.69	-1.32
	O5	0	0	0.35	-1.31	0.35	-1.31
	O6	1.38	-0.07	1.30	-0.44	2.68	-0.51
	O7	1.28	-3.91	2.98	-6.06	4.26	-9.97
	O8	1.75	-0.15	1.81	-0.55	3.56	-0.70
Nexus objectives – Water	Water availability	0.84	-0.08	2.65	-0.33	3.49	-0.41
	Reduce water consumption	1.32	-0.06	1.03	-0.42	2.35	-0.48
	Water efficiency	0.80	-0.56	0.53	-0.70	1.33	-1.26
	Water quality	0.40	-0.03	0.58	-0.12	0.98	-0.15
Nexus objectives – Energy	Reduce energy consumption	1.11	-0.49	1.53	-0.63	2.64	-1.12
	Energy efficiency	0	0	0.05	-0.2	0.05	-0.2
	Renewable energy	0	0	0.35	-1.31	0.35	-1.31
Nexus objectives – Food	Food productivity	0.33	-1.68	1.14	-2.515	1.47	-4.195
	Food supply	0.65	-1.52	1.36	-2.26	2.01	-3.78
	Resilient agricultural sector	1.00	-0.71	1.13	-1.49	2.13	-2.20
Nexus objectives – Ecosystems	Land ecosystems	1.05	-0.15	1.16	-0.35	2.21	-0.50
	Reduce emissions	1.38	-0.07	1.30	-0.44	2.68	-0.51
	Water ecosystems	0.74	-0.03	0.80	-0.16	1.54	-0.19

Fig. 8 Synergies (green) and trade-off (red) of the WP solution on policy objectives and nexus objectives in Andalusia. Source: Own elaboration

Regarding energy security, the total influence was also positive. Reduce energy consumption has high synergies (2.64), mainly between paths WP→V07→V10 and WP→V03→V10, while the trade-offs (− 1.12) are through the paths WP→V14 and WP→V03→V14. Energy efficiency is the nexus objective with the lowest influence, has synergies (0.05) with the path WP→V12→V11, and has trade-offs (− 0.2) with the path WP→V12→V09. Renewable energy has synergies (0.35) with the path WP→V04→V01, and trade-offs (− 1.31) with the path WP→V03→V01.

The most intense negative influence was observed in the food sector. Food productivity and food supply has high trade-offs (− 4.195 and − 3.78, respectively) through the paths WP→V03, WP→V07 and WP→13; however, they also have considerable synergies (1.47and 2.01, respectively) through the paths WP→V04 and WP→V06. Resilient agricultural sector has synergies (2.01), mainly through paths WP→V07 and WP→V16, and trade-offs (− 2.20), mainly related to the decrease in indicators V03 and V07.

Finally, regarding ecosystems conservation, land ecosystems have synergies (2.21) with paths WP→V07, WP→V08, and WP→V03→V08, and has trade-offs (− 0.5) with some small influences. Reduce emissions has synergies (2.68) with paths WP→V07→V10 and WP→V05 and also has trade-offs (− 0.51) with paths WP→V06 and WP→V04→V05. Water ecosystems have synergies (1.54) with paths WP→V03→V02 and WP→V07→V02, and trade-offs (− 0.19) with some small influences.

Discussion of findings

The WEFE nexus is a complex system with excessive cross-sectoral interactions; these features make the WEFE nexus very difficult to model and evaluate. According to Sušnik and Staddon (2021), there is no 'one-size-fits-all' nexus methodology, which is also due to the diversity in nexus challenges, spatial and temporal scales, and the focus of different studies. Rather than presenting a 'one-size-fits-all' methodology, this study presents an adaptable and flexible evaluation framework capable of suiting different case studies, considering their own given context with their specific geography (spatial scale), time period (temporal scale), governance arrangements, and technological options.

The GoNEXUS SEF is a framework that aims to co-design and evaluate nexus solutions capable of addressing cross-sectoral challenges. GoNEXUS SEF is a novel evaluation framework that combines qualitative and quantitative approaches through systemic approaches. The methodologies used for nexus dialogues and the model toolbox may vary and should be adequate for each case study. In this study, we present a practical case study that evaluates an irrigation water pricing scenario in Andalusia, Spain. FCM has been used for nexus dialogues (Martinez et al. 2018), and SDM for the model toolbox (González-Rosell et al. 2020). Finally, the N-CIA methodology combines and analyses these results in a clear manner, showing synergies and trade-offs in different nexus sectors, which gives it an advantage over other nexus assessment methodologies.

The main limitations of the proposed evaluation framework are the amount of time, effort, and resources required for execution. Completing all the process phases can take several years for a single case study. However, as previously mentioned, the WEFE nexus has complex cross-sectoral challenges that cannot be solved immediately; thus, an in-depth and detailed analysis is required. Therefore, a framework with analytical approaches that go beyond statistical data and guesswork is required. The second limitation is the reconciliation of the spatial and temporal scales. The spatial scale has limitations because the governance of the different sectors is often on different scales (i.e., local, provincial, regional, river basin, national, continental, and global scales). Temporary scales make it difficult to predict future cross-sectoral impacts. Stakeholders tend to align their predictions with their perceptions of compliance with policy objectives according to the fulfilment date. In the models, the analysis time was based on data projections and assumptions defined by the modellers. Therefore, it is necessary to align these scales to obtain adequate data and information. The third limitation is the integration of the qualitative and quantitative results. For this, we designed N-CIA; although the resulting measurement unit can be perceived as abstract, it allows the integration of both approaches. Various studies have used similar approaches (Malagó et al. 2021; Fernández-Ríos et al. 2021). Rather than seeing numerical results, this approach allows for the identification of the trend of synergies and trade-offs of a solution in each policy and nexus objective.

The main advantage of GoNEXUS SEF is that it complies with the crucial aspects identified in the literature to conduct significant cross-sectoral evaluations. The framework can be adapted to analyse any spatial scale of governance, also considering the temporal scale. Furthermore, stakeholder engagement can provide valuable insights that are often difficult to obtain through models; in contrast, models can provide factual information that is sometimes not anticipated by stakeholders. According to Dargin et al. (2019) "coordination between the stakeholders relevant to addressing specific resource challenges is necessary to generate the data required to quantitatively assess the synergies and trade-offs involved in the WEF nexus". Another advantage is that it allows the evaluation of multiple solutions and can assess the combinations of different solutions in a single nexus system. Some authors have mentioned that the analysis of multiple solutions is essential to perform a policy coherence assessment and present clearly articulated political options (Allouche et al. 2019; Simpson and Jewitt 2019). In this sense, future research could focus on performing nexus coherence assessments of various solutions.

Regarding the practical case study, the analyses and results shown are from an actual case study and help illustrate the application of the GoNexus SEF and N-CIA. We study how water pricing in irrigation water impacts different policy and nexus objectives in Andalusia, Spain, using 2030 as the period of analysis from the model toolbox. We selected 8 relevant policy objectives and 13 corresponding nexus objectives at the regional level.

The results show that the solution has positive effects on the conservation of water bodies (O1), the rational use of water (O2), and consequently on the availability of water, reducing water consumption, water efficiency, and water quality. Some studies corroborate this trend (Iglesias and Blanco 2008; Borrego-Marín et al. 2020), although Expósito and Berbel (2017) reported that the demand for water is inelastic, particularly in cases with deficit irrigation schemes. However, the results show that the irrigated area (1000 ha) has negative impacts, while the rainfed area (1000 ha) has positive impacts, which can be explained by the changes in irrigation systems from irrigation to rainfed irrigation in crops such as olives, which finally affects the water demand. This trend has been revealed by Borrego-Marín et al. (2020) and González-Rosell et al. (2020). Consequently, the decrease in the use of water and the change in the irrigation system have a positive impact on aquatic ecosystems. To promote the use of regenerated and desalinated water (O3), no studies have examined these effects. The results show a negative influence, although of low intensity, the trend seems logical given that the irrigated area decreases and less water is required, which discourages this objective.

In the food sector, improving the sustainable competitiveness of the agricultural sector (O7) has some positive influence; however, food productivity and food supply have a high negative effect. As previously mentioned, increasing water costs lead to a change in rainfed irrigation; thus, less food is produced, and in irrigated areas, production is more expensive. However, the transition to rainfed agriculture also has positive effects. It promotes energy saving (O4) and energy efficiency, and reduces GHG emissions (O6). This is because of the high correlation between energy consumption and irrigation systems. In addition, it increases the resilience of the agricultural sector due to less dependence on water and energy resources in the context of climate change and possible energy crises. Finally, intensive agriculture decreases, collaborating with the conservation of terrestrial ecosystems and territorial and ecological planning (O8).

In general, there is a sensitive relationship between water availability, irrigation costs and agricultural production, mainly due to the large investment made in irrigation systems. A water pricing policy, as a nexus solution, can encourage water savings to reduce overexploitation of water ecosystems and to overcome impending water scarcity. We recommend a policy coherent assessment, through the joint study of various policies complementing the water pricing policy, to reduce the trade-offs on agricultural productivity. Some potential complementary policies are the use of reclaimed water in irrigation, the improvement of energy efficiency in agriculture, or the change towards less irrigation-dependent crops.

Concluding remarks

In this study, we present a Solution Evaluation Framework (GoNEXUS SEF) that allows the operationalisation of the WEFE nexus approach through the co-design and evaluation of nexus solutions to improve governance across sectors. The GoNEXUS SEF is an adaptable framework that is suitable for analysing the nexus in different case studies at different spatial and temporal scales. It is also capable of integrating different methodologies from qualitative to quantitative. To perform the nexus-coherence assessment, the framework proposes the N-CIA methodology, a powerful tool for measuring cross-sectoral synergies and trade-offs, by combining model results and experts opinion, in an analytical approach that goes beyond model-projected data or stakeholders' guesswork. N-CIA highlights hidden properties and identifies leverage points and key aspects of a complex cross-sectoral system to apply nexus solutions more effectively to promote sustainable development.

Within this framework, the crucial aspects necessary to develop suitable methodologies capable of assessing the nexus were considered. This methodological framework was applied to a practical but real case study. Beyond the results obtained, the evaluation of this case allowed us to examine the applicability, usefulness, and potential of the framework. Although one solution has been analysed, the framework can evaluate various solutions. In this sense, future research could focus on conducting a policy coherence assessment with the GoNEXUS SEF. A participatory process that combines qualitative and quantitative approaches with systemic approaches appears to be the right way to design and evaluate nexus solutions capable of addressing cross-sectoral challenges. The use of methodological frameworks capable of adapting to different spatial scales, assessing future scenarios and simulating the nexus system at different time scales is essential to govern the WEFE nexus puzzle.

The GoNEXUS SEF has the potential to operationalise the WEFE nexus, as it is capable of incorporating scientific knowledge into policymaking. It helps provide policy advice and recommendations to enhance water, energy, and food security and promote ecosystems conservation by improving the governance of the nexus to guide the transition towards sustainable development.

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Declarations

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