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A Water-Energy-Food-Ecosystems nexus coherence assessment of solutions in the Danube River Basin

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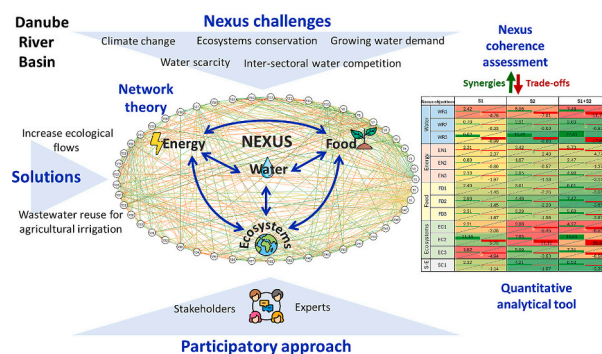
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HIGHLIGHTS

- WEFE nexus coherence assessment to address cross-sectoral challenges in the Danube
- Participatory approach to co-design and evaluate policy solutions
- Quantitative analytical tool to assess cross-sectoral synergies and trade-offs
- Assess the increase of ecological flows to support the health of aquatic ecosystems
- Evaluate the expansion of wastewater reuse for agricultural irrigation

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change and socio-economic development are intensifying pressure on natural resources in the Danube River Basin, leading to more frequent droughts and water scarcity, and threatening both ecosystem conservation and economic activities. The Water-Energy-Food-Ecosystems (WEFE) nexus approach analyses interconnections between sectors to enhance resource efficiency. To address these challenges, this study conducted a nexus coherence assessment of two water-related solutions: increasing ecological flows and expanding wastewater reuse for agricultural irrigation. A participatory process was applied to co-design and evaluate these measures, involving around 158 stakeholders across dialogues and workshops, complemented by expert consultation. Additionally, Nexus Cross-Impact Analysis (N-CIA), a quantitative analytical tool grounded in network theory was used to assess cross-sectoral synergies and trade-offs.

Evaluation results indicate that increasing ecological flows creates synergies for aquatic ecosystems but entails trade-offs in terms of reduced hydropower generation and increased greenhouse gas emissions. In contrast, expanding wastewater reuse creates synergies with agricultural production and socio-economic development,

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although it may also involve trade-offs for aquatic ecosystems. When considered jointly, the two solutions show potential to balance trade-offs while addressing water scarcity. The study highlights the importance of quantitatively assessing impacts across sectors to move beyond intuition and ensure coherent policy evaluation. It also demonstrates how stakeholder participation and expert input can enhance the design and assessment of solutions. The applied framework reveals hidden dynamics and leverage points within the nexus, providing a stronger basis for integrated resource management. Beyond technical results, the study fostered dialogue among diverse actors, supporting sustainability in the Danube.

1. Introduction

Climate change and socio-economic activities are placing increasing pressure on natural resources, posing significant risks to water, energy, and food security, as well as to ecosystem conservation. The Danube River Basin (DRB), the second-largest in Europe, exemplifies how these challenges are becoming increasingly pronounced, affecting more than 79 million people who live along the Danube and its tributaries (Feldbacher et al., 2016; Stolz et al., 2018; Mauser et al., 2018). Rising droughts and water scarcity, among other impacts, highlight the critical importance of water and the fragile balance between its availability and demand. This affects many water-dependent sectors, such as agriculture (both irrigation and livestock), energy production and cooling, navigation, urban water supply, and also ecosystem conservation (Bisselink et al., 2018).

The Water-Energy-Food-Ecosystems (WEFE) nexus is a systemic approach that examines how different sectors are interrelated. It aims to enhance resource efficiency, reduce trade-offs, promote synergies, and strength governance across sectors (Hoff, 2011). To effectively address the growing water-related challenges and their cross-sectoral impacts describe above, it is essential to design, evaluate, and implement solutions through a nexus approach that tackles these issues in an integrated manner. In this sense, we define a nexus solution as a policy, measure, or instrument designed to tackle one or more challenges affecting one or more sectors within the nexus, while analysing these challenges as part of an interconnected system. Thanks to its holistic perspective, the WEFE nexus approach has gained significant traction in the assessment of solutions in recent years (de Andrade Guerra et al., 2021; Taguta et al., 2022).

Some studies have applied the nexus approach to analyse these issues in the DRB. Pistocchi et al. (2015) used climate scenarios as input to simulate water resources and determined the resulting long-term average water balance figures. Karabulut et al. (2016) mapped and assessed water provisioning services and associated benefits to support the WEFE sectors, considering environmental flows requirements for riverine ecosystems. Dogaru et al. (2019) carried out an extensive review of experimental field studies, considering current policies, and strategies to assess irrigation water use in the basin. Probst et al. (2024) examined the potential expansion of maize irrigation and the resulting trade-offs among agriculture, hydropower, and aquatic ecosystems when irrigation water is withdrawn from rivers. At the sub-basin level, Salam et al. (2022) assessed the water supply and demand gap across WEFE sectors under three climate scenarios (dry, normal, and wet years) in the lower Danube stretch.

Several authors have emphasized the importance of engaging multiple stakeholders and experts to ensure a more holistic and inclusive nexus assessment (Martinez et al., 2018; Sušnik and Staddon, 2021; Malamataris et al., 2025). However, applying a nexus approach reveals that complexity is a major obstacle, given the multitude of actors and competing objectives involved, which often results in coordination difficulties and potential conflicts (Al-Saidi and Elagib, 2017; Pahl-Wostl et al., 2021; Sievers et al., 2025). It is also crucial to examine how different policy instruments can be coordinated (de Andrade Guerra et al., 2021). In this context, conducting a nexus coherence assessment becomes essential. This process quantitatively measures cross-sectoral synergies and trade-offs associated with the implementation of policy

solutions. Moreover, analysing complex systems such as the WEFE nexus requires methodologies that go beyond capturing only the direct and more evident influences. In this regard, the use of network theory has emerged as a practical approach, as it enables the identification of indirect, second-order interactions that are often overlooked by other methodologies, including the Driver-Pressure-State-Impact-Response (DPSIR) framework (Kristensen, 2004) or WEFE balance indices (El-Gafy, 2017). The value of this type of approach is further supported by Martinez et al. (2018), González-Rosell et al. (2020), González-Rosell et al. (2023), Hurtado et al. (2024) and Blicharska et al. (2024).

Although a few recent studies (e.g., Lucca et al., 2025; Mooren et al., 2025) have integrated stakeholder engagement with quantitative coherence metrics, none has yet conducted a comprehensive nexus coherence assessment to the full DRB. Moreover, several authors emphasize that the confluence of academic ideas and actual execution is essential for addressing the management, governance, and policy difficulties of the nexus (Nhamo et al., 2019; Simpson and Jewitt, 2019). In that sense, the present study aims to contribute to WEFE nexus research through the evaluation of solutions in the DRB. Water plays a central role in the nexus approach (Hoff, 2011), and in the DRB it is also a key element for both socio-economic activities and environmental sustainability (Karabulut et al., 2016; Bisselink et al., 2018; Salam et al., 2022; Probst et al., 2024). Building on this background, the research is guided by two questions: (RQ1) Which water-related solutions can help address the challenges generated by climate change and competition among sectors for water use in the DRB? (RQ2) What cross-sectoral synergies and trade-offs may arise from implementing these solutions? To answer these questions, we use the GONEXUS Solution Evaluation Framework (GoNEXUS SEF) (González-Rosell et al., 2023), a participatory methodological framework grounded in the WEFE nexus approach. To carry out the nexus coherence assessment, the framework relies on Nexus Cross-Impact Analysis (N-CIA). This analytical tool, based on network theory (Newman, 2003), enables the quantitative evaluation of synergies and trade-offs resulting from the implementation of solutions. In this context, and based on stakeholders' input, this study focuses on two solutions. We examine the potential of increasing ecological flows to support the health of aquatic ecosystems and explore the expansion of wastewater reuse for agricultural irrigation. Around 158 stakeholders took part in three rounds of dialogues. The first two rounds focused on understanding the WEFE interconnection, identifying challenges, objectives, solutions, and indicators, while the third round was centred on the nexus coherence assessment and was conducted through local workshops in Hungary. In this sense, the results should be interpreted as reflecting a regional-level perspective.

The remainder of the paper is structured as follows: Section 2 presents the methodology used to conduct the nexus and policy coherence assessment. Section 3 introduces the case study and describes the application of the methodological framework, including the nexus challenges, objectives and solutions identified. Section 4 presents the results of the evaluation, while Section 5 discusses the main findings. Finally, the last section outlines the key insights and draws the main conclusions.

2. Methodology

2.1. GoNEXUS Solution Evaluation Framework

GoNEXUS SEF is a framework developed to co-design and evaluate nexus solutions through a participatory approach. It can be adapted to suit different contexts, considering geographical scale, governance structures, and technological options. In this study, the framework is tailored to the DRB, following a dynamic and iterative process of five phases and eleven steps (see Fig. 1). The phases and steps are presented in a logical sequence; however, due to the interactive nature of the framework, they were not necessarily carried out in that exact order. The process involves multiple feedback loops and interconnected phases. Some steps belong to more than one phase, while others occur simultaneously or are repeated several times throughout the entire process.

The five phases are:

- A. **Identify nexus solutions:** Determine nexus challenges, objectives and potential solutions, and prioritise the most pertinent to the case study.
- B. **Nexus dialogues:** Facilitate cross-sectoral stakeholder collaboration and run stakeholder events to examine nexus interlinkages and co-design policy solutions.
- C. **Nexus system analysis:** Develop a network model to represent the dynamics of the nexus system and evaluate solutions.
- D. **Nexus evidence:** Build a nexus indicator system and gather evidence derived from both stakeholder dialogues and nexus system analysis.
- E. **Nexus-coherence assessment:** Combine qualitative and quantitative evidence to evaluate solution and provide policy advice and recommendations.

In more detail, the eleven steps are:

1. **Identify nexus challenges and objectives** (phases A and B): Diagnose main sectoral and cross-sectoral nexus challenges and objectives to guide solution development in the case study.
2. **Identify nexus solutions** (phases A and B): Map out solutions addressing the challenges identified.
3. **Prioritise nexus solutions** (phases A, B and C): Select the most relevant policy solutions for further evaluation.

4. **Conduct cross-sectoral dialogues** (phase B): Engage stakeholders through workshops and surveys to validate nexus interlinkages and support policy co-design and evaluation.
5. **Represent the nexus system** (phase C): Apply network theory by developing a network model and a cross-impact matrix to represent the dynamics of the nexus system.
6. **Analyse solutions** (phases B and C): Work with stakeholders to determine how each solution influences the nexus system.
7. **Develop a nexus indicator system** (phases B, C and D): Define and select nexus indicators and metrics to represent the nexus system and evaluate solutions.
8. **Generate evidence derived from dialogues** (phases B and D): Condense qualitative and quantitative insights from stakeholder engagement.
9. **Generate evidence derived from nexus system analysis** (phases C and D): Aggregate network model outputs for evaluation.
10. **Conduct a nexus-coherence assessment of synergies and trade-offs** (phase E): Apply N-CIA to evaluate the impacts of a solution on the WEF nexus.
11. **Provide policy advice and recommendations** (phase E): Synthesize assessment results into coherent, context-specific advice and recommendations.

2.2. Stakeholder and expert engagement and supporting analysis

The co-design and evaluation of policy solutions in the DRB supported by a combination of stakeholder engagement, expert consultation, and literature-based analysis, structured across the different phases of the framework.

Stakeholders participated actively throughout phase B, engaging in three rounds of dialogues. The first round (1st Dialogues) included three workshops: the first was held online and covered the entire basin, while the other two focused on the Tisza River at sub-basin and local levels and were organised in hybrid and in person formats at the Middle Tisza District Water Management Directorate¹ (in Szolnok, Hungary). This round focused on understanding interconnections within the nexus and identifying key challenges. The second round (2nd Dialogues) also included three workshops with a similar format. It focused on proposing potential solutions and selecting key indicators to represent the nexus system. Finally, the third and last round (3rd Dialogues) was held in person and included a workshop designed to evaluate how the proposed solutions would impact the selected indicators. Accordingly, the results obtained should be interpreted as reflecting a regional-level perspective. Around 158 stakeholders took part across the three rounds. They included representatives from private associations, civil society, international organisations, NGOs, academia, and policymakers across WEF sectors in the DRB. Stakeholders were carefully selected and formally invited to take part in the dialogues. Table 1 shows the number of stakeholders who participated in the 2nd Dialogues, detailing their occupation.

To assess the degree of agreement among stakeholders during 3rd Dialogues workshop, Krippendorff's Alpha (K-Alpha) was used as the evaluation method (Krippendorff, 2018). Furthermore, to assess the variability of the results, a nonparametric bootstrap was employed as a statistical resampling method to compute confidence interval.

Experts contributed during phases B and C. They were academics and researchers who, although not necessarily specialised in the DRB, provided strong technical expertise across nexus dimensions. Their involvement included a seminar to develop a Causal Loop Diagram (CLD) (Bala et al., 2017) representing the WEF nexus system. This diagram was refined several times to better reflect the DRB and served as the basis for building the cross-impact matrix. Ongoing communication

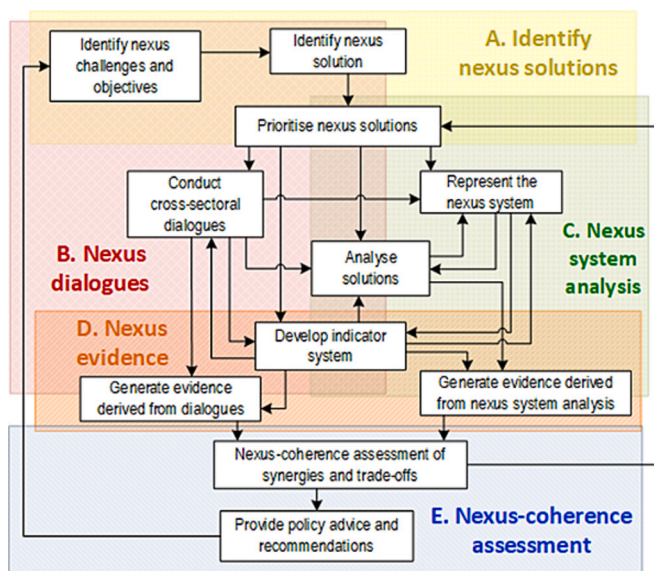


Fig. 1. GoNEXUS Solution Evaluation Framework. Source: our own elaboration.

¹ In Hungarian: Közép-Tisza-vidéki Vízügyi Igazgatóság www.kotivizig.hu.

Table 1
Stakeholders by number and occupation in the 2nd Dialogues.

	Danube basin level	Tisza sub-basin level	Local level
International organisation	3	0	0
Governmental	4	3	14
Municipal	0	0	3
Agriculture	0	0	2
Water management	3	4	11
Public water supply	0	0	1
Recreation/tourism	0	0	1
Academic research	1	2	2
University	3	3	6
NGO	1	0	2
Other	1	2	7
Total	16	14	49

Source: our own elaboration.

with experts ensured iterative refinement of the network model representing the nexus system.

The identification of challenges, indicators, and solutions, as well as the network modelling process, was further supported by a comprehensive review of relevant literature on the WEF E nexus, the DRB, existing policy measures, and regional, national, and local strategic objectives.

2.3. Nexus Cross-Impact Analysis

For the nexus coherence assessment, the N-CIA methodology is used (González-Rosell et al., 2023). Grounded in network theory, N-CIA is a systemic and analytical tool designed to quantitatively assess interlinkages across the WEF E nexus. It enables the analysis of how one or more solutions are interrelated with a set of nexus indicators, measuring both synergies and negative impacts, on a set of different nexus objectives. It can be applied in contexts with different time horizons, governance mechanisms, and specific technological options; moreover, it allows for the integration of qualitative and quantitative information.

This methodology employs a seven-point typology (ranging from -3 to +3) proposed by Nilsson et al. (2016) to represent the relationships between indicators, as well as the relationships of proposed solutions on those indicators. The influences can be directly or inversely proportional, with varying degrees depending on the assigned value. This enables the development of a cross-impact matrix (Weitz et al., 2018), which represents the WEF E nexus system in the analysed case study. Based on this matrix, network theory is applied to develop a tree network and calculate the influences of the solution on the nexus indicators up to a second order of influence (I_n) using the following equation:

$$I_n = \sum_i (I_i^{S \rightarrow V_i} \times W_{i,n}^{V_i}) + \frac{1}{2} \sum_{ij} (I_i^{S \rightarrow V_i} \times I_{ij}^{V_i \rightarrow V_j} \times W_{j,n}^{V_j}) \dots \forall n$$

where n represents the different objectives across the various nexus sectors. i is the edge (or arrow) from the solution S to the indicator V_i , and therefore, $I_i^{S \rightarrow V_i}$ is the first-order influence of the solution on the indicator. Similarly, j is the edge from indicator V_i to V_j , and thus $I_{ij}^{V_i \rightarrow V_j}$ represents the influence of the first indicator on the second. Conceptually, the indicators V_i are the same as V_j , but in a different order of influence. An indicator cannot influence itself, so in all cases $i \neq j$. Additionally, $W_{i,n}^{V_i}$ and $W_{j,n}^{V_j}$ are the weights of the indicators on the nexus objectives n , respectively. By multiplying these weights by the calculated influences, the overall impact on the nexus objectives can be determined. The results are numerical, dimensionless values derived from the modelled network representing the nexus system. These values enable the assessment of both synergies and negative impacts that one or

more solutions may have on the various nexus objectives analysed. To assess the sensitivity of the network model, a Monte Carlo simulation is used, introducing a $\pm 20\%$ perturbation to all assigned weights and analysing the resulting impact on the related objective score. To further explore the implications of the complex interrelationships within the nexus system, one of the solutions was analysed by extending the assessment to third-order influences, applying a one-third factor to these impacts, in line with the approach suggested by Weitz et al., 2018.

3. Analysis of the WEF E nexus in the Danube River Basin

3.1. Impacts of climate change and human activities on the WEF E nexus in the Danube River Basin

With a length of 2850 km and a basin covering approximately 800,000 km², the Danube is the second largest river in Europe. The Danube catchment area is home to more than 79 million people from 19 countries (ICPDR, 2021), accounting for around 20 % of the EU population (Stagl and Hattermann, 2016). Its surface area spans 10 % of continental Europe's territory, making it the most international drainage basin in the World (Karabulut et al., 2016). The DRB is commonly divided into three main sub-regions (Fig. 2): the Upper Basin, the Middle Basin, and the Lower Basin. Beyond this division, it also encompasses several ecoregions, each with distinct geographical features, fauna, flora, and environmental characteristics (ICPDR, 2021).

The water resource is central to the WEF E nexus approach (Hoff, 2011). It is essential for human well-being and socio-economic development, as well as for sustaining ecosystems. In the DRB, climate change has emerged as one of the most significant and pressing challenges affecting the water sector. Feldbacher et al. (2016) highlight that climate change is increasing hydrological extreme events (e.g., water scarcity, droughts, severe flooding), which threaten water availability and management. Although the effects of climate change vary across the sub-regions of the DRB (Bisselink et al., 2018; Mauser et al., 2018; Stolz et al., 2018), droughts are becoming increasingly frequent, more intense, and are no longer limited to the summer months (Gregorić et al., 2019). Also, extremes floods are becoming more frequent and intense. This trend is attributed to the increase in heavy precipitation events (Hattermann et al., 2018; Popa et al., 2025). Looking ahead, water stress is projected to intensify, particularly in the southern and eastern parts of the basin. Smaller tributary rivers are expected to be especially vulnerable due to declining summer precipitation (Mauser et al., 2018). This is further supported by Bisselink et al. (2018), who identify climate change as the primary driver of increasing water scarcity in the region. However, they also note that rising water demand and land use changes, such as urbanization, contribute to this trend.

The implications of water scarcity are particularly critical given the distribution of water use across sectors. According to Karabulut et al. (2016), 44 % of water use in the DRB is allocated to the energy sector,

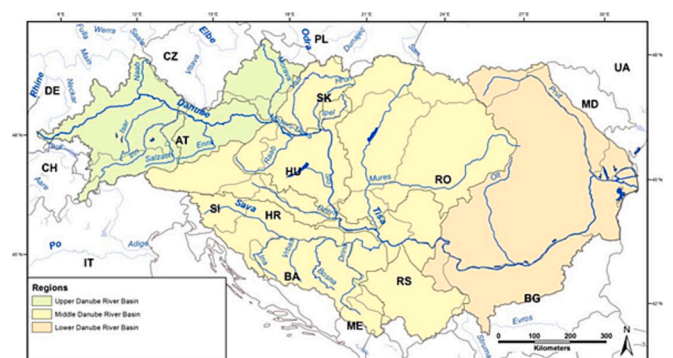


Fig. 2. Main sub-regions of the Danube River Basin. Source: Mauser et al. (2018).

20 % to agricultural irrigation, and 6 % to livestock. Urban and industrial uses together account for 30 %. This distribution suggests that any water shortages could have serious consequences to the economy of the region, as they would impact key income generating sectors, and it is expected that the water supply cannot fulfil the water demands in coming decades (ICPDR, 2021).

Traditionally, hydropower has dominated renewable electricity generation in the Danube Basin (REKK, 2013). Climate change affects water-dependent energy production by altering water availability, seasonal flows, and increasing hydrological extreme events (Wasti et al., 2022). While annual runoff may show minor changes, projections suggest lower summer runoff and higher winter runoff (Probst and Mauser, 2022), leading to reduced hydroelectric power generation in summer and moderate increases in winter (Mauser et al., 2018). In addition, thermal power plants, which rely on water for cooling, will also face challenges from rising water temperatures (Pekárová et al., 2023) and lower summer flows (Probst and Mauser, 2022), likely reducing generation when energy demand for cooling is highest. Overall, extreme weather events could impact energy production, increasing the risk of energy shortages and price volatility (Mauser et al., 2018).

Crop cultivation is also highly dependent on water and climate. In the DRB, climate change is increasing crops water requirements (Potopová et al., 2022; Probst and Mauser, 2022) while simultaneously affecting water availability and flow regime variability (Bisselink et al., 2018). Additionally, contributes to more extreme weather events and leads to a rise in pest outbreaks that negatively impact agriculture (Feldbacher et al., 2016; Gregorič et al., 2019). In the Upper Basin, water still appears to be sufficient for agriculture (Mauser et al., 2018). In contrast, the southern and eastern DRB will face significant water shortages. Irrigation demand will rise across the region, but dry areas in the Middle and Lower Basin may lack enough freshwater to meet agricultural needs, threatening productivity and food security (Mauser et al., 2018; Bisselink et al., 2018; Potopová et al., 2022).

The DRB presents a remarkable ecological diversity (ICPDR, 2021). It serves as a crucial ecosystem that sustains rich biodiversity and provides essential ecosystem services (Karabulut et al., 2016; Perosa et al., 2021). However, the impacts of climate change and human activities such as the construction of infrastructure, the expansion and intensification of agriculture (Racoviceanu et al., 2023), nutrient pollution (Feldbacher et al., 2016), and changes in land use including urbanization (Bisselink et al., 2018), are putting this ecosystem at risk (Stagl and Hattermann, 2016; Funk et al., 2019). These pressures contribute to habitat loss, a decline in biodiversity, and hydro-morphological changes. Achieving a “good ecological status” for the Danube River and its tributaries is a key requirement of the European Water Framework Directive (WFD) (EC, 2007). Also, the goals of River Basin Management Plan include the conservation and restoration of biodiversity while also striving to maximize the benefits provided by ecosystem services (ICPDR, 2021).

Governance plays a crucial role in river basins that involve multiple sectors and cross several national borders, such as the DRB. Effective river basin management is essential, especially as future droughts and water scarcity are expected to increase. These conditions create interdependencies among regions and sectors, which may lead to both sectoral and regional water conflicts (Farinosi et al., 2018).

3.2. Nexus challenges and objectives

Considering the context of the DRB, an extensive literature review was carried out to identify nexus challenges in the region. These findings were then discussed and validated with stakeholders during 1st Dialogues. The three main nexus challenges identified are as follows:

1. **Water scarcity and increased flood risk due to climate change**, which may require changes in land use management. As a consequence of climate change and land use changes (urbanization), significant alterations have been observed in surface runoff, water

retention, and storage capacity. These changes directly affect water availability and increase the frequency and severity of extreme events such as droughts and floods.

2. **Growing irrigation demand due to a warmer and drier climate, leading to water scarcity in areas with large inter-sectoral competition for water.** Agriculture is the main water-consuming sector in the basin. Climate change is increasing crop water requirements, while demographic shifts, changing consumption patterns. As a result, water-intensive food and energy producers are under growing pressure to find alternative water sources, particularly in areas facing water scarcity and strong competition between sectors for water resources.
3. **Increasing vulnerability of aquatic and terrestrial ecosystems due to water scarcity and land use changes driven by agriculture and energy sectors.** The growing demand for water and land, necessary to sustain increasing agricultural and energy production, is placing pressure on natural habitats. This has both direct and indirect impacts on aquatic and terrestrial ecosystems. Water scarcity particularly affects floodplains and wetlands, especially those connected to freshwater bodies used for irrigation. Additionally, hydropower development disrupts the longitudinal connectivity of rivers and water bodies, negatively impacting ecosystem health.

The nexus challenges identified and validated by stakeholders in the DRB underscore the need for policies that primarily address pressures on water resources and ecosystems, while also supporting the sustainable development of the energy, and agricultural sectors.

To effectively address the challenges, it is first essential to establish a set of objectives. In this regard, we conducted a selection of relevant WEFE Nexus objectives. The selection process was also supported by an extensive literature review. This review included relevant policy documents and strategic frameworks at local, regional, national and EU levels.

In order to ensure a balanced representation of impacts across the nexus sectors, three objectives were selected for each of the WEFE sectors. Additionally, one socio-economic development objective was included to reflect broader aspects of sustainability. The Table 2 show the WEFE objectives, the sectors addressed and the code used for further evaluation.

3.3. Selected solutions

Based on the identified challenges, a set of potential policy solutions was proposed. Among these, two were prioritized for further evaluation. The process of identifying and selecting these solutions was carried out in collaboration with stakeholders during 2nd Dialogues and further supported by expert input. The two prioritized solutions are:

Table 2
WEFE objectives.

Nexus sector	Objective_code	Objective_name
Water	WR1	Reduce water consumption
Water	WR2	Increase water use efficiency
Water	WR3	Increase water availability
Energy	EN1	Increase renewable energy share
Energy	EN2	Increase energy efficiency
Energy	EN3	Secure energy supply
Food	FD1	Secure food supply
Food	FD2	Increase agricultural productivity
Food	FD3	Resilient agricultural sector
Ecosystems	EC1	Conserve terrestrial ecosystems
Ecosystems	EC2	Conserve aquatic ecosystems
Ecosystems	EC3	Reduce GHG ^a emissions
Socio-economic	SC1	Socio-economic development

^a Greenhouse gases (GHG) emissions.

Source: our own elaboration.

S1. Increase ecological flows to support the health of aquatic ecosystems.

River flow dynamics play a key role in supporting aquatic ecosystems (Stagl and Hattermann, 2016). Ecological flow refers to the quantity, quality, and timing of water flows needed to maintain healthy aquatic ecosystems (Ramos et al., 2017). This idea is central to the WFD, which focuses on achieving and sustaining good ecological status in all water bodies (EC, 2016). A broader concept is “environmental flow”, which includes not only ecological requirements but also the human livelihoods and well-being that depend on river systems (Karabulut et al., 2016). Several studies aim to define the ecological or environmental flow requirements needed to support aquatic ecosystems in the DRB and its sub-regions (Karabulut et al., 2016; Gălie et al., 2021; Stănescu and Moldoveanu, 2023). Building on this concept, solution S1 focuses on water management measures that ensure an ecological flow capable of meeting the requirements for supporting aquatic ecosystems. This solution directly addresses nexus challenge number three.

S2. Expand wastewater reuse for agricultural irrigation.

As droughts and water scarcity become increasingly common, the reuse of wastewater (or reclaimed water) can play a key role (particularly in coastal areas) in meeting agricultural irrigation needs while easing the pressure on natural water bodies (Pistocchi et al., 2017; Hristov et al., 2021). Also, by replacing a fraction of groundwater abstraction, wastewater reuse can contribute to a more sustainable management of groundwater resources (De Roo et al., 2023). The use of reclaimed water is currently regulated in the European Union (EU) under the Water Reuse Regulation (EU, 2020). Solution S2 focuses on specific measures such providing subsidies and support to investment in reuse of treated water in irrigation, and support for innovation in circular water use. This solution is aimed at addressing nexus challenges one and two.

Other solutions that were also considered include:

- Construction of small reservoirs to support irrigation.
- Transitioning from large-scale monocultures to more mosaic-like agricultural landscapes.
- Cultivation of more drought-tolerant crops.
- Restricting surface water withdrawals to conserve aquatic habitats.
- More efficient allocation of agricultural subsidies to support irrigation system modernization.
- Increase in the irrigation water price.

3.4. Nexus indicator system

Schlemm et al. (2024) highlight the importance of involving stakeholders in the identification and development of relevant nexus indicators tailored to the specific case study. Developing an appropriate set of indicators allows for a more accurate characterization of the nexus system in the case study, capturing its specific features in greater detail.

In our study, the indicator system was developed through a dynamic, iterative and participatory process involving both stakeholders and experts. The selection of indicators was carried out in parallel with other steps of the process. We began by selecting a preliminary list of indicators to represent the WEFE nexus system, which was later refined to address the identified challenges. During the 2nd Dialogues, stakeholders actively contributed by emphasizing the key nexus indicators. The list was subsequently validated by experts, who also suggested additional indicators for the development of the CLD. Further indicators were later added to support the evaluation of the selected solutions. Table 3 presents the final set of indicators, along with their codes and measurement units. These indicators were then used to describe and assess the WEFE nexus system through the development of a cross-impact matrix.

Table 3
Nexus indicator system.

Code	Indicator
V1	Climate change global temperature increase (°C)
V2	Population (pop)
V3	Food demand (t)
V4	Energy demand (ktoe)
V5	Water demand (hm ³ /year)
V6	Emissions (tCO ₂ eq)
V7	Freshwater withdrawals (hm ³ /year)
V8	Freshwater withdrawals for hydropower/cooling (hm ³ /year)
V9	Groundwater withdrawal (m ³ /year)
V10	Agricultural production (t)
V11	Non-renewable energy generation (ktoe)
V12	Bioethanol and biodiesel production (ktoe)
V13	Hydropower generation (GWh)
V14	Nuclear energy generation (GWh)
V15	Renewable energy generation (ktoe)
V16	Precipitation pattern (changes in distribution in a year/over an area)
V17	Land use change (urbanization) (ha)
V18	Rainfall (l/m ² /year)
V19	Land surface runoff (m ³ /month)
V20	Evaporation rate from water bodies (mm/m ²)
V21	Danube River flow rate (m ³ /s)
V22	Tributary rivers discharge (m ³ /s)
V23	Magnitude of Flooding (m ³ /s)
V24	Flood inundation extent (ha)
V25	Index of hydrological alteration
V26	Reservoirs water volume (m ³) / Total dam capacity (km ³)
V27	Water availability (km ³)
V28	Amount of water diverted/extracted from water bodies (Water transfer)
V29	Water flow requirement for navigation (m ³ /s)
V30	Water requirement (flow, temperature, etc.) for habitats and fish migration
V31	Water temperature (°C)
V32	Freshwater species richness
V33	Groundwater table depth (m)
V34	Forest and ecological area (including wetlands and floodplains) (ha)
V35	Urban and industrial area (ha)
V36	Crop land area (ha)
V37	Irrigated area (ha)
V38	Rainfed area (ha)
V39	Percentage of irrigated area equipped for technical irrigation (%)
V40	Irrigation water required for optimal production of irrigated crops (m ³ /ha)
V41	Irrigation efficiency (kg/m ³)
V42	Crop yield (kg/ha)
V43	Irrigated crop yield (kg/ha)
V44	Rainfed crop yield (kg/ha)
V45	Producer prices in agriculture (Euro/ton)
V46	Total treated municipal wastewater (m ³ /year)
V47	Wastewater recycled (m ³ /year)

Source: our own elaboration.

4. Evaluation results

4.1. Cross-impact matrix

To construct the matrix, two clearly differentiated processes were carried out. First, the influence of the solutions on each indicator was assessed, and second, the interrelationships among indicators were analysed. To assess the influence of the solutions on each indicator, a workshop was held with stakeholders (during 3rd Dialogues), during which participants individually evaluated the impact of each solution on each indicator using the seven-point scale. Five stakeholders participated in the evaluation of S1, while seven took part in the evaluation of S2. The individual results were then averaged and incorporated into the matrix. Table 4 presents the outcomes of these dialogues. Furthermore, it can be observed that the proposed solutions have no influence on indicators V1 to V5. This is because these variables are considered driving forces, and we assume that the selected solutions do not have a direct influence on them. To determine the degree of agreement among stakeholders in this evaluation, K-Alpha was calculated considering the 7-point typology interval. The K-Alpha for the evaluation of solution S1 was 0.074, while for solution S2 it was 0.14.

Table 4
Influence of the solutions on each indicator: 3rd Dialogues workshop and nonparametric bootstrap results.

	S1											S2												
	3rd dialogues workshop results								NB - CI90 % (p-value)				3rd dialogues workshop results								NB - CI90 % (p-value)			
	-3	-2	-1	0	1	2	3	mean	0 %	5 %	95 %	100 %	-3	-2	-1	0	1	2	3	mean	0 %	5 %	95 %	100 %
V6				4	1		0.20	0.00	0.00	0.60	1.00				3	2	2		-0.14	-1.00	-0.71	0.43	1.00	
V7				3	1	1	0.60	0.00	0.00	1.20	2.00			3	1	3			-1.00	-2.00	-1.57	-0.43	0.00	
V8				4	1		0.20	0.00	0.00	0.60	1.00			2	1	3	1		-0.57	-1.86	-1.29	0.00	0.71	
V9			1	3	1		0.00	-1.00	-0.40	0.40	1.00				4	1		2	0.00	-1.00	-0.86	0.86	2.00	
V10		1			3	1	0.60	-2.00	-0.60	1.40	2.00				3	1	3		1.00	0.00	0.43	1.57	2.00	
V11				3	2		0.40	0.00	0.00	0.80	1.00	1	1	1	1	4			-0.86	-2.71	-1.57	-0.14	0.00	
V12			1	4			-0.20	-1.00	-0.60	0.00	0.00				3	4			0.57	0.00	0.29	0.86	1.00	
V13			1	4			-0.20	-1.00	-0.60	0.00	0.00	1			2	4			0.14	-2.57	-0.86	0.86	1.00	
V14				4	1		0.20	0.00	0.00	0.60	1.00	1		1	3	2			-0.29	-2.29	-1.14	0.43	1.00	
V15				5			0.00	0.00	0.00	0.00	0.00	1			3	2	1		0.14	-2.57	-0.86	1.00	1.57	
V16				4	1		0.20	0.00	0.00	0.60	1.00		1		4	1		1	0.29	-1.71	-0.57	1.14	2.57	
V17				5			0.00	0.00	0.00	0.00	0.00				2		4	1	1.57	-2.14	-0.86	0.86	1.86	
V18				5			0.00	0.00	0.00	0.00	0.00	1			4	1	1		0.00	-2.14	-0.86	0.86	1.43	
V19				4	1		0.20	0.00	0.00	0.60	1.00		1	2	2	1	1		-0.14	-1.86	-0.86	0.57	1.57	
V20				3		1	1.00	0.00	0.00	2.00	2.80				3	4			-0.43	-1.00	-0.71	-0.14	0.00	
V21				3		2	0.80	0.00	0.00	1.60	2.00	1			3	3			0.00	-2.14	-0.86	0.71	1.00	
V22				4		1	0.40	0.00	0.00	1.20	2.00	1			3	3			0.00	-2.00	-1.00	0.71	1.00	
V23		1		4			-0.40	-3.00	-1.80	0.00	0.00	1			2	4			-0.71	-2.57	-1.43	-0.14	0.00	
V24		1		4			-0.40	-3.00	-1.80	0.00	0.00	1			3	3			-0.86	-2.43	-1.57	-0.29	0.00	
V25			1	3	1		0.00	-1.00	-0.40	0.40	1.00		1		5	1			-0.14	-1.43	-0.71	0.29	0.71	
V26				3	2		0.40	0.00	0.00	0.80	1.00			1	5		1		0.00	-1.43	-0.57	0.57	1.43	
V27				3	2		0.40	0.00	0.00	0.80	1.00				2	2	1	2	1.43	0.00	0.71	2.14	3.00	
V28		1		4			-0.40	-2.00	-1.20	0.00	0.00	1	1		1	1		3	0.71	-2.43	-0.71	2.14	3.00	
V29				4	1		0.20	0.00	0.00	0.60	1.00	1			1	5			-0.57	-2.29	-1.29	0.00	0.00	
V30			2	2		1	-0.40	-2.00	-1.80	0.40	2.00	1	1	1	3	1			-0.71	-2.86	-1.57	0.00	0.71	
V31	1	1		3			-1.00	-3.00	-2.00	0.00	0.00		1		6				-0.29	-1.71	-0.86	0.00	0.00	
V32				3		2	0.80	0.00	0.00	1.60	2.00	1			4	1	1		0.00	-2.57	-0.86	0.86	1.43	
V33			2	1	1	1	-0.20	-2.00	-1.40	1.00	1.80				1	4	2		1.14	0.29	0.71	1.57	2.00	
V34				2	2	1	0.80	0.00	0.20	1.40	2.00		1		5		1		0.00	-1.71	-0.57	0.57	1.43	
V35				5			0.00	0.00	0.00	0.00	0.00	1			6				-0.43	-2.57	-1.29	0.00	0.00	
V36				3	2		0.40	0.00	0.00	0.80	1.00				3	2	2		0.86	0.00	0.29	1.43	2.00	
V37			1	3	1		0.00	-1.00	-0.40	0.40	1.00	1			4	1		1	0.14	-2.14	-0.86	1.14	2.29	
V38				3	2		0.40	0.00	0.00	0.80	1.00				3	4			0.57	0.00	0.29	0.86	1.00	
V39			1	3	1		0.00	-1.00	-0.40	0.40	1.00	1			6				-0.43	-2.57	-1.29	0.00	0.00	
V40				4	1		0.20	0.00	0.00	0.60	1.00	1	1		4		1		-0.43	-2.86	-1.29	0.57	1.43	
V41				4	1		0.20	0.00	0.00	0.60	1.00	1			5			1	0.00	-2.14	-0.86	0.86	2.57	
V42				4	1		0.20	0.00	0.00	0.60	1.00				4	2	1		0.57	0.00	0.14	1.00	1.57	
V43			1	3	1		0.00	-1.00	-0.40	0.40	1.00				4	1	1	1	0.86	0.00	0.14	1.57	2.57	
V44		1	1	3			-0.60	-2.00	-1.20	0.00	0.00	1			3	3			0.00	-2.14	-1.00	0.71	1.00	
V45				4	1		0.20	0.00	0.00	0.60	1.00		1		4		1	1	0.43	-1.43	-0.57	1.29	2.57	
V46				4	1		0.20	0.00	0.00	0.60	1.00	1	1	2	1		1	1	-0.29	-2.43	-1.43	1.00	2.71	
V47				2	2	1	1.00	0.00	0.20	1.80	3.00						7	3.00	3.00	3.00	3.00	3.00		

NB: Nonparametric Bootstrap; CI90 %: 90 % confidence interval.

Source: our own elaboration.

	WR1	WR2	WR3	EN1	EN2	EN3	FD1	FD2	FD3	EC1	EC2	EC3	SC1
V1	-0.3			0.2	0.05		-0.1		-0.1	-0.05	-0.05	0.05	-0.1
V2	-0.4							0.3					0.3
V3	-0.05		-0.05				-0.55	0.2		-0.05	-0.05	-0.05	
V4					-0.5	-0.2				-0.05	-0.05	-0.2	
V5	-0.35		-0.35						-0.1	-0.1	-0.1		
V6													-1
V7	-0.3		0.3				0.1	0.1			-0.2		
V8	-0.05			0.3		0.25					-0.2	0.2	
V9	-0.3		0.3							0.3		-0.1	
V10	-0.15		-0.1	-0.05			0.2		0.1	-0.1	-0.1	-0.1	0.1
V11				-0.3		0.2						-0.5	
V12				0.2		0.2	-0.2		0.05	-0.2		0.1	0.05
V13	-0.2			0.2		0.2	-0.1				-0.1	0.15	0.05
V14	-0.2					0.3					-0.1	0.4	
V15				0.2	0.2	0.2						0.25	0.15
V16			-0.2				-0.2	-0.2	-0.2	-0.1	-0.1		
V17			-0.2	0.2		0.1	0.1			-0.3			0.1
V18	-0.2		0.2					0.3		0.25	0.05		
V19			0.3							0.35	0.35		
V20			-0.6				-0.1			-0.05	-0.25		
V21			0.25	0.25					0.1		0.4		
V22			0.25	0.25					0.1		0.4		
V23			0.1	-0.2	-0.2	-0.2	0.05				0.25		
V24					-0.3	-0.15	-0.15		-0.15		0.25		
V25			-0.5			-0.1			-0.1	-0.15	-0.15		
V26	-0.05		0.5			0.1			0.1		-0.15		0.1
V27	-0.2		0.6										0.2
V28	-0.2		0.5				0.05	0.05			-0.2		
V29	-0.1		-0.5								0.25		0.15
V30			-0.1								0.9		
V31						-0.2		0.2	-0.1		-0.25	-0.25	
V32											1		
V33			0.5					0.2	0.1		0.2		
V34			0.1					-0.2		0.5		0.2	
V35	-0.2									-0.3	-0.2	-0.2	0.1
V36							0.2	0.3	0.2	-0.3			
V37	-0.2						0.2	0.35	0.1		-0.05	-0.1	
V38	0.2						-0.25	-0.1	-0.3		0.15		
V39	-0.1	0.1					0.2	0.3	0.1		-0.05	-0.05	0.1
V40	-0.4		-0.2					0.2			-0.15	-0.05	
V41	0.05	0.75						0.05	0.05		0.05		0.05
V42	-0.1						0.25	0.5	0.15				
V43	-0.2		-0.15	0.05			0.25	0.2	0.1			-0.05	
V44			0.15				0.25	0.2	-0.3			0.1	
V45								-0.5	-0.3				-0.2
V46			0.3								0.4		0.3
V47		0.3	0.2						0.1		0.2		0.2

Fig. 4. Weights of each indicator on the WEFE objectives.
Source: our own elaboration.

impacts. However, this parameter helps assess the degree of distribution of the network system and the overall importance of an indicator within the system. These parameters are visualized in Fig. 5, where each node in the network is represented as a bubble. The abscissa axis represents the SUM row (influence), and the ordinate represents the SUM column (influenced). The colour of each bubble represents the NI, and the size reflects the SIAV.

Analysing Fig. 5 indicators V1 and V10 stand out in the first quadrant with a more intense yellow colour, corresponding to net influence values of 30 and 28.6, respectively. The indicator with the highest SIAV is V22, with a total value of 47.4, located in the second quadrant. It is followed by variable V7, which has a SIAV of 45.6 and is positioned in the upper-left corner of the fourth quadrant. The solutions S1 and S2 are located along the abscissa axis, with influence values of 5.6 and 3.6, and SIAV values of 14.8 and 20.1, respectively.

Fig. 6 presents the network graph representing the cross-impact matrix. This figure enables a visual analysis of the network by highlighting both positive and negative influences, as well as the indicators where these influences are concentrated. The graph includes 49 nodes, corresponding to 47 indicators and 2 policy solutions. The colour of the edges reflects the degree of influence using the same continuous colour scale as in the matrix. The figure shows a high density of outgoing arrows from both solution nodes, S1 and S2. Among the indicators, V28 stands out with 32 interconnections, followed by V7 with 31 and V10 with 26.

4.3. Nexus coherence assessment

After completing the network analysis, the proposed solutions were evaluated with a nexus coherence assessment of synergies and trade-offs. First, each solution (S1 and S2) was evaluated individually by tracing its influence through the network to identify both positive and

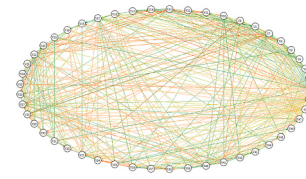


Fig. 6. Network graph based on the cross-impact matrix. Source: our own elaboration.

negative impacts across different nexus objectives. Then, the results of both solutions were combined to assess the overall impact of implementing them together (S1 + S2). Fig. 7 shows the resulting impacts. The heat map helped us identify the overall net impacts by summing the synergies and trade-offs in each grid cell. Green indicates positive impacts, while red indicates negative ones. In our analysis, when we state that an indicator or objective increases or decreases, or exhibits positive or negative impacts, we are referring respectively to the synergies and trade-offs that may result from implementing a solution.

The analysis results show that solution S1 has the highest positive impact on the conservation of aquatic ecosystems EC2 (11.18). Other positive impacts were also observed, such as on the socio-economic development objective SC1, with a score of 2.32. Cross-Impact Analysis suggests that this benefit is linked to a potential increase in Danube River flow V21 and improved river navigability V29. Stakeholders also mentioned a rise in agricultural production V10, which in turn has slight positive effects on food-related objectives, such as FD1 (2.4), FD2 (2.98), and FD3 (2.31), but have negative impacts on reducing water consumption WR1 (-4.78). In relation to this, a slight increase has also been observed in the variable groundwater withdrawal V9. Other negative impacts were also identified. Increasing ecological flows S1 and the resulting rise in variables like Danube River flow rate V21 and tributary



Fig. 5. Analysis of the degree of distribution of the network system. Source: our own elaboration.

Nexus objectives		S1	S2	S1+S2
Water	WR1	2.42 -4.78	5.06 -7.01	7.48 -11.79
	WR2	0.79 -0.33	2.91 -0.60	3.69 -0.93
	WR3	9.02 -8.99	13.41 -8.86	22.43 -17.86
Energy	EN1	2.31 -2.37	3.42 -2.40	5.73 -4.77
	EN2	0.80 -0.80	1.67 -0.57	2.47 -1.37
	EN3	2.13 -1.97	2.85 -1.18	4.98 -3.14
Food	FD1	2.40 -1.43	3.61 -2.26	6.01 -3.68
	FD2	2.98 -1.45	4.49 -2.20	7.47 -3.65
	FD3	2.31 -1.67	3.29 -1.96	5.60 -3.63
Ecosystems	EC1	2.21 -3.08	2.06 -5.45	4.27 -8.53
	EC2	11.18 -9.23	7.65 -11.11	18.83 -20.33
	EC3	1.62 -4.94	5.69 -3.63	7.31 -8.56
S-E*	SC1	2.32 -1.14	4.21 -1.07	6.53 -2.20

Fig. 7. Nexus coherence assessment results: synergies (green) and trade-off (red) of the solutions on WEFE objectives. Source: our own elaboration.

rivers discharge V22 reduce water availability V27, negatively affecting the objective WR3, with a significant negative impact of -8.99. Negative effects were also observed on the conservation of terrestrial ecosystems EC1 (-3.08). This is mainly due to the increase in flood inundation extent (ha) V24 and potential expansion of cropland area V36. Further negative effects were observed in the energy sector. The solution is expected to increase the use of non-renewable energy sources V11 and reduce hydropower generation V13, leading to a negative impact on the objective of increasing the share of renewable energy EN1 (-2.37). These changes are also expected to raise emissions V6, resulting in a negative impact (-4.94) on the objective of reducing greenhouse gas emissions EC3.

At first glance, the heatmap from the analysis of solution S2 shows mostly positive net impacts, although some negative effects are also present. Looking more closely at the synergies, we see a strong positive impact on the objective of increasing water availability WR3, with a

score of 13.41. This is partly due to an increase in recycled wastewater V47 and a reduction in freshwater withdrawals V7. There are also several positive impacts on food sector objectives, secure food supply FD1 (3.61), increase agricultural productivity FD2 (4.49), and a more resilient agricultural sector FD3 (3.29). This is logical, as the main use of the reused water is for irrigation. In turn, this also positively affects socio-economic development SC1 (4.21). Regarding the conservation of aquatic ecosystems EC2, the trade-offs are more significant, with a total negative impact of -11.11. This is because, with more water being reused, stakeholders identified a reduction in water flow, including water flow for habitats and fish migration V30 and the magnitude of flooding V29, which affects freshwater species richness V32. However, EC2 also shows some positive impacts, related to the reduction in freshwater withdrawals V7 and increases in water availability V27. Similarly, negative impacts were observed on the conservation of terrestrial ecosystems EC1, due to potential increases in cropland area

V36. On the other hand, stakeholders determined that this solution reduces non-renewable energy generation V11 and increase the production of bioethanol and biodiesel V12, which in turn lowers emissions V6 and has some positive effects on the energy sector.

By combining both solutions, we can perform a policy coherence assessment. First, we can see that solution S1 helps reduce the negative impacts on EC2 caused by S2. Similarly, solution S2 helps mitigate the negative impacts on EC3 generated by S1. The objectives where negative impacts increase are WR1 and EC1. For all other objectives, we observe positive combined effects.

In addition to the nexus coherence assessment of synergies and trade-offs, we measured the variability of stakeholder responses. For this, we applied a nonparametric bootstrap as a statistical resampling method (10,000 iterations) to compute the possible range of stakeholder responses and calculated the 90 % confidence intervals, including their upper and lower bounds (see Table 4). These results were then incorporated into the network model to estimate a plausible range of outcomes. 8a presents the variability of stakeholder responses and their impacts on WEFE objectives, resampled using a nonparametric bootstrap. The mean values, ranges of maximums and minimums responses and the 90 % confidence intervals for Solution S1, Solution S2, and the combined solution S1 + S2. The line with dots represents the average results, while the shaded area illustrates the range between the maximum and minimum values based on the calculated confidence intervals.

In several objectives, the average results do not lie at the midpoint between the confidence intervals. This is due to the complexity of the system and the fact that the influence deviations introduced into the network model are not distributed linearly. The results indicate that

stakeholder response variability is generally higher in Solution S2 compared to Solution S1. Specifically, Solution S1 shows greater variability in impacts related to objectives WR1, FD2, and EC2. Similarly, Solution S2 exhibits higher variability in outcomes, particularly in impacts associated with objectives WR1, WR3, FD2, EC1, EC2, and EC3. According to the bootstrap simulation results, there is no statistically robust evidence of an effect different from zero at the chosen confidence level for most of the objectives analysed in both solutions.

To assess the sensitivity of the network model, a Monte Carlo simulation with 10,000 iterations was performed, introducing a $\pm 20\%$ perturbation to all indicator weights on the objectives, while considering a 90 % confidence level. The confidence interval obtained from the simulation are narrow and, in most cases, do not include zero (Fig. 8b). The greatest uncertainty arises in the influence of solution S1 on objective WR3.

Finally, Fig. 9 illustrates the third-order impacts of Solution S1 on the nexus objectives. The results reveal stronger positive and negative influences, with a greater incidence of trade-offs particularly affecting objectives WR3 and EC2.

5. Discussions of findings

To co-design and assess solutions that address the growing pressures of climate change and socio-economic activities on the WEFE nexus in the DRB, we used the GoNEXUS SEF, a participatory methodological framework grounded in the WEFE nexus approach. The WEFE nexus dynamics shape a complex system with multi-directional interrelations, these features make it very difficult to evaluate (Pahl-Wostl et al., 2021; Sievers et al., 2025). Several authors recommend involving multiple

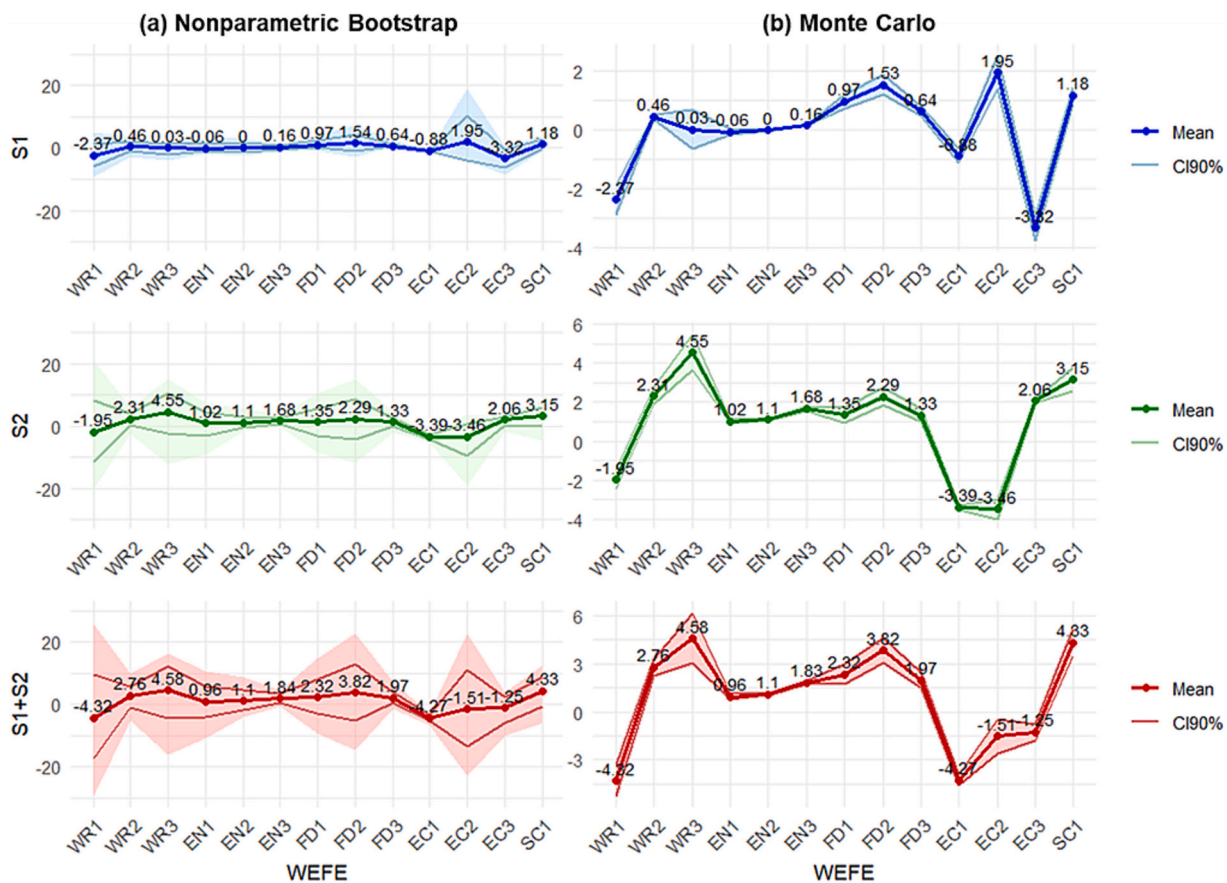


Fig. 8. (a) Stakeholder response variability and its impacts on WEFE objectives, resampled with a nonparametric bootstrap. (b) Monte Carlo simulation to assess the sensitivity of the network model to changes in the assigned weights. Source: our own elaboration. CI90 %: 90 % confidence interval.

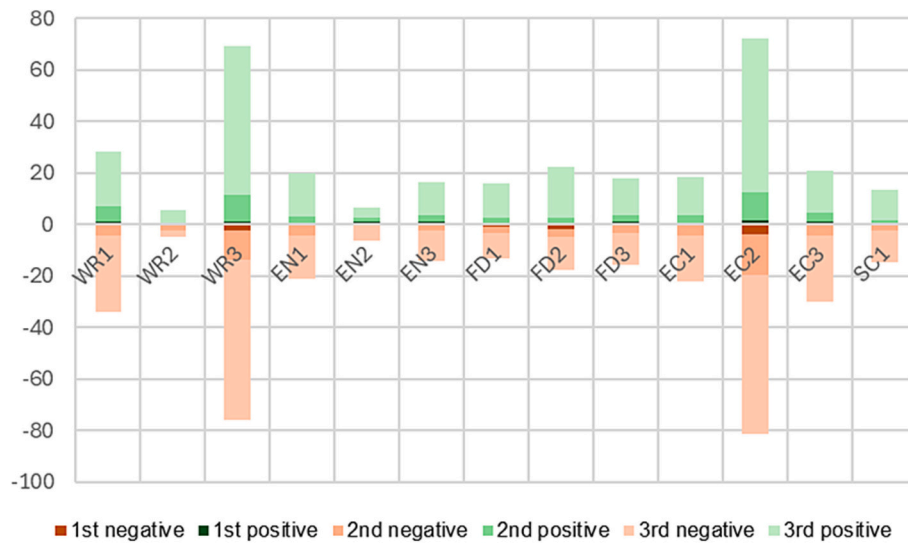


Fig. 9. Impacts of Solution S1 at the Third-Order Level. Source: our own elaboration.

stakeholders and experts to ensure that the interlinkages across all sectors of the nexus are fully captured (Sušnik and Staddon, 2021; Malamataris et al., 2025). In our study, we engaged stakeholders responsible for decision-making across the WEF sectors in the DRB. We also worked with a panel of experts who, although not deeply familiar with the DRB, bringing technical expertise across the different dimensions of the nexus. Both stakeholders and experts were involved in various stages of the process, including the identification of challenges, indicators, and solutions, as well as in the analysis of the selected solutions. This entire process was further supported by a comprehensive literature review.

Regarding the tool used, N-CIA is based on network theory, which has gained traction as a framework for understanding the WEF nexus and the impacts of human activity on natural resources (Martinez et al., 2018; Khiali-Miab et al., 2022; Hurtado et al., 2024). However, it presents several limitations. First, network models often oversimplify complex and dynamic interactions by reducing them to static nodes and links, potentially overlooking important feedbacks and temporal dynamics (González and Parrott, 2012). Second, the selection of variables and the aggregation of complex processes into single nodes may obscure internal variability. For example, grouping different types of water use into one node can overlook important differences in consumption, leading to misinterpretations. Third, assuming linear relationships in edge weights may not reflect the nonlinear nature of many WEF interactions, which are often shaped by thresholds and tipping points. This can distort indirect effects and compromise the validity of model outputs (Khiali-Miab et al., 2022). In this context, González-Rosell et al. (2023) present N-CIA as a complementary tool to more quantitative approaches such as System Dynamics Models (SDM), emphasizing its ability to integrate both model-derived outputs and stakeholder input. Unlike more complex modelling frameworks that require detailed datasets and advanced mathematical formulations, N-CIA offers a more accessible way to incorporate stakeholder knowledge, which is particularly valuable when such insights are difficult to formalize within more complex models. To further justify the use of N-CIA in this study, it is important to compare it to alternative modelling frameworks commonly applied in nexus research. System Dynamics models, for example, are powerful tools to capture feedback loops and temporal dynamics, but they require extensive quantitative datasets and advanced calibration, which are not always available at basin scale. Hydrological models such as Soil & Water Assessment Tool (SWAT) provide robust and spatially explicit simulations of water flows, yet they are sector-specific and less suitable for analysing cross-sectoral trade-offs within the WEF nexus.

Computable General Equilibrium or optimization models are valuable for assessing economic efficiency and policy costs, but they tend to overlook ecological processes and are often expert driven, leaving little room for meaningful stakeholder integration. In contrast, N-CIA offers a more accessible and transparent approach that directly integrates stakeholder and expert knowledge, while still allowing a structured quantitative analysis of synergies and trade-offs across multiple sectors.

Research Question RQ1 highlights the need to identify water-related solutions that can help address the challenges posed by climate change and competition among sectors for water use in the DRB. To this end, extensive work was carried out with stakeholders and experts to identify a set of potential solutions, from which two were ultimately prioritized: increasing ecological flows to support the health of aquatic ecosystems and expanding wastewater reuse for agricultural irrigation. Analysing multiple solutions is essential for conducting a policy coherence assessment and presenting clearly articulated policy options (Simpson and Jewitt, 2019).

Research Question RQ2 highlights the need to identify cross-sectoral synergies and trade-offs that may arise from implementing these solutions. Regarding the results obtained, we will focus on discussing the most significant findings. Firstly, the solution of increasing ecological flows shows the highest positive impact on the conservation of aquatic ecosystems. This outcome was expected, as enhancing ecological flows was primarily intended to support this objective, and it is further supported by several authors (Stagl and Hattermann, 2016; Karabulut et al., 2016; Funk et al., 2019; Gălie et al., 2021; Stănescu and Moldoveanu, 2023). Positive impacts are also observed on socio-economic development, which aligns with existing literature highlighting the benefits that ecosystem services provide to socio-economic development (Funk et al., 2019; Perosa et al., 2021). Stakeholders further reported that this solution contributed to improvements in agricultural production, which was reflected in the achievement of objectives related to the agricultural sector. Initially, this result appeared counterintuitive, since it might be expected that more water reserved for ecosystems would reduce irrigation water availability, as indicated by Bisselink et al. (2018) and Probst et al. (2024). However, this can be explained by the fact that higher ecological flows could raise groundwater levels and enhance the productivity of rainfed agriculture under certain hydro-geologic conditions. Some authors have also described and supported these dynamics (Wang et al., 2011; De Graaf et al., 2019). On the other hand, this measure negatively affects the water available for consumption, which logically follows from diverting more water to ecosystems. This solution

also negatively affects renewable energy generation (hydropower). Our results show a net trade-off of -0.06 , which is consistent with Kuriqi et al. (2019, 2021), who reported a 5–12 % reduction in hydropower generation associated with increased ecological flows, a change that simultaneously contributes to increase GHG emissions. Finally, negative effects are also observed on terrestrial ecosystem conservation due to the potential expansion of agriculture (Racoviceanu et al., 2023).

Regarding the second solution, the expansion of wastewater reuse for agriculture, the most immediate positive impact is observed in the objective of increasing water availability. This is a logical outcome, as it directly aligns with the purpose of the solution. Positive effects are also evident in objectives related to the agricultural sector, since the reused water would be allocated for irrigation, which in turn contributes to socio-economic development, especially in water-scarce regions (Pistocchi et al., 2017; Hristov et al., 2021). However, wastewater reuse may entail certain negative effects that had been overlooked in the assessment, such as nutrient and contaminant loads, salinity, and pathogen risks (Al-Hazmi et al., 2023; Trotta et al., 2024). The new EU Regulation 741/2020 establishes quality standards to mitigate these risks (Di Marcantonio et al., 2025). Negative impacts were also identified on aquatic ecosystems. These effects appear to be linked to the intensification of agriculture (Racoviceanu et al., 2023) and reduced river flows caused by the collection of water for reuse, as mentioned by the stakeholders. Negative impacts were also observed on terrestrial ecosystems, mainly due to the potential expansion of agricultural activities (Feldbacher et al., 2016).

Regarding the degree of agreement among stakeholders, the K-Alpha values for both solutions (S1: 0.074 and S2: 0.14) are below the 0.67 threshold and close to zero. This indicates a very low level of agreement among stakeholders. Such lack of agreement may reduce the reliability of the findings. Furthermore, due to the variability of the results, there is no statistically robust evidence of an effect different from zero at the chosen confidence level for most of the objectives analysed in both solutions. However, the work carried out goes beyond whether there is agreement among stakeholders when evaluating a solution. Being able to capture these disagreements and variability reflects the inherent complexity of the nexus and the engagement of diverse stakeholders with different, and often opposing, perspectives and opinions (Al-Saidi and Elagib, 2017; Pahl-Wostl et al., 2021; Sievers et al., 2025). An alternative could have been to build consensus among stakeholders, for instance through methods such as Borda or Delphi, rather than relying on calculated averages. However, due to time constraints during the workshop, this was not feasible. Nonetheless, stakeholders were actively involved in discussions on the WEFE nexus and the proposed solutions, contributing valuable insights throughout the process.

The Monte Carlo sensitivity analysis indicates that, overall, ± 20 % perturbations in the assigned weights result in mostly narrow 90 % confidence intervals, suggesting limited variability in the outcomes. The exploratory analysis of the third-order impacts of Solution S1 reveals significant synergies and trade-offs on the objectives Increase water availability and Conserve aquatic ecosystems, with trade-offs being more dominant. Interpreting third-order impacts is more complex due to the high number of interactions in the matrix and the large set of variables involved. Nevertheless, identifying these effects is valuable, as it helps anticipate and remain cautious about potential impacts that are far less evident at lower levels of analysis.

GoNEXUS SEF has proven to be a flexible framework for evaluating solutions across different contexts, taking into account geographical scale, governance structures, and technological options. In the case of the DRB, it was adapted through the careful selection of indicators relevant to the study area, in close collaboration with stakeholders. An appropriate choice of indicators enables a better characterization of the nexus system under analysis. Furthermore, the framework allows for greater adaptability by examining the interrelations among indicators through Cross-Impact Analysis, enabling a more accurate representation of the case study.

The main limitation of our study was the significant amount of resources required to carry out the process. Coordinating teams, organising meetings and workshops, and engaging stakeholders and experts demanded considerable time and effort. Completing the evaluation of solutions in the DRB took several years of work. However, we believe that the extensive collaboration with stakeholders and experts, although demanding, was essential to co-design the solutions and ensure that the analysis produced meaningful results. Another limitation lies in the subjectivity involved in representing the nexus system through the cross-impact matrix and assigning weights to the WEFE objectives. This subjectivity must be acknowledged and carefully considered. Methodologies such as fuzzy cognitive mapping (Martinez et al., 2018) allow for a more objective characterization of a nexus system. To mitigate it, multiple stakeholders and experts were involved throughout the process. However, stakeholder participation was higher at the local level in Hungary, which may have introduced a geographic bias, potentially underrepresenting issues in upstream (Germany) or downstream (Romania) areas. Likewise, the solution assessment workshops were conducted locally, and although stakeholders are likely to have broad knowledge of the Danube Basin, similar biases may have influenced the evaluation. To further address this limitation, the GoNEXUS SEF also enables the integration of results from quantitative models (González-Rosell et al., 2023). Future research could focus on incorporating simulation outputs from basin-scale system dynamics or SWAT models to better capture temporal dynamics and enhance the robustness of the analysis. Authors such as González-Rosell et al. (2020), Deng et al. (2023), or Widén et al. (2024) provide examples of how to develop this type of model. Another opportunity for future research could be to address different solutions and extend beyond water-related measures to include energy-efficiency or crop-choice interventions that have been identified as leverage points by some stakeholders and mentioned by Probst et al. (2024).

6. Concluding remarks

This study focused on the co-design and evaluation of water-related solutions to address the growing pressures on the WEFE nexus caused by climate change and socio-economic development in the Danube River Basin. To achieve this, we applied the GoNEXUS SEF, a participatory methodological framework grounded in the WEFE nexus approach. The collaboration involved stakeholders from private associations, civil society, and academia, as well as policymakers across the WEFE nexus. Additionally, we consulted a panel of academic experts to further enrich the analysis.

Through a comprehensive analysis of the DRB, we identified three main nexus challenges. First, climate change is making water scarcer while also increasing the risk of floods. Second, as the climate becomes warmer and drier, the demand for irrigation is rising, which puts even more pressure on already limited water resources. Third, both aquatic and land ecosystems are becoming more vulnerable due to water shortages and changes in land use, particularly from agriculture and energy production. To tackle these issues, we looked into two promising water-related solutions: increasing ecological flows and expanding wastewater reuse for agricultural irrigation. A nexus coherence assessment was conducted to evaluate these policy solutions.

The assessment of the DRB was carried out from a regional perspective. However, during the evaluation process, a wide divergence of opinions was observed among stakeholders regarding the impacts of the solutions on the different indicators. This highlights the level of uncertainty surrounding the synergies and trade-offs within the WEFE nexus. Moreover, this lack of consensus negatively compromised the statistical significance of the results. Nevertheless, the evaluation was carried out using the average values. Evaluation results indicate that increasing ecological flows brings benefits to aquatic ecosystems, as well as socio-economic gains and some improvements in agricultural production. However, potential trade-offs include reduced renewable

energy generation and possible increases in GHG emissions. Negative effects may also occur in terrestrial ecosystems due to agricultural expansion and increased flooding. Conversely, expanding wastewater reuse for irrigation supports agricultural production by boosting water availability and benefits socio-economic development, but may have adverse impacts on aquatic ecosystems. Combining both solutions can help mitigate negative effects on aquatic ecosystems while addressing water scarcity.

Despite the limited statistical significance of the results, the analysis highlights the importance of assessing nexus coherence. This involves quantitatively measuring synergies and trade-offs across water, energy, agriculture, and ecosystem sectors when implementing sectoral or cross-sectoral policies. This requires a framework that goes beyond intuition. The applied methodology identifies hidden dynamics and key indicators in a multi-sector system, revealing leverage points where nexus solutions can most effectively promote sustainable development. Beyond the results, this research served as a meeting point where stakeholders and researchers came together to better understand and address the key challenges of the WEF nexus, and promote sustainability in the Danube River Basin.

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CRedit authorship contribution statement

Adrián González-Rosell: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Beáta Pataki:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **János Fehér:** Writing – review & editing, Project administration, Investigation, Data curation, Conceptualization. **Imen Arfa:** Writing – review & editing, Validation, Methodology. **Attila Lovas:** Investigation, Data curation. **Maria Blanco:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Microsoft Copilot in order to improve the readability and language of the published article. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content.

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Declaration of competing interest

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Data availability

The article data has been uploaded as a draft to Zenodo under the DOI <https://doi.org/10.5281/zenodo.16615120>. Once the article is accepted, the data will be published.

References

- Al-Hazmi, H.E., Mohammadi, A., Hejna, A., Majtacz, J., Esmaeili, A., Habibzadeh, S., Saeb, M.R., Badawi, M., Lima, E.C., Makinia, J., 2023. Wastewater reuse in agriculture: prospects and challenges. *Environ. Res.* 236, 116711. <https://doi.org/10.1016/j.envres.2023.116711>.
- Al-Saidi, M., Elagib, N.A., 2017. Towards understanding the integrative approach of the water, energy and food nexus. *Sci. Total Environ.* 574, 1131–1139. <https://doi.org/10.1016/j.scitotenv.2016.09.046>.
- Bala, B.K., Arshad, F.M., Noh, K.M., Bala, B.K., Arshad, F.M., Noh, K.M., 2017. Causal loop diagrams. In: *System Dynamics: Modelling and Simulation*, pp. 37–51. https://doi.org/10.1007/978-981-10-2045-2_3.
- Bisselink, B., de Roo, A., Bernhard, J., Gelati, E., 2018. Future projections of water scarcity in the Danube River Basin due to land use, water demand and climate change. *J. Environ. Geol.* 11 (3–4), 25–36. <https://doi.org/10.2478/jengeo-2018-0010>.
- Blicharska, M., Smithers, R.J., Kuchler, M., Munaretto, S., van den Heuvel, L., Teutschbein, C., 2024. The water–energy–food–land–climate nexus: policy coherence for sustainable resource management in Sweden. *Environ. Policy Gov.* 34 (2), 207–220. <https://doi.org/10.1002/eet.2072>.
- de Andrade Guerra, J.B.S.O., Berchin, I.I., Garcia, J., da Silva Neiva, S., Jonck, A.V., Faraco, R.A., Ribeiro, J.M.P., 2021. A literature-based study on the water–energy–food nexus for sustainable development. *Stoch. Env. Res. Risk A.* 35 (1), 95–116. <https://doi.org/10.1007/s00477-020-01772-6>.
- De Graaf, I.E., Gleeson, T., Van Beek, L.P.H., Sutanudjaja, E.H., Bierkens, M.F., 2019. Environmental flow limits to global groundwater pumping. *Nature* 574 (7776), 90–94. <https://doi.org/10.1038/s41586-019-1594-4>.
- De Roo, A., Bisselink, B., Trichakis, I., 2023. Water-Energy-Food-Ecosystems Pathways Towards Reducing Water Scarcity In Europe–Analysis Using the Water Exploitation Index Plus. Publications Office of the European Union. <https://doi.org/10.2760/478498>
- Deng, Z., Ma, Q., Zhang, J., Feng, Q., Niu, Z., Zhu, G., Chen, H., 2023. A new socio-hydrology system based on system dynamics and a SWAT-MODFLOW coupling model for solving water resource management in Nanchang City, China. *Sustainability* 15 (22), 16079. <https://doi.org/10.3390/su152216079>.
- Di Marcantonio, C., Mangiagli, F., Boni, M.R., Bartolucci, J., Bongiorolami, S., Romano, R., Martelli, A., Rapinesi, D., Altobelli, F., Chiavola, A., 2025. Are we ready for the application of the EU regulation on wastewater reuse in agriculture? A techno-economic preliminary evaluation based on a case-study. *J. Environ. Manage.* 373, 123973. <https://doi.org/10.1016/j.jenvman.2024.123973>.
- Dogaru, D., Mauser, W., Balteanu, D., Krimly, T., Lippert, C., Sima, M., Frank, A., 2019. Irrigation water use in the Danube Basin: facts, governance and approach to sustainability. *J. Environ. Geol.* 12 (3–4), 1–12. <https://doi.org/10.2478/jengeo-2019-0007>.
- EC, 2007. Towards Sustainable Water Management in the European Union. First Stage in the Implementation of the Water Framework Directive 2000/60/ec. In: Accompanying Document to the Communication from the Commission to the European Parliament and the Council; Com 128 Final, 2007. European Commission, Brussels, Belgium. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52007DC0128>.
- EC, 2016. Ecological flows in the implementation of the Water Framework Directive. In: European Commission: Directorate-General for Environment. Guidance document No 31, 2016. Publications Office of the European Union. <https://data.europa.eu/doi/10.2779/775712>.
- El-Gafy, I., 2017. Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. *Appl Water Sci* 7 (6), 2857–2868. <https://doi.org/10.1007/s13201-017-0551-3>.
- EU, 2020. Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. European Union. Official Journal of the European Union, L 177, 32–55. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0741>.

- Farinosi, F., Giupponi, C., Reynaud, A., Ceccherini, G., CarmonaMoreno, C., De Roo, A., Gonzalez-Sanchez, D., Bidoglio, G., 2018. An innovative approach to the assessment of hydrological risk: a spatially explicit, data driven indicator of hydrological issues. *Glob. Environ. Chang.* 52, 286–313. <https://doi.org/10.1016/j.gloenvcha.2018.07.001>.
- Feldbacher, E., Paun, M., Reckendorfer, W., Sidoroff, M., Stanica, A., Strimbu, B., Hein, T., 2016. Twenty years of research on water management issues in the Danube Macro-region—past developments and future directions. *Sci. Total Environ.* 572, 1297–1306. <https://doi.org/10.1016/j.scitotenv.2015.12.133>.
- Funk, A., Martínez-López, J., Borgwardt, F., Trauner, D., Bagstad, K.J., Balbi, S., Hein, T., 2019. Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems. *Sci. Total Environ.* 654, 763–777. <https://doi.org/10.1016/j.scitotenv.2018.10.322>.
- Gălie, A.C., Mătreasă, M., Tănase, I., Rădulescu, D., 2021. The Romanian ecological flow method, RoEflow, developed in line with the EU water framework directive. Concept and case studies. *Sustainability* 13 (13), 7378. <https://doi.org/10.3390/su13137378>.
- González, R., Parrott, L., 2012. Network theory in the assessment of the sustainability of social-ecological systems. *Geogr. Compass* 6 (2), 76–88. <https://doi.org/10.1111/j.1749-8198.2011.00470.x>.
- González-Rosell, A., Blanco, M., Arfa, I., 2020. Integrating stakeholder views and system dynamics to assess the water–energy–food Nexus in Andalusia. *Water* 12 (11), 3172. <https://doi.org/10.3390/w12113172>.
- González-Rosell, A., Arfa, I., Blanco, M., 2023. Introducing GoNEXUS SEF: a solutions evaluation framework for the joint governance of water, energy, and food resources. *Sustain. Sci.* <https://doi.org/10.1007/s11625-023-01324-1>.
- Gregorič, G., Moderc, A., Sušnik, A., Žun, M., 2019. Better Prepared for Drought – Danube Drought Strategy. Slovenian Environment Agency, Ljubljana, Slovenia. https://www.droughtmanagement.info/literature/Interreg-Danube_Drought_Strategy_2019.pdf.
- Hattermann, F.F., Wortmann, M., Liersch, S., Toumi, R., Sparks, N., Genillard, C., Drews, M., 2018. Simulation of flood hazard and risk in the Danube basin with the Future Danube Model. *Clim. Serv.* 12, 14–26. <https://doi.org/10.1016/j.cliser.2018.07.001>.
- Hoff, H., 2011. Understanding the Nexus: Background Paper for the Bonn 2011 Nexus Conference (51 pp.). www.seiinternational.org/publications?pid=1977.
- Hristov, J., Barreiro-Hurle, J., Salputra, G., Blanco, M., Witzke, P., 2021. Reuse of treated water in European agriculture: potential to address water scarcity under climate change. *Agric. Water Manag.* 251, 106872. <https://doi.org/10.1016/j.agwat.2021.106872>.
- Hurtado, A.R., Mesa-Pérez, E., Berbel, J., 2024. Systems modeling of the Water-Energy-Food-Ecosystems Nexus: insights from a region facing structural water scarcity in southern Spain. *Environ. Manag.* 74 (6), 1045–1062. <https://doi.org/10.1007/s00267-024-02037-6>.
- ICPDR, 2021. Danube River Basin Management Plan – Update 2021. International Commission for the Protection of the Danube River. https://www.icpdr.org/sites/default/files/nodes/documents/drbmp_update_2021_final_lores.pdf.
- Karabulut, A., Egoh, B.N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Mubareka, S., 2016. Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. *Ecosystem Serv.* 17, 278–292. <https://doi.org/10.1016/j.ecoser.2015.08.002>.
- Khiali-Miab, A., Grêt-Regamey, A., Axhausen, K.W., van Strien, M.J., 2022. A network optimisation approach to identify trade-offs between socio-economic and ecological objectives for regional integrated planning. *City Environ. Interact.* 13. <https://doi.org/10.1016/j.cacint.2021.100078>.
- Krippendorff, K., 2018. Content Analysis: An Introduction to Its Methodology. Sage Publications. <https://doi.org/10.4135/9781071878781>.
- Kristensen, P., 2004. The DPSIR Framework. National Environmental Research Institute, Denmark. https://greenresistance.wordpress.com/wp-content/uploads/2008/10/dp_sir-1.pdf.
- Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Garrote, L., 2019. Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants. *Appl. Energy* 256, 113980. <https://doi.org/10.1016/j.apenergy.2019.113980>.
- Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., Garrote, L., 2021. Ecological impacts of run-of-river hydropower plants—current status and future prospects on the brink of energy transition. *Renew. Sustain. Energy Rev.* 142, 110833. <https://doi.org/10.1016/j.rser.2021.110833>.
- Lucca, E., Kofinas, D., Avellán, T., Kleemann, J., Mooren, C.E., Blicharska, M., Teutschbein, C., Sperotto, A., Sušnik, J., Milliken, S., Fader, M., Đorđević, D., Dasić, T., Vasilčić, V., Taiwo, B., Baubekova, A., Pineda-Martos, R., Spyropoulou, A., Baganz, G.F.M., Laspidou, C., 2025. Integrating “nature” in the water-energy-food Nexus: current perspectives and future directions. *Sci. Total Environ.* 966, 178600. <https://doi.org/10.1016/j.scitotenv.2025.178600>.
- Malamataris, D., Pisanaras, V., Pagano, A., Barattella, V., Vanino, S., Bea, M., Panagopoulos, A., 2025. Managing water-ecosystem-food nexus using participatory approaches: insights from an innovative methodological approach developed in two Mediterranean areas. *Front. Water* 7, 1469762. <https://doi.org/10.3389/frwa.2025.1469762>.
- Martinez, P., Blanco, M., Castro-Campos, B., 2018. The water–energy–food nexus: a fuzzy-cognitive mapping approach to support nexus compliant policies in Andalusia (Spain). *Water* 10 (5), 664. <https://doi.org/10.3390/w10050664>.
- Mauser, W., Stolz, R., Weber, M., Ebner, M., 2018. Integrating and editing new scientific results in climate change research and the resulting impacts on water availability to revise the existing adaptation strategies in the Danube River basin. ICPDR, Final report. https://www.icpdr.org/main/sites/default/files/nodes/documents/danube_climate_adaptation_study_2018.pdf.
- Mooren, C.E., Papadopoulou, C.-A., Munaretto, S., Levedi, K., Papadopoulou, M.P., 2025. A methodological framework for assessing the coherence of Water-Energy-Food-Ecosystem nexus policies: illustration and application at the river basin level. *Environ. Sci. Policy* 170, 104113. <https://doi.org/10.1016/j.envsci.2025.104113>.
- Newman, M.E., 2003. The structure and function of complex networks. *SIAM Rev.* 45 (2), 167–256. <https://doi.org/10.1137/S003614450342480>.
- Nhamo, L., Mabhaudhi, T., Mpandeli, S., Nhemachena, C., Senzanje, A., Naidoo, D., Modi, A.T., 2019. Sustainability Indicators and Indices for the Water-Energy-Food Nexus for Performance Assessment: WEF Nexus in Practice—South Africa Case Study. <https://doi.org/10.1016/j.envsci.2020.04.010>.
- Nilsson, M., Griggs, D., Visbeck, M., 2016. Policy: map the interactions between Sustainable Development Goals. *Nature* 534 (7607), 320–322. <https://doi.org/10.1038/534320a>.
- Pahl-Wostl, C., Gorris, P., Jager, N., Koch, L., Lebel, L., Stein, C., Withanachchi, S., 2021. Scale-related governance challenges in the water–energy–food nexus: toward a diagnostic approach. *Sustain. Sci.* 16, 615–629. <https://doi.org/10.1007/s11625-020-00888-6>.
- Pekárová, P., Bajtek, Z., Pekár, J., Vyleta, R., Bonacci, O., Miklánek, P., Gorbachova, L., 2023. Monthly stream temperatures along the Danube River: statistical analysis and predictive modelling with incremental climate change scenarios. *J. Hydrol. Hydromech.* 71 (4), 382–398. <https://doi.org/10.2478/johh-2023-0028>.
- Perosa, F., Fanger, S., Zingraff-Hamed, A., Disse, M., 2021. A meta-analysis of the value of ecosystem services of floodplains for the Danube River Basin. *Sci. Total Environ.* 777, 146062. <https://doi.org/10.1016/j.scitotenv.2021.146062>.
- Pistocchi, A., Beck, H., Bisselink, B., Gelati, E., Lavalle, C., Feher, J., 2015. Water Scenarios for the Danube River Basin: Elements for the Assessment of the Danube Agriculture-Energy-Water Nexus. Publications Office. European Union. <https://doi.org/10.2788/375680>.
- Pistocchi, A., Aloe, A., Dorati, C., Alcalde, S., Bouraoui, F., Gawlik, B., Vigiak, O., 2017. The Potential of Water Reuse for Agricultural Irrigation in the EU – A Hydro-economic Analysis, 2017. Publications Office. <https://data.europa.eu/doi/10.2760/263713>.
- Popa, V.I., Rusu, E., Chiroasca, A.M., Arseni, M., 2025. Danube River: hydrological features and risk assessment with a focus on navigation and monitoring frameworks. *Earth* 6 (3), 70. <https://doi.org/10.3390/earth6030070>.
- Potopová, V., Trnka, M., Vizina, A., Semerádová, D., Balek, J., Chawdhery, M.R.A., Clothier, B., 2022. Projection of 21st century irrigation water requirements for sensitive agricultural crop commodities across the Czech Republic. *Agric. Water Manag.* 262, 107337. <https://doi.org/10.1016/j.agwat.2021.107337>.
- Probst, E., Mauser, W., 2022. Climate change impacts on water resources in the Danube River basin: a hydrological modelling study using EURO-CORDEX climate scenarios. *Water* 15 (1), 8. <https://doi.org/10.3390/w15010008>.
- Probst, E., Fader, M., Mauser, W., 2024. The water-energy-food-ecosystem nexus in the Danube River Basin: exploring scenarios and implications of maize irrigation. *Sci. Total Environ.* 914, 169405. <https://doi.org/10.1016/j.scitotenv.2023.169405>.
- Racoviceanu, T., Cazacu, C., Adamescu, M., Giucă, R., Bucur, M., Fedoriak, M., Angelstam, P., 2023. Agricultural intensification reduces the portfolio of wetland ecosystem services: European Danube River lowlands as a global biodiversity hotspot. *Land* 12 (3), 722. <https://doi.org/10.3390/land12030722>.
- Ramos, V., Formigo, N., Maia, R., 2017. Ecological flows and the water framework directive implementation: an effective coevolution. *European Water* 60 (Arthington 2012), 423–432. https://www.ewra.net/ew/pdf/EW_2017_60_58.pdf.
- REKK, 2013. Renewable electricity market monitoring in the countries of the Danube Region. MVM Plc, Regional Centre for Energy Policy Research (REKK). https://en.energy.danube-region.eu/wp-content/uploads/sites/6/sites/6/2019/09/Renewable_Electricity_Market_Monitoring_in_the_Countries_of_the_DR.pdf.
- Salam, S., Popescu, I., Scricieiu, A., 2022. Defining a Water-Energy-Food nexus framework for water allocation in the lower Danube between Iron Gates and Zimnicea. *GeoEcoMarina* 28. <https://doi.org/10.5281/zenodo.7491458>.
- Schlemm, A., Mulligan, M., Tang, T., Agramont, A., Namugize, J., Malambala, E., van Griensven, A., 2024. Developing meaningful water-energy-food-environment (WEFE) nexus indicators with stakeholders: an Upper White Nile case study. *Sci. Total Environ.* 931, 172839. <https://doi.org/10.1016/j.scitotenv.2024.172839>.
- Sievers, E., Canovas, I., Kristensen, D., Hüesker, F., 2025. Assessing to act: a water-energy-food-ecosystem (WEFE) nexus governance assessment for the Inkomati-Ushuthu river basin in South Africa. *Environ. Sci. Policy* 164, 103986. <https://doi.org/10.1016/j.envsci.2025.103986>.
- Simpson, G.B., Jewitt, G.P., 2019. The water-energy-food nexus in the anthropocene: moving from ‘nexus thinking’ to ‘nexus action’. *Curr. Opin. Environ. Sustain.* 40, 117–123. <https://doi.org/10.1016/j.coesust.2019.10.007>.
- Stagl, J.C., Hattermann, F.F., 2016. Impacts of climate change on riverine ecosystems: alterations of ecologically relevant flow dynamics in the Danube River and its major tributaries. *Water* 8 (12), 566. <https://doi.org/10.3390/w8120566>.
- Stănescu, S.V., Moldoveanu, M., 2023. Flow assessment downstream the water abstraction by integrating the ecological flow—an approach at the water body level. *Adv. Environ. Sci.* 15 (1), 1–11. <https://www.proquest.com/scholarly-journals/flow-assessment-downstream-water-abstraction/docview/2906427315/se-2>.
- Stolz, R., Prasch, M., Weber, M., Koch, F., Weidinger, R., Ebner, M., Mauser, W., 2018. Climate change impacts on the water resources in the Danube River Basin and possibilities to adapt—the way to an adaptation strategy and its update. *J. Environ. Geol.* 11 (3–4), 13–24. <https://doi.org/10.2478/jengeo-2018-0009>.
- Sušnik, J., Staddon, C., 2021. Evaluation of Water-Energy-Food (WEF) Nexus research: perspectives, challenges, and directions for future research. *JAWRA J. Am. Water Resour. Assoc.* <https://doi.org/10.1111/1752-1688.12977>.

- Taguta, C., Senzanje, A., Kiala, Z., Malota, M., Mabhaudhi, T., 2022. Water-Energy-Food Nexus tools in theory and practice: a systematic review. *Front. Water*. <https://doi.org/10.3389/frwa.2022.837316>.
- Trotta, V., Baaloudj, O., Brienza, M., 2024. Risks associated with wastewater reuse in agriculture: investigating the effects of contaminants in soil, plants, and insects. *Front. Environ. Sci.* 12. <https://doi.org/10.3389/fenvs.2024.1358842>.
- Wang, P., Yu, J., Zhang, Y., Fu, G., Min, L., Ao, F., 2011. Impacts of environmental flow controls on the water table and groundwater chemistry in the Ejina Delta, northwestern China. *Environ. Earth Sci.* 64 (1), 15–24. <https://doi.org/10.1007/s12665-010-0811-0>.
- Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M., Karki, P., 2022. Climate change and the hydropower sector: a global review. *Wiley Interdiscip. Rev. Clim. Chang.* 13 (2), e757. <https://doi.org/10.1002/wcc.757>.
- Weitz, N., Carlsen, H., Nilsson, M., Skånberg, K., 2018. Towards systemic and contextual priority setting for implementing the 2030 Agenda. *Sustain. Sci.* 13 (2), 531–548. <https://doi.org/10.1007/s11625-017-0470-0>.
- Widén, Å., Renöfält, B.M., Jansson, R., 2024. Environmental flows in a future climate: balancing hydropower production and ecosystem rehabilitation in the Ume River system, Sweden. *Sci. Total Environ.* 955, 176622. <https://doi.org/10.1016/j.scitotenv.2024.176622>.