Water-Energy-Food-Ecosystems-Climate Nexus in the Water Reuse Sector. Current State, Gaps, and Challenges for Practical Applications

Chapter 26: Water-Energy-Food-Ecosystems-Climate Nexus in the water reuse sector. Current state, gaps and challenges for practical applications

V.G. Barros$_1$[a], J. González-Camejo$_2$[b], L. Tombolini[b], M. Sgroi[b], A. Foglia[b], A.L. Eusebi$_3$[b], F. Fatone$_4$[b*]

[a]Department of Civil Engineering, DEC, Santa Catarina State University (UDESC), 200 Paulo Malschitzki St, 89219-710, Joinville, Brazil

[b]Department of Science and Engineering of Matter, Environment and Urban Planning, SIMAU, Università Politecnica delle Marche (UNIVPM), Via Brecce Bianche 12, 60131, Ancona, Italy

* Corresponding author. E-mail: f.fatone@univpm.it

Abstract

Under the current socio-economic situation, water security will get harder and harder to be assured, especially in the areas that would be more deeply affected by climate change such as the Mediterranean. It is paramount to diversify sources of water that cover the needs of agricultural, industrial and domestic activities. But water reuse is tightly related to other sectors such as energy, food, and ecosystems, which are all also affected by climate. In this context, the water-energy-food-ecosystems-climate (WEFEC) Nexus concept emerges with the aim to provide comprehensive understanding of all those interlinked sectors, with the goal to develop and implement economic activities, political decision and regulations that promote the efficient use of natural resources. The Nexus is a relatively new and evolving concept, which is highly related to plenty other emerging concepts such as sustainable development, circular economy, reuse and recycling, industrial symbiosis, etc. Since 2017, the scientific community has witnessed a sudden surge in popularity for the WEFE Nexus (and its variations). However, despite its potential benefits, its practical application is still in its early stages, primarily limited to WEFC/WEFE Nexus R&D&I works. The great challenge is related to the implementation of standard assessment methodologies that could integrate all the elements and sectors involved in the Nexus in a way that they could properly represent local and global realities while expressing the results in an understanding way to approach them to wide audiences and relevant stakeholders.

This chapter provides an overview of the role of the WEFEC Nexus in the water reuse topic. A review of current scientific articles and R&D&I projects was conducted to analyze the current state of the art. From this review, a list of methods and tools that have been used so far for preliminary Nexus assessment was collected. The review also enabled to detect current gaps that are also described in this chapter. Finally, based on the authors' experience, some guidelines related to the future developments of the Nexus topic are provided.

Keywords

Assessment; circular economy; Nexus tools; water reuse; WEF Nexus;

1. Introduction

The concept of water scarcity is linked to the lack of freshwater resources to meet water demand [1] and it is a growing concern globally [2,3]. As water supports and stabilizes ecosystems and socioeconomic sectors such as food and energy production, its availability is affected by climate change [4], and the world faces population growth, planners and decision-makers must consider multiple water sources. Traditional water management considers water separately when dealing with different water users (industries, agriculture, public water supply, etc.), water balances, and policies. This approach is no longer admissible because of current water-related challenges. While global demands for water, energy, and food rise day by day, relevant impacts on natural resources, vegetation coverage, ambient quality, biodiversity, as well as water imbalances are observed, putting existing ecosystems under increasing hydric pressure [5–7]. In this respect, by the year 2030, half of river basins in the European Union are believed to be affected by water scarcity [8]. This is expected to become even more dramatic in the future due to increasing extreme events [9], such as floods, extreme temperatures, droughts, and others related to climate change issues and water pollution [10,11]. Conflicts caused by lack of water, energy, food and climate change trigger environmental, economic, social and political crises [12,13]. Water scarcity and food crises can threaten political systems inside countries and across national borders. For instance, the Arabian Spring in 2011 affected food production and motivated the mass migration of rural workers to the Syrian region [14]. In 2014, São Paulo State, Brazil, faced a drought that affected the reservoirs of the Cantareira System (that supplies 8.8 million inhabitants), displaying how insufficient supply from one of the resources affects diverse users (population, industry, and agriculture) and energy production [15]. From the above mentioned, it is possible to observe that the global economy relies on various sectors that are interconnected in five key ways: (a) water, energy, and food are interconnected at their core; (b) economic sectors are linked to at least one of these three elements; (c) changes in any of these elements trigger chain reactions in related segments; (d) society bears the negative consequences of consuming these elements; and (e) the interdependencies among these elements are becoming more evident in the current crisis and resource scarcity scenario [16]. The global economy's impact on ecosystems is also concerning because it results in the annual loss of vital natural resources. Moreover, climate variability affects entire ecosystems and, consequently, the availability of natural resources. Thus, the search for solutions aimed at sustainable development, climate resilience and/or mitigation of the effects of those extreme events, including water scarcity issues have become necessary. In this regard water reuse could be included as a valuable and strategic resource, because it can help on building resilience. In fact, other than Sustainable Development Goal (SDG) 6 "Clean water and sanitation", water reuse can affect water and non-water-related sustainable development goals (SDGs), such as SDG 2 "Zero Hunger", SDG 7 "Affordable and Clean Energy", SDG 12 "Responsible consumption and production", and SDG 13 "Climate Action" [17], SDG 14 "Life bellow water" and SDG 15 "Life on land". To manage such a challenging matter, the NEXUS approach [18] emerged to identify trade-offs and synergies among water, energy, and food systems, internalize social and environmental impacts, and guide the development of cross-sectoral policies. Different land uses have different water reuse challenges and opportunities. Rural, industrial, and urban zones can benefit from reusing water where and when it is possible or needed. Considering complex systems, the Nexus approach could be valuable in framing water reuse in a broader picture [19]. Unfortunately, the use of the water, energy food (WEF) Nexus has been restricted to identify and assess WEF interlinkages. Little has been done to support the development of socially and politically relevant policies [20] to achieve sustainable development. Moreover, the different government sectors continue to formulate fragmented policies [21] and projects. The definition of plans, programs, and actions followed that fragmented conception, neglecting the necessary integration between the government and public policies. For example, governments often design agricultural policies and subsidy programs, such as fertilizer regulations and their associated projects and initiatives, without considering the complexity of the links to energy and water in the production chain. Similarly, many countries provide energy subsidies to agriculture without considering their implications for surface water, groundwater depletion, and degradation [16]. All these mentioned issues have impacts on water security. According to UN Escape [22], water security is the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability. As reported by the UN [23], the urban population represents 57% of the total world population. This way, in an urban context, water is important for both urban water supply and in rural zones for food production. To maintain water security in urban zones in climate change insecurity scenarios, two issues need to be addressed: the reduction of water losses and the search for alternative water sources, i.e., water reuse [7]. Water loss in water supply systems is a global problem [24]. On a global scale, the total water loss is 30% [25], although it can reach significantly higher values. For instance, water losses in Italy were estimated to account for 47.6% [26] and can reach up to 50% in developing countries [27]. Water system infrastructure issues like age and maintenance significantly impact these numbers. According to Liemberger and Wyatt [25], if losses were reduced by one-third, the savings could provide enough water for 800 million people, assuming consumption of 150 liters per day. Regarding the reuse of treated wastewater, today, projects for wastewater reclamation and reuse are significantly increasing around the world, although the amount of wastewater that is reused still remains under low values (<15%) in most cases, with some exceptions such as Cyprus, which reuses more than 99% of its wastewater [28]. Irrigation in agriculture, managed aquifer recharge (including seawater intrusion barriers), industrial uses (pavement washes, cooling and processing water), and other urban uses can all benefit from the use of treated wastewater [17] and urban storm water [29], but some concerns remain regarding contaminants and health issues [30].

2. Water-Energy-Food-Ecosystems-Climate nexus (WEFEC)

2.1. Nexus: an evolving concept

The first concepts linked to the Nexus gained prominence at the 2008 World Economic Forum [18,31], but it was at the Bonn Conference, held in 2011 in Germany, that topics related to water security, energy and food, were discussed creating the first concepts for an integrated approach to these elements, i.e., the WEF Nexus. Hoff [12] presented his impressions about the Nexus approach as a perspective for the development of integrated management based on synergy and interdependence between sectors. The Food and Agriculture Organization of the United Nations (FAO), together with the German Federal Ministry for Economic Cooperation and Development (BMZ) contributed to the propagation of the perspective. In 2012 the World Economic Forum published Water security: the water-food-energy-climate (WEFC) Nexus, expanding the dimensions of the concept and Nexus complexity with the inclusion of climate issues. As the Nexus concept evolved, other important elements were considered over the years.

According to Rezaei & Celico [32], the creation of WEF Nexus for the Himalayan ecosystem in 2012 evidenced the importance of ecosystems as a key factor in this framework, thus implementing the WEFE Nexus. In 2012, other natural resources were integrated into the Nexus approach, such as water, energy, food, minerals, and land [33]. Moreover, physical, economic, political, environmental, and equity were also considered additions to the framework [33]. In 2014, the United Nations Food and Agriculture Organization [13] published a concept note framing the Water-Energy-Food Nexus within the broader sustainability debate. Other issues, such as considering the complexity of transboundary river basins, were observed by UNECE [34]. Melo et al. [35] also added forests to Nexus. So, the concept is considerably new and in continuous evolution, expanding its dimensions and sectors for application, mostly remaining water as central point. As mentioned before, water is used in several sectors, notably energy generation, irrigation and human and industrial supply. After being used, wastewater requires adequate treatment to remove contaminants and become reclaimed water that can be reused, so that the water sector becomes circular [36]. As water scarcity grows, water reuse projects that assess the Nexus and circularity gain more visibility and interest [37].

2.2. Current situation of the Nexus topic

From a literature review at Web of Science in April 2024, significant increase in the use of the term Water-Energy-Food-Ecosystem - WEFE Nexus in scientific papers was noticed, i.e., 96.3% from a total of 483 papers within WEFE Nexus topic were published after 2017 (Figure 1a). They are distributed globally as shown in Figure 1b.

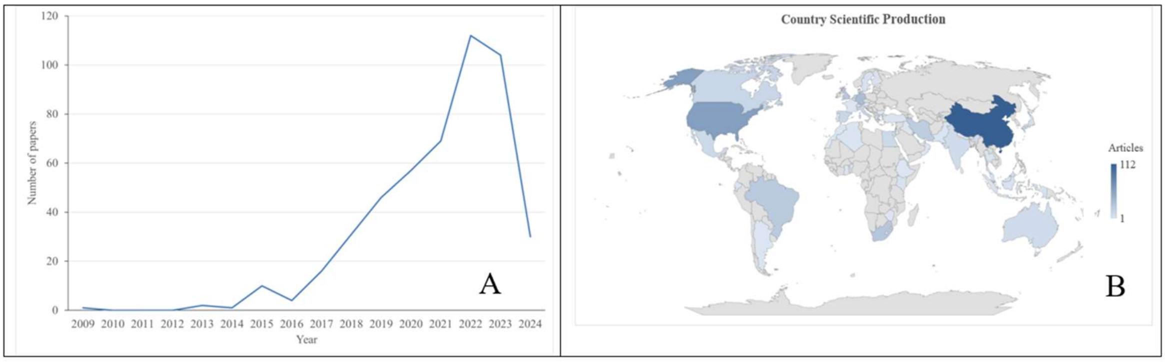


Figure 1. a) Yearly evolution of WEFE Nexus scientific papers worldwide; b) global distribution of WEFE Nexus scientific papers.

From this initial review on the WEFE Nexus, the word “security”, followed by “climate change”, “perspective” and “management” were the most frequent words (Figure 2).

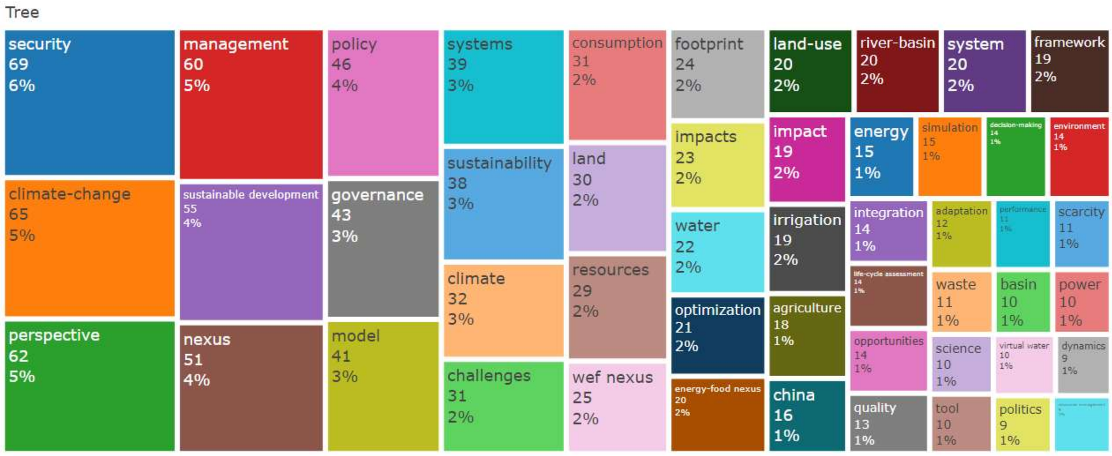


Figure 2. Most frequent words in scientific articles on the WEFE Nexus.

When Nexus dimensions increase, other than water, energy, food and ecosystem, the number of publications drops. For instance, considering water, energy, food, ecosystem, and climate pillars, 233 documents were found (48% of previous number). If the term water reuse is also included, it is possible to find only 12 documents. This was surprising, as the water pillar of the Nexus is highly related to circular economy, and in turn to water reuse [10,36,37]. This therefore suggests that the nomenclature used in current scientific papers are not generally aligned in these topics. For these 12 articles, the main words were: “climate change” and “trends”. The percentage was quite homogeneous, as the previous case, but in this case, it was possible to observe the word “health” (Figure 3). This is a frequent concern in literature regarding water reuse [30].

Figure 3. Most frequent words in scientific articles on the WEFEC Nexus

Apart from reviewing scientific articles, a mapping of EU-funded R&D&I projects that focused on WEFC/WEFE Nexus was carried out in April 2024 to analyze the current situation of this topic. The mapping of R&D&I projects was done considering international projects of the following database:

i) CORDIS (Community Research and Development Information Service, European Commission), using the following content type='project' AND ('nexus') AND ('water energy food' OR ('water energy food climate') OR ('water energy food ecosystems');
ii) PRIMA (WEFE calls);
iii) NEXUS cluster (www.nexuscluster.eu).

A total of 45 projects were found. The analysis of the main results suggests that:

The water element is present in all the projects. It is followed very closely by the energy sector (Figure 4), as they are highly connected. In fact, water and energy were the first pillars of the Nexus approach (WE Nexus), which concerns are growing globally [2,3]. In fact, for human activities, water and energy are linked during the abstraction process for supply (both surface and groundwater), treatment, distribution, collecting (as wastewater), wastewater treatment, and power production (hydropower or thermoelectric power).

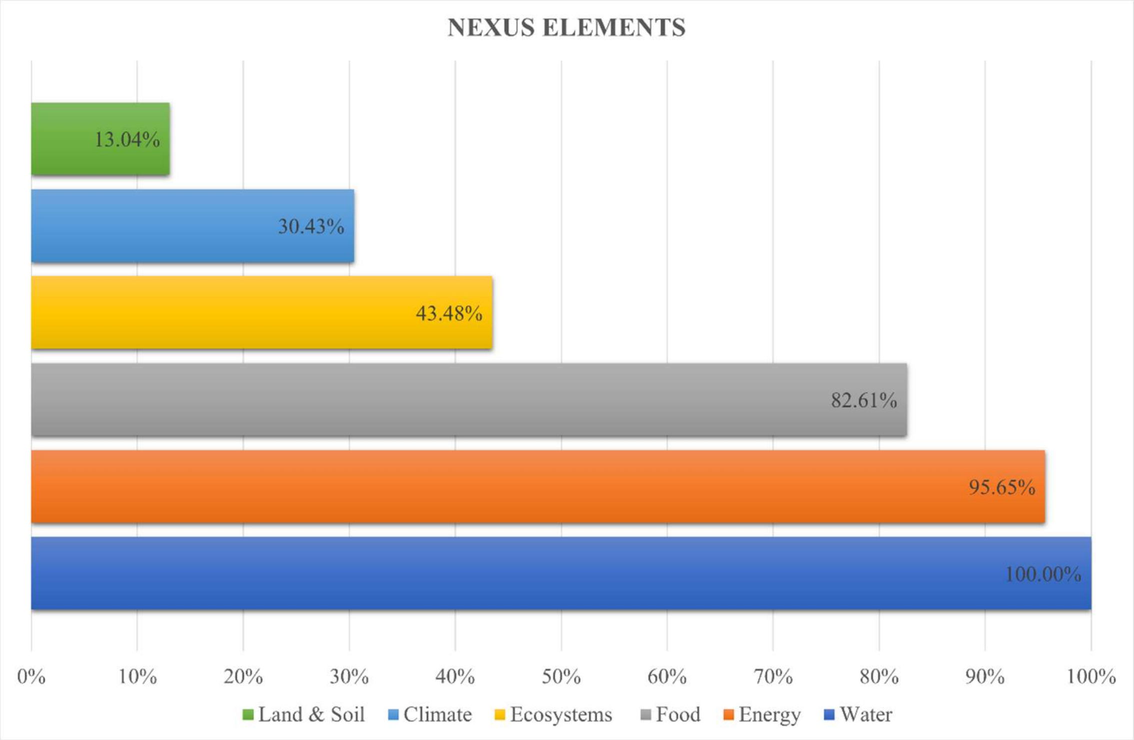


Figure 4. Nexus elements present in EU-funded R&D&I projects

Other than energy, as mentioned before, water is a vital resource in different nature and human activities and connects both natural and socioeconomic aspects. Evidencing the connections among Nexus elements and how they change in diverse contexts is a challenging issue. The relationship between its elements characterizes the WEFEC Nexus, as well as the trade-offs. Nexus thinking deals with all the life cycle of water, in addition to the resources contained in it, and other related processes [36,39]. Therefore, to develop measures aimed at the security and availability of these resources [40,41], it is necessary to understand their interrelationships/interconnections (Figure 5, Table1) present among the Nexus pillars.

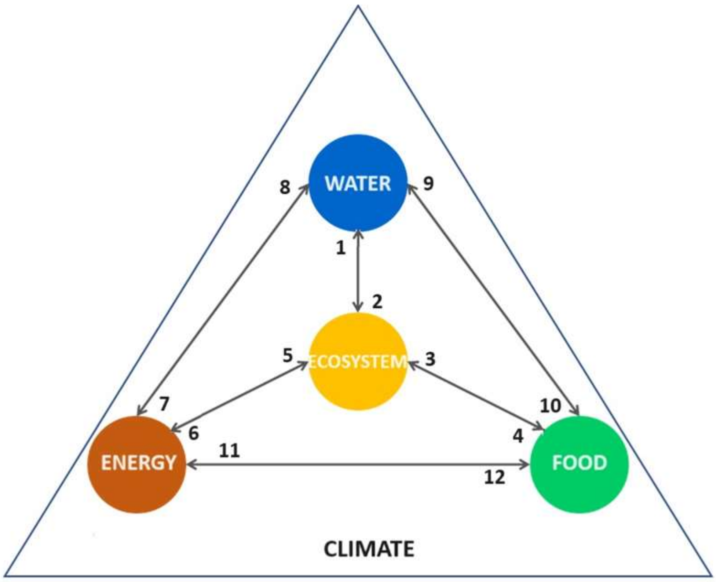


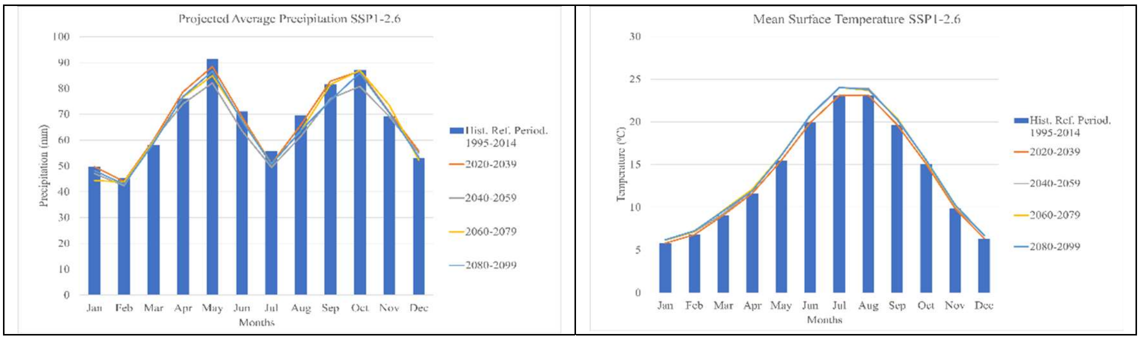
Figure 5. Interconnections in the water-energy-food-ecosystem-climate nexus

Table 1 Some function/uses related to Nexus interactions

Interconnection	Function/Use
1-2: Water - Ecosystem	Maintenance; Supply; Conservation; Habitat functions; Transport; etc.
3-4: Food - Ecosystem	Supply; Regulation; Conservation; etc.
5-6: Energy - Ecosystem	Supply; Support; Flow; etc.
7-8: Water - Energy	Generation; Abstraction; Distribution; Treatment; Cooling; etc.
9-10: Water - Food	Irrigation; Animal watering; Fisheries; Mulching; Siltation; Pollution; etc.
11-12: Food - Energy	Biorefinery; Harvesting; Transportation; Processing; etc.
Climate: Climate variability can alter all the interactions, by excess or reduction of rainfall, temperature, winds and humidity.	

Nexus interconnections must be analyzed in all their existing forms in nature, politics, economics, governmental and all societal issues in general. Water can be found in various forms, including surface, underground, and atmospheric. Its quality should be adequate for maintaining healthy ecosystems, and for consumption, it mainly depends on their final uses. Energy can be seen in its electrical, thermal and biomass forms, and it is also important its source (renewable or non-renewable). Regarding food, it can be obtained through agriculture, livestock, aquaculture, and even from emerging sectors such as algae [42]. All these processes involve the use of resources in an integrated way [20,43]. The climate is most addressed in association with climate change [44], whereas land is mostly used in the agricultural and bioenergy sectors [45,46]. In addition, there exist some trade-offs between pillars; for instance, potential food can be used to obtain renewable energy from biomass such as biodiesel, water can be consumed for the direct production of energy; energy from pumping and other machinery can be used for re-structuring ecosystems, etc. Although trade-offs are case-dependent, it has been reported that about 0.6–4 kWh/m^3 are needed to produce water for consumption; around 30% of global energy is used in food production, whereas 100 m^3 (on average) is needed to produce a ton of durum wheat pasta [47]. This implies that huge amounts of water are wasted to produce some food that would be lost within the food supply chain as food wastage [48], which water footprint has been estimated as 250 km^3, which is approximately equivalent to three times the volume of Lake Geneva [10,49].

Quantifying the interactions present among water, energy, food, ecosystems is an important step towards modeling and managing solutions [50]. These interactions both contribute to and are subject to climate change, as their effects will be noticeable in the pillars, for instance, by affecting agricultural production, water supply, cooling and heating demands, etc. [51]. The Mediterranean Basin Region, for example, has shown an increase of 1.4°C above late-nineteenth-century levels in annual mean temperatures [52], which points out the increase in frequency and severity of heat waves besides longer and warmer summers. Indeed, the Mediterranean region presents a warming average nearly twice the global trend [53] and precipitation patterns are sensitive to any change in the radiative balance of the Earth [54]. CMIP6 simulations [55] show that projected mean precipitation in Mediterranean Basin Region tends to decrease in all projected scenarios. Figures 6 and 7 show the projected average precipitation and mean surface air temperature trends for Catalonia (Spain) and South Aegean (Greece) regions, as representative of agricultural sector (wine production) and tourism, respectively, which are two main economic activities in the Mediterranean. In all figures, it can be observed that the climate change effect is more pronounced in the Shared Socioeconomic Pathway 5 (SSP5) and from 2040. This pattern can lead to a meteorological drought because of the prolonged and abnormal moisture deficiency. Deviations in hydrological responses and fluxes caused by climate change have the potential to imbalance not only human activities such as food and energy production, but entire ecosystems. This is highly relevant as the Mediterranean region is susceptible to overallocation of natural resources, especially water, which is already insufficient enough to satisfy the demands of all sectors [45]. Coupled with lower precipitation and higher temperatures, atmospheric evaporative demand tends to increase [56], impacting even more the water imbalance of the region.



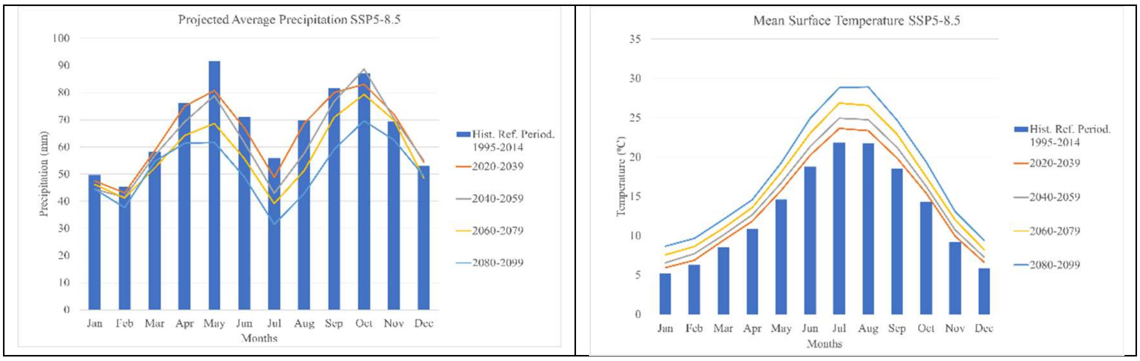


Figure 6: Average monthly precipitation (mm) and average mean surface air temperature (ºC) Projections SSP1 – 2.6 (upper), SSP5 – 8.5 (down) and 20-year climatological windows for the future (2020-2039, 2040-2059, 2060-2079, and 2080-2099) for Catalonia Region. Authors' own, based on data from the World Bank Group's Climate Change Knowledge Portal [57].

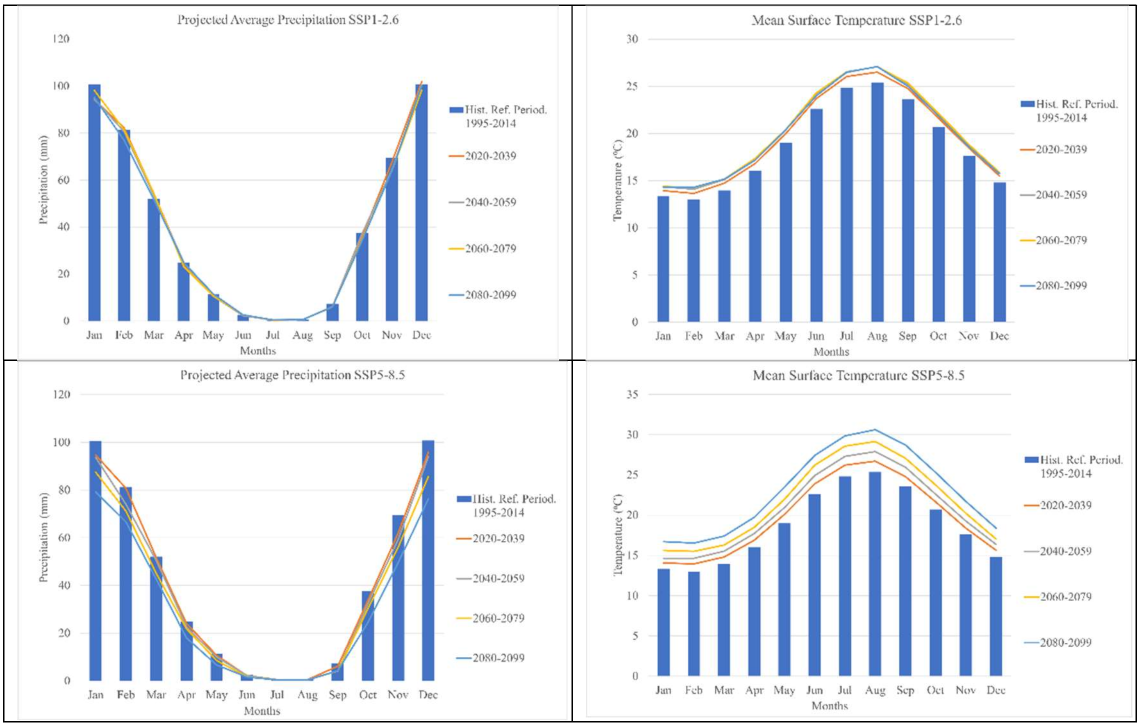


Figure 7: Average monthly precipitation (mm) and average mean surface air temperature (ºC) Projections SSP1 – 2.6 (upper), SSP5 – 8.5 (down) and 20-year climatological windows for the future (2020-2039, 2040-2059, 2060-2079, and 2080-2099) for South Aegean region. Authors' own, based on data from the World Bank Group's Climate Change Knowledge Portal [57].

2.4. The role of WEFEC Nexus in the water reuse sector

According to predictions, water scarcity will affect over half of EU river basins by 2030. This growing pressure on water resources raises concerns about the need to increase water availability and plan water resources at finer spatial scales than watershed territory (locally), improving water use efficiency, and real-time monitoring and modeling of water reserves and demands [17]. It will also force decision-makers to consider alternative water sources for supply such as water reuse (Water reuse Europe (2020)). According to Tzanakakis et al. [17], industrial uses and irrigation (for agriculture and landscape) are still the largest global markets for water reuse. From a review of the sector performed in 2017 by Water Reuse Europe [8], 787 reuse practicing schemes were identified and distributed across 16 European countries, being 250 of them were in Northern Europe, specifically, 112, 36, and 28 were set in France, Germany, and the Netherlands, respectively. In contrast, 537 schemes (68%) were identified in Southern Europe, being Spain, Italy, and Greece the more participative countries with 361, 99, and 44 schemes, respectively. This was, probably because this area is highly concerned about water scarcity issues [58]. In fact, 47% of the listed schemes were located along the Mediterranean coast, with over 200 schemes situated on the Eastern coast of Spain (Murcia, Valencia, and Catalonia regions). 17% of the schemes were located on islands, such as the Greek islands (16 sites), the Canary Islands (14) in Spain, Cyprus (8), and Noirmoutier or La Réunion (2) in France. In all these cases, where freshwater resources are limited, environmental issues such as droughts and over-abstraction of water due to tourism and agricultural activities particularly affect these locations [59].

These identified schemes include both non-potable and indirect potable uses for a wide range of purposes, from irrigation in agriculture and landscaping (including golf courses) to industrial uses and contributions to water supplies. In Europe, agricultural reuse is the most prevalent kind of water reuse, accounting for 39% of all schemes. This is followed by industrial reuse at 15% and recreational purposes at 11%. Most of the schemes classified as industrial (68%) are in Northern Europe [8].

3. Assessing the Nexus

Despite the potential benefits of the Nexus in the water reuse sector, its practical application is in a very early stage [16]. As mentioned before, WEFC/WEFE Nexus are still mainly limited to R&D&I works based on strong theoretical background. There are plenty of methodologies, techniques and models to evaluate the WEFEC Nexus and quantify or simulate the interconnections between the Nexus pillars. Moreover, the Nexus concept has been used in multiple disciplines such as environmental management, economy, system analysis, geospatial analysis, hydrology, biochemistry, engineering, agriculture, social science, medicine, computer science, etc. [20]; as well as in multiple sectors contexts, and scales [16]. However, scarce applications of these Nexus tools can be found in industry, policies and society, which is one of the main challenges of the topic, as will be discuss afterwards.

One of the main difficulties of achieving practical applications of the Nexus lies on the complexity of merging the multiple sectors where the Nexus is approached, such as biochemistry, engineering, agricultural and biological sciences, energy, social Science, environmental Science [20]. This forces the Nexus assessment to define the system boundaries for each socio-economic sector to be evaluated [36]. Consequently, depending on the context of application, as well as other criteria such as the geographic scale (global, national, regional, basin-based, local) and the kind of data used for the assessment (experimental, databases, literature, simulations), the type methods and tools to evaluate the Nexus can be very diverse and can present significantly different approaches. In this respect, Fernandes Torres et al. [16] divided the main methods and tools for Nexus evaluation as qualitative, quantitative, or their combinations (Table 2).

Table 2 Current methods and tools proposed for Nexus assessment

Classification		Examples	References
Quantitative	Scenario analysis		[20,60]
	Indicators and indices	Resource fluxes Efficiency indicators Environmental indicators Water indicators Food indicators	[16,36,61–64]
	Footprinting	Combination of water, energy, carbon footprints.	[65–67]
	Software Tools	WEF Nexus Tool 2.0 WEAP LEAP CLEWs Musiasem PRIMA—Platform for Regional Integrated Modeling and Analysis SWAT—Soil and Water Assessment Tool AND Indicators SEWEM—System-Wide Economic–Water–Energy Model	[16,19,45,68–72]
	Decision support		[20]
	Statistics	Principal Component analysis (PCA) Machine learning techniques Regression statistics Trend analysis	[20,73]
	Benefit analysis		[20]
	Integrated modelling	Multi-Sectoral Water Circularity Assessment (MSWCA) Integrated environmental models Hydro-economic modeling IMPACT3 GLOBE: Global computable general equilibrium model	[36,37,74–77].

Qualitative	Economic techniques	Input-output analysis Cost-benefits analysis Trade-off analysis Social accounting matrix Econometric modelling Dynamic panel modeling Value chain analysis Supply chain analysis SWOT analysis	[16,20,78,79]
	Social science	Institutional analysis Questionnaires Historical analysis SH analysis Workshops Policy analysis Delhi process Critical discourse analysis	[16,79,80]
Quantitative and qualitative	System analysis	Multi-sectorial system analysis Material flow analysis System informatics and analytics Causal loop diagrams and system feedbacks Resource flows Network analysis Building information models Energy and bioclimatic analysis tools Multicriteria decision analysis	[16,60,81]
	Geospatial	Spatial analysis Remote sensing Footprinting+GIS	[16,82–85]

3.1. Gaps in Nexus methods and tools

As can be deduced from Table 2, the approach of the cited methods and tools is highly variable depending on their scope. They are also wide-reaching, so that it is highly difficult that any single tool or method is wholly sufficient for comprehensive understanding of the Nexus interconnections [20,86]. This is probably related with the scarce level of implementation of Nexus practices. In fact, even with a growing literature on the Nexus topic, studies reveal that practical cases and challenges in governance, decision-making and integrative and coherent policies are still incipient [87–89]. Apart from this, other issues were detected:

- The unalignment on the type of data and geographical scales to apply the Nexus concept (i.e., lack of standardisation) makes results difficult to compare. Authors tend to define different groups of methodologies, pillars, etc., according to their field of knowledge and main interests, so that decision-makers are often hindered to make holistic decisions regarding resource management options [16,36].

- The models and tools reported so far tend to be too general (either at large scale or considering multiple sectors), or too specific. In the case of generic models, information is not detailed enough to consider local specificities, so that there is the risk of not making appropriate Nexus-based decisions. On the contrary, specific tools are usually site specific, so that they cannot be directly replicated in other socio-economic environments. By means of example, the WEF Nexus Tool 2.0 [68] is only applied to Qatar, which limits its practical application.
- Most of the assessed methods and tools implemented so far consider the WEF Nexus. However, the presence of other sectors (ecosystems, climate, land) is less common, and their inclusion would increase the complexity of Nexus models significantly.
- The role of Climate pillar within the Nexus is unclear. Some authors defend it should be assessed as single element within the Nexus by considering the associated greenhouse gas emissions (WEFC) [65,66]. However, other authors think of climate as a transversal factor affecting the whole Nexus interconnections due to the aforementioned climate change issues commented in Section 2. Similarly, some authors believe that ecosystems are the central element of the nexus as water, energy, and food production depend on it [16].
- The role of health is also unclear. Considering the importance of health security in water reuse [30], its relevance within the Nexus should be high. Issues related to endocrine-disrupting chemicals, microplastics, and antibiotic-resistant genes, among others, could be of concern [17,90–92]. However, from the best of our knowledge, few authors have considered health issues in Nexus assessment.
- Most of Nexus-based analysis have been carried out in the short-term. Long-term impacts considering climate change scenarios (also including adverse climatic) should be also considered, although this is highly challenging, and the uncertainty of those analyses would be probably very high.
- It is unclear whether most of the Nexus tools and methods shown in Table 2 are really modelling the Nexus interactions. In this respect, Carvalho et al. [47] pointed out that WEF Nexus is often included as keyword in scientific publications, but barely mentioned or properly discussed in the documents.
- Plenty of them seem to be dominated by the water element of the Nexus (hydrological modelling, MSWCA methodology, etc), which is the most common sector within the topic as discussed in Section 2.2.
- The majority of the tools implemented so far contain prominent scientific backgrounds. They are made by scientists and mainly approached to them. The transition to policy makers and the general public is limited. This transition to wider public is challenging, as current policies are generally isolated in sectors and rather focused on economic growth than in resource efficiency and climate change mitigation and adaptation [93].
- Another challenge lies in weighing the different elements of the Nexus to quantify their interconnections and evaluate which one(s) present higher relevance for the sustainable use of resources. As water is the main element of the Nexus and most of Nexus practitioners come from the water sector, higher weight for the water component would be expected. However, Fernandes Torres et al. [16] defend that Nexus specialists should not prioritize one element over the other as the Nexus concept was developed in a multicenter manner. Similar issues apply to the

different sectors involved in the Nexus, i.e., policy-making, social, economic, etc. [47].

3.2. Taking the Nexus from concept to practice

As observed in the previous section, the current gaps in the Nexus topic are relevant and challenging. Below some recommendations can be found, future lines of action and opportunities to go beyond the current state of the art and try to overcome current barriers:

- One important step to develop Nexus practices will be the standardization of Nexus framework for the development of a common theoretical and methodological framework which can contribute to the definition of the Nexus, making results comparable. Other assessment methodologies such as LCA, social LCA, techno-economic assessment (TEA), etc., were implemented some time ago and nowadays they are quite well-established, whereas methodologies such as the Multi-Sectoral Water Circularity Assessment [36] have been recently implemented and can serve as model for future Nexus-based methodologies. Nexus methodologies can be also developed by integrating current assessment techniques that focus on single elements of the nexus [65].
- Private companies, politicians and the general public seem not to be highly engaged in the Nexus concept, as it is multidisciplinary and complex. It is therefore highly important to develop tools for simple visualization of Nexus results. This is demanding, but the increasing knowledge in digitalization and data analysis techniques can play a significant role in boosting digital Nexus tools.
- Beyond standardization of methodologies, the implementation of certification schemes for Nexus practices can be a tool for green marketing that can motivate companies and general society in improving the sustainable use of resources according to Nexus' philosophy.
- The establishment of green policies that consider the Nexus approach could also encourage its practical application. In this respect, recent European policies and initiatives derived from the EU Green Deal objectives such as Green Public Procurement (GPP), EU taxonomy [94], the 'Do Not Significant Harm' (DNSH) principle either forces economic activities to implement sustainable practices or motivate them by providing some subsidies [7]. For instance, the NextGenerationEU programme is a temporary economic instrument for the recovery and modernization of the European economic activities after the Covid-19 crisis with the goal to promote repair economic damage. It is to be applied by EU members in the period 2021-2026, but from the best of authors' knowledge, no national plans have included the implementation of Nexus in their activities.
- The acquisition of reliable and free data is of high importance to develop Nexus tools. The quality of the data used for implementing Nexus models will directly influence the accuracy and sensitivity of the results obtained, so that real-time monitoring local data would be necessary to produce powerful Nexus tools. However, there exists some issues that hinder the full exploitation of the potentiality of digitalization such as cybersecurity, need of high investment, technical difficulties to keep digitals systems and the personnel updated, and others [30]. As pointed out by Giest & Mukherjee [95], data collection will require wide-ranging coordination across governance levels and national institutions. Efforts have been undertaken in this regard. For instance, Reportnet, a platform for reporting environmental and climate data to the European Environment Agency (EEA), is in its third version and aims to integrate data flows under the

EU environmental legislation. Furthermore, EEA has established the Shared Environmental Information System (SEIS) and the Mediterranean Information System on Environment and Development (SIMEDD) with the objective of creating a standardized database for water-related activities. As observed by Markantonis et al. [40], it is paramount that data across Nexus sectors be comparable in accuracy and resolution. As already mentioned, the interconnections between the different fields of knowledge involved in the Nexus (social, economic, environmental, engineering, etc.) require the participation of multiple organizational actors, although their dynamics and implications in this empirical context are not well understood yet. This normally tends to reduce collaborative actions between actors, as has been demonstrated by Klessova et al. [96], so that it is big challenge in the Nexus topic. In this respect, management science [32,97] can play a significant role in covering many of current gaps of the Nexus. But this field of knowledge is barely represented as main actor in this topic.

3.3 European Innovation Actions implementing demonstrators and Nexus optimization.

Within Digital Water City (www.digital-water.city), which was an Horizon2020 innovation action, the water–energy–food–climate Nexus in an integrated peri-urban wastewater treatment and reuse system was assessed. A specific methodology was applied to the municipal wastewater treatment plant (WWTP) of Peschiera Borromeo (Milan, Italy) and its peri-urban district to define the most possible affirmations and conflicts following the EU regulations 741/2020. Results of this work showed that transferring the WEFC Nexus from theory to practice can realize sustainable resource management in the operating environment by providing a reduction in greenhouse gas (GHG) emissions, overall energy savings, reduction in water stress and optimization of agricultural practices. Particularly, it was found that if the plant configuration is upgraded to reach water quality class C for water reuse, instead of wastewater discharge, energy savings are estimated to reach up to 7.1% and carbon emissions are supposed to be reduced up to 2.7%. In addition, enhancing water quality from class C to class A resulted in increments in energy and carbon footprint of 5.7% and 1.7%, respectively. Nevertheless, higher quality crops can be cultivated with reclaimed water in class A, with bigger economic revenues and high recovery of nutrients (e.g., recovery of 154450 kg N/y for tomato cultivation) [65].

Within CARDIMED (https://cordis.europa.eu/project/id/101112731), which is part of the EU mission on Adaptation to Climate Change, case studies aim to enhance Climate Resilience in the Mediterranean by mainstreaming Nature-based Solutions in systemic transformation. One of the demonstrators, located in Sardinia, will deal with crop rotation (wheat, alfalfa, maize) that will be irrigated with treated wastewater from San Marco wastewater treatment plant (Alghero), where additional tertiary and quaternary treatment will be implemented to further improve water quality and safety. Renewable energy from solar panels will be used to power either the irrigation system or the treatment technologies. Crop rotation will be used to alleviate water stress and improve crop health. Additionally, a free water surface constructed wetland, high-rate algae pond, and a riparian buffer, all operating in parallel, will treat agricultural drainage and runoff water. Part of the treated water will be utilized in aquaculture, while the rest will be checked in terms of water quality before being discharged into a nearby river. The physiological responses of the fish will be closely evaluated, focusing on target pathways such as oxidative stress, heavy metal exposure, and immune response

Conclusions

The water-energy-food-ecosystems-climate (WEFEC) Nexus concept has emerged as a transformative approach to provide an opportunity for sustainable development by promoting the efficient use of natural resources. By evidencing the complex interconnections that directly impact global sustainability and societal well-being, the Nexus is a new and evolving concept, highly related to other emerging concepts. Water has a central role in the Nexus, so the growing concern with water scarcity and its interplay with energy, food, and ecosystems, other than how it is impacted by climate change, caused the Nexus to gain prominence in scientific research. Nonetheless, practical applications, decision-making, governance, and political interest are still lacking. Reflecting on the fragmentation of the water sector, the WEFE Nexus could tailor a better way to insert water reuse on the stage, creating opportunities toward sustainable water management. Reliable data acquisition could align opportunities with innovation in wastewater treatments, services, and planning on small scales. This could also improve transparency in the decision-making process. Embracing the Nexus perspective allows us to view water reuse not just as a technical solution but as a catalyst for systemic change, promoting the integrated management of water, energy, food, and ecosystems in harmony with the climate. The acquisition of reliable and free data is of high importance to develop Nexus tools However, to achieve this, current gaps in Nexus methodology and tools must be overcome to translate theoretical frameworks into practical solutions. This includes the need for standardization, visualization tools for clear communication, and the engagement of private industries and policymakers. Certification schemes and green policies could be helpful for incentivizing and empowering sustainable practices within the Nexus framework. This is particularly important to address health concerns related to water reuse, ensuring quality, and maintaining healthy ecosystems.

Acknowledgments

This work has received funding from the SureNexus project, which is part of the PRIMA programme supported by the European Union under the Grant Agreement number: [2142] [SURE_NEXUS] [Call 2021 Section 1 Nexus IA]. Co-author J. González-Camejo also acknowledges the support of the Horizon Europe's MSCA European Postdoctoral Fellowships by funding the 'MicroAlgae 4.0' project under grant agreement 101067621. Co-author Virginia Grace Barros also acknowledges the support of FAPESC - call 12/2022 - FAPESC ABROAD 2024TR000110.

References

1. Tzanakakis VA, Paranychianakis N V., Angelakis AN. Water Supply and Water Scarcity. Water (Basel). 2020;12:2347.

2. McLennan M. The Global Risks Report 2021. 16th Edition. Cologny, Switzerland: World Economic Forum. 2021.

3. Kummu M, Guillaume JHA, de Moel H, Eisner S, Flörke M, Porkka M, et al. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci Rep. 2016;6:38495.

4. Gosling SN, Arnell NW. A global assessment of the impact of climate change on water scarcity. Clim Change [Internet]. 2016;134:371–85. Available from: https://doi.org/10.1007/s10584-013-0853-x

5. GIATTI LL, JACOBI PR, FAVARO AKMDI, EMPINOTTI VL. O nexo água, energia e alimentos no contexto da Metrópole Paulista. Estudos Avançados. 2016;30:43–61.

6. Amaral MH, Benites-Lazaro LL, Antonio de Almeida Sinisgalli P, Prates da Fonseca Alves H, Giatti LL. Environmental injustices on green and blue infrastructure: Urban nexus in a macrometropolitan territory. J Clean Prod. 2021;289:125829.

7. Foglia A, González-Camejo J, Radini S, Sgroi M, Li K, Eusebi AL, et al. Transforming wastewater treatment plants into reclaimed water facilities in water-unbalanced regions. An overview of possibilities and recommendations focusing on the Italian case. J Clean Prod. Elsevier Ltd; 2023.

8. WRE. Water Reuse Europe (WRE) - (water-reuse-europe.org). Accessed 8-8-22. 2022.

9. Kreibich H, Van Loon AF, Schröter K, Ward PJ, Mazzoleni M, Sairam N, et al. The challenge of unprecedented floods and droughts in risk management. Nature. 2022;608:80–6.

10. EIT Water Scarcity. Innovative Solutions to Cope with Water Scarcity. White Paper. 2021.

11. Water Europe. THE VALUE OF WATER Multiple Waters for Multiple Purposes and Users Multiple Waters for Multiple Purposes and Users. Towards a Future-Proof Model for a European Water-Smart Society. 2022.

12. Hoff H. Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm. 2011.

13. FAO. The Water-Energy-Food Nexus at FAO, Concept Note. Food and Agriculture Organisation of the United Nations, Rome. 2014.

14. Lazaro LLB, Bellezoni RA, Puppim de Oliveira JA, Jacobi PR, Giatti LL. Ten Years of Research on the Water-Energy-Food Nexus: An Analysis of Topics Evolution. Frontiers in Water. 2022;4.

15. Bellfield H. Water, Energy and Food Security Nexus in Latin America and the Caribbean. 2015. Available from: https://api.semanticscholar.org/CorpusID:132478558

16. Torres CJF, de Lima CHP, Goodwin BS de A, de Aguiar Junior TR, Fontes AS, Ribeiro DV, et al. A literature review to propose a systematic procedure to develop "nexus thinking" considering thewater-energy-food nexus. Sustainability (Switzerland). MDPI; 2019.

17. Tzanakakis VA, Capodaglio AG, Angelakis AN. Insights into Global Water Reuse Opportunities. Sustainability (Switzerland). Multidisciplinary Digital Publishing Institute (MDPI); 2023.

18. WEF Water Initiative. Water security: The water-food-energy-climate nexus. In World Economic Forum Water Initiative (p. 39). 2011.

19. Dias IYP, Lazaro LLB, Barros VG. Water–Energy–Food Security Nexus—Estimating Future Water Demand Scenarios Based on Nexus Thinking: The Watershed as a Territory. Sustainability. 2023;15:7050.

20. Albrecht TR, Crootof A, Scott CA. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters. Institute of Physics Publishing; 2018.

21. Oneda TMS, Barros VG. On stormwater management master plans: comparing developed and developing cities. Hydrological Sciences Journal. 2021;66:1–11.

22. UN-Water. Water security & the global water agenda: A UN-water analytical brief. United Nations University (UNU). 2013.

23. UN. United Nations, Department of Economic and Social Affairs, Population Division (2019). World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations. 2019.

24. AL-Washali T, Sharma S, Kennedy M. Methods of Assessment of Water Losses in Water Supply Systems: a Review. Water Resources Management. 2016;30:4985–5001.

25. Liemberger R, Wyatt A. Quantifying the global non-revenue water problem. Water Supply. 2019;19:831–7.

26. The European House - Ambrosetti. Libro Bianco 2022. Valore acqua per l'Italia. 3 Edizione. 2022.

27. Dighade RR, Kadu MS. Challenges in Water Loss Management ofWater Distribution Systems in DevelopingCountries. Int J Innov Res Sci Eng Technol [Internet]. 2014;3. Available from: https://api.semanticscholar.org/CorpusID:20373279

28. Aquastat. Aquastat. https://www.fao.org/aquastat/en/. 2022.

29. Page D, Bekele E, Vanderzalm J, Sidhu J. Managed Aquifer Recharge (MAR) in Sustainable Urban Water Management. Water (Basel). 2018;10:239.

30. Radini S, González-Camejo J, Andreola C, Eusebi AL, Fatone F. Risk management and digitalisation to overcome barriers for safe reuse of urban wastewater for irrigation – A review based on European practice. Journal of Water Process Engineering. Elsevier Ltd; 2023.

31. Zhang C, Chen X, Li Y, Ding W, Fu G. Water-energy-food nexus: Concepts, questions and methodologies. J Clean Prod. 2018;195:625–39.

32. Rezaei Kalvani S, Celico F. The Water–Energy–Food Nexus in European Countries: A Review and Future Perspectives. Sustainability. 2023;15:4960.

33. Andrews-Speed P, Bleischwitz R, Boersma T, Johnson CM, Kemp G, Vandeveer SD. The Global Resource Nexus: The Struggles for Land, Energy, Food, Water, and Minerals. 2012. Available from: https://api.semanticscholar.org/CorpusID:106626007

34. UNECE. Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus. 2015;

35. Melo FPL, Parry L, Brancalion PHS, Pinto SRR, Freitas J, Manhães AP, et al. Adding forests to the water–energy–food nexus. Nat Sustain. 2020;4:85–92.

36. Nika CE, Vasilaki V, Expósito A, Katsou E. Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems. Water Res. 2020;187.

37. Nika CE, Vasilaki V, Renfrew D, Danishvar M, Echchelh A, Katsou E. Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus. Water Res. 2022;221.

38. Byrne MP, O'Gorman PA. The Response of Precipitation Minus Evapotranspiration to Climate Warming: Why the "Wet-Get-Wetter, Dry-Get-Drier" Scaling Does Not Hold over Land*. J Clim. 2015;28:8078–92.

39. Endo A, Tsurita I, Burnett K, Orencio PM. A review of the current state of research on the water, energy, and food nexus. J Hydrol Reg Stud. 2017;11:20–30.

40. Markantonis V, Reynaud A, Karabulut A, El Hajj R, Altinbilek D, Awad IM, et al. Can the Implementation of the Water-Energy-Food Nexus Support Economic Growth in the Mediterranean Region? The Current Status and the Way Forward. Front Environ Sci. 2019;7.

41. Bidoglio G, Vanham D, Bouraoui F, Barchiesi S. The Water-Energy-Food-Ecosystems (WEFE) Nexus. Encyclopedia of Ecology. Elsevier; 2019. p. 459–66.

42. Ścieszka S, Klewicka E. Algae in food: a general review. Crit Rev Food Sci Nutr. 2019;59:3538–47.
43. Liu J, Hull V, Godfray HCJ, Tilman D, Gleick P, Hoff H, et al. Nexus approaches to global sustainable development. Nat Sustain. 2018;1:466–76.
44. Dale LL, Karali N, Millstein D, Carnall M, Vicuña S, Borchers N, et al. An integrated assessment of water-energy and climate change in sacramento, california: how strong is the nexus? Clim Change. 2015;132:223–35.
45. Karabulut AA, Udias A, Vigiak O. Assessing the policy scenarios for the Ecosystem Water Food Energy (EWFE) nexus in the Mediterranean region. Ecosyst Serv. 2019;35:231–40.
46. Sušnik J, Chew C, Domingo X, Mereu S, Trabucco A, Evans B, et al. Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. Water (Basel). 2018;10:139.
47. Carvalho PN, Finger DC, Masi F, Cipolletta G, Oral HV, Tóth A, et al. Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies. J Clean Prod. Elsevier Ltd; 2022.
48. González-Camejo J, Andreola C, Maceratesi V, Toscano G, Eusebi AL, Fatone F. Biorefineries to improve water and resource recovery in the seafood-processing industry. Advanced Technologies in Wastewater Treatment. 2023.
49. FAO. Food wastage footprint: impacts on natural resources: summary report. FAO, Rome. 2013.
50. Chang Y, Li G, Yao Y, Zhang L, Yu C. Quantifying the Water-Energy-Food Nexus: Current Status and Trends. Energies (Basel). 2016;9:65.
51. Mohtar RH, Lawford R. Present and future of the water-energy-food nexus and the role of the community of practice. J Environ Stud Sci. 2016;6:192–9.
52. Cramer W, Guiot J, Fader M, Garrabou J, Gattuso J-P, Iglesias A, et al. Climate change and interconnected risks to sustainable development in the Mediterranean. Nat Clim Chang. 2018;8:972–80.
53. Zittis G, Almazroui M, Alpert P, Ciais P, Cramer W, Dahdal Y, et al. Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. Reviews of Geophysics. 2022;60.
54. Houghton JT, Jenkins GJ, Ephraums JJ. Climate change: the IPCC scientific assessment. American Scientist;(United States), 80(6). 1990.
55. Tebaldi C, Debeire K, Eyring V, Fischer E, Fyfe J, Friedlingstein P, et al. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Earth System Dynamics. 2021;12:253–93.
56. Noto L V., Cipolla G, Francipane A, Pumo D. Climate Change in the Mediterranean Basin (Part I): Induced Alterations on Climate Forcings and Hydrological Processes. Water Resources Management. 2023;37:2287–305.
57. The World Bank Group. Climate change knowledge portal. The World Bank, Washington DC. https://climateknowledgeportal.worldbank.org. 2021.
58. Malagó A, Comero S, Bouraoui F, Kazezyılmaz-Alhan CM, Gawlik BM, Easton P, et al. An analytical framework to assess SDG targets within the context of WEFE nexus in the Mediterranean region. Resour Conserv Recycl. 2021;164:105205.
59. González-Camejo J, de Simoni L, Eusebi AL, Fatone F. Replicability of HYDRO solutions for alternative water recovery in 15 European decentralised regions. WICC-Water Innovation & Circularity Conference. Athens, Greece; 2023.
60. Villarroel Walker R, Beck MB, Hall JW, Dawson RJ, Heidrich O. The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. J Environ Manage. 2014;141:104–15.

61. Arthur M, Liu G, Hao Y, Zhang L, Liang S, Asamoah EF, et al. Urban food-energy-water nexus indicators: A review. Resour Conserv Recycl. Elsevier B.V.; 2019.

62. Fotia K, Mehmeti A, Tsirogiannis I, Nanos G, Mamolos AP, Malamos N, et al. LCA-Based Environmental Performance of Olive Cultivation in Northwestern Greece: From Rainfed to Irrigated through Conventional and Smart Crop Management Practices. Water (Basel). 2021;13:1954.

63. Arfelli F, Ciacci L, Vassura I, Passarini F. Nexus analysis and life cycle assessment of regional water supply systems: A case study from Italy. Resour Conserv Recycl. 2022;185:106446.

64. Lu Z, Broesicke OA, Chang ME, Yan J, Xu M, Derrible S, et al. Seven Approaches to Manage Complex Coupled Human and Natural Systems: A Sustainability Toolbox. Environ Sci Technol. 2019;53:9341–51.

65. Marinelli E, Radini S, Akyol Ç, Sgroi M, Eusebi AL, Bischetti GB, et al. Water–energy–food–climate nexus in an integrated peri-urban wastewater treatment and reuse system: From theory to practice. Sustainability (Switzerland). 2021;13.

66. Radini S, Marinelli E, Akyol Ç, Eusebi AL, Vasilaki V, Mancini A, et al. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: Cyber-physical framework and innovations. Appl Energy. 2021;298.

67. Lopez AM, Fitzsimmons JN, Adams HM, Dellapenna TM, Brandon AD. A time-series of heavy metal geochemistry in sediments of Galveston Bay estuary, Texas, 2017-2019. Science of The Total Environment. 2022;806:150446.

68. Daher BT, Mohtar RH. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. 2015;40:748–71.

69. Howells M, Hermann S, Welsch M, Bazilian M, Segerström R, Alfstad T, et al. Integrated analysis of climate change, land-use, energy and water strategies. Nat Clim Chang. 2013;3:621–6.

70. Giampietro M. Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism. 2023. p. 109–21.

71. Bekchanov M, Lamers J. The Effect of Energy Constraints on Water Allocation Decisions: The Elaboration and Application of a System-Wide Economic-Water-Energy Model (SEWEM). Water (Basel). 2016;8:253.

72. Kraucunas I, Clarke L, Dirks J, Hathaway J, Hejazi M, Hibbard K, et al. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Clim Change. 2015;129:573–88.

73. Ioannidou S, Litskas V, Stavrinides M, Vogiatzakis IN. Placing Ecosystem Services within the Water–Food–Energy–Climate Nexus: A Case Study in Mediterranean Mixed Orchards. Agronomy. 2022;12:2224.

74. Jalilov S, Keskinen M, Varis O, Amer S, Ward FA. Managing the water-energy-food nexus: Gains and losses from new water development in Amu Darya River Basin. J Hydrol (Amst) [Internet]. 2016;539:648–61. Available from: https://api.semanticscholar.org/CorpusID:132270308

75. Yang YCE, Wi S, Ray PA, Brown CM, Khalil AF. The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. Global Environmental Change. 2016;37:16–30.

76. Ringler C, Willenbockel D, Perez N, Rosegrant MW, Zhu T, Matthews N. Global linkages among energy, food and water: an economic assessment. J Environ Stud Sci [Internet]. 2016;6:161–71. Available from: https://api.semanticscholar.org/CorpusID:155714128

77. Baustert P, Othoniel B, Rugani B, Leopold U. Uncertainty analysis in integrated environmental models for ecosystem service assessments: Frameworks, challenges and gaps. Ecosyst Serv. 2018;33:110–23.

78. de Strasser L, Lipponen A, Howells M, Stec S, Bréthaut C. A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. Water (Basel). 2016;8:59.

79. Endo A, Burnett K, Orencio P, Kumazawa T, Wada C, Ishii A, et al. Methods of the Water-Energy-Food Nexus. Water (Basel). 2015;7:5806–30.

80. Smajgl A, Ward J, Pluschke L. The water–food–energy Nexus – Realising a new paradigm. J Hydrol (Amst). 2016;533:533–40.

81. Wolfe ML, Ting KC, Scott N, Sharpley A, Jones JW, Verma L. Engineering solutions for food-energy-water systems: it is more than engineering. J Environ Stud Sci. 2016;6:172–82.

82. Zambrano-Prado P, Muñoz-Liesa J, Josa A, Rieradevall J, Alamús R, Gasso-Domingo S, et al. Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area. Sustain Cities Soc. 2021;75:103287.

83. Kati V, Kassara C, Vrontisi Z, Moustakas A. The biodiversity-wind energy-land use nexus in a global biodiversity hotspot. Science of The Total Environment. 2021;768:144471.

84. Viccaro M, Caniani D, Masi S, Romano S, Cozzi M. Biofuels or not biofuels? The "Nexus Thinking" in land suitability analysis for energy crops. Renew Energy. 2022;187:1050–64.

85. Daccache A, Ciurana JS, Rodriguez Diaz JA, Knox JW. Water and energy footprint of irrigated agriculture in the Mediterranean region. Environmental Research Letters. 2014;9:124014.

86. Lucca E, El Jeitany J, Castelli G, Pacetti T, Bresci E, Nardi F, et al. A review of water-energy-food-ecosystems Nexus research in the Mediterranean: evolution, gaps and applications. Environmental Research Letters. 2023;18:083001.

87. Leck H, Conway D, Bradshaw M, Rees J. Tracing the Water–Energy–Food Nexus: Description, Theory and Practice. Geogr Compass. 2015;9:445–60.

88. Purwanto A, Sušnik J, Suryadi FX, de Fraiture C. Water-Energy-Food Nexus: Critical Review, Practical Applications, and Prospects for Future Research. Sustainability. 2021;13:1919.

89. Aggestam F, Miedzinski M, Bleischwitz R. The mirage of integration: Taking a street-level perspective on the nexus approach. Environ Innov Soc Transit. 2023;46:100700.

90. Yadav D, Rangabhashiyam S, Verma P, Singh P, Devi P, Kumar P, et al. Environmental and health impacts of contaminants of emerging concerns: Recent treatment challenges and approaches. Chemosphere. 2021;272:129492.

91. Glassmeyer ST, Burns EE, Focazio MJ, Furlong ET, Gribble MO, Jahne MA, et al. Water, Water Everywhere, but Every Drop Unique: Challenges in the Science to Understand the Role of Contaminants of Emerging Concern in the Management of Drinking Water Supplies. Geohealth. 2023;7.

92. de Jesus RA, Barros GP, Bharagava RN, Liu J, Mulla SI, Azevedo LCB, et al. Antibiotics and hormone residues in wastewater: Occurrence, risks, and its biological, physical and chemical treatments. 2023. p. 1–15.

93. Lifset R, Hertwich E, Makov T. Policy for material efficiency in homes and cars: Enabling new climate change mitigation strategies. WIREs Climate Change. 2024;

94. EC. European Commission, Directorate-General for Research and Innovation, Horizon Europe : strategic plan 2021-2024. https://data.europa.eu/doi/10.2777/083753. Publications Office; 2021.

95. Giest S, Mukherjee I. Evidence integration for coherent nexus policy design: a Mediterranean perspective on managing water-energy interactions. Journal of Environmental Policy & Planning. 2022;24:553–67.

96. Klessova S, Engell S, Thomas C. Dynamics of couplings and their implications in inter-organizational multi-actor research and innovation projects. International Journal of Project Management. 2022;40:547–65.

97. Dzwigol H. Research Methodology in Management Science: Triangulation. Virtual Economics. 2022;5:78–93.