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TOPICAL REVIEW

WEFE nexus unveiled: a comprehensive review of monitoring and modelling methods in the water-energy-food-ecosystems nexus

Maria Vrachioli[1,*], Nikos Mellios[2], Emre Alp[3], Nils Borchard[4,5], Cristina Sousa Coutinho Calheiros[6], Giulio Castelli[7,8], Virginia Rosa Coletta[9], Pedro N Carvalho[10], Julieta Domínguez-Soberanes[11], Marianela Fader[12], Raffaele Giordano[13], Cristina Madrid-López[14], Hasan Volkan Oral[15], Chrysaida-Aliki Papadopoulou[16], Maria Papadopoulou[16], Sofia I A Pereira[17], Rocío Pineda-Martos[18], Tadej StepisnikPerdih[19], Lydia Vamvakeridou-Lyroudia[20], Konstantinos Ziliaskopoulos[21,22], Giannis Adamos[23], Floor Brouwer[24] and Chrysi Laspidou[2]

[1] Production and Resource Economics, Technical University of Munich, Munich, Germany
[2] Civil Engineering, University of Thessaly, Volos, Greece
[3] Environmental Engineering, Middle East Technical University, Ankara, Türkiye
[4] German Agricultural Society, Frankfurt a.M., Germany
[5] School of Economics and Management, Universidade de Lisboa, Lisboa, Portugal
[6] Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Porto, Portugal
[7] Agriculture, Food, Environment and Forestry, University of Florence, Firenze FI, Italy
[8] Environmental Governance and Territorial Development Hub, University of Geneva, Geneva, Switzerland
[9] Water Research Institute, National Research Council, Rome, Italy
[10] Environmental Science, Aarhus, Denmark
[11] Ingineria, Universidad Panamericana, Mexico City, Mexico
[12] Geography, Ludwig-Maximilians Universität Munich, Munich, Germany
[13] Istituto di Ricerca Sulle Acque, Verbania, Italy
[14] Institute for Environmental Science and Technology, Universitat Autònoma de Barcelona, Barcelona, Spain
[15] Civil Engineering, İstanbul Aydin University, Istanbul, Türkiye
[16] Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens, Athens, Greece
[17] Centro de Biotecnologia e Química Fina, Universidade Católica Portuguesa, Lisbon, Portugal
[18] Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla, Sevilla, Spain
[19] Water Resources and Environmental Engineering, National Technical University of Athens, Athens, Greece
[20] KWR Water Research Institute, Nieuwegein, The Netherlands
[21] Environmental Sciences, University of Thessaly, Volos, Greece
[22] Industrial and Systems Engineering, Auburn University, Auburn, AL, United Stated of America
[23] Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
[24] Institute for Integrated Management of Material Fluxes and of Resources, United Nations University, UNU-FLORES, Dresden, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: maria.vrachioli@tum.de

Keywords: WEFE nexus, monitoring, modelling, policy

Abstract

Sustainable resource management in the face of climate change is a pressing challenge for our society. This paper delves into the water-energy-food-ecosystems (WEFE) nexus, a scientific framework that supports the integrated assessment and management of the interconnected resources. Shifting from sectoral to cross-sectoral and transdisciplinary perspectives, the WEFE nexus addresses interdependencies and interactions among water, energy, food, ecosystems, and climate. This paper focuses on the extended nexus, incorporating ecosystems as a fourth pillar, underscoring the importance of considering ecosystems on an equal footing with water, energy, and food sectors. In addition, the paper emphasizes the significance of monitoring and modelling techniques, laying the foundations for understanding the nexus complexities and assessing uncertainty. The paper offers an overview of integrated nexus modelling, system analysis and socio-economic modelling, bridging the gap between nexus science and practice. It highlights the role of multifaceted stakeholder engagement methods, policy assessment, and institutional analysis in nexus models. Quantifying the nexus through indicators, and its alignment with the Sustainable Development Goals, EU Green Deal, and EU Blue Deal are also key focal points. Finally, the last part of the paper addresses challenges in existing nexus modelling attempts, advocates for the integration of transdisciplinary information, and presents lessons learned. The paper concludes with recommendations for the future of the WEFE nexus, emphasizing its potential in fostering transformative change toward sustainable resource management and inclusive policymaking.

Keywords: WEFE nexus, monitoring, modelling, policy

1. Introduction

Sustainable resource management is fundamental to societal well-being, particularly as climate change intensifies environmental pressures. This growing urgency demands innovative and integrated policy approaches fostering adaptation and mitigation that go beyond traditional sectoral thinking (UNEP 2021, IPCC 2022). The 'Nexus' approach provides an integrated framework for managing resources, emphasizing interdependencies among water, energy, food, ecosystems, and climate. It shifts focus from sectoral to cross-sectoral strategies, addressing tradeoffs, conflicts, and synergies. For instance, hydroelectric power depends on water; wastewater treatment consumes energy; and agriculture, a key water user, impacts ecosystems threatened by expansion (Altdorff *et al* 2021, Unc *et al* 2021). The nexus approach identifies critical hotspots and supports improved cross-sectoral decision-making (Laspidou *et al* 2018, Carmona-Moreno *et al* 2019, Lucca *et al* 2023, Sušnik and Mellios 2025).

The water-energy-food (WEF) nexus concept was formally introduced to the international community by Hoff (2011) during the Bonn conference entitled 'The Water, Energy, and Food Security Nexus: Solutions for the Green Economy' (Brouwer 2022). This concept emerged to address the interrelatedness and complexity of water, energy, and food sectors and their critical roles in achieving sustainable development. The WEF nexus highlights the interconnected nature of these sectors and their direct associations with several United Nations Sustainable Development Goals (SDGs) such as Goals 2, 6, and 7, while also influencing other SDGs indirectly (Fader *et al* 2018). As such, understanding these interactions has become essential for effective policymaking and sustainable resource management.

Recent discussions have highlighted the need to incorporate ecosystems into the WEF nexus framework, leading to the development of the WEF-Ecosystems (WEFE) nexus. This evolution reflects the growing recognition that ecosystems are vital to water, energy, and food security due to their role in providing essential services and supporting human health and well-being (Pahl-Wostl 2019, Melloni *et al* 2020, Lucca *et al* 2025). Ecosystems interact with the traditional WEF sectors in both positive and negative ways, highlighting the necessity of considering them on equal footing with water, energy, and food production (Pahl-Wostl *et al* 2018, Bidoglio *et al* 2019). Different authors have considered ecosystems in the nexus approach in different ways, either as a new pillar or as the foundation. A recent study by Lucca *et al* (2025) assessed these different approaches and suggests a hybrid approach that integrates ecosystems as both a distinct component and a foundational layer within the WEF nexus while embedding it in broader social-ecological systems. Building on this, the WEFE nexus provides a better understanding of resource interactions and underscores the need for integrated strategies to achieve sustainable management across all four sectors.

This study examines the WEFE nexus by discussing various modelling and monitoring approaches, which are important for understanding interconnected systems. Modelling helps explore interactions and project dynamics, while monitoring tracks real-time status, supports model parameterization, and evaluates past interactions. Monitoring also introduces performance indicators crucial for assessing trade-offs, synergies and uncertainties. This study also emphasizes stakeholder involvement to improve modelling, and reviews relevant policy and institutional frameworks. Additionally, it connects nexus concepts with global frameworks like the SDGs and summarizes current challenges with lessons learned and future directions in the WEFE nexus research.

In summary, this extensive synthesis of monitoring and modelling approaches within the WEFE nexus offers a comprehensive overview of existing literature to identify key trends and knowledge gaps. The goal is not to catalog every available model and application, as this would go beyond the scope of this study, but rather to offer an overview of approaches from multiple research disciplines relevant to nexus assessments. By performing this interdisciplinary review of existing research, this study seeks to deepen the understanding of current nexus-related approaches and highlight opportunities for future research with an explicit focus on the WEFE nexus to highlight the added complexity and critical role of ecosystem integration in advancing sustainable resource management.

2. WEFE nexus monitoring and modelling: an interdisciplinary review framework

The WEFE Nexus is characterized by its intricate relationships, necessitating interdisciplinary collaboration and its transdisciplinary nature, which is to be considered in order to assure adoption and/or implementation. Transdisciplinary approaches integrate knowledge and concepts from multiple scientific fields while considering the perceptions of relevant stakeholder groups. Effectively addressing the complex, multi-scale, and cross-sectoral interactions within the Nexus requires input from a range of specialists: biophysical scientists offer perspectives on hydrology, soils, agriculture, and energy; ecosystem scientists emphasize biodiversity and nature-based solutions (NbS); and social scientists contribute expertise on governance, power relations, and the interface between science and policy (Albrecht *et al* 2018, Pahl-Wostl *et al* 2020).

This article introduces an interdisciplinary framework for reviewing the most recent WEFE Nexus modelling and monitoring approaches, developed during an 18 month collaborative process of knowledge collection as part of the COST Action NEXUSNET (https:// nexusnet-cost.com/), to take stock and comprehensively review the Nexus monitoring and modelling approaches. To address this, the authors utilized an iterative co-development process, combining structured literature syntheses and online dialogues.

This review provides a comprehensive overview of modelling and monitoring methods dedicated to the WEFE Nexus, integrating insights from a wide range of peer-reviewed literature and international frameworks. Drawing from an extensive and multidisciplinary set of recent works (from 2010 onwards), studies were included if they addressed interconnections across all WEFE sectors or provided systematic methods for simulating or monitoring these coupled systems. The review spanned major disciplines including hydrology, engineering, ecology, economics, and social sciences. Both conceptual and applied studies were considered, provided they presented modelling frameworks, or developed novel indicators relevant to the WEFE Nexus. The analysis covers approaches ranging from biophysical modelling to participatory frameworks, with special attention to operationalization, interdisciplinarity, and policy. The modelling and monitoring approaches identified in the literature can be grouped into six main framework components, each reflecting both disciplinary expertise and areas of methodological integration (table 1).

We conducted a comprehensive literature review, focusing on peer-reviewed journal articles published in the English language, primarily drawing from the Scopus database. Accordingly, we expanded our search beyond standard terms (e.g. 'WEFE', 'nexus', 'modelling', 'monitoring') to capture relevant studies that may use alternative terminology such as the ones provided in table 1. To further mitigate limitations inherent in database-driven approaches and to ensure inclusion of interdisciplinary contributions, we conducted supplementary searches in Google Scholar and Web of Science, and applied snowball sampling from references in the most relevant articles. Additionally, we drew upon the individual scientific knowledge of the expert team involved in this review to identify key studies, monitoring frameworks, and modelling approaches that might otherwise be overlooked in conventional bibliometric searches. This inclusive strategy sought to maximize representation of cutting-edge, interdisciplinary, and ecosystem-inclusive WEFE Nexus research, as reflected in the extended diverse reference list provided in this study including 203 citations from most of the disciplines involved in the WEFE Nexus research from 2010 onwards. This is further illustrated in figure 1, which displays the annual distribution of citations included in the review, highlighting a clear increase in WEFE Nexus research publications from 2010 onwards, with a notable peak in recent years.

To provide a more analytical assessment of the review framework, we introduced a comparative table (table 2) that evaluates each of the six framework components based on key criteria such integration level (extent of water, energy, food, and ecosystems coverage), spatial/temporal scale (from local/daily to global/decadal), stakeholder involvement, model complexity, data requirements, and policy relevance. This structured synthesis highlights both the diversity and complementarity of modelling and monitoring approaches within the WEFE Nexus and helps identify trade-offs, strengths, and research gaps across methodologies.

From table 2, System dynamics (SD) modelling and Stakeholder & Policy Integration both excel in integrating across the WEFE nexus, though they differ in focus: SDs emphasizes complex, data-intensive simulations with moderate stakeholder input, while Stakeholder & Policy Integration prioritizes participatory approaches and co-design with lower data needs. Biophysical and engineering models provide detailed physical process simulations at various scales but involve limited stakeholder engagement and often lack ecosystem integration or direct policy

Table 1. Framework components and common keywords in WEFE nexus research.

Framework component	Description	Keywords mostly used
1. System dynamics modelling	Models feedback loops and cross-sector dynamics using system dynamics (SD) tools like causal loop diagrams (CLDs)	System dynamics, feedback loops, CLD, Stock and Flow
	Degree of operationalization via stock and flow or quantitative models	stock and flow, SD simulation, adaptive models, scenario analysis
2. Mathematical, biophysical & engineering models	Simulates physical processes across nexus sectors	Biophysical models, river catchment models, crop production models, hydrological models, vegetation models, energy models
	Degree of model coupling and interlinkages	Integrated modelling, model coupling, optimization models, impact models, earth system models, model interoperability, cross-sector model integration
	Use of climate and biodiversity parameters	Climate change, climate scenarios, GHG emissions, ecosystem, biodiversity, threatened species, protected areas, land use,
3. Systems-based decision-support models	Combines tools like material flow analysis (MFA), life cycle assessment (LCA), (multi-scale integrated analysis of societal and ecosystem metabolism) MuSIASEM for sustainability analysis	LCA, MFA, MuSIASEM, scenario
	Handles spatial/temporal/multi-sector complexity	Multi-scale, network analysis, cross-sectoral
	Supports development or use of indicators	Indicator, performance, resource tracking
4. Socio-economic modelling	Incorporates economic, cost-benefit analysis (CBA), and global trade-focused methods	CBA, econometric, computable general equilibrium (CGE) model, equilibrium, trade, economic modelling
	Assesses trade-offs, viability, policy impacts	Cost, benefit, scenario analysis, regression, trade-offs, synergies
5. Indicators & quantification tools	Uses indicators for monitoring, evaluation, comparison	WEF€ Nexus Index, footprint, SDGs
	Inclusion of ecosystem-specific metrics	GHG, NEDI, biodiversity index, river flow
6. Stakeholder & policy integration	Engages stakeholders in modelling or decision-making	Agent-based modelling (ABM), policy Delphi, focus groups, QST, living labs, participatory
	Links to global/EU policy frameworks	SDGs, Green Deal, Blue Deal, policy coherence

Source: Authors' findings.

uptake. Decision-support models like life cycle assessment (LCA), material flow analysis (MFA), and MuSIASEM offer a balanced approach with moderate complexity and policy relevance, yet limited stakeholder participation. Socio-Economic Models contribute macro-level economic insights, though with lower cross-sector integration and stakeholder involvement. Indicators and Quantification Tools require minimal data and technical effort but have strong policy applicability, especially when ecosystem metrics are included. Together, these approaches bring complementary strengths in technical rigor, integration, policy relevance, and stakeholder engagement. The following sections provide a detailed review of each of these six conceptual frameworks, highlighting their roles and applications within Nexus assessments.

3. Assessing and managing WEFE nexus complexity through modelling and monitoring

The WEFE nexus is a complex, interconnected system that requires comprehensive tools and methodologies for effective assessment and management. This section explores various modelling frameworks that enable a deeper understanding of the interdependencies and trade-offs between water, energy, food, and ecosystems. Water, energy, and food are essential for ensuring human health and well-being,

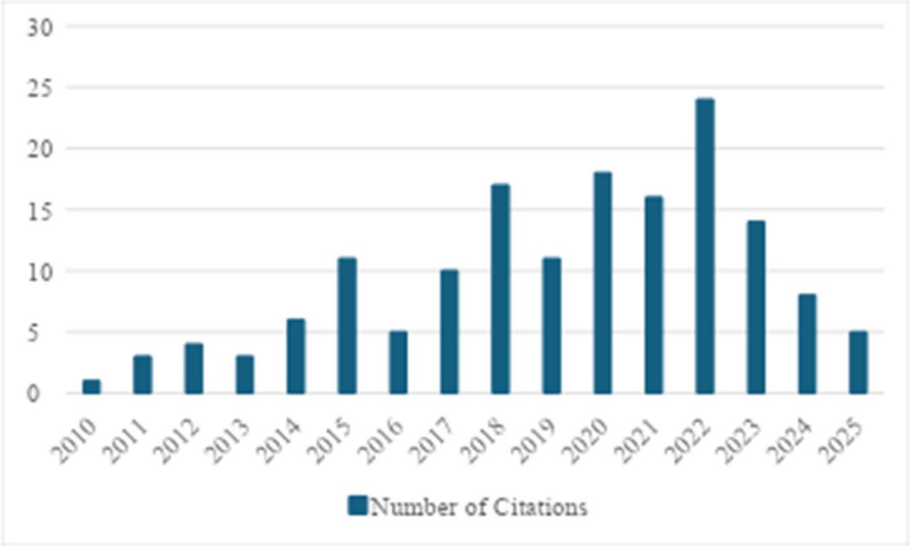

Figure 1. Number of citations per year.

Table 2. Summary of key criteria for WEFE nexus analysis for modelling and monitoring.

Framework component	Integration level (WEFE sectors)	Spatial/ temporal scale	Stakeholder involvement	Model complexity	Data requirements	Policy relevance
1. System dynamics modelling	High (dynamic feedback across sectors)	Medium–large (basin/ national; yearly to decadal)	Medium (some participatory use)	Medium–high	Medium–high	Medium–high
2. Biophysical & engineering models	Medium–High (focus on WEF)	Fine—large (field to watershed; daily to yearly)	Low (mostly technical use)	High	High	Medium
3. Decision-support models	Medium (resource flow focus)	Multi-scale (local to regional)	Low-medium	Medium	Medium	High
4. Socio-economic modelling	Low-Medium (mainly economic-trade)	Global to regional	Low	Medium	Medium	High
5. Indicators & quantification tools	Medium (cross-sector metrics)	Variable (context-dependent)	Medium–high	Low	Low-medium	High
6. Stakeholder & policy integration	High (all WEFE sectors)	Local to Regional	High	Low-medium	Medium	Very high

Source: Authors' findings.

while ecosystems play an indirect but crucial role by providing the ecosystem services that enable the delivery of these resources (Haynes-Young and Potschin 2018). Inclusion of ecosystems assures consideration of sustainability as the ecosystems' capacity to provide ecosystem services, governing the provision of water, energy, and food, respecting planetary boundaries (Gerten *et al* 2020) and enabling cross-sectoral views, highlighting the interlinked routes among resources and materials recovery and energy cascades (Laspidou *et al* 2019, Langergraber *et al* 2021a, Langergraber *et al* 2021b, Remme *et al* 2024).

To structure this literature overview, we have classified the models into four groups: (i) SD modelling; (ii) mathematical, biophysical and engineering modelling, focusing mainly on analysing physical (and ecological) interlinkages between the WEFE nexus sectors; (iii) systems-based decision-support modelling that simulate nexus interactions, explore future trends and scenarios, and provide recommendations for developing strategies that balance resource efficiency with environmental sustainability; (iv) and socio-economic modelling, evaluating the economic feasibility and efficiency of policies and interventions within the nexus framework. This classification reflects the interdisciplinary nature of WEFE nexus modelling, where SD models capture feedback dynamics (Sterman 2000), mathematical models provide analytical and numerical formulations, biophysical models simulate hydrological, ecological, and environmental processes, and engineering models focus on optimizing and designing technological solutions. While some overlaps may exist between these categories, this framework allows for a structured assessment of the diverse methodologies used in nexus studies.

3.1. SDs modelling

SD is a holistic approach for modelling complex systems, focusing on feedback loops and interactions between system components (Forrester 1969). It is widely used in areas like water resources management and environmental analysis (Simonovic 2009). In nexus modelling, SD excels at representing the interactions within and across sectors (e.g. water, energy, food), integrating sectoral models, and including stakeholder input. It addresses temporal aspects, such as delays and nonlinear behaviours, and supports scenario-based analysis to evaluate policy impacts and trade-offs, facilitating long-term decision-making (Mirchi *et al* 2012, Coletta *et al* 2024, Coletta *et al* 2024a).

A core element of SD is the causal loop diagram (CLD), which represents system feedback and causal relationships (Coletta *et al* 2021). CLDs map variables linked by causal effects, identified as positive (+) or negative (−), helping to hypothesize system behaviour and policy outcomes (Abebe *et al* 2021). CLDs are crucial in nexus modelling, addressing sectoral conflicts, feedback dynamics, and delays that cause inertia, influencing trade-offs between short- and long-term effects (Sterman 2000). They also help identify balancing loops (stabilizing the system) and reinforcing loops (promoting growth or decline) (Mirchi *et al* 2012). Analysing this feedback aids in predicting system behaviour, and thus, supporting decision-making. CLDs are especially valuable when working with non-experts, as they provide a clear visual representation of complex relationships, making them accessible to practitioners and decision-makers. This visual clarity also allows for the active involvement of various stakeholders in the development of CLDs, ensuring the integration of local knowledge. One of the key advantages of CLDs is their flexibility in being applied to physical, environmental, and social systems, along with the opportunity to engage participants in the model-building process. When used within a SDs approach, CLDs can serve as a framework for quantitative systems analysis (Halbe *et al* 2015). However, as systems grow increasingly interconnected, there is a risk of CLDs becoming cluttered. Additionally, CLDs require mathematical models for operationalization, which can be complex. Given the large number of variables and causal linkages, effectively utilizing data within CLDs presents a significant challenge (Albrecht *et al* 2018).

To test adaptive strategies, SD uses quantitative models like Stock and Flow models, which simulate system behaviour with mathematical equations (Richmond 1993). By explicitly defining ‘stocks’ and ‘flows’ these models offer more detailed insights, such as the interactions between water, energy, and food systems (Pahl-Wostl 2006). Smajgl *et al* (2016) and Ravar *et al* (2020) demonstrated SD’s utility in understanding cross-sectoral interactions and evaluating management practices. However, challenges remain, such as inconsistent frameworks for nexus-specific models and limited stakeholder involvement (Kaddoura and El Khatib 2017, Albrecht *et al* 2018, Estoque 2023), or the lack of explicit representation of spatial processes within the model (Gao and Liu 2018). Compared to CLDs, Stock and Flow models are less accessible to non-experts and struggle to capture qualitative aspects. Addressing these limitations is crucial for enhancing the effectiveness of SDs in managing the WEFE nexus.

3.2. Mathematical, biophysical and engineering modelling

Mathematical, biophysical and engineering modelling is crucial for analysing complex systems by using equations and computational methods to simulate behaviour under various conditions (Leung Pah Hang *et al* 2016). In the WEFE nexus, these models simulate interactions among water, energy, food, and ecosystems, aiding in resource allocation and sustainability. Employing these techniques helps identify strategies for efficient resource use, such as water in agriculture and energy production (Peña-Torres *et al* 2022). These models also assess risks related to climate change, water scarcity, and energy disruptions, helping to evaluate policy interventions for achieving sustainability and resilience goals (Lucca *et al* 2023, Mirzaei *et al* 2023).

The nexus modelling community utilizes a range of biophysical models that capture dynamic interactions across different sectors. For instance, river catchment models–centred on water resources, discharge and usage–can provide insights into trade-offs and synergies within the nexus system (Endo *et al* 2017). Examples include integrated and transdisciplinary modelling tools such as WaSim, which incorporates irrigation simulation, as well as the SWAT model (Devia *et al* 2015) and the HEC-HMS model (Kourtis *et al* 2025), both of which are used for hydrological analysis, water footprint and flood risk assessment (Sahu *et al* 2023). Also, Sabo *et al* (2017) further illustrate how optimizing river flow management can simultaneously enhance hydropower production and improve food security, demonstrating the critical role of integrated water management in the Mekong Basin. Other important biophysical models, such as crop and vegetation models like PROMET, LPJmL and DSSAT (Beringer *et al* 2011, Fader *et al* 2016, Probst *et al* 2024) integrate considerations of water fluxes, natural ecosystems and bioenergy production. Some of these models address, in addition to cross-sectoral impacts, climate change policies and economic issues (Mellios *et al* 2018, Trabucco *et al* 2018, Lucca *et al* 2023).

Engineering models are also critical in nexus assessments, as they emphasize system optimization, infrastructure planning, and technological solutions to balance resource efficiency with sustainability. Examples include WEAP-LEAP, a model coupling water resource management with energy pathways (Karlberg *et al* 2015, Özcan *et al* 2025), and models applied in energy and agricultural engineering. The combined WEAP-MODFLOW model helps to assess how local changes affect the overall interactions. However, calibrating and validating the combined model is a complex process that necessitates a multi-objective approach, considering parameters such as river discharge and groundwater levels (Tekle *et al* 2025).

Furthermore, machine learning algorithms, control algorithms and data-driven modelling are emerging as tools to enhance system identification, policy design and analysis of complexities (Mellios *et al* 2020, Jonsson *et al* 2024). Notably, some models in this section were originally developed and primarily used in other scientific fields. As a result, nexus modelling evolves both as a distinct approach and through contributions from these scientific domains. A representative example is the large potential of the so-called impact models (IM) and earth system models (ESM) for nexus simulations. These evolved mainly for the assessment of climate change dynamics and impacts (many IMs are analysed in the ISIMIP project[25], while this is a list of European ESMs).

Regardless of whether it comes from the nexus community or another research field, a key requirement for nexus modelling is the consideration of dynamic interactions within the nexus areas. In this case, some simplified assumptions are often necessary, which can lead to inaccuracies as real-world interactions are complex (Bian and Liu 2021) or the availability of high-quality data can be limited (Abdi *et al* 2020). Trans-disciplinary collaboration is also challenging due to differences in terminologies, methodologies, and objectives across sectors (Kumazawa *et al* 2017). Furthermore, issues like competition for water between the energy generation and food production sectors, global consumption and production patterns, complex trade-offs, the increasing interdisciplinary nature of nexus research, differentiated policy and governance models and intricate forecasts on population needs put an additional degree of complexity that in some cases researchers try to manage by using ensembles of models (D'Odorico *et al* 2018) and integrated indices (Daher and Mohtar 2017, Simpson *et al* 2022). However, data availability, standardization requirements and compatibility adjustments are critical factors in order models and indicators to be integrated. These difficulties are often compounded by a water-centric bias in many models, which can overlook broader interconnections among food, energy, and ecosystems (Di Baldassarre *et al* 2019). In summary, mathematical, biophysical and engineering modelling offer valuable insights into the interactions within the WEFE nexus. However, addressing the limitations associated with simplifying assumptions, data availability, and interdisciplinary collaboration is crucial for improving the applicability and effectiveness of these models. The diverse array of model types highlights the evolving landscape of nexus modelling, emphasizing the need for tailored approaches based on specific study objectives.

3.3. Systems-based decision-support models

Understanding the complexity of the WEFE nexus requires robust models that capture dynamic interactions and trade-offs. Several analytical tools, including MFA, LCA, network analysis, the multi-scale integrated assessment of socio-ecosystem metabolism (MuSIASEM) and Multicriteria decision analysis (MCDA) offer insights into nexus dynamics, resource management, and policy formulation, supporting sustainable decision-making.

MFA quantifies material flows within a system, tracking resource inputs, outputs, and inefficiencies. While LCA is a standardized methodology, MFA is more flexible and focuses on optimizing resource use within the WEFE nexus. It identifies areas of waste and environmental impacts, promoting sustainable practices and circular economy principles. This approach has proven valuable in improving resource efficiency and reducing waste (Hua *et al* 2020, Weidema *et al* 2020). MFA is particularly effective at analysing flows across different scales, including regional and national levels, but it is important to note that it requires high-quality data for accurate analysis. From a geographical perspective, in the context of the WEF nexus, MFA enables the identification of regional flows by considering the direct consumption of resources. Additionally, it does not necessitate extensive data collection and processing. However, when analysing the WEF nexus in terms of goods, services, or organizations, LCA footprints or WEF-LCA techniques may be more appropriate, as they account for all resources used throughout the entire life cycle (Vásquez-Ibarra *et al* 2024).

Network Analysis complements MFA by examining the relationships and resource flows within the

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[25] www.isimip.org/

WEFE nexus. It explores interactions between water, energy, food, and ecosystems, identifying vulnerabilities and assessing trade-offs. Network analysis aids in understanding nexus complexities and informs policies that enhance resource efficiency and sustainability (Font Vivanco *et al* 2019, Wang *et al* 2021). By visualizing these networks, stakeholders can simulate different management strategies and make informed decisions to minimize risks.

Even though not defined as a model, the MuSIASEM (Giampietro *et al* 2014) offers a transdisciplinary framework where water, food, energy and environmental assessments can be soft linked. MuSIASEM provides a method for contextualizing and benchmarking the results of impact and resource assessment such as those provided by LCA and MFA. The social viability and environmental feasibility checks would examine these results against the social and environmental constraints imposed by the WEFE nexus. Despite its high data requirements, MuSIASEM offers sophisticated analysis which can operate across multiple scales, from local to national and across sectors, allowing comprehensive socio-economic and environmental analysis of different scenarios. This makes it particularly useful for evaluating policy options.

Finally, MCDA is crucial for evaluating alternatives in complex nexus scenarios. It integrates social, economic, and environmental criteria, allowing stakeholders and experts to prioritize actions and address trade-offs (Saaty 2008). MCDA enhances transparency and participatory decision-making, ensuring that outcomes align with sustainability goals. The main challenge of MCDA lies in assigning weights to different criteria. Since stakeholders often have conflicting priorities, the weights in MCDA can become overly subjective. Managing and eliminating subjective biases can be difficult using traditional MCDM techniques. In such cases, fuzzy MCDM techniques, which allow for more objective judgments and effectively address uncertainties in the available data, serve as an alternative to traditional MCDA methods in less optimal MCDM environments (Haji *et al* 2024). Furthermore, different MCDA methods may lead to varying scenario rankings in the nexus assessment, necessitating additional applications such as sensitivity analysis.

3.4. Socio-economic modelling

Economic modelling helps in evaluating the economic feasibility and efficiency of policies and interventions within the nexus framework. Econometric tools are essential in this context, offering empirical evidence to support hypotheses and decision-making. Correlation analysis measures the linear relationship between two variables, while linear regression defines an equation for this relationship, and multivariate analysis expands this by exploring interactions among multiple variables, such as the link between water changes and multiple agricultural dynamics (Barik *et al* 2017).

Cost-benefit analysis (CBA) is essential in nexus studies, comparing the benefits (e.g. profits) with project costs to assess viability. CBA can be applied to assess nexus projects, providing a clear evaluation of the trade-offs in specific regions where one or more nexus components are implemented. It helps evaluate the net benefits of these trade-offs within the WEF nexus, while managing the distribution of resources among water, energy, and food (Endo *et al* 2015). Applied in environmental contexts, such as flood protection, CBA includes both tangible benefits and intangible factors like biodiversity and environmental externalities (Halytsia *et al* 2022). It involves stakeholder engagement to quantify costs and benefits while managing biases. CBA addresses various costs, including direct, indirect, and opportunity costs, and considers broader benefits like water, food, and energy security. By providing a clear framework to weigh benefits against costs, CBA serves as a powerful tool for decision-makers to quantify trade-offs. Techniques like scenario analysis and Monte Carlo simulations support decision-making by accounting for uncertainties in the analysis of costs and benefits.

Beyond econometric and CBA methods, economic models accounting for global trade such as computable general and partial equilibrium models provide additional insights into global connections and dynamics between nexus components (Doelman *et al* 2022, Castelli *et al* 2024). Combinations are also possible, e.g. with life-cycle environmental assessment that tested in Ica Valley (Peru) to support efficient resource management and the application of improved agricultural practices (Correa-Cano *et al* 2022). Macro-econometric models such as the Energy-Environment-Economy Macro-Econometric (E3ME) tool, enable the development of linkages between the general macro-economic framework, the physical supply/demand of energy and material resources (Dwesar *et al* 2022). Complementary tools, including social accounting matrices, value chain analysis, and supply chain analysis, further enhance the understanding of nexus interactions. Together, these approaches offer a comprehensive framework for analysing and addressing the socio-economic impacts of the intricate interdependencies within the nexus.

3.5. Quantifying the nexus through indicators

The growing interest in using indicators to quantify the WEFE nexus underscores their importance in conveying information to policymakers, stakeholders, and researchers, serving as essential tools for assessing sustainable performance and progress (Pahl-Wostl *et al* 2023; Wolde *et al* 2022, Pacetti *et al* 2024). Indicators are important for operationalizing and quantifying complex systems, allowing for a clearer understanding of data and assisting in decision-making by highlighting areas that require attention or improvement (Endo *et al* 2015, Endo *et al* 2020, Yi *et al* 2020). Moreover, they allow for the assessment of policy impacts on resource use, revealing existing policy gaps and setting the ground for the design of improved, integrated and more efficient WEFE nexus governance schemes (Papadopoulou *et al* 2022). Indicators can bridge the gap between complex information and practical insights, and although traditionally used for economic assessments, they can also offer valuable measures for tracking sustainability in different contexts (Ciegis *et al* 2009). Quantitative indicators can simplify the comparison between objectives, but the complex relationships between these indicators often require computerized approaches (Albrecht *et al* 2018). Furthermore, the absence of reliable and useful data can pose significant challenges (Endo *et al* 2015).

A comprehensive indicator system is essential for objectively evaluating the sustainability of the nexus across different locations. Commonly used approaches include the pressure-state-response (PSR) model, the driving force- PSR model, theme-based frameworks, and aggregated indicators (Sun *et al* 2022). For instance, the widely adopted PSR model illustrates the relationship between anthropogenic activities and environmental changes (Gu *et al* 2022). However, the definitions of pressure, state, and response can be ambiguous, sometimes leading to interchangeable classifications of indicators. Aggregated indicators primarily focus on environmental factors such as ecological and water footprints, while the theme-based framework offers flexibility, allowing modifications to align with assessment goals and policy concerns (Sun *et al* 2022).

In addition, Stylianopoulou *et al* (2020) identified various indicators and tools, such as the WEF nexus tool 2.0, while Forbes *et al* (2021) developed sustainability indicators and interactive visualization tools for decision-making. Simpson *et al* (2022) applied the WEF Nexus Index to assess regional challenges and opportunities, highlighting its utility in identifying food security issues and potential water and energy projects. Arthur *et al* (2019) reviewed urban indicators, categorizing them into three groups: resource fluxes, environmental impacts, and efficiency, and emphasizing the need for evolving indicators to better represent complex issues by integrating relevant factors.

However, the integration of ecosystems within the WEFE Nexus remains relatively underexplored. Vargas *et al* (2023) emphasize the significance of the WEF-Biodiversity Nexus in sustainable agri-food systems. In their recent study, Lucca *et al* (2025) emphasized the need to recognize the role of 'nature' within the WEFE Nexus, a concept that has been represented in the literature through ecosystems, ecosystem services, the environment, and biodiversity. Similarly, network-based models have been applied to assess trade-offs in hydropower development, biodiversity, and food security. For example, Ziv *et al* (2012) evaluated the impact of dam construction on migratory fish species and local livelihoods in the Mekong River Basin, while Deng *et al* (2023) demonstrated how hydrologic anomalies influence fish migration and biodiversity in flood pulse systems. Existing studies largely focus on environmental impacts, with indicators such as carbon intensity (Venkatesh *et al* 2014) and environmental footprint (Silalertruksa and Gheewala 2018) but often overlook ecosystem health. Some notable contributions include the natural flow maintenance (Momblanch *et al* 2019), GHG emissions (Saladini *et al* 2018), and the biodiversity vulnerability index (Kebede *et al* 2021). Recent developments, such as the SIGMA Nexus project's farm-level WEFE Nexus Index (Halytsia *et al* 2024) and Teutschbein *et al* (2022) use of the normalized ecosystem drought index (NEDI), highlight ongoing efforts to incorporate ecosystem dimensions into nexus related indicators.

The evolution of nexus research points to a need for more sophisticated indicators that incorporate ecosystems. These indicators should be drawn from advancements in ecological research to provide a more comprehensive assessment of the nexus, reflecting the integral role of ecosystems in sustainable development (European Commission Directorate-General for Research and Innovation *et al* 2021).

3.6. Overview of nexus modelling and monitoring

The WEFE nexus is analysed using diverse assessment methods that provide distinct insights. Table 3 presents 29 models and frameworks, categorized by approach and addressed nexus nodes—i.e. water, energy, food, ecosystems, climate, ecosystem services, land use. The model categories are four: SDs modelling; mathematical, biophysical and engineering modelling; systems-based decision-support modelling; and indicator-based assessment (table 3). Models, including WATNEEDS (Chiarelli *et al* 2020), WEAP (SEI 2016), LEAP (Heaps 2022), LPJmL (Schaphoff *et al* 2018), MuSIASEM (Giampietro *et al* 2014) and Sim4Nexus (Laspidou *et al* 2020) explore dynamic interactions and capture temporal and spatial variations, revealing complex feedback loops. Mathematical optimization tools, like IOA (Zhang *et al* 2014), WEFO (Zhang and Vesselinov 2017) and OPTIMA (Fedra and Harmancioglu 2005), focus on optimal resource management, aiding strategic planning. Lifecycle assessment models, the EWF nexus tool (Al-Ansari *et al* 2014) and Hybrid LCA (Feng *et al* 2014) assess environmental impacts and sustainability opportunities. Macro-level indicator-based assessments, like TWO (Phillips *et al* 2008), RDM-CRUNCH (University of Portsmouth 2018), and CLEW (Howells *et al* 2013), offer broad insights

Table 3. Nexus models.

Model	Nexus nodes	Advantages	Limitations	References
System Dynamics modelling				
WEAP	Water	User-friendly, supports scenario analysis, calibration, and adaptive water management	No detailed design, data import needed, lacks water quality	(SEI 2016, Zhang *et al* 2023)
MSA	Water	Hydrological model, useful for watershed analysis	Mainly hydrology-focused, less integration of energy and food	Villarroel Walker *et al* (2014)
POLES	Energy	Energy system forecasting, policy-oriented	Does not explicitly model water-food	Després *et al* (2018)
REAP	Energy, Food	Combines economic and energy analysis	Lacks spatial representation, mainly economic	Mannan *et al* (2018)
MuSIASEM	Water, energy, food, Ecosystems	Holistic multi-scale analysis, integrates multiple sectors	High data requirements, complex methodology	Giampietro *et al* (2014)
DDM-ANN	Water, energy, food	AI-driven, good for predictive modelling	Requires extensive data training, black-box nature	Namany *et al* (2019)
WEF Nexus Tool 2.0	Water, energy, food	User-friendly, supports policy decisions, estimates nexus flows, interactions, and GHG emissions	Simplified modelling approach, may lack detail	Daher and Mohtar (2015), Taguta *et al* (2022)
Sim4Nexus	Water, energy, food, land use, climate	Advanced integration of multiple nexus components	Computationally intensive, high learning curve	Sušnik *et al* (2018), Laspidou *et al* (2020), Ramos *et al* (2022)
Mathematical, biophysical and engineering modelling				
IWROM	Water	Optimizes water resources, effective for planning	Limited integration of economic aspects	Mayer and Muñoz-Hernandez (2009)
SWAT	Water	Open-source, widely used, simulates pollutants, supports calibration, coupling with other models	No 2D/3D hydraulics, empirical formulas, limited snowmelt, erosion modelling	Arnold *et al* (2012)
OPTIMA	Water	Decision support for water management	Simplified optimization, lacks broader integration	Fedra (2005)
LEAP	Energy	Energy scenario for policy planning; flexible, lifecycle analysis of energy	Limited in water-food interactions, energy-focused	(Heaps 2022, Manirambona *et al* 2022)
IOA	Energy	Energy optimization, used in various sectors	Limited spatial resolution in energy systems	Zhang *et al* (2014)
MARKAL/TIMES	Energy	Robust energy modelling, long-term projections	Requires high computational power, complex calibration	(IEA 2011, Loulou *et al* 2005)

(Continued.)

Table 3. (Continued.)

WATNEEDS	Water, energy, food	Prioritize water needs for sustainable development, considers regional variations	Assumes uniformity in water needs, limited scope for non-quantitative factors	Chiarelli *et al* (2020)
WEFO	Water, energy, food	Integration of water-energy-food system optimization	Difficult to apply to small-scale projects	Zhang and Vesselinov (2017)
SPATNEX-WE	Water, energy	Spatial analysis of water-energy interactions	Limited representation of economic factors	Khan *et al* (2018)
LPJmL	Water, energy, food, ecosystems	Highly detailed biophysical modelling	Data-intensive, requires significant computational resources	Schaphoff *et al* (2018)
Systems-based decision-support modelling				
Water-Energy nexus chart	Water, energy	Visual representation of water-energy interactions	Limited analytical depth beyond visualization	Li *et al* (2019)
EWF nexus tool	Water, energy, food	Practical for decision-makers in WEF policy	May not capture complex interdependencies fully	Al-Ansari *et al* (2014)
Hybrid LCA	Water, energy, food	Life-cycle perspective on nexus interactions	Data-intensive, challenging to apply at large scales	Feng *et al* (2014)
SimaPro 7	Water, energy, food	LCA approach applied to sustainability assessment	High software cost, requires expertise	Pacetti *et al* (2015)
GaBi V6.4	Water, Energy, Food	Comprehensive LCA tool, widely used	Requires extensive data for accurate results	Jeswani *et al* (2015)
Indicator-based assessments				
TWO	Water	Simple water assessment, useful for screening	Simplified methodology, may lack detail	Phillips *et al* (2008)
WREI	Water	Water resource efficiency assessment	Limited integration with energy and food	Kurian (2017)
GCAM	Water, energy	Integrates global and regional water-energy policies	Less focus on food systems, mainly energy-water	Davies *et al* (2013)
DTI in Water for Agriculture	Water, energy, food	Designed for agriculture-based water-energy-food systems	May not be suitable for non-agricultural contexts	Salman (2013)
RDM-CRUNCH	Water, energy, food, climate	Climate-focused WEF model, useful for adaptation studies	Focuses heavily on climate, may miss other nexus factors	University of Portsmouth (2018)
CLEW	Water, energy, food, climate	Considers multiple climate-related interactions	May overlook non-climate nexus factors; biodiversity integration in CLEWS remains limited	Howells *et al* (2013), Keairns *et al* (2016), Ramos *et al* (2022)
(WEFE Nexus indicator	Water, energy, food, ecosystems	Ecosystem perspective on WEF nexus, holistic approach	High data demand	Halytsia *et al* (2024)

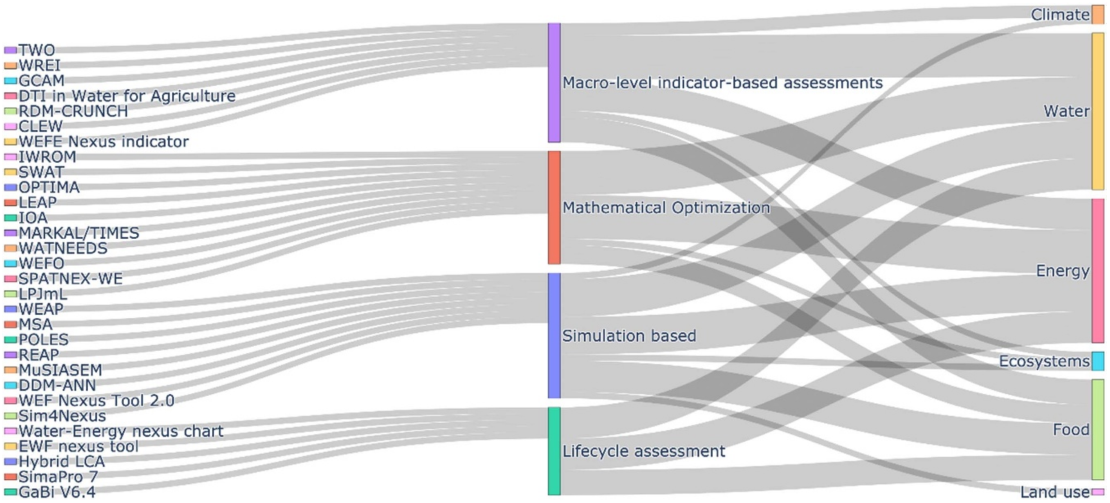

Figure 2. Sankey diagram of nexus models organized by nexus nodes.

into system performance by using indicators to analyse trends and interactions across nodes.

The Sankey diagram in figure 2 illustrates 28 nexus-assessing models, categorized by methodology and addressed nexus nodes. Out of these, 10 models use simulation methods, while 6 employ macro-level indicator-based assessments and mathematical optimization. Lifecycle assessment features are part of 5 models. The diagram shows water and energy as primary focuses, addressed by 23 and 21 models, respectively. Food is analysed in 14 models, while ecosystems and climate receive attention in only 3 models each. Although climate change and ecosystem health are vital for sustainable development, the diagram reveals their limited inclusion in nexus modelling. Enhancing their representation in models is crucial for effective, sustainable resource management and achieving development goals.

4. Enhancing nexus modelling through multifaceted stakeholder engagement methods: questionnaires, surveys, interviews, stakeholder workshops

In WEFE nexus modelling, integrating stakeholder perspectives is crucial for developing accurate, context-specific models. Methods such as questionnaires, interviews, and surveys help capture diverse viewpoints. Questionnaires gather standardized data from large groups, revealing common trends. Interviews provide in-depth insights into stakeholder perceptions (Howarth and Monasterolo 2016). Surveys, combining structured and open-ended questions, balance quantitative and qualitative data, enriching the understanding of resource use and management practices (Howells *et al* 2013). Agent-based modelling (ABM) simulates complex interactions within the WEFE nexus, using autonomous agents to represent individuals or entities. ABM captures real-world system complexity and adaptability, helping understand decision-making processes. A complementary approach is the one of quantitative story telling (QST) that engages stakeholders in defining agent behaviours, ensuring contextual relevance of the analytical choices made (Di Felice *et al* 2023). Both ABM and QST may be used as collaborative tools for educating stakeholders about their roles and impacts within the WEFE system.

Participatory workshops, expert exchanges, and focus groups foster collaboration and knowledge sharing. Stakeholder workshops facilitate knowledge co-creation and sharing, enhance capacity building and strengthen collaborative efforts towards co-design of models (e.g. conceptual models and SDMs) and co-decide on future solutions and policies (Avellán *et al* 2025). They also promote joint problem-solving and scenario development, while focus groups provide more relaxed settings for guided discussions and offer the opportunity for gaining in-depth knowledge in a short amount of time (Bertrand *et al* 1992). These methods build consensus and integrate diverse perspectives. The Delphi method, based on expert panels and forecasting, aids decision-making in nexus modelling (Dalkey and Helmer 1963). Soares Dal Poz *et al* (2022) and Albrecht *et al* (2018) used Delphi to involve stakeholders in nexus decision-making. Canessa *et al* (2022) presented a methodological framework using Delphi and focus group methods to integrate expert, practitioner, and local stakeholder perspectives on the WEFE nexus.

Finally, living labs are collaborative environments that co-produce knowledge and innovative solutions, addressing challenges like climate change. In nexus modelling, they enhance stakeholder engagement and support practical solutions for sustainable development (Voytenko *et al* 2015, Bouwma *et al* 2022, Moreira 2022). These participatory activities improve model credibility, guiding real-world decisions and empowering stakeholders in sustainable resource management (Perrone and Hornberger 2014).

5. Policy assessment and institutional analysis in nexus models

This section explores how policy, institutional, historical, and critical discourse analyses enhance modelling, stakeholder engagement, and decision-making. Policy analysis is crucial for defining problems, assessing level of coherence among nexus-related policies, exploring existing policy gaps, formulating well-informed and more effective policies, and assessing their impact on the WEFE nexus. It aligns stakeholder perspectives, clarifies trade-offs, and fosters consensus through evidence-based insights (Cairney and Weible 2017, Dunn 2017). Integrated assessment models (IAMs) help analyse system interactions, showing how changes in one system affect others (Kling *et al* 2017, Albrecht *et al* 2018). IAMs combine disciplines like hydrology, energy, agriculture, and economics to offer a comprehensive view of resource management (Fischer *et al* 2005, Bizikova *et al* 2014). Using SDs, IAMs depict feedback loops, delays, and nonlinear relationships, enabling dynamic understanding and scenario exploration (Sterman 2000, Voinov and Bousquet 2010, Rasul and Sharma 2016, Peters and Hertel 2016).

Institutional analysis explores the structures and mechanisms that govern cooperation within nexus systems, ensuring the involvement of relevant stakeholders. By examining how institutions influence behaviour and decision-making, it improves understanding of stakeholder dynamics and resource management strategies (Liu *et al* 2018, Kharanagh *et al* 2020). Historical analysis provides context by examining past trends, challenges, and successes in the WEFE nexus. This perspective promotes scenario development and policy formulation, offering insights that guide decision-making for current and future challenges (Ringler *et al* 2016, Han *et al* 2022, Lazaro *et al* 2022, Dias *et al* 2023).

Policy coherence analysis sheds light on positive and negative interactions and interdependencies among policy goals and between policy goals and policy instruments (Papadopoulou *et al* 2020, Mooren *et al* 2024). It supports the exploration of synergies, conflicts and trade-offs at governance level contributing to the design of improved, integrated, well-informed and more efficient WEFE nexus policies. A complete methodological framework was proposed and applied by Nilsson *et al* (2012), Nilsson *et al* (2016) and Weitz *et al* (2018) for evaluating coherence among SDGs and among environmental/energy EU policies based on a seven-point scale illustrating if the implementation of a policy is indivisible, reinforcing, enabling, consistent, constraining, counteracting or cancelling from/for the implementation of another policy. Therefore, while designing and assessing policies governing the WEFE nexus, policy makers should consider that policy inconsistencies are reflected in the physical system during policy implementation and vice-versa, existing conflicts and trade-offs in the physical system offer valuable feedback to the decision-making process in order future policies to be ameliorated. It is thus evident that modelling and policy design constitute retroactive processes that each one 'feeds' the other.

Lastly, critical discourse analysis (CDA), combining social network analysis and DA, fosters transparency and inclusivity in stakeholder discussions, uncovering governance concepts within the nexus. By clarifying governance issues, CDA strengthens stakeholder engagement and enhances the modelling process (Urbinatti *et al* 2020) supporting collaborative innovation and decision-making (Bizikova *et al* 2014, Howells *et al* 2013, Welsch *et al* 2014). These analyses promote more robust nexus modelling, address challenges like fragmented structures and data inaccuracies, and provide reliable insights for policymakers (Ackerman *et al* 2009, Rising 2020, Asefi-Najafabady *et al* 2021).

6. Bridging complex systems and sustainability: SDGs, EU Green and EU Blue deals

The WEFE nexus is vital for addressing sustainability challenges and achieving the SDGs, the EU Green Deal, and the EU Blue Deal. WEFE nexus indicators are broadly used for reviewing several dimensions of the water, energy, food and ecosystems sectors while integrated indices allow for assessing the WEFE nexus footprint and the level of sectoral integration (Nika *et al* 2022, Papadopoulou *et al* 2022, Ioannou and Laspidou 2023, Abera *et al* 2024, Halytsia *et al* 2024, Rhouma *et al* 2025). Apart from assessing the physical WEFE nexus system, indicators offer valuable insights on governance assessment and support the design of tailored solutions and policies ensuring sustainable resource use. SDGs, as a global sustainability framework, use indicators that align with the WEFE nexus to assess sustainability and resource efficiency, spotlighting sector connections, knowledge gaps, and guiding policy. The nexus directly supports SDGs 2, 6, 7 and 9 through sustainable agricultural, water, and energy practices. It also contributes to SDGs 11, 12, 13, 14 and 15 enhancing resource efficiency, ecosystems viability and climate resilience (table 4).

The EU Green Deal aims to make the EU climate neutral by 2050, with 26 indicators to monitor policy effectiveness. About half of these indicators are linked to the WEFE nexus. These indicators, which are also aligned with SDGs, focus on areas like agricultural water management, renewable energy, and ecosystem protection. Figure 3 illustrates the links

Table 4. Proposed WEFE nexus indicators and related SDGs.

INDICATOR	SDGs	References
Reduction of agricultural water losses	SDG 6, SDG 12, SDG 13, SDG 15	Papadopoulou *et al* (2022)
Reduction of irrigated agricultural land	SDG 2, SDG 6, SDG 13, SDG 15	Papadopoulou *et al* (2022)
Carbon footprint	SDG 9, SDG 13	Vanham *et al* (2019)
Ecological footprint	SDG 11, SDG 15	Vanham *et al* (2019)
Water Footprint	SDG 2, SDG 6, SDG 9	Fader *et al* (2011), Pacetti *et al* (2015)
Nitrogen footprint, phosphorus footprint	SDG 6, SDG 14	Vanham *et al* (2019)
Proportion of sustainable agricultural production per unit area	SDG 2	Mabhaudhi *et al* (2021)
Forest area as a proportion of total land area	SDG 15	Mabhaudhi *et al* (2021)
Energy consumption per m^3 of treated wastewater	SDG 7, SDG 9, SDG 11, SDG 12	Nika *et al* (2022)
Amount of agricultural residues used for energy purpose	SDG 7, SDG 9, SDG 12, SDG 13	Saladini *et al* (2018)
Cereal yield	SDG 2, SDG 15, SDG 6	Saladini *et al* (2018)
Flood hazard indicator	SDG 6, SDG 11, SDG 13, SDG 15	Ward *et al* (2017)
Electricity produced by hydropower	SDG 6, SDG 7, SDG 13	Bogaart (2023)
River flow	SDG 6, SDG 15	Schlemm *et al* (2024)
Nutrient pollution	SDG 6, SDG 14, SDG 15	Schlemm *et al* (2024)
Aquatic biodiversity	SDG 14	Schlemm *et al* (2024)
Level of water stress	SDG 6, SDG 13, SDG 14	Song *et al* (2023)
Water use efficiency	SDG 2, SDG 6, SDG 15	Song *et al* (2023)
Energy sufficiency	SDG 7	Song *et al* (2023)
Biomass energy consumption	SDG 7	Song *et al* (2023)
Arable land	SDG 2, SDG 15	Song *et al* (2023)
Food production index	SDG 2	Song *et al* (2023)
Ecological deficit	SDG 13, SDG 14, SDG 15	Song *et al* (2023)
Biocapacity	SDG 14, SDG 15	Song *et al* (2023)

Source: Modified after Papadopoulou and Mellios (2023).

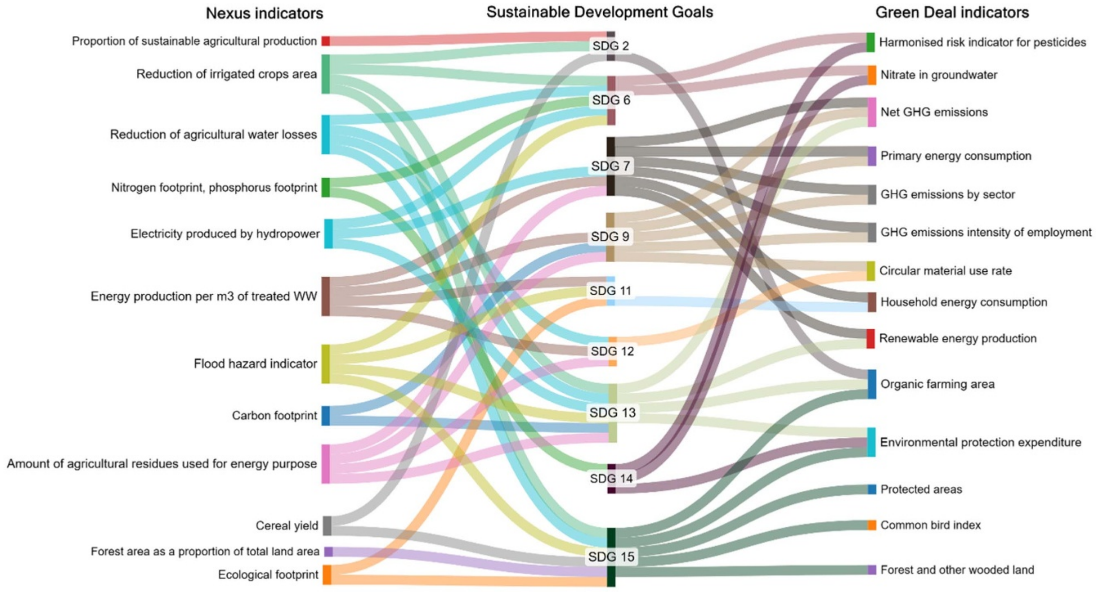

Figure 3. WEFE nexus, SDGs and EU Green deal indicators.

Table 5. Challenges in modelling and monitoring WEFE nexus.

Challenges	Details
Data	Barriers in data sharing across sectors; policy and stakeholder collaboration challenges; issues with ontologies and standardized labelling.
Climate scenarios	Difficulties in using different climate projections (RCP, SSP); need for guidelines to compare long-term results (50–100 years); debate on whether climate should be a nexus node or an umbrella affecting other nodes.
Ecosystems in the nexus	Unclear methods for ecosystem integration; lack of understanding of feedback loops and trade-offs across dimensions (technological, financial, social).
Geographical coverage	Uncertainty in the optimal spatial scale for nexus management; lack of examples from diverse geographies with different challenges.
Data-driven methodologies and AI	Underutilization of AI and data-driven approaches; need for more research in reinforcement learning and small data AI; models often not integrated for cross-sectoral analysis.
Inclusion of narratives and semantics	Challenges in integrating multiple narratives and semantics (water, energy, food, land, climate), especially in high-stake transitions with uncertainty.

Source: Authors' insights based on their nexus expertise and observations.

between nexus indicators, SDGs, and Green Deal indicators[26] shedding light on overlapping areas of influence.

Compared to the WEFE nexus indicators, water remains underrepresented in the Green Deal framework. The EU Blue Deal, adopted in 2023, emphasizes water's role and integrates the WEFE nexus through different principles that promote water efficiency and ecosystem restoration. These key principles include Principle 2 (Water-Ecosystems) and Principle 6 (WEFE), which promote efficient, sustainable practices. Principles 8 (Water-Food) and 9 (Water-Energy) emphasize sustainable agriculture and energy linkage, while Principle 14 underscores international cooperation for water efficiency and ecosystem restoration.

The alignment of SDG indicators, the European Green Deal, and the emerging EU Blue Deal represents an example of growing awareness of the importance that the WEFE nexus has in informing sustainable development. While the SDGs provide a global framework, European initiatives—especially the EU Blue Deal—emphasize the critical need for stronger and more explicit integration of water-related concerns at a different but still extensive geographical framework.

7. Challenges and outlook

The WEFE nexus has proven to be an essential framework for understanding the intricate interdependencies among water, energy, food, and ecosystems and their services. Several challenges remain, especially regarding effective modelling and monitoring of these interconnected systems. Table 5 presents a concise overview of them followed by a detailed discussion.

One significant challenge is the integration and standardization of data from various sectors and sources, such as water, energy, agri-food, biodiversity, and climate. This is complicated by divergent databases, data qualities, policies, reluctance to collaborate, and inconsistent data standards. The need for standardized efforts in data sharing, uncertainty analysis and ontology alignment is critical for addressing these issues.

Another challenge lies in the role of climate within the nexus framework. There is ongoing debate about whether climate should be treated as a separate sector or an overarching factor influencing all components. This is a rather complicated question as climate could be identified either as an external factor that sets the conditions under which the WEFE nexus sectors will be developed or as an internal component interacting with the rest. In the first case, climate is a regulatory factor affecting water resources management, energy production and consumption patterns, food production and ecosystems preservation. It determines the physical conditions that constitute the framework under which resilience on infrastructures, confrontation of drought and floods, food security, energy security and ecosystems sustainability should be managed accordingly. In the second case, climate remains a regulatory factor, but it is also a nexus sector, interacting with the rest of the WEFE nexus sectors. Precipitation rates, evapotranspiration, increasing temperatures, emissions, etc. are linked to each of the WEFE nexus sectors through direct and indirect interlinkages that should be deeply analysed and incorporated into the respective models. The use of different climate projections, like

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[26] https://ec.europa.eu/eurostat/cache/egd-statistics/ and https://data.europa.eu/en/news-events/news/statistics-european-green-deal

Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), further complicates the integration of climate impacts into nexus models. Standardized guidelines are essential for harmonizing these projections and improving long-term modelling reliability. In addition, geographical considerations also present challenges in modelling, as appropriate spatial scales for water, energy, and agricultural management often vary. The watershed scale, suitable for water management, is not always compatible with energy and agriculture systems that may extend beyond watershed boundaries. The lack of diverse geographical case studies with unique challenges makes comprehensive modelling efforts difficult.

Incorporating ecosystems and their services into the nexus framework is another challenge, due to limited understanding of ecosystem feedback loops and trade-offs among various nexus dimensions. The underuse of advanced, data-driven methods such as artificial intelligence (AI) limits the potential of nexus models, which often focus on individual sectors instead of integrating the complex interconnections between water, energy, food, and ecosystems. AI methods, particularly machine learning and deep learning, offer significant opportunities to enhance the accuracy and efficiency of integrated nexus models by analysing large datasets and uncovering complex interdependencies. Recent literature highlights the growing importance of AI in nexus modelling. For instance, Richards *et al* (2023) discuss how AI can be deployed responsibly in water systems to improve decision-making, addressing both the rewards and risks associated with its implementation in the water sector. Additionally, Nishant *et al* (2020) emphasize the potential of AI to drive sustainability across sectors, including food, energy, and water, by offering innovative solutions for managing these interconnected challenges. Additionally, incorporating diverse social narratives into modelling introduces further complexity. Different perceptions and values among stakeholders can shape model outcomes, and frameworks like Quantitative Storytelling are proposed to address this by making explicit the various narratives involved in decision-making.

Looking ahead, several priorities can enhance the effectiveness of the WEFE nexus modelling and monitoring efforts. Standardizing and refining nexus indicators is vital for quantifying resource interactions and assessing sustainability outcomes. WEFE nexus indicators have the potential to contribute to SDGs' performance assessment, supporting the exploration of critical issues that need to be improved to advance efficient resource use. Such indicators intertwine nexus sectors, reveal knowledge gaps and guide the design of effective policies. According to the literature, emphasis should be placed on the spatial scale considered as in many cases indicator specialization and adaptation to local characteristics and peculiarities is required. Consistent metrics will enable better decision-making through accurate and comparable results across sectors.

Expanding stakeholder engagement, particularly through transdisciplinarity, is essential for developing inclusive and effective strategies. Interdisciplinary approaches are crucial for addressing the complex challenges of the WEFE nexus, as integrating knowledge across disciplines fosters a comprehensive understanding of sustainability issues, breaks down silos, builds common understanding, and promotes collaboration. Involving diverse stakeholders ensures that all WEFE nexus sectors are represented, leading to robust and widely accepted decisions on equitable resource allocation. Co-creation processes—encouraging the joint exploration of existing pressures, co-design of solutions, and collaborative decision-making on future policy frameworks—promote social acceptance and help establish stakeholder coalitions that support the practical implementation of the WEFE nexus. This approach ensures that solutions consider both social and environmental factors, reduce unintended consequences, and align with community needs.

Aligning the WEFE nexus with broader policy initiatives, such as the EU Green and Blue Deals, and SDGS, will embed nexus principles into global sustainability frameworks, advancing international goals. Context-specific policies are also required so that local needs and problems are effectively addressed.

Enhancing the integration of ecosystems and ecosystem services within nexus applications will underscore their pivotal role in ensuring water, energy, and food security. Future work should emphasize the role of NbS, and their specific contribution as providers of ecosystem services, and circular economy approaches (Nika *et al* 2022, Sowińska-Świerkosz and García 2022). Circularity minimizes waste while balancing social, economic, and environmental factors. NbS leverage natural processes to manage resources and mitigate environmental degradation. However, integrating these approaches fully into the nexus remains challenging (Carvalho *et al* 2022). Efforts must improve assessment tools and broaden applications, especially in agriculture (Junge *et al* 2021, Canet-Martí *et al* 2021).

This study highlights the critical role of quantitative and methodological advancements in enhancing and systematizing WEFE nexus research. It establishes a foundation for future studies, emphasizing the necessity of standardized metrics, improved data integration, and innovative modelling techniques. By strengthening analytical frameworks and promoting interdisciplinary methodologies, this study contributes to aligning WEFE nexus research with global sustainability objectives, supporting more informed decision-making and effective resource management.

8. Concluding remarks

Sustainable resource management is a critical challenge in today's globalized society. Climate change further intensifies pressures on both the natural and built environments, necessitating the design of effective policies and solutions to strengthen adaptation and mitigation efforts. The nexus approach offers an innovative scientific framework for the integrated assessment and management of resources. It highlights the interdependencies and interactions across sectors—such as water, energy, food, ecosystems, climate, and land use—shifting the focus from sectoral to cross-sectoral and interdisciplinary perspectives. This approach uncovers trade-offs, conflicts, and synergies, while addressing the complexity of the nexus and identifying key hotspots of interaction. By doing so, it lays the foundation for more informed decision-making and the exploration of best practices in both management and policy implementation.

A comprehensive synthesis of existing interdisciplinary nexus monitoring and modelling methodologies reveals several key research gaps. The lack of standardized indicators for cross-sectoral assessments hampers comparability and consistency across studies. Additionally, inconsistencies in data integration and policy alignment complicate the implementation of effective nexus strategies. To address these gaps, this study calls for the development of interdisciplinary, policy-relevant assessment frameworks.

Monitoring and modelling techniques form the foundation of nexus science. Modelling serves as the first step in understanding the complex nature of the nexus, exploring interactions, and interpreting causal relationships. Monitoring, on the other hand, plays a crucial role in advancing nexus sustainability by introducing performance indicators, managing trade-offs, and assessing uncertainty.

This paper has focused on exploring nexus quantification, modelling, and monitoring techniques, identifying current gaps, and outlining future challenges based on a review of literature and insights from WEFE nexus-related projects. While there are no universally established methods for nexus monitoring and modelling, a wide range of tools and approaches are employed, each tailored to specific research questions, scales, and contexts. This study provides a comprehensive overview of these methodologies, highlighting their applications and limitations to guide future nexus assessments and enhance understanding of their potential contributions.

Efforts to advance WEFE nexus modelling and monitoring should prioritize the standardization and refinement of indicators, expand stakeholder engagement, and align nexus principles with broader policy frameworks. Standardized metrics can quantify resource interactions, uncover sectoral interdependencies, and inform policy design, facilitating better decision-making across various scales. Moreover, integrating interdisciplinary approaches, such as NbS and circular economy strategies, is essential for addressing governance gaps, fostering collaboration, and ensuring long-term resource security and sustainability.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

The authors declare no conflict of interest.

ORCID iDs

Maria Vrachioli 0000-0001-5573-3568
Nikos Mellios 0000-0002-8540-5597
Emre Alp 0000-0001-8140-3394
Cristina Sousa Coutinho Calheiros 0000-0003-3159-3497
Giulio Castelli 0000-0002-0209-0869
Virginia Rosa Coletta 0000-0002-3724-9139
Julieta Domínguez-Soberanes 0000-0001-8476-3352
Marianela Fader 0000-0001-9937-8297
Cristina Madrid-López 0000-0002-4969-028X
Hasan Volkan Oral 0000-0002-5743-1931
Chrysaida-Aliki Papadopoulou 0000-0002-8004-3160
Maria Papadopoulou 0000-0001-9252-4255
Sofia I A Pereira 0000-0002-5897-687X
Rocío Pineda-Martos 0000-0002-7176-1531
Tadej StepisnikPerdih 0000-0003-3326-0725
Lydia Vamvakeridou-Lyroudia 0000-0002-8888-532X
Konstantinos Ziliaskopoulos 0000-0001-8323-3392
Giannis Adamos 0000-0002-2639-1607
Floor Brouwer 0000-0002-7308-1185

Chrysi Laspidou 0000-0001-5225-4844

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