Sustainability Science
https://doi.org/10.1007/s11625-025-01691-x

OVERVIEW ARTICLE

Water–energy–food–ecosystem nexus: how to frame and how to govern

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Received: 17 June 2024 / Accepted: 29 April 2025

Abstract

The food, energy, and water domains are strongly interrelated. The body of literature investigating these interlinkages developed into water–energy–food and, more recently, ecosystem (WEFE) nexus thinking. The WEFE nexus is concerned with cross-sectoral resource management requiring dedicated WEFE governance approaches. Among the existing WEFE nexus conceptualizations, the one that places the ecosystem at the center emphasizes the importance of ecosystem services for human well-being and as the basis for the functioning of the water, energy, and food domains. Such conceptualization, however, lacks clear definition and explanation of implications for WEFE nexus governance as well as practical tools for implementation. Accordingly, based on an in-depth analysis of WEFE nexus interlinkages, associated governance challenges, and practical experience, we propose the WEFE Nexus Governance Approach as an operationalization of the ecosystem-centric WEFE nexus conceptual framework. This approach takes policy coherence and stakeholder co-creation at its core, integrated with quantitative modeling of WEFE nexus interlinkages, and is organized in four steps: problem identification; formulation of substantive ambitions through stakeholder dialogue; embedding of ambitions and action into a stakeholder agreement; and implementation of actions. The approach is oriented to practical application and can be implemented by any actor (e.g., research institutes, governments, non-governmental organizations) having the ambition to initiate a stakeholders co-creation process toward nexus governance in a specific context. Furthermore, it can be applied to different scales and

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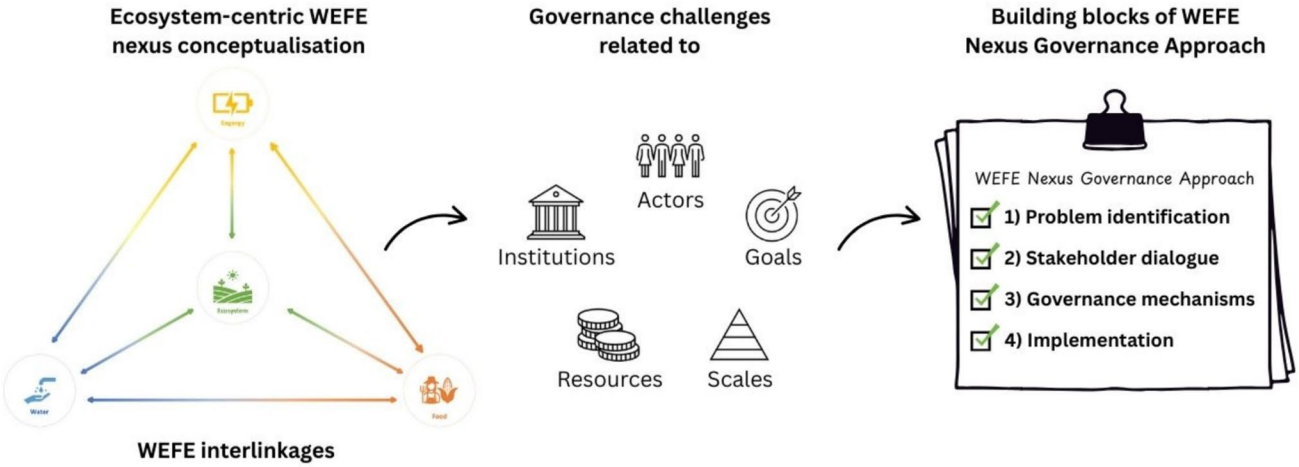
Published online: 28 May 2025

nexus domains depending on the identified nexus problems, while accounting for the vital role of ecosystem services. The approach's applicability and needs for future research are discussed.

Graphical abstract



Keywords Water–energy–food–ecosystem nexus · Water–energy–food–ecosystem nexus governance · Governance challenges

Introduction

In the past decades, human development has made tremendous progress in various areas. However, large parts of the global population still lack food security and have limited access to energy, sanitation, and safe drinking water (Hoff 2011; UN 2021; UNICEF 2021). Simultaneously, many planetary boundaries are crossed leading to diminishing and degraded ecosystem services, while the demand for natural resources is increasing (Hoff 2011; Kacyira 2012; Rockström et al. 2024; Steffen et al. 2015). The food, energy, and water domains and the ecosystem domain (hereafter the ecosystem) are strongly interrelated. Ecosystem services are used for energy production and provide fertile land and fresh water (Laspidou et al. 2017; Sušnik et al. 2021; van den Heuvel et al. 2020). The provision of energy, agricultural products, and fresh water for both industrial and domestic purposes may harm the ecosystem and its ability to provide these services (Laspidou et al. 2017). This calls for new approaches to manage biophysical systems more efficiently and sustainably (Rockström et al. 2024).

An increasing body of literature investigating the interlinkages between the water, food, and energy domains resulted in the water–energy–food (WEF) nexus research field (Benson et al. 2015; De Grenade et al. 2016). The WEF nexus provides a structure for cross-sectoral governance and knowledge production based on the principle that all domains have equal importance and progress in one domain should not penalize the others (van den Heuvel et al. 2020). The fundamental principle of the nexus is that these domains are interdependent, with actions in one domain directly influencing the others (Avellán et al. 2017; Benson et al. 2015; Papadopoulou et al. 2020; Urbinatti et al. 2020). By understanding this interconnectedness and acknowledging equal importance of the domains, decision-makers and researchers can identify synergies and manage trade-offs to sustainably meet human demand for natural resources (Bizikova 2019; Hoff 2011).

Early WEF nexus debate revolved around water, energy, and food security (Hoff 2011). More recently, natural resource management and efficiency have been included (Cairns and Krzywoszynska 2016; Papadopoulou et al. 2020; Shannak et al. 2018). As a result, new conceptualizations of the nexus have emerged, and scholars started to include the ecosystem as a new dimension, forming the water–energy–food–ecosystem (WEFE) nexus (De Strasser et al. 2016; Malagó et al. 2021; Roidt and de Strasser 2018). In early WEF nexus conceptualizations, water was considered the connector of all domains (Hoff 2011; Pahl-Wostl 2019). Including the ecosystem in the nexus has raised scholarly debate. While there is no consensus yet on its place with respect to the other domains, scholars deem

it important to reflect on the role of ecosystem services in the nexus context (Lucca et al. 2025; Sušnik and Staddon 2021). On this point, while the ecosystem can exist independently from humans (De Grenade et al. 2016), most ecosystems are man-altered, requiring human intervention to guarantee ecosystem service provision. Furthermore, defining the ecosystem and its boundaries in relation to the WEF nexus domains is necessary to operationalize the WEFE nexus, as water, climate, and land may also be viewed as part of the ecosystem. Accordingly, we start by defining the WEFE domains (see Table 1). These definitions are based on the understanding that the boundary between nexus domains is placed where human activities start to exploit ecosystem services. Having defined the WEFE nexus domains, an important next step is to understand what they entail for nexus governance.

Much WEF(E) nexus research has focused on understanding the bio-geophysical interactions between nexus domains. The systematic literature review of Urbinatti et al. (2020) shows that nexus governance research is still underdeveloped, focusing mostly on technical and administrative aspects. However, there is an increased focus on nexus governance (e.g., González-Rosell et al. 2023; Hoolohan et al. 2018; Jones-Crank 2024; Kimengsi et al. 2022; Kurian and Ardakanian 2015; Kurian et al. 2018; Lebel et al. 2020; Pahl-Wostl 2019). These scholars tend to agree that an important aspect of nexus governance is to focus on cross-domain collaboration and coordination between multi-level stakeholders and on coherence of policies (Jones and White 2021; Scott et al. 2011). Policy coherence, in particular, is a core aspect of the WEFE nexus governance (Roidt and Avellán 2019). Current policies often target single domains and parts of specific problems, leading to increased resource management vulnerability (Briassoulis 2004; Rasul and Sharma 2016). Nexus governance literature shows the tendency to overlook governance challenges, including insufficient attention to: political and cognitive factors influencing policy change; cross-sectoral collaboration and coordination conditions needed for policy coherence (institutional-, and actor- related challenges) (Urbinatti et al. 2020; Weitz et al. 2017); scalar fit between bio-geophysical problems and administrative/political institutions that address them (scale challenge) (Pahl-Wostl et al. 2021); managing power asymmetries and related stakeholder negotiations and balancing different perspectives on resource use (goal- and resource-related challenges) (Purwanto et al. 2019; Salmoral et al. 2019; van den Heuvel et al. 2020). Accordingly, we understand WEFE nexus governance as the entirety of societal decision-making processes that tackle goal-, actor-, scale-, institutional-, and resource-related challenges for the management of the WEFE nexus (Mooren et al. 2024) after (Benson et al. 2015; Pahl-Wostl 2019; Stein and Jaspersen 2019; Urbinatti et al. 2020).

Another important aspect for nexus governance is that nexus issues are cross-sectoral resource management issues. Common approaches attempting to foster cross-sectoral integration include integrated water resource management, integrated natural resource management, and integrated solid waste management (Avellán et al. 2017; Benson et al. 2015; La Jeunesse and Quevauviller 2016; Roidt and Avellán 2019).These typically sectoral governance approaches (De Strasser et al. 2016; Roidt and Avellán 2019) have not yet lived up to the expectations, as integration is often limited and lacks tangible results (de Andrade Guerra et al. 2021; Pahl-Wostl et al. 2021). This underperformance can be explained by insufficient attention to existing local formal and informal institutional structures (Al-Saidi 2017), and the fact that these approaches typically originate from and are strongly influenced by natural sciences (Fritsch and Benson 2019; McDonnell 2008). This results in integration often occurring from a natural science perspective (e.g., integrated modeling), while the institutions involved in these domains are not necessarily domain/sector specific. These approaches, despite their limitations, are first steps toward a more comprehensive, integrated WEF(E) nexus governance approach (Scott et al. 2018).

Several WEF(E) nexus governance approaches exist in the literature (see e.g., Harwood 2018; De Strasser et al. 2016; Halbe et al. 2015; Hoff et al. 2019; Mohtar and Daher 2016; González-Rosell et al. 2023; Daher and Mohtar 2015; Pereira Ramos et al. 2022). These approaches share elements such as a focus on policy trade-offs and synergies, and broad stakeholder engagement for mapping and assessing nexus issues and discussing integrated solutions. However, they

Table 1 Proposed definitions of the WEFE nexus domains

Water domain	The chain of water management activities for human water use including water extraction, drinking water, (waste) water treatment, water allocation, and water security (in line with Morseletto et al. (2022))
Energy domain	The energy production chain from extraction/harvesting of resources to distribution to end users (in line with IPCC (Bruckner et al. 2014))
Food domain	The food production chain from production to consumption including food loss and waste (in line with IPCC (Mbow et al. 2019))
Ecosystem domain	The natural system that can exist without human interference and that provides ecosystem services (ecosystem aspects used for human benefit (Fisher et al. 2009)) to the other domains

lack a clear definition of nexus governance, do not address the governance implications of including the ecosystem in the WEF nexus, and do not propose specific WEFE nexus governance instruments for more effective cross-sectoral collaboration and better policy coherence. This research addresses these knowledge gaps, building on the suggestion of Sušnik and Staddon (2021) to combine stakeholder engagement, social science, and quantitative modeling to increase the effectiveness of nexus governance approaches. Specifically, we believe nexus governance research and practice can benefit from approaches that help better understand the performance and potential of governance systems to shift toward WEFE nexus governance as well as governance mechanisms fostering the design and implementation of more coherent WEFE policies. Furthermore, we posit that WEFE nexus governance can benefit from a more explicit and centrally placed role of ecosystem in the WEFE nexus along with a clear conceptualization accounting for the specific governance challenges that arise from such framing.

Against this backdrop, in this paper, we conceptualize an ecosystem-centric "WEFE Nexus Governance Approach" built around literature and reflection on the central role of the ecosystem in the WEFE nexus and related nexus governance challenges. The approach takes policy coherence and stakeholders co-creation at its core and includes quantitative modeling of bio-geophysical nexus interlinkages, governance and policy assessment methods, stakeholder engagement approaches and governance mechanisms for co-creating coherent WEFE policies.

The "Methodology" illustrates our methodology. An overview of the main WEFE nexus interlinkages is presented in "WEFE interlinkages". The overview of the governance challenges that arise from these interlinkages is found in "Nexus governance challenges". "Toward a WEFE Nexus Governance Approach" presents the WEFE Nexus Governance Approach set out to address these challenges. The practical application of the approach is beyond the scope of this overview paper; however, "Discussion and conclusion" offers some reflections on its initial application in 5 river basins. The WEFE Nexus Governance Approach was designed and is currently being tested within the European-funded NEXOGENESIS project.

Methodology

The WEFE Nexus Governance Approach is based on an extensive literature review of well-established integrated and collaborative governance approaches and methods combined with experience of the authors. The approach was developed in four steps as illustrated in Fig. 1.

First, a review of the nexus literature yielded an overview of the main WEFE nexus interlinkages (step 1). Our goal was to capture the most important interlinkages, rather than providing a complete overview of all of them. To this purpose, we reviewed scientific and gray literature drawing on the bodies of literature on the WEF(E) nexus interlinkages, interdependencies and modeling collected through Google Scholar and Scopus (Annex 1 for search terms). Additionally, two nexus and nexus modeling experts reviewed and validated our analysis of the WEFE nexus interlinkages. The experts involved in validating the analysis have published 10+ scientific articles between 2019 and 2024 on the WEF nexus bio-geophysical interlinkages and related modeling.

Second, we conducted a narrative literature review of both governance and governance assessment literature, and nexus governance literature to identify key nexus governance challenges related to the identified WEFE nexus interlinkages (step 2). Specifically, we drew on the bodies of literature from WEF(E) nexus governance, policy coherence, environmental policy integration, policy change, Institutional change, policy design, and transboundary resource management (see Annex 2 for details). Narrative or semi-systematic literature reviews can be used to create an overview of a certain topic and require the research team to apply their own selection standards (Snyder 2019).

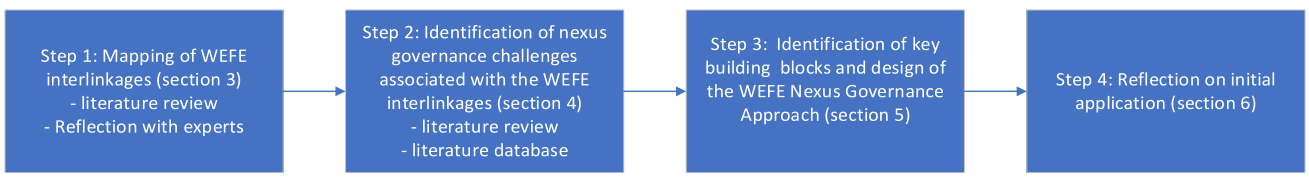


Fig. 1 Outline of the research methodology

Accordingly, we formulated 33 search terms (see Annex 1) to collect relevant literature via Google Scholar and Scopus in a database. Per search term, we selected the ten most cited papers with no time limitation, and the ten most recently published articles until 2022, resulting in a manageable yet relevant sample of 200 articles. The authors made a further selection of the articles relevant for this study based on their abstract, resulting in a final set of 68 publications. These publications were investigated in detail using guiding questions (see Annex 1) to extract relevant information, which was manually collected into an Excel database. Adopting a snowballing approach while reading the articles, we complemented this initial set of papers with 26 additional ones. The review led to the identification of five types of governance challenges and an inventory of commonly used governance assessment methods and tools.

The WEFE Nexus Governance Approach was developed over three months of bi-weekly meetings and six dedicated workshops between January and March 2022. The bi-weekly meetings served as regular progress updates, where insights from the literature review database were shared, discussed, and an initial joint reflection upon the usefulness for the WEFE nexus governance approach. The workshops were dedicated sessions to critically evaluate the applicability and relevance of the various approaches and related components, based on literature insights and the authors' practical experiences. The research team was an interdisciplinary team of nine researchers (all co-authoring this paper) with expertise in water governance, political science, environmental governance, governance assessment, and experience in nexus research. Specifically, research team members reflected individually and collectively on the capacity of the identified WEF nexus governance approaches, and governance and policy assessment methods and tools (detailed in Annex 2) to address the identified nexus governance challenges (illustrated in "Nexus governance challenges"). Hence, the relevance to the WEFE nexus governance challenges was the determining factor for including or discarding elements of existing approaches. This analysis led to identify the four key building blocks of our approach. Finally, we briefly reflect on the initial application of the approach (step 4) in "Discussion and conclusion".

WEFE interlinkages

The WEFE nexus consists of complex interlinkages that must be untangled to better understand synergies and trade-offs (Hoff et al. 2019; Salmoral et al. 2020). Past studies (e.g., Purwanto et al. 2019, 2021; Sušnik et al. 2021) have provided a clear overview of interlinkages between the WEF nexus domains. Including the ecosystem in the nexus is, however, relatively new (Sušnik and Staddon 2021; van den Heuvel et al. 2020). Previous studies including the ecosystem in the nexus have not reflected on its role and place (e.g., Cristiano et al. 2021; De Roo et al. 2021). We argue, in line with De Strasser et al. (2016) and González-Rosell

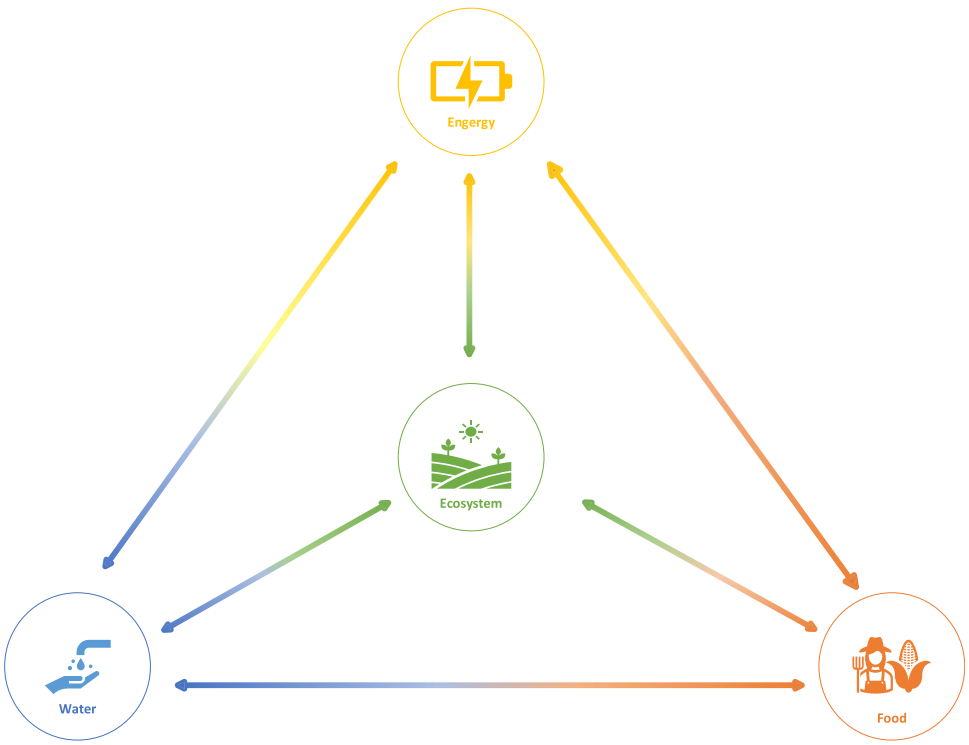


Fig. 2 Ecosystem-centric conceptualization of the water–energy–food–ecosystem (WEFE) nexus based on: Van den Heuvel et al. (2020), Laspidou et al. (2017), Laspidou et al. (2020), Purwanto et al. (2019), Purwanto et al. (2021), and Sušnik et al. (2021) in line with De Strasser et al. (2016), González-Rosell et al. (2023), and Pahl-Wostl (2019)

et al. (2023), that the ecosystem should be at the center of the nexus (Fig. 2). In this section, we illustrate the main WEFE nexus interlinkages and conclude with a reflection on the importance of placing the ecosystem at the center of the WEFE nexus.

Ecosystem–energy interlinkages

The energy domain and ecosystem are strongly intertwined. The ecosystem provides services for the energy domain, such as land and water for crops for biofuel production, solar and wind power, and hydropower plants (Laspidou et al. 2017; Sušnik et al. 2021; van den Heuvel et al. 2020). Energy domain activities negatively impact the ecosystem through emission of hazardous substances as a side effect of mining, fracking and drilling of fossil fuels, energy infrastructure, and deforestation as a result of using firewood as energy source (Felix and Gheewala 2011; Laspidou et al. 2017; van den Heuvel et al. 2020). Especially, carbon dioxide emissions from fossil fuels largely contribute to climate change, which is at increased risk of surpassing its planetary boundary (Scott et al. 2015; Steffen et al. 2015). The energy domain can also cause biodiversity loss due to land conversion (e.g., land use for infrastructure or flooding of land for water reservoirs) and deforestation (Hoff 2011). Moreover, construction of hydropower plants hinders fish migration and alters the hydromorphological system of rivers (Laspidou et al. 2017; van den Heuvel et al. 2020).

The ecosystem itself is not dependent on the energy domain, but is influenced by it. However, ecosystem protection regulations may directly affect activities in the energy domain. This interaction requires attention for coherence between ecosystem and energy policies (see institutional challenges). Although the ecosystem can exist independently of the energy domain, synergies can be created, such as green roofs that increase the energy efficiency of buildings, while simultaneously improving biodiversity (Benvenuti 2014).

Ecosystem–food interlinkages

The relation between the food domain and the ecosystem is not based on equal dependency. The food domain depends on ecosystem services such as nutrient-rich soil and availability of arable land. Concurrently, food production can damage the ecosystem through land conversion (Winkler et al. 2021), resulting in deforestation and habitat loss, and soil compaction and erosion. In addition, nitrogen and phosphorus overload in freshwater bodies lead to algae blooms and eutrophication. The food domain is responsible for a quarter of global greenhouse gas emissions (Hua et al. 2020; Laspidou et al. 2017; Purwanto et al. 2021; Sušnik et al. 2021; van den Heuvel et al. 2020). At present, emissions of nitrogen and phosphorus exceed planetary boundaries and, based on global population growth projections, are likely to increase by 250–270% by 2050 (Hua et al. 2020; Steffen et al. 2015). Simultaneously, land use change and the conversion of any type of land to cropland are at increased risk of exceeding their planetary boundary (Hua et al. 2020; Steffen et al. 2015; Zisopoulou et al. 2018). Moreover, overfishing and freshwater fish farms affect biodiversity and interactions between trophic levels (Laspidou et al. 2017; van den Heuvel et al. 2020). Finally, the planetary boundaries for biochemical flow and changes in the biosphere are also at critical risk (Kurian et al. 2019).

In contrast, the ecosystem itself does not rely on the food domain for its existence. Nevertheless, degrading ecosystem services impact the food domain by reducing the availability of fertile land with sufficient nutrient cycling. In general, synergies between the ecosystem and food domain exist through agricultural stewardship practices (Kay et al. 2009) and agroecology, a form of agriculture based on ecosystem services instead of external inputs, which fosters biodiversity and landscape diversity, and reduces adverse effects on the ecosystem (Runhaar 2021).

While the nexus assumes equality between all nexus domains, in practice, actors do not have the same influencing capacity, especially when one domain is economically dominant in a region (Purwanto et al. 2019). This is often the case with the food and ecosystem domains where food advocates have more lobby power on decisions about the use and preservation of ecosystem services (see actor-related challenges).

Ecosystem–water interlinkages

The water domain and ecosystem are closely interlinked. The water domain is dependent on ecosystem services, for example groundwater and surface water serve as natural pollutant removers (Laspidou et al. 2017). Moreover, wetlands serve both as pollutant remover and water buffers. When groundwater or surface water sources are over-extracted, the water domain can negatively affect the ecosystem. Discharge or insufficient treatment of wastewater affects natural biochemical ecosystem cycles, especially in water bodies with little flow (Laspidou et al. 2017; Scott et al. 2015; van den Heuvel et al. 2020). Interventions to protect the ecosystem should match the bio-geophysical levels at which the water and ecosystem operate (see scale-related challenges) (Pahl-Wostl et al. 2021). There are synergies between the water sector and the ecosystem. New sanitation developments such as water-conservation behavior and water-saving showers or

recirculation showers reduce water consumption, lowering the pressure on the ecosystem services used by the water sector (Bouziotas et al. 2019; Koop et al. 2019). However, realizing these synergies requires specialist knowledge and is often costly (e.g., requiring changes in the built environment and infrastructure, see resource-related challenges).

Water–energy–food interlinkages

The "conventional" WEF interlinkages are typically characterized by mutual dependency. The energy domain needs a significant amount of water for the production of biofuels, cooling of power plants, mining, and hydropower generation (Bakhshianlamouki et al. 2020; Laspidou et al. 2017, 2020; Purwanto et al. 2019; Scott et al. 2015, 2018; Sušnik et al. 2021). The water used by the energy domain accounts for around 15% of the freshwater availability globally (Simpson and Jewitt 2019). The water domain on the other hand requires energy for potabilization and wastewater treatment (Laspidou et al. 2017, 2020; Purwanto et al. 2019). The water domain uses around 8% of the energy generated worldwide (Simpson and Jewitt 2019).

The food domain is dependent on the energy domain for operations in all stages of the food chain, from producing and applying fertilizers and pesticides to irrigating fields and processing food and waste (Laspidou et al. 2017; Purwanto et al. 2019; Sušnik et al. 2021). The food domain uses around 30% of global energy production (Simpson and Jewitt 2019). Simultaneously, the food domain can be a source of energy when food residues or crops are used for biofuel production. The latter accounts for approximately 1% of the crops produced globally (Simpson and Jewitt 2019; Sušnik et al. 2021). Furthermore, the energy and food domains compete for land, primarily when biofuels represent an alternative to fossil fuels or achieve more energy independence (Laspidou et al. 2017). This competition increases the chance of conflicts (Zisopoulou et al. 2018). This implies trade-offs and negotiation between stakeholders of different domains to reach mutually beneficial arrangements (see goal-related challenges).

The interlinkages between the water and food domain differ slightly. The food domain relies on the water domain for crop irrigation, drinking water for farm animals and aquaculture activities, and uses around 71% of the available water (Bakhshianlamouki et al. 2020; Purwanto et al. 2019; Simpson and Jewitt 2019; Sušnik et al. 2021). Water quality and availability are therefore crucial to the food domain, but are also put at risk by agricultural practices. Examples include deteriorating water quality from excessive nitrogen, phosphorus, and pesticide use, and reduced water availability due to increased irrigation and over-extraction (Bakhshianlamouki et al. 2020; Koop and van Leeuwen 2017; La Jeunesse and Elliott 2004; Laspidou et al. 2017; Lefrancq et al. 2017). At present, such agricultural practices have put the planetary boundary for freshwater use at critical risk (Kurian et al. 2019).

Moving away from an anthropocentric view of the WEF nexus: placing the ecosystem at the center of the WEFE nexus

The WEFE interlinkages take on various forms. Some are based on competition (e.g., food–energy), others on mutual dependency (e.g., water–energy), and still others on unequal dependency (e.g., energy–ecosystem, food–ecosystem). All interlinkages are increasingly affected by climate change and population growth (e.g., water conflicts becomes more frequent due to increasing periods of droughts, while the total water demand increases due to population growth (La Jeunesse and Quevauviller 2016)). Different authors refer to the ecosystem as environment, earth system, or natural system (Lucca et al. 2025). We choose to keep the term ecosystem because it evokes a key aspect of ecosystems in relation to the other domains, namely the services provided to society. We argue that vital services provided by ecosystems represent the primary way through which the ecosystem interacts other with nexus domains. Ecosystems supply essential services that enable the functioning of the WEF domains, are affected by human-driven actions within those domains, yet can exist independently from humans. However, if humans want to continue exploit ecosystem services, proper management is essential to ensure that their capacity to support overall human well-being is not exceeded (De Grenade et al. 2016; Rockström et al. 2009; Scott et al. 2018; Steffen et al. 2015).

By placing the ecosystem at the center, we challenge the traditional anthropocentric perspective of the nexus that views ecosystems as supplying unlimited services to the WEF domains. This ecosystem-centric view highlights the interlinkages between the ecosystem and the WEF domains, making the finite capacity of ecosystems to support human activities explicit. In addition, this view of the WEFE nexus legitimizes the explicit integration of bio-geophysical indicators into policy frameworks, thereby enhancing the effectiveness of natural resource management policy and ultimately promoting more sustainable decision-making.

Nexus governance challenges

The interlinkages between WEFE nexus domains raise five types of governance challenges: *scale-related, institution-related*, *resource-related, goal-related,* and *actor-related challenges.*

Scale-related challenges

The WEFE nexus is a multi-scale resource system (Scott et al. 2011). Adopting an ecosystem-centric approach shifts the focus of policies and decision-making to the bio-geophysical characteristics of resource management issues, rather than prioritizing the interests of the water, energy, or food sectors. This calls for a scalar fit between the bio-geophysical scale of the resource systems and the political and administrative scales of the governance system that manages them. For this purpose, the governance system needs to be supra-sectoral, including horizontal (cross-sectoral) and vertical (across different levels of governance) coordination (Märker et al. 2018; Pahl-Wostl et al. 2018, 2021). To realize this, structural levels of the governance system that deal with the WEFE domains need to match the different bio-geophysical scales at which these domains operate (Pahl-Wostl et al. 2021). Therefore, interlinkages between the domains should be addressed at the scale at which they occur. For instance, water quality measures for a river (bio-geophysical scale of the resource system) are more effective if implemented both upstream and downstream (Suttles et al. 2021). However, administrative boundaries and governance structures are often designed around (economic) sectors, leading to inefficiencies in resource management, and tensions that must be addressed.

Institution-related challenges

Complex cross-sectoral management issues such as WEFE nexus issues can be effectively addressed via a governance architecture where different formal decision-making centers acknowledge and manage potential conflicts and strive for collaboration, known as polycentric governance (Ostrom 2010). Such architecture can help understand the relations and conditions underlying the types of interactions between different decision-making centers in the WEFE nexus (Srigiri and Dombrowsky 2022). However, in practice polycentric governance is prone to several institutional challenges that are particularly related to the above-mentioned scalar issues.

Institutions can be defined as formal and informal repetitive, structured, and multi-level rules of the game that influence social, economic and political interactions (North 1991; Ostrom 2008). Institutions are context dependent. They are influenced by (and influence) norms and rules of institutions with whom they interact. Their ability to effectively address resource management issues often depends on their ability to collaborate with other institutions (Pahl-Wostl et al. 2021). For example, sectoral policies like farmer subsidies in the agriculture domain make it difficult for institutions in the ecosystem domain to exert influence on farmers in reducing surface water pollution, especially when pollution reduction measures are not jointly agreed upon by both domains. Such interaction between institutions is called institutional interplay (Pahl-Wostl et al. 2021; Stein et al. 2014; Young 2002). The nexus governance challenge lies in understanding the institutional interplay across nexus domains and governance scales. This interplay is often the result of power negotiations among actors that operate within a given set of governance strategies and instruments (Pahl-Wostl et al. 2021).

Most actors are part of larger organizations and align their agendas with their organizational goals, which can give rise to institutional challenges. A polycentric governance architecture implies various venues where WEFE actors can influence the resource management process and negotiate intended outcomes, leading to a scalar strategies challenge (Pahl-Wostl et al. 2021). Actors might have motivations that cause them to strategically intervene at a particular scale to create benefits, while disadvantages can occur at a different scale.

The two challenges are embedded in informal rules, yet the formal rules also pose institutional challenges. Olawuyi (2020) identified several institutional challenges. First, the mismatch between sectoral regulatory models. Rules and regulations in respective nexus domains are applied differently due to the nature of the domains (e.g., the often privatized energy domain vs public water domain (Scott et al. 2018)). Moreover, the energy domain is typically characterized by long-term contracts compared to the other domains, complicating the design of overarching nexus policies that match all domains. This can be further complicated by institutional contexts characterized by high levels of bureaucracy (Mooren et al. 2024). Second, policies and legislations in one nexus domain do not necessarily refer to other nexus domains, creating legislative gaps and dispersed responsibilities. Third, institutions have limited institutional capacity to understand and act upon nexus interlinkages (Pahl-Wostl and Knieper 2023). Finally, successful polycentric governance not only requires institutional capacity, but also coordination (Carlisle and Gruby 2019), and managing of power imbalances (Carlisle and Gruby 2019).

Lastly, adding the ecosystem to the nexus raises question of what governmental institution represents it. Often, the ecosystem, is not represented by a specific governmental institution. In the Netherlands, for instance, there is no dedicated ministry for the environment. Environment currently falls under the Ministry of Agriculture, Fisheries, Food security and Nature, and Ministry of Infrastructure and Water Management, and the Ministry of Climate Policy and Green Growth. The environmental personhood debate, assigning legal rights to nature to protect it, ties into this representation question (Gordon 2018; Łaszewska-Hellriegel 2023). Legal tools could be used to protect the ecosystem, however, there are few cases demonstrating their effectiveness (Łaszewska-Hellriegel 2023).

Resources-related challenges

Resources, including knowledge, financial, and human capital, are linked to institutional capacity. Fostering synergies between nexus domains requires awareness and understanding of the resources stakeholders have at their disposal to address nexus issues, and a lack thereof poses a governance challenge (Koop et al. 2017; Salmoral et al. 2020; Scott et al. 2018). For instance, fostering synergies between water, ecosystem, and food domains through gray and black water recycling in urban households requires large investments, as the existing infrastructure is not designed for it, a challenge common to many sustainability issues and potential solutions (Abdalla et al. 2021). Moreover, resources are often allocated to sectoral organizations with competing interests, which are typically limited, or not designed for fostering cross-sectoral interactions (Olawuyi 2020). Instead, there should be a clear political ambition about which issues to prioritize (Koop et al. 2017). If one is in place, enough financial resources must be allocated to implement appropriate policies. Financial continuation should be assured to make policies less influenced by political cycles (Koop et al. 2017; Sievers et al. 2024). Furthermore, to ensure long-term commitment, stakeholder participation should be enabled (Salmoral et al. 2020). Besides knowledge, commitment, and budget, implementation of nexus policies requires human capacity both in terms of staff and nexus expertise at all scales (from national to local); this is often a problem at all scales, but in particular at the local one.

Goal-related challenges

WEFE nexus interlinkages reveal cross-domain interdependencies. This means that managing resources from one domain perspective leads to unintended consequences to one or more of the other domains. In particular, a lack of coordination between domains and their policies often leads to problem shifting. For instance, based on an assessment of 125 cities, Koop et al. (2022) observed that improved access to safe sanitation and sewer networks led to large-scale water pollution, because the wastewater is efficiently collected but not treated. Such a silo approach to resource management often leads to conflicting policy goals across WEFE domains, which can result in natural resource mismanagement and shifting or exacerbating of problems (La Jeunesse 2019). Simultaneously, nexus interdependences create opportunities for cross-sectoral synergies. A key challenge for nexus governance is integrating policy goals across domains both at policy level and in practice to ensure policy coherence (de Andrade Guerra et al. 2021; Scott et al. 2018). Adopting an ecosystem-centric approach prevents governance mistakes, as the ecosystem sets the boundaries for human activities. However, there is a tendency to overlook these boundaries in policymaking. For instance, the Dutch nitrogen crisis illustrates how economic and political interests of certain sectors led policy makers to overlook the bio-geophysical limits of these nutrients. As a result, policies that failed to adequately address the issue and Dutch rivers did not meet water quality standards (Hoppe et al. 2016). A nexus perspective that accounts for interlinkages between domains is needed in decision-making for designing and implementing resource management strategies.

Actor-related challenges

Addressing goal-related challenges implies that not all actors' goals across domains can be met, making trade-offs inevitable (Purwanto et al. 2019; van den Heuvel et al. 2020). It also means recognizing opportunities for synergies and exploiting them. Managing trade-offs and synergies requires negotiations and collaborations between actors across domains, grounded on mutual understanding of nexus problems and opportunities, and on willingness to collaborate and to compromise (Salmoral et al. 2020). This leads to three types of actor challenges in nexus governance: managing power imbalances among actors and networks, managing different perspectives on problems and solutions, an absence of trust and lack of communication.

Concerning power, there is a tension between the nexus principle of equal importance of nexus domains and power imbalances in practice (Pahl-Wostl et al. 2021; Purwanto et al. 2019; Salmoral et al. 2019). Adding the ecosystem domain to the nexus further complicates power dynamics, as it does not function as distinct economic sector, making it unclear which type of actor should represent it. In practice, it is often represented by NGOs and environmental agencies who have arguably less economic power than actors represented by economic sectors. Consequently, powerful actors and their interests need to be identified to be managed, and less powerful actors should be identified to make sure their voice is heard (La Jeunesse et al. 2015). Power imbalances do not only exist between the actors of

nexus domains, but also between different scales. Local actors often have limited influence in countering decisions from the national level due to limited capacity and authority (Martín-López et al. 2019; Scott et al. 2011).

Concerning perspectives, nexus issues are highly context dependent, requiring awareness of local views on resources availability, use, and value to local communities (Purwanto et al. 2019). Often conflicts about resource management are rooted in political, cultural, and religious ideas and tend to depend on human values and perspectives (Link et al. 2016). For example, ecosystem services have traditionally strongly influenced the forming of social interactions (Kuslits et al. 2021). The multi-scale nature of the nexus further complicates this, as a difference in the chosen boundary between actors of the problem can result in conflicts over suitability of solutions (Hoolohan et al. 2018). Therefore, actor-related governance challenges of the nexus entail understanding, respecting, and connecting various views, and acknowledging power differences between different stakeholders across domains.

Cross-sectoral collaboration is frequently further complicated by a lack of trust and communication. In their WEFE nexus governance assessment, Mooren et al. (2024) showed that a history of distrust between sectors reduces willingness to collaborate and compromise, resulting in a vicious cycle, hampering collaboration and trustworthy relationships.

Toward a WEFE nexus governance approach

The WEFE Nexus Governance Approach consists of four building blocks: (1) problem identification; (2) stakeholder dialogue; (3) governance mechanisms; and (4) implementation See Fig. 3. While the building blocks may seem applicable to general governance approaches, the specific tools proposed in each of them are tailored to foster transformation from sector-driven governance to WEFE nexus governance (see Hüesker et al. 2022 for more details).

Our approach is rooted in stakeholder co-creation, with the entire process characterized by consistent exchanges among stakeholders as the foundation for knowledge generation (Kliskey et al. 2023). Aligned with the quadruple helix framework, we consider stakeholders to encompass representatives from government, academia, civil society, and industry, ensuring a comprehensive and inclusive process (Grundel and Dahlström 2016; Nguyen and Marques 2022). Including the ecosystem in the nexus ensures that stakeholders who might otherwise be excluded are involved and given a voice in decision-making processes, as demonstrated by Stein et al. (2014). The type of stakeholder engagement evolves across the building blocks of the WEFE Nexus Governance Approach. It begins with stakeholder consultation and involvement to ensure different perspectives are included. As the process progresses, it transitions to collaborative and empowering engagement, enabling stakeholders to actively participate in solution development and shared decision-making power (Kliskey

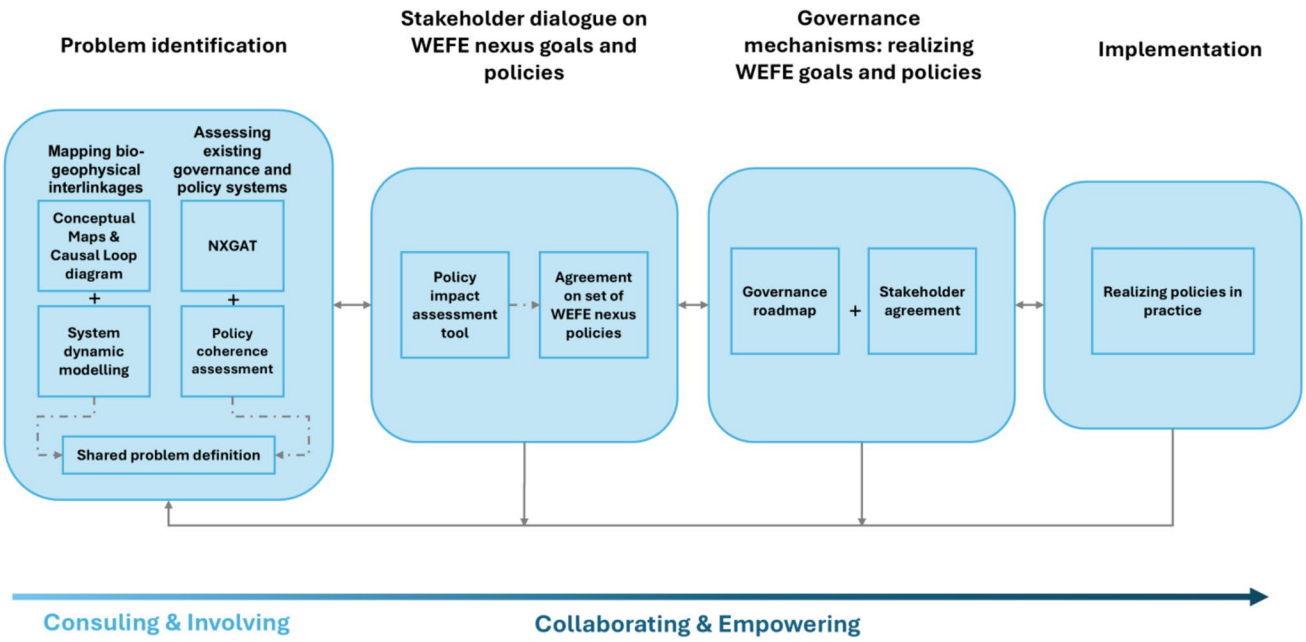


Fig. 3 Visual representation of the WEFE Nexus Governance Approach (adapted from S. Khan in Mooren et al. (forthcoming)

Table 2 Definition of governance quality criteria in NXGAT source La Jeunesse et al. (forthcoming) inspired by Bressers et al. (2016), Pahl-Wostl et al. (2021), and Vatn and Vedeld (2012)

Governance quality criteria	Definition of governance quality criteria
Comprehensiveness	The degree to which the current governance system includes relevant WEFE nexus elements
Coherence	The degree to which the elements of the governance system are strengthening rather weakening each other
Flexibility	The capacity of the current governance system to provide different pathways toward the WEFE nexus governance
Intensity	The capacity of the current governance system to urge more WEFE nexus-oriented actions
Fit	The degree to which the current governance system matches ecosystems' properties and dynamics

et al. 2023). This dynamic and inclusive approach not only integrates diverse perspectives, but also fosters a shared understanding, which is essential for addressing complex resource management challenges within the WEFE nexus.

Problem identification: mapping bio-geophysical interlinkages and assessing existing governance and policy systems

The problem identification consists of two parts: mapping the bio-geophysical interlinkages and assessing the related societal challenges along with the existing policies and governance arrangements to address them.

Mapping bio-geophysical interlinkages

At the beginning of a stakeholder co-creation process for WEFE nexus governance, stakeholder engagement is combined with quantitative modeling as a strategy to identify the nexus problem to address. Tools to map bio-geophysical WEFE nexus interlinkages that we use in our approach include causal loop diagrams (CLDs), conceptual maps (CMs), and system dynamic modeling (SDM) (Halbe et al. 2015; Pereira Ramos et al. 2022). CLDs and CMs visually map and qualitatively model nexus interlinkages and are developed based on scientific and local stakeholder knowledge. CLD and CM are used as basis for developing SDM to quantitatively assess the trade-offs between domains of different actions on the WEFE nexus (Purwanto et al. 2019, 2021; Sušnik et al. 2021). Local stakeholders' knowledge is crucial for mapping and quantifying nexus interlinkages since they are highly context dependent. Starting very broadly with mapping the WEFE nexus interlinkages allows to identify nexus problems, which in turn influence the definition of nexus governance boundaries. This analysis helps to address the goal- and scale-related nexus governance challenges.

Governance assessment and policy coherence

Existing governance practices developed around the identified interlinkages and the degree of policy coherence are analyzed to identify barriers and drivers toward WEFE nexus governance. Similarly to De Strasser et al. (2016), we propose to conduct a governance assessment, albeit one tailored to the WEFE nexus and its governance challenges. To this purpose, a novel tool, the Nexus Governance Assessment Tool (NXGAT), was developed and can be used (publication forthcoming La Jeunesse et al.; for its implementation in practice see Mooren et al. (2024) and Sievers et al. (2025)). NXGAT builds upon the Governance Assessment Tool developed by Bressers et al. (2016) and is tailored to the WEFE nexus governance challenges identified in "Nexus governance challenges". NXGAT is a qualitative assessment tool that analyzes the five governance dimensions identified by Bressers et al. (2016), namely levels and scales, actors and networks, problems perspectives and goal ambitions, strategies and instruments, and resources and responsibilities. These governance dimensions are assessed against five governance quality criteria (see Table 2). Extent, coherence, flexibility, and intensity are quality criteria for successful implementation in complex situations (Bressers et al. 2016). We added fit to account for the scale-related challenges and renamed extent to comprehensiveness for clarity. Coherence is specifically relevant for the nexus, as it takes into account the goal- and institutional-related challenges (de Andrade Guerra et al. 2021). NXGAT provides an understanding of how nexus governance challenges arising from WEFE nexus bio-geophysical interlinkages play out in practice; how the governance system performs in relation to these specific challenges; and what barriers, opportunities, and entry points for change toward WEFE nexus governance exist.

Policy coherence is a policy characteristic pursued by fostering synergies and reducing inconsistencies between (external) and within (internal) policy domains to develop jointly agreed-upon policy goals (Nilsson et al. 2012; Papadopoulou et al. 2020). Given that policy coherence is a key aspect of nexus governance (Giest and Mukherjee 2022; Roidt and Avellán 2019), NXGAT is complemented with

an analysis of the coherence among policy documents and in practice. The policy coherence approach investigates the presence and stringency of provisions within WEFE policy documents that aim to minimize trade-offs or exploit synergies across nexus domains, thereby addressing challenges associated with achieving multiple sectoral goals. The document analysis is complemented by stakeholders' knowledge and experiences. Via focus groups, stakeholders provide insights into the coherence of policy implementation in practice. Combining this practical perspective with an analysis of coherence among policy documents allows for assessing alignment between policy design and its implementation in practice.

The policy coherence and nexus governance assessment establishes a foundation for developing a common vision, identifying shared goals and formulating desired policies, as well as ways to integrate them into the current context-specific governance system to make it more nexus oriented. In addition, by analyzing power distribution, these assessments guide the design of the stakeholder dialogue.

Stakeholder dialogue on WEFE goals and policies

Participatory approaches proved effective in many situations with complex resource interdependencies by building consensus, human and social capital, and legitimacy of decisions (Carr 2015; Driessen et al. 2001). In our WEFE Nexus Governance Approach, the stakeholder dialogue entails a process whereby stakeholders negotiate cross-sectoral solutions to address jointly identified WEFE nexus problems (De Strasser et al. 2016).

In our approach, differently from De Strasser et al. (2016), the stakeholder dialogue is facilitated through a policy impact assessment tool including an artificial intelligence-powered decision support system (DSS) (Echeverria et al. 2022; Echeverria et al. 2024; Hüesker et al. 2022). The policy impact assessment tool allows the stakeholders to (virtually) apply a combination of policies and directly see the impact of these policies on the WEFE nexus domains, allowing them to explore and create understanding of the impact of sectoral policies on the nexus. The DSS can also recommend an optimal set of policies to achieve set goals, thus showing synergies among WEFE nexus domains that can be used to guide the stakeholder dialogue toward the feasibility of specific solutions.

Important aspects of the stakeholder dialogue phase are building trust and fostering shared understanding and learning; identifying and prioritizing WEFE nexus problems and related trade-offs and synergies; developing a collective vision, goals, and a strategy around WEFE nexus problems; negotiating integrated solutions including compensation measures for penalized stakeholders; defining an action plan for implementation of the agreed solutions; and securing stakeholders' commitment to the plan implementation (Taylor et al. 2013). These aspects help address the actor-, scale-, resource- and goal-related challenges.

Finally, for successful stakeholder dialogue, it is important to establish clear and agreed-upon decision-making rules for the stakeholder dialogue process. Moreover, it is crucial to understand stakeholders' losses associated with different solutions, as a basis to identify compensation measures (Wehn et al. 2018). This requires well-considered facilitation for which many tools and methods exist such as presented in van den Ende et al. (2021) (Taylor et al. 2013). Despite clear rules, agreement on compensation measures, and good facilitation, stakeholder dialogue cannot be expected to fully overcome conflicting interests, and it can remain difficult to reach consensus. However, a well-structured and facilitated dialogue prepares stakeholders to better navigate these conflicts (Driessen et al. 2001). Furthermore, when there is consolidated practice of stakeholder engagement, it paves the way for gradually building consensus over time. Therefore, it is key to set up continuous dialogue structures (Sievers et al. 2024).

Governance mechanisms: realizing WEFE goals and policies

Successful stakeholder dialogues, in which solutions are collaboratively agreed upon, should be formalized through clear commitments and well-defined implementation pathways to ensure stakeholder collaboration. Therefore, we propose governance roadmaps and stakeholder agreements.

In the literature, roadmap approaches are increasingly used as a way to plan and implement policies and achieving sustainability goals and transitions (McDowall 2012; Miedzinski et al. 2022). Specifically, policy or governance roadmaps should have a shared vision or goal to work toward, an action plan, including timelines and actions and collaborative efforts (Iida and Sakata 2019; Miedzinski et al. 2022). Since nexus thinking is often not translated into practice (Al-Saidi and Elagib 2017), governance roadmaps can promote its implementation by developing actionable frameworks.

There are different stakeholder agreements for natural resource management, including river contracts and agreements for nature management (e.g., Bocchi et al. 2012; La Jeunesse et al. 2003; Galassi et al. 2020; Taylor et al. 2013; Cialdea and Cacucci 2017; Polajnar Horvat and Smrekar 2021; Rosillon et al. 2005; Schulte 2012). These are typically formalized acts (though not into law) stemming from collaborative bottom-up, private and public initiatives, aimed at addressing local issues within the broader context of higher-level policy frameworks such as river basin management plans or wetlands conservation laws. These agreements are

meant not to compete with or replace existing formal policies, but to complement them, enhancing their implementation (Brun 2014; Galassi et al. 2020; Papadopoulou et al. 2020; Polajnar Horvat and Smrekar 2021).

Governance roadmaps and stakeholder agreements are powerful governance mechanisms for securing stakeholder commitment across WEFE nexus domains. By fostering collaboration in a structured way, these instruments can drive implementation of actions to address cross-sectoral WEFE nexus challenges effectively. However, to our knowledge, such instruments remain unused in current nexus governance approaches. We define stakeholder agreement for WEFE nexus governance as a voluntary, co-created, and negotiated commitment to jointly pursue pathways, outcomes, and/or actions outlined on an agreed-upon governance roadmap for the integrated management of WEFE nexus resources. Stakeholders take responsibility for implementing agreed-upon actions, each within their respective roles and competences. These actions may include capacity building and knowledge generation to support policy implementation, technical measures such as pilot projects, policy design and revision, participatory processes involving different stakeholder groups (social, economic and political), or blended financing from multiple sources (Hüesker et al. 2022). Ideally, the design and signing of a stakeholder agreement is the end product of a successful stakeholder dialogue effectively addressing the institutional and resource-related challenges.

Implementation: realizing WEFE policies in practice

Depending on the context, implementation pathways for stakeholder agreed solutions vary. The capacity of stakeholders to influence policy design and decision-making depends on multiple factors. For example, Edelenbos et al. (2017) show that it depends on the government's openness and responsiveness to stakeholder initiatives, the extent to which decision-makers are involved in co-creation processes, empowerment of stakeholders, and alignment of stakeholder initiatives with the timing of policymaking processes. In governance systems where local stakeholders have limited influence on policymaking, change can emerge from small, yet targeted stakeholder initiatives, such as riverbed cleanup days, citizen science projects,or crowd funding efforts, which collectively contribute to meaningful impact.

Successful implementation of the agreed-upon governance roadmap, whether through formal or informal actions, depends on each committed stakeholder fulfilling their obligations. Failure to do so risks making the agreement void, undermining trust and jeopardizing collaboration. Generally, implementation challenges could emerge because of delays in implementing actions due to technical, political, or financial reasons, or stakeholders withdrawing from the agreement. Moreover, implementation of the agreed-upon actions may not lead to the expected results. Reasons for this implementation gap may be unrealistic expectations, (scalar) mismatches between ideas and policies and local realities, and short-term political interest due to short policy cycles (Hudson et al. 2019; Sievers et al. 2024). Literature shows how to overcome this implementation gap. Good understanding of (local) contexts is important (Hudson et al. 2019). Furthermore, the agreement should include realistic financial, human, and organizational resources and mechanisms for sustained commitment of all stakeholders involved (see resource- and institutional-related challenges) (Berruti and Moccia 2016; Gunton et al. 2010; Voghera 2016). Stakeholders' commitment is easier to maintain when there is a sense of ownership of the agreement (Brun 2014; Pappalardo et al. 2018). Ownership can be fostered through a transparent and fair division of responsibilities and operational power, aligning agreed-upon actions with each stakeholders' capabilities, expertise, and capacity (Molle and Closas 2020); clear procedures, activities, and resources allocated for monitoring and evaluation (Pappalardo et al. 2018); and a coordinating body with agreed-upon representatives acting as implementation support agency (Hessels 2013; Hudson et al. 2019; Olawuyi 2020). Transparency allows the coordinating body to hold the participating parties accountable despite the voluntary process. Therefore, it is important that stakeholders understand the interdependencies between the domains and the need to collaborate to reach their respective goals (Driessen et al. 2001). In several cases, the use of citizen science for environmental monitoring has contributed to maintaining commitment of involved stakeholders (Brouwer and Hessels 2019; Metcalfe et al. 2022; Wehn et al. 2018). Citizens' support provides additional motivation for the signing parties, especially public authorities and local businesses, to uphold their commitments, as it holds them accountable for their promises and actions.

Discussion and conclusion

This research set out to fill a knowledge gap on the ecosystem's role within the nexus and to propose an ecosystem-centric WEFE Nexus Governance Approach that acknowledges the ecosystems constraints on human activities and the associated governance challenges. Unlike other WEF(E) nexus governance

approaches (e.g., De Strasser et al. 2016; González-Rosell et al. 2023), our approach places policy coherence and stakeholders co-creation at its core and integrates quantitative modeling of bio-geophysical nexus interlinkages, governance and policy assessment methods, stakeholder engagement approaches, and governance mechanisms such as governance roadmaps and stakeholder agreements for co-creating coherent WEFE policies. Moreover, an ecosystem-centric approach that acknowledges the boundaries for human activities set by the ecosystem could prevent governance mistakes. The WEFE Nexus Governance Approach provides building blocks that highlight key aspects of WEFE nexus governance. While we do recognize the importance of aspects commonly addressed in governance approaches, such as stakeholder selection processes, institutional provisions, equity, justice, and solidarity, we chose not to discuss them. Although relevant to the nexus governance process, in our approach we chose to focus on specific governance tools to foster transformative change.

The WEFE Nexus Governance Approach is based on an analysis of WEFE nexus interlinkages and related governance challenges. Dealing with goal-related challenges is about formulating coherent policies (de Andrade Guerra et al. 2021). While policy coherence is essential for avoiding negative cross-sectoral conflicts, it should be considered as a means not an end, as coherent policies are not necessarily sustainable (Yunita et al. 2022). Instead, it should drive transformation of toward WEFE nexus governance, with the ultimate goal of sustainable natural resource management. Actor-related challenges, such as power imbalances (Purwanto et al. 2019; Salmoral et al. 2019) and diverging perspectives (Link et al. 2016; Purwanto et al. 2019), are assessed in the problem identification building block and paid special attention to in the stakeholder dialogue building block. The scale-related challenges (Pahl-Wostl et al. 2021) are assessed in the problem identification building block, setting the stage for actions at the appropriate scale. Institution-related challenges concerning the institutional interplay of different sectors (Pahl-Wostl et al. 2021) are revealed in the problem identification building block, as well as the stakeholder dialogue and governance mechanism building block. Finally, the resource-related challenges are assessed during the problem identification, negotiated during the stakeholder dialogue and secured in both the governance mechanism and implementation building block.

We acknowledge that our methodological choices may have certain limitations. First, our proposed WEFE Nexus Governance Approach is based on an extensive literature review and the practical nexus experience of the authors. A literature review is subjected to the authors' interpretation and could therefore introduce a bias to the results. We tried to limit this bias by having a rather large research team consisting of researchers of various backgrounds to ensure a diversity of perspectives on the literature. Moreover, the transdisciplinary nature of the research team also accounts for the transdisciplinary nature of the nexus itself.

Second, while the approach, informed by insights from the literature, appears promising in bringing nexus governance from theory to practice, its relevance for practice remains to be proven as the entire approach is not yet implemented in practice. Therefore, any conclusions on its usefulness are preliminary. However, an initial implementation of the approach has started in 5 river basins in Europe and South Africa in the context of the NEXOGENISIS project. Conceptual maps for the five case studies were developed through the consultation and involvement of stakeholders (Laspidou et al. 2023). Co-creating the CM helped stakeholders to adopt a system-thinking approach and more easily identify nexus issues and a range of possible solutions together (Ibid.). Mooren et al. (2024) reported on the application of NXGAT and policy coherence assessment in the Lielupe and Mesta-Nestos river basin. Sievers et al. (2025) applied NXGAT in South Africa. Aside from yielding insights into the barriers and drivers toward WEFE nexus governance, the problem identification phase helped stakeholders to reflect and better understand the interdependencies between the WEFE nexus domains, creating stakeholder commitment and knowledge needed for the stakeholder dialogue building block.

Despite its promising initial application, the approach needs further testing and validation in practice. Anyone aiming to shift toward WEFE nexus governance in relation to specific issues could use it. The analysis of nexus interlinkages and related governance challenges is what should guide the definition of the boundaries of nexus-oriented actions (e.g., a river basin, an administrative region, a group of municipalities, etc.). Furthermore, we tailored the WEFE Nexus Governance Approach to the WEFE nexus. Depending on the nexus interlinkages and related governance challenges of a specific context, it can be useful to include other nexus domains. Operationalizing the WEFE Nexus Governance Approach in context-specific case studies may present challenges, as political contexts can affect the applicability of its tools and methods. To enhance versatility, we formulated these tools in a general manner; however, adapting them to local realities is crucial. For instance, Sievers et al. (2025) suggest including traditional leadership structures or informal governance systems in NXGAT to assess social inequalities in South Africa more effectively. Future research should refine the proposed tools to account for contextual specificities.

Appendix 1: Search terms and reading questions

(WEF) nexus governance	Transboundary river basin governance/management
(WEF) nexus transboundary governance	Integrated river basin governance/management
(WEF) nexus management	Water/climate risk governance
IWRM	Resource security (water, energy, food security)
Institutional change (nexus/water regime)	Power relations in resource management/governance
Water governance	Culture of resource management/governance
(WEF) nexus policy coherence	(WEF) nexus policy
(WEF) nexus policy integration	(WEF) nexus policy design
(WEF) nexus policy change	Nexus/water policy entrepreneurs/entrepreneurship
Transboundary river basin policy	Water policy
(WEF) nexus policy interaction	(WEF) nexus policy coordination
Water/nexus/WEF governance assessment frameworks/tools/approaches	(WEF) nexus governance assessment
Water governance assessment	Transboundary/integrated river governance assessment
Policy assessment framework/approaches	Transboundary policy assessment
Water policy assessment	Nexus policy assessment
Policy integration frameworks	Policy coordination frameworks
Policy coherence frameworks	WEF(E) links
WEF(E) interlinkages	WEF(E) interdependencies
WEF(E) connections	WEF(E) modeling

Topic	Reading questions
Nexus governance	What are key definitions? What are key elements of nexus governance/policy? How can nexus governance be developed? What are the differences with other approaches, e.g., IWRM? What are critiques to nexus approaches? What are different perspectives on nexus governance and management? What are the pre-conditions for nexus governance to be successful?
Governance assessment tools and co-creation frameworks	How can key elements of the WEFE nexus governance assessment framework be defined? How are assessment methods defined? What are the indicators used (e.g., qualitative scoring of indicators, matrix reporting scoring, graphs, etc.)? What are data collection methods (e.g., interviews, focus groups, etc.)? What are critiques to this approach?
Policy coherence assessments	How is policy integration/coherence/ coordination defined? What are the key elements of the key elements of policy coherence/ integration, coordination? Where have policy integration/coherence/coordination approaches been applied? What was the purpose of the policy coherence/integration/coordination approach? Critiques to policy coherence/integration/coordination approaches? Pre-conditions for successful policy coherence/integration/coordination?

Appendix 2: Overview of reviewed nexus governance approaches

References	What	Nexus domains	Scale	Elements
De Strasser et al. (2016)	TBRNA	Water, energy, food, ecosystem	Transboundary river basin	Survey to gather Key actors and sectors Socio-economic context Desk study Analysis of sectors, resources, and governance analysis Questionnaire on intersectoral issues Nexus dialogue Report on nexus issues and solutions and benefits
Pereira Ramos et al. (2022)	SIM-4NEXUS approach	Water, energy, food, land, climate	Diverse: regional, national, transboundary, continental	A six steps approach Development of knowledge Preliminary nexus assessment Model development Science–policy interface Conclusions Recommendations
Olawuyi (2020)	Legal and governance aspects for implementing nexus	Water, energy, food	Local	Legal focus Creating policy coherence Creating a central institution for coordinating collaboration and knowledge exchange across domains Promotion of regional collaboration
Harwood (2018)	The cybernetic methodology	Water, energy, food	River basin	First, understanding the nexus issues Gathering insights from stakeholders Evaluation of governance context Agreement on governance context Modeling potential solutions Implementation of solutions

References	What	Nexus domains	Scale	Elements
Halbe et al. (2015)	Methodological framework to assess strategies and innovations for transition toward sustainable development in the WEF nexus	Water, energy, food	National	Problem and stakeholder analysis in which causal loop diagrams (CLD) are built to visualize their nexus perspective Individual modeling, in which the drivers and barriers for innovations are identified Integrative assessment of the CLDs Learning requirements for the implementation and wider uptake are identified based on the integrative assessment
Hoff et al. (2019)	A nexus approach for the MENA region—from concept to knowledge to action	Water, energy, food	MENA region	Framing the nexus Identification of the nexus opportunities Assessment of technical and economic nexus opportunities Specification of stakeholders Implementation of the approach and identification of relevant conditions Monitoring and evaluation
Mohtar and Daher (2016)	Water–energy–food nexus framework for facilitating multi-stakeholder dialogue	Water, energy, food	Region or other scale	Quantifications of nexus interlinkages and trade-off identification Supply chain dialogue Political economy dialogue
Daher and Mohtar (2015)	WEF Nexus Tool 2.0	Water, energy, food	National	Creating conceptual scenarios-based framework Quantification of nexus interlinkages Running of WEF Nexus Tool 2.0 to run scenarios Scenarios can be used for decision-making

Acknowledgements The authors would like to thank J. Sušnik, S. Masai, J. Frijns, and S.H.A. Koop for their valuable and constructive feedback on the manuscript and S. Khan for the inital visualisation of the WEFE nexus governance approach in NEXOGENESIS in Fig. 3

Funding This research took place in the context of NEXOGENESIS, a research project funded by the European Union's Horizon 2020 research and innovation program under grant agreement No 101003881.

Data availability No data was used for the research described in the article.

Declarations

Conflict of interest The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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