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ORIGINAL ARTICLE

Water strategies and water–food Nexus: challenges and opportunities towards sustainable development in various regions of the World

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Abstract
The twenty-first century is witnessing an explosion in global population, environmental changes, agricultural land disintegration, hunger, and geopolitical instabilities. It is difficult to manage these conditions or standardize improvement systems without thinking of the three main elements or subsystems that are necessary for any meaningful development—namely water (W), energy (E), and food (F). These key elements form what is globally agreed upon as the "WEF Nexus." While considering them, one should think about the other key factors that influence WEF Nexus, including population's growth, impacts of environmental changes (including climate change), moderation and adaptation regimes to climate change and climate resilience, loss of biodiversity, and sustainable nature. Together, the WEF Nexus subsystems represent a framework to ensure environmental protection that should be seen as an ethical and socioeconomic obligation. Issues, such as protection of water resources, and strategies and management tools or mechanisms for the use of water assets and agricultural innovations under the obligations of sustainable use, are investigated in this paper. Attention is paid to the relationship between water and food (WF Nexus) or water for food security in various world regions, including the Gulf Cooperation Council (GCC) countries, Central Asia countries and the Caucasus, China, Africa, and Canada. This paper also presents analyses of a great number of up-to-date publications regarding the "Nexus" perspective and its applications and limitations. This paper suggests that the Nexus' approach, in its different concepts (WEF, WE, WF and EF), can promote sustainable development and improve the quality of life of communities, while preserving natural, human, and social capital, addressing sustainability challenges, and protecting natural resources and the environment for long-term use.

Keywords Water, water efficiency, water strategies, water security, and water infrastructure · Water as a human right · Agriculture and food · Climate change · Water–food Nexus (WF Nexus)

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Abbreviations

3H	The Huaihe, Haihe, and Huanghe waterways' basins (ponds), China
ADRB	Amu Darya River Basin (Afghanistan's northern border with Tajikistan, Uzbekistan, and Turkmenistan)
AIT	Artificial intelligence technique
AWV 2025	Africa Water Vision 2025
CD	Canadian Dollar
CF	Capacity Factor (energy measure)
CLEW Nexus	Climate–land–energy–water Nexus
CLEWF Nexus	Climate–land–energy–water–food Nexus
COVID-19	Coronavirus disease 2019
DR	Demand response
E	Energy
EC' JRC	European Commission's Joint Research Center
EF Nexus	Energy–food Nexus

ETRB	Euphrates and Tigris Rivers' Basin (Turkey, Iraq, and Syria)
EU	European Union
F	Food
FAO	Food and Agriculture Organization, UN
FNI	First Nations' Indigenous communities, Canada
FVC	Food value chain
FWQ	Five W questions: why, what, where, when, and who
GARCH	Generalized auto-regressive conditional heteroskedasticity
GCC	Gulf Cooperation Council countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and UAE)
GDP	Gross domestic product
GERD	Grand Ethiopian Renaissance Dam, Ethiopia
GHG	Greenhouse gas (emissions)
GIS	Geographical information system
IHP	Intergovernmental Hydrological Program, UNESCO
IWRM	Integrated water resources management
LEAP	Long-range energy alternatives planning (software program)
LMRB	Lower Mekong River Basin (Thailand, Laos, Cambodia, and Viet Nam)
MLT	Machine-learning technique
OECD	Organization for Economic Cooperation and Development, UN
OPT	Occupied Palestinian Territories (part of Historic Palestine)
PV	Photovoltaic (solar energy)
SEA Protocol	Strategic Environmental Assessment Protocol
SMHI	Swedish Meteorological and Hydrological Institute
SNWDP	South-to-North Water Diversion Project, China
SNWTP	South-to-North Water Transfer Project, China
SUGI-IFWE	Sustainable urbanization' global initiative: inviting food, water, and energy
TSL	Tonle Sap Lake, Cambodia
UAE	United Arab Emirates
UK	United Kingdom
UMRB	Upper Mekong River Basin (China and Myanmar)
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund
UN MDGs	United Nations' Millennium Development Goals
UN SDGs	United Nations' Sustainable Development Goals
USA	United States of America
USAID	United States Agency for International Development
USD	US Dollar
W	Water
WASH	Water, sanitation, and hygiene
WEAP	Water evaluation and planning (software program)
WE Nexus	Water–energy Nexus
WEF Nexus	Water–energy–food Nexus
WEFE Nexus	Water–energy–food–ecosystems Nexus' project
WF Nexus	Water–food Nexus
WORLD	Water–food–energy–climate change–land (perspective)

Units

BCM	Billion cubic meters
BCM/year	Billion cubic meters per year
ha/ca	Hectares per capita
kg	Kilogram
km	Kilometer
km^2	Kilometer square
l/ca/day	Liter per capita per day
mm/year	Millimeter per year
MT	Million tons
m^3/ca/year	Cubic meter per capita per year
m^3/s	Cubic meter per second

Introduction

Managing the water assets of many countries around the world is a challenge due to immense difficulties and vulnerabilities, rapid industrialization and urbanization processes, and the effects of environmental changes, including global warming and climate change, as well as population's growth and geopolitical instabilities. The increase in water stress and shortages facing many countries worldwide is one of the main difficulties confronting practical progress globally (Yuan and Lo 2022). According to FAO's Director-General—José Graziano da Silva—this challenge will increase as the global population swells and as environmental changes continue to rise (FAO 2017).

According to the World Health Organization (WHO 2019), one in three people globally (or one-third of the world's population) does not have access to safe drinking water. Also, regarding inequalities in access to water, sanitation, and hygiene (WASH), more than half of the world does not have access to safe sanitation services. Some 2.2 billion people around the world do not have safely managed drinking water services, 4.2 billion people do not have safely managed sanitation services, and 3 billion people lack basic hand-washing facilities. "Children and their families in poor and rural communities are most at risk of being left behind. Governments must invest in their communities if we are going to bridge these economic and geographic divides and deliver this essential human right," said Kelly Ann Naylor, Associate Director of WASH, UNICEF (WHO 2019). Every year, approximately 300,000 children, who are less than 5 years old, die due to diarrhea linked to inadequate WASH. Poor sanitation and contaminated water are also linked to transmission of diseases, such as cholera, dysentery, hepatitis A, typhoid, and so forth. "Closing inequality gaps in the accessibility, quality, and availability of water, sanitation and hygiene should be at the heart of government funding and planning strategies. To relent on investment plans for universal coverage is to undermine decades' worth of progress at the expense of coming generations," said K.A. Naylor (WHO 2019).

Competition for water will escalate more than ever, as the world's total population is projected to reach 8.6 billion by 2030 and 9.8 billion by 2050 (Islam and Karim 2019). It means that an additional 2.4 billion people are projected to be added to the global population between 2015 and 2050, whereas Africa will be the major contributor. On the other hand, the global water demand is projected to increase by 55% between 2000 and 2050 (Day 2019; Islam and Karim 2019). Effectively, many farmers in developing countries are suffering and will continue to suffer the ill-effects of the lack of access to freshwater, while clashes revolve regarding water resources arise around the world, especially in the presence of various scenarios related to the impacts of climate change (Salem 2009, 2011; Islam and Karim 2019; Avgoustaki and Xydis 2020; Do et al. 2020; Zhang et al. 2020; Salem et al. 2021; ZamanZad-Ghavidel et al. 2021). An example of the old–new conflicts over water resources is that amongst Ethiopia, Sudan, and Egypt, which share the Nile River waters in the African continent. Conflict amongst the three countries has been escalating recently, especially after Ethiopia had completed construction of the Grand Ethiopian Renaissance Dam (GERD) and finished the second filling of the Dam in July 2021, and recently started producing electricity (Yihdego et al. 2017a; Aljazeera 2020; Mbaku 2020; Colton 2021; El-Gundy 2021; Tadesse 2022; Tesfamichael 2022).

While there are clear indications of approaching water emergencies around the world, as confirmed by more ongoing events, including dry seasons and droughts, long-term pollution of water resources, and climate change impacts, policy- and strategy-makers have yet to deal with the resulting consequences (Zhang et al. 2020; ZamanZad-Ghavidel et al. 2021). The full range of difficulties, resulting from water scarcity in the short and long terms, will have heavy impacts on many countries worldwide, politically, socially, financially, and economically (Yihdego et al. 2019)—and these may lead in some regions, to military confrontations.

When focusing on changes and advances in strategies and management of water resources in the presence of extraordinary challenges, there is the need to overcome the latter. Regli and Heissermanb (2013) summarized such challenges into three basic elements—namely water (W), energy (E), and food (F), or WEF; and, in general, health and education, which can be explained in more detail as follows: (1) WEF will be major requirements for the human race's ability to supply the global population, where the three WEF elements or subsystems are deeply interlinked and, thus, defined as "Nexus." An example: energy and fertilizers are used to produce food and feedstock; water and feedstock are used to deliver meat (for example, it takes about 10 kg of feed and 15 L of water to deliver 1 kg of meat); and different food and non-food crops are used to provide biofuels (Ruel et al. 2018); (2) public welfare will continue to be a test and will be further affected by the provision of clean water and proper nutrition, the spread of diseases, and the transfer of medical services, such as the breakout of the Coronavirus (COVID-19) pandemic since December 2019 and ongoing (Worldometer 2022a); and (3) Education will be of increased importance, as it can lead to socioeconomic changes that can impact population's development (Regli and Heissermanb 2013; Grant 2017; Yihdego and Salem 2017; Salem 2020).

The relationship between water, energy, and food (WEF Nexus) is fundamental to sustainable development. The WEF Nexus is a concurrent global assessment solution for developing and implementing different approaches focusing on the security and adequacy of the three resources or subsystems (water, energy, and food). The WEF Nexus' approach aims to promote sustainable development and improve the quality of life of communities, while preserving natural, human, and social capital, addressing long-term sustainability challenges, and protecting natural resources and the environment. WEF Nexus is a holistic vision of sustainability that strives to balance the various goals, interests, and needs of people, as well as the well-being of the environment, by assessing water, energy, and food interrelationships, inter-linkages, and inter-dependences through qualitative and quantitative modeling, as well as developing research and resource management to deliver important strategies for sustainable development in today's dynamic and complex world.

This paper investigates the relationship between water and food (WF Nexus) in several regions across the globe, as they are presently facing water problems related to stress, shortages, pollution, distribution, and climate change, as well as inequity in water distribution, representing a violation of the "water right" as being a basic human right. Several water issues, including the WF Nexus, are investigated in this paper, focusing on five regions of the world, including the Gulf Cooperation Council (GCC) countries, Central Asia countries and the Caucasus, China, Africa, and Canada. These regions and the WF Nexus, in particular, are investigated in this paper for the following reasons:

(1) The authors are knowledgeable and have work experience about the five investigated regions, regarding various issues, such as population's growth, socio-economic and environmental vulnerabilities, water resources' mismanagement, inequalities, and so forth; (2) Some of the investigated regions are extensively considered as water-stressed areas, such as the Arab countries in the Gulf region (GCC countries); others have plenty of water, such as Canada, but suffer from water distribution inequity regarding the Canadian Native (Indigenous) population, and also from water pollution to some extent; while some other regions, like China and Africa, have enough water but suffer from the high population—a fact that considerably affects water resources. In addition, the countries of the GCC and Africa suffer from poor management or better saying mismanagement of their water resources. These criteria are negatively reflected, quantitatively and qualitatively, on the food security in the WF Nexus in these regions. Indeed, there are some other geographical regions around the world—such as northeastern Brazil, India, and others—that are suffering from acute water stress, shortages, drought, and other problems which, hopefully, will be investigated by another research paper and compared with the regions investigated by this one; 3) Several studies cited in this paper also focused on the water–food Nexus (Table 1) without giving attention to the energy element. Meanwhile, some other studies focused on the water–energy Nexus (WE Nexus) without giving attention to the food element, the energy–food Nexus (EF Nexus) without giving attention to the water element, and other studies focused on the three elements together, in terms of the WEF Nexus (Table 1); (4) The paper also investigates other issues referring to the water and food sectors, particularly when not directly related to the energy sector; and (5) Many regions around the world have no access to energy sources to generate electricity, meaning that they can live without energy—but they absolutely cannot live without water and food, despite the importance and necessity of energy for living.

Methodology

To compare the different water-food challenges experienced in different regions of the world—which have different climatic and socio-economic conditions, this paper investigates water and food challenges in five different regions. It is based on a literature review and on data analysis, combined with the authors' ample experience of the water situation in these regions. For this approach, quantitative and qualitative data were utilized and analyzed for the five regions investigated. Furthermore, several valuable, up-to-date articles were studied, analyzed, and provided in Table 1 to present a better and deeper understanding of the conditions and challenges facing the WF Nexus, as well as the WE Nexus, the EF Nexus, and the WEF Nexus in various regions of the world.

Results and discussion

WEF Nexus, WE Nexus, WF Nexus, and EF Nexus, globally

The water–energy–food Nexus (WEF Nexus), the water–energy Nexus (WE Nexus), the water–food Nexus (WF Nexus), and the energy–food Nexus (EF Nexus) guarantee access to safe and enough water, national food security and availability (in terms of quality and quantity), and national energy security, in an economically and environmentally sustainable manner. Recently (i.e., for the period 2008–2022), many researchers have studied the Nexus (WEF, WF, WE, EF), as well as other related issues mentioned above, regarding different countries and regions around the world (Table 1).

Based on the studies provided in Table 1, the Nexus' approach (in terms of WEF, WE, WF, and EF) can promote sustainable development and improve the quality of life of communities, while preserving natural, human, and social capital, addressing sustainability challenges, and protecting the environment and natural resources for long-term use. Table 1 shows that the Nexus' approach can help create effective commercial programs and synergies amongst the three subsystems (water, energy, and food) or two of them, taking into account cross-sectoral, environmental, social, political, and geopolitical dimensions, as well as social justice and equity. Thus, the Nexus' concept is greatly relevant, especially in the presence of the impacts of climate change, population's growth, and many other influencing factors (Table 1).

The Nexus amongst water, energy, and food (WEF Nexus) and how their complex interactions can be defined are essential approaches to understanding such a complex relationship amongst the three elements or subsystems. Such a Nexus can be defined as the very close links amongst the three elements (WEF) and how changes in one of them can have impacts on the other two (individually or both together) (Fig. 1). For countries worldwide, the WEF Nexus affects national water, energy, and food security and, thus, enabling socioeconomic developments.

Table 1 Various studies of the Nexus' concepts (WEF, WE, WF, and EF), regarding countries and regions worldwide for the 2008–2022 period

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Hellegers et al. (2008) and McCornick et al. (2008)	Water policy	Investigated the WEF-Environment synergies and trade-offs for India, Ethiopia, Jordon, and the USA. Presented the nature of trade-offs in various hydrological, energy, agricultural, and environmental contexts. Provided some anecdotal evidence and illustrative cases of policy options available to reduce conflicts, while maximizing the synergies amongst the Nexus subsystems (WEF) and the environment
Khan and Hanjra (2009)	Food policy	Investigated the WEF–Environment Nexus and recommended that the investments to enhance water usage and improve energy efficiency in crop production are two pathways to reduce environmental impacts, which can result, globally, in a good balance of the WEF–Environment Nexus
Mushtaq et al. (2009)	Energy Policy	Investigated the increasingly complex relationships between energy and agriculture, in terms of EF Nexus, and concluded that such relationships require an in-depth understanding of the water and energy trade-offs. Contributed to energy and food policies by analyzing complex water, energy, and economic dynamics across selected major rice-growing countries. Concluded that, of all the countries investigated, China has the highest water productivity due to its water-saving irrigation policies and practices
Hoff (2011)	International Conference	Provided initial evidence of how a Nexus' approach can enhance water, energy, and food security by increasing efficiency, reducing trade-offs, building synergies, enhancing policies, and improving governance across the three sectors (WEF)
Scott et al. (2011)	Energy Policy	Advanced understanding of the water–energy Nexus by illustrating how these resources are coupled at multiple scales, and by revealing institutional opportunities and obstacles to the decision-making. Three interdependencies between water and energy were examined for different regions in the USA, whereas socioeconomic–environmental dimensions were taken into account
Hardy et al. (2012)	International Journal of Water Resources Development	Studied the water–energy Nexus in Spain and provided accounts for both the energy used in the water sector and the water required to operate the energy sector. Provided assessments of policy goals for biofuels and other renewable energy sources. Concluded that (1) approximately 6% of the total electricity demand in Spain is used in the water sector; (2) irrigated agriculture is one of the Spanish water sectors showing the greatest growth in energy requirements; and (3) search for more efficient ways to use farming water, urban treated wastewater, and desalinated water should include the energy component

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Kumar et al. (2012)	Food Security	Studied the food security challenge that affects the food-land–water Nexus in India. Showed that the real challenge to food security and water management lays in the mismatch between water availability and agricultural water demands. Indicated that high water demands occur in water-scarce but agriculturally prosperous areas, and low water demands occur in areas that are naturally rich in water but agriculturally backward. To face this challenge, several strategies were recommended
Bizikova et al. (2014)	IISD (International Institute for Sustainable Development) Report	Presented a central concept that the rural poor (those who benefit most from investments in agricultural productivity) would be better off if the key environmental determinants of WEF Nexus' security were protected and strengthened. Provided a practical, spatially clear, and ecosystem-based framework for designing and managing land investments that provide greater water, energy, and food security. Presented specific objectives, approaches, and tools, as well as illustrative examples of the key steps to implement a comprehensive process, to improve the WEF Nexus' security
Keskinen et al. (2015)	Water	Investigated the WEF Nexus' approach for the Tonle Sap Lake (TSL) region, Cambodia. Concluded that the WEF Nexus is closely related—both in the TSL and in the transboundary Lower Mekong River Basin (LMRB) in general. The current trend of large-scale hydropower threatens water and food security at the local and national levels. Hence, the WEF Nexus provides a suitable starting point for promoting sustainable development in TSL and LMRB. (Note: The LMRB is made up of the Northern Highlands, the Khorat Plateau, the Tonle Sap Basin, and the Mekong Delta, covering Thailand, Laos, Cambodia, and Viet Nam. The Upper Mekong River Basin (UMRB) comprises the Tibetan Plateau, the Three Rivers Area and the Lancang Basin in China and Myanmar.)
Kibaroglu and Gürsoy (2015)	Water International	Analyzed cross-border (transboundary) evolution of water resources management in the Euphrates and Tigris Rivers' Basin (ETRB) with special reference to the interdependences (Nexus) of the water, energy, and food policies at the national (Turkey) level and the regional (Turkey, Iraq, and Syria) level. Explored how the WEF Nexus' policy has changed at the highest level of decision-making, and how it has worked to produce synergies of cooperation between the three riparian countries of the ETRB

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Hang et al. (2016)	Journal of Cleaner Production	Developed process system engineering tools along with resource accounting concept to design local production systems. Proposed a general design framework that includes an optional initial design phase followed by a concurrent design phase based on mathematical optimization. The initial design phase took into account each supply subsystem (water, energy, food) individually, which allowed insight into the potential interactions amongst the WEF Nexus' subsystems. This approach was illustrated through a case study on the integrated design of the WEF Nexus for a designated eco-town in the UK
Gilmont et al. (2016), Gilmont et al. (2017), Gilmont et al. (2018a), Gilmont et al. (2018b), Gilmont et al. (2018 in Arabic); Gilmont et al. (2019)	International Conference; Book; Book Chapter; Book on a Special Issue; Book Chapter in Arabic; Book Chapter	Carried out a regional joint project on water–agriculture decoupling concept, with the focus on water–food Nexus, in Jordan, Palestine, and Israel, which was led by the Oxford University and funded by the British Council, London, UK Demonstrated the relative ease with which economic and population growths can be decoupled from water resources' needs, to mobilize the growing natural freshwater resources. This can be achieved through diversifying economies away from agriculture, importing more water-intensive food needs, and improving agricultural water productivity, developing non-natural water sources (including wastewater recycling and seawater desalination). Provided revised conceptual models, using water and agricultural implements. Explored examples of decoupling trends achieved through economic diversification and food trade in the regions studied (Israel, Palestine, and Jordan). The analysis and evaluation processes used economic growth data from the World Bank and food balance data from FAO. The project resulted in numerous polymorphic publications, including journal articles, chapters in books, books, and presentations given at international conferences

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Jalilov et al. (2016)	Journal of Hydrology	Argued that it is impossible to project development strategies without taking into account the WEF Nexus' elements or subsystems to meet the demands of a growing population. Studied two possible modes to operate the Rogun Dam on the Vakhsh River in southern Tajikistan, which are power mode (guaranteeing the hydroelectric needs) and irrigation mode (guaranteeing water for downstream agriculture). Concluded that societies should choose between, for example, using land, water, and fertilizers to produce food, bioenergy, or other kinds of renewable energy resources, and between using fresh water to produce energy and irrigate crops, whereas both choices can lead to the WEF Nexus' approach
Smidt et al. (2016)	Science of The Total Environment	Analyzed the WEF Nexus over the High Plains' Aquifer System in the USA, as a framework for isolating the major drivers that have shaped the history, and will guide the future, regarding water use in modern agriculture. Concluded that future water management strategies can benefit from (i) prioritizing farmers' profits to encourage decision-making in line with strategic objectives; (ii) managing water as an input into the WEF Nexus, as interdependence and key incentive for farmers; (iii) adapting frameworks that enable farmers to achieve short-term and long-term agricultural goals; (iv) putting innovative strategies that fit within restrictive policy frameworks; (v) reducing production risks to help farmers make decisions; and (vi) increasing political willingness to preserve valuable water resources

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
EcoPeace Middle East and Konrad Adenauer Stiftung (2017)	Technical Report	Provided a preliminary feasibility study for a hydropower initiative's exchange between Israel, Jordan, and Palestine (the Occupied Palestinian Territories—OPT) as a means of salt-water desalination and energy generation in an economically efficient and environmentally sound manner. The idea is that Israel and/or Palestine (OPT) can produce desalinated water and supply Jordan with it, while Jordan can generate solar energy and supply Palestine (OPT) and Israel with it. As such, all parties will gain from such a WE Nexus of the regionally integrated water and energy sectors. Presented a practical WE Nexus' framework through (i) evaluating the various technological options to achieve a possible WE Nexus' arrangement, considering the geopolitical disagreements, obstacles, and political conflicts amongst the peoples in the three countries; (ii) conducting a preliminary socioeconomic analysis of the project to be undertaken in the three countries; and (iii) determining the benefits and identifying political and geopolitical challenges of the project when will be implemented
Eftelioglu et al. (2017)	Book Chapter	Described a vision of the role of spatial computing in understanding the WEF Nexus from a spatial data life cycle perspective. Provided details of each of the spatial computing components (data collection, management, modeling, and visualization). Listed, for each of the WEF components, new technical challenges that likely to drive spatial computing research in the future, regarding the WEF Nexus' approach

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Endo et al. (2017)	Journal of Hydrology: Regional Studies	Selected 37 projects, through which 4 types of interrelated research have been identified, including WF-, WE-, WEF Nexus-, and climate-related. Amongst them, 6 projects (16%) are closely related to WF Nexus; 11 projects (30%) are closely related to WEF Nexus; 12 projects (32%) are closely related to WE Nexus; and 8 projects (22%) are closely related to climate issues. The regions investigated were divided into Asia, Europe, Oceania, North America, South America, the Middle East, and Africa. North America and Oceania tended to focus on a specific type of interdependence, including WE Nexus (46%) and climate issues (43%), while Africa had a lower focus on WE Nexus (7%). Recommended that it is essential to develop a unifying framework of Nexus' research to share solution-oriented common goals amongst projects' members and stakeholders, to develop methods to integrate results of research and to understand the WEF Nexus' complexities. Also, recommended that the framework can be used within interdisciplinary and transdisciplinary approaches under the Future Earth Framework, and to encourage local-to-global connected Nexus' systems. Concluded that such a framework will contribute to reducing trade-offs and increasing synergies of the use of the three elements or subsystems of the WEF Nexus
Engström et al. (2017)	Sustainable Cities and Society	Proposed a technology-independent "resource-to-service reference system" framework for the simultaneous assessment of water and energy subsystem interventions (WE Nexus) for the New York city, USA. Indicated that interventions, primarily driven by water management objectives, can significantly reduce energy use and contribute to mitigating greenhouse gas (GHG) emissions. Likewise, energy efficiency interventions can significantly reduce water use and GHG emissions. Recommended that more useful research should be conducted, and the existing analysis should be expanded to consider a broader range of resource interactions towards a full climate–land–energy–water (CLEW) Nexus' approach. Concluded that evaluating the impacts, trade-offs, and co-benefits of the WE interventions can enhance resources' (water and energy) efficiency through the integration of decision-making

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Mohtar (2017)	Policy Brief	Based on the fact that climate change is already happening, and according to the Intergovernmental Panel on Climate Change (IPCC), the Earth has warmed faster in the past three decades than at any time since 1850. Ocean temperature has increased by about 0.11 °C per decade for the past 40 years. The rate of sea-level rise is now more than 3 mm per year since the 1990s (due to climate change and other aspects) (IPCC 2014). These and other changes in climate, such as precipitation, have severe effects on human systems. Accordingly, indicated that understanding the links amongst climate change, on the one hand, and water, energy, and food resources (in terms of WEF Nexus), on the other, is critical to developing effective strategies, in order to adapt to expected changes and to ensure adequate access to these resources for a growing global population. Identified some of the key factors and specific impacts of climate change on the WEF Nexus, and presented possible adaptation strategies
Peri et al. (2017)	Sustainability	Analyzed the fluctuations' implications between the indexes that represent the financial component of the WEF Nexus. Used the Generalized Auto-Regressive Conditional Heteroskedasticity (GARCH) model with daily data, in which the water variable is a proxy for a stock index that represents the performance of the industry involved in the water business at the local and global levels. The findings highlighted a financial relationship amongst water, energy, and food (WEF Nexus) that was, particularly, exacerbated during the 2008 global economic crisis. Recommended the need to better investigate policy options that can be used to reduce price volatility in the context of the increasing importance of sustainability issues, with respect to the WEF Nexus. (Note: GARCH is a statistical modeling technique used to help predict the volatility of returns on financial assets.)
Ramaswami et al. (2017)	Environmental Research Letters	Developed a general framework to analyze the WEF Nexus, from an urban system perspective, that links interactions within and across borders. Identified the multiple environmental impacts at the community level for cities. Visualized the few supply chain risks that the environment poses to cities, taking into account the New Delhi city, India, as a case study. Found that more than 75% of the water use for food is devoted to urban agriculture and that over 76% of the energy used for food is generated from cooking fuels

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Albrecht et al. (2018)	Environmental Research Letters	Pointed out that the Nexus' approach aims to identify trade-offs and synergies amongst water, energy, and food subsystems. Evaluated social and environmental impacts and guided policy development across the three sectors. Indicated that, while the WEF Nexus offers a promising conceptual approach, the use of various methods and models, to systematically assess the WEF linkages and support the development of socially and politically relevant resource policies, have some limits. To help overcome these limits, four key features of the Nexus' analysis tools and methods were obtained from the literature. These features, reflecting the interconnected thinking of the WEF Nexus, are innovation, context, collaboration, and implementation. Recommended that inter- and multi-disciplinary approaches that incorporate the social and political dimensions of water, energy, and food are needed, and also stakeholders and decision-makers should be engaged, to meet complex resource and development challenges that face the WEF Nexus
Brouwer et al. (2018)	Energy Strategy Reviews	Suggested that the Nexus' is better defined as the interconnection amongst climate, land, energy, water, and food (CLEWF Nexus). Such interconnection enables trade-offs to be addressed and synergies sought. Accordingly, some models were used to support the design and testing of coherent strategies for sustainable development, regarding the CLEWF Nexus
Cai et al. (2018)	Advances in Water Resources	Stressed on the importance of current and continuing research needs within the water community, to understand the WEF Nexus (linkage processes and subsystems) and implement WEF solutions through innovations in technologies, infrastructures, and policies
Chandrasekharam (2018)	Water–Energy Nexus	Investigated the WEF Nexus' potential in Saudi Arabia, and suggested that a renewable energy option can provide fresh water for the domestic and agricultural sectors and secure food and water in the country. Indicated that Saudi Arabia may appear as a leader in supporting the agricultural sector in all the GCC countries if the WEF Nexus would be implemented. Recommended that the most cost-effective way to obtain fresh water from the sea is to adopt technology based on solar photovoltaic (PV) or geothermal energy sources. Indicated that PV is not cost-effective, as it needs supporting facilities, while geothermal can provide base-load electricity and the system can operate with $>90\%$ efficiency all year round at reasonable cost

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Chen (2018)	Water (Special Issue)	Indicated that there is a growing policy focus and scientific emphasis on the relationship amongst water, energy, and food subsystems (WEF Nexus), as a framework for analyzing human and ecological systems at global and local levels, and for suggesting more sustainable pathways to a secure future. However, the issue of water quality in relevance is often a secondary consideration. Evaluating the role of water quality in the WEF Nexus, and discussed approaches to assessing water quality within the WEF Nexus, with case studies and at different levels. Covered the following topics: (i) case studies examining water quality and quantity in the WEF Nexus; (ii) regional/global analyses and models of water quality/quantity in the WEF Nexus; (iii) water quality/quantity monitoring and evaluation in the WEF Nexus, including current methods and new technologies; and (iv) water quality/quantity management approaches informed by the WEF Nexus
Dai et al. (2018)	Applied Energy	Based on a comprehensive survey of the recent scientific literature on the water–energy Nexus, 70 studies were identified and 35 were selected as comprehensive case studies for review. Categorized and evaluated the reviewed studies according to a clustering based on the geographical scale and Nexus' scope. Found that fewer approaches were designed to support governance and implement technical solutions, which can be considered as a priority challenge for the scientific community if aimed at achieving greater impact on resources' policy and management. Recommended that this requires a better use, more effectively, of the existing knowledge, and also requires putting of a greater emphasis on managing and implementing the WE Nexus
Hoolohan et al. (2018)	Sustainability Science	Identified four aspects of Nexus research, considering the value and potential challenges of interdisciplinary research regarding each of the four aspects. Focused on evaluating and visualizing Nexus subsystems; and understanding governance, capacity building, significance of scale, and implications for future changes and challenges. Described a new, multi-method approach that integrates stakeholders' knowledge with insights from multiple disciplines

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Kibler et al. (2018)	Waste Management	Characterized the waste generated from food in the WEF Nexus. Found that many food waste management options (such as waste prevention, landfilling, composting, anaerobic digestion, and incineration) offer variable pathways for WEF impacts and opportunities. Recommended that comprehensive sustainable management of food waste should involve different mechanisms and actors at multiple levels of governance and consumption. Proposed a "food-waste subsystems" approach within the WEF Nexus, to address the complex problem of food waste, and to protect and optimize resources
Chang et al. (2018); Uen et al. (2018)	Geophysical Research Abstracts; Science of The Total Environment	Within the scope of the Sustainable Urbanization' Global Initiative: Inviting Food, Water, and Energy (SUGI-IFWE), promoted the green urban centers of tomorrow. That can be established by creating effective exchange mechanisms for the three subsystems (WEF) from sources to urban centers, and then improving WEF Nexus related to public health. Used the Artificial Intelligence Technique (AIT), big data, system dynamics, and scenario analysis to build optimal resource allocation models, to understand the interrelationship amongst the three subsystems. Provided feasible solutions that address the allocation and use of WFE resources. Indicated that during the wet year, water shortage rates can be reduced by 10% at most, food production rate can be improved by 45% at most, and annual revenue of hydropower can be increased to USD 9 million. Concluded that the proposed methodology could be a promising tool to increase the collaborative benefits of the WEF Nexus, in response to future urban's water requirements. Also recommended that the methodology used can provide decision-makers with reference guidance for the sustainable management of water, energy, and food resources
White et al. (2018)	Applied Energy	Illustrated the mismatch amongst regional water, energy, and food availability, as well as final resources' consumption and the lack of attention to environmental impacts in national economic growth strategies for East Asian countries. Concluded that resource-scarce countries, such as China, must incorporate, in their strategic regional development policies, trade-offs' decisions related to pursuing national economic growth, eliminating environmental degradation, and having food security

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Yang and Wi (2018)	Agricultural Water Management	Studied the water-intensive activities in the Usangu plains and Ruaha National Park in southern Tanzania, Africa, as these areas present a typical case of aquatic competition in the WEF Nexus. Found that the combination of improvements in irrigation efficiency, reductions in the proposed expansion of irrigated lands, and management of wetland areas, significantly reduce the number of the zero-flow days. This means increasing ecosystem function, which leads to positive impacts on the agricultural sector within the WEF Nexus' approach
Zaidi et al. (2018)	Big Earth Data	Indicated that the Machine-Learning Technique (MLT) can help explain distinct patterns of the water–energy Nexus, with respect to water availability, transportation, power generation, fuel supply, and customer demand. Discussed ways in which statistical data and MLT can be applied to challenges facing the WE Nexus. Investigated MLT that can provide solutions to WE Nexus' problems. Identified future research directions and opportunities for collaboration between MLT communities and the WE Nexus' concept, which can lead to mutually synergistic advantages
Zhang et al. (2018)	Journal of Cleaner Production	Provided a review of concepts, research questions, and methodologies in the field of WEF Nexus. Discussed eight modeling approaches, in terms of their advantages, disadvantages, and applications. Provided guidance on choosing an appropriate modeling approach. Identified future research challenges, including WEF Nexus' boundaries and limitations, data modeling and uncertainty, system performance' evaluation, and the mechanisms of correlation issues. Addressed challenging questions, with respect to interconnected research and development of sustainable and resilient water, energy, and food subsystems within the WEF Nexus' approach

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Al-Saidi and Saliba (2019)	Water	Proposed a view of resource supply security, based on the characteristics of the systems under change and their ability to deal with risks and shocks, in terms of resilience. Presented internal and external risk factors for the WEF supply subsystems (WEF Nexus) in the GCC countries (Gulf region), and highlighted recent knowledge regarding those risks. Explained the vulnerability of WEF supply's subsystems for risks related to growth, technology, market, and climate change. In light of these risks, highlighted the importance of investing in risk management and resilience policies in infrastructure planning. Recommended measures to respond to future risks, such as warehousing, knowledge, diversification of energy sources (fossil and renewables), and most importantly, promoting regional cooperation and synergies from joint infrastructure planning across the GCC countries, with respect to the WEF Nexus' mechanisms
Araujo et al. (2019)	Current Opinion in Environmental Sustainability	Applied a collaborative research practice framework to the São Francisco River Basin, which is a hotspot of climate vulnerability in northeastern Brazil. Built cause-and-effect research on climate change from a WEF Nexus' perspective, considering the added value of resilience and adaptability of the concept. Proposed an additional underpinning of the Nexus' approach—namely socioecological security, which can be defined as a political–territorial dimension of the associated socioecological system. Recommended that the climate component should be included in the WEF Nexus to address social and environmental sustainability

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Campana et al. (2019)	International Conference organized by the American Geophysical Union	Used the Artificial Intelligence Technique for the WEF Nexus' management during drought in Sweden. Concluded that, unlike farming practices in southern European countries where irrigation is a well-known practice, Swedish farmers generally lack sufficient means and incentives to know water use of crops, actual irrigation applications, responses of crop yields to different water management practices, and current water efficiency levels on farms. Used grid climatic data, made available by the Swedish Meteorological and Hydrological Institute (SMHI), in order to develop a WEF Nexus' model to estimate the effects of drought on the Swedish agricultural sector. In addition to SMHI data, used also a genetic algorithm for optimal allocation of natural resources (water, energy, and food), and long-term memory networks for seasonal predictions. The WEF Nexus' model aimed at building a pioneering model to provide instant information, regarding management of irrigation water, crop yield conditions, and natural resources' allocation in Sweden. Concluded that the WEF Nexus' model, based on SMHI data and AIT, can serve as a demonstration of a future operational service, especially for farmers interested in crop growing conditions and irrigation guidelines, but also for agencies related to WEF Nexus' management
Djehdian et al. (2019)	Sustainable Cities and Society	Developed a new measure of the WEF Nexus that quantifies and visualizes direct and indirect exposures to urban water scarcity in the USA. Improved understanding of vulnerability to water scarcity, with respect to food and bioenergy resources, enabling policy-makers to improve the reliability of WEF Nexus in urban US areas
Hong et al. (2019)	Sustainable Cities and Society	Integrated multi-regional input–output data analysis to investigate the WE Nexus in the construction industry at the provincial level through the entire industrial supply chain in China. Showed that the construction industry makes up approximately 9% and 27% of China's virtual water and embodied energy, respectively. Also showed that the western, eastern, and central areas of China are suffering from imbalance in the WE Nexus, with respect to the industrial activities, regarding inefficient usages of the water and energy resources

Table 1 (continued)

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Nashashibi and Gal (2019)	Action Plan	Pointed out that only a comprehensive action plan led by the donor community, in cooperation with the Israeli and the Palestinian governments, along with local infrastructure institutions, can address the interrelated and interconnected problems of water, energy, and governance (WE-Governance Nexus) that affect the Gaza Strip in the Occupied Palestinian Territories. This is with the consideration of the extremely complicated political and socioeconomic conditions affecting the Gaza Strip's population. Urged the donor community to take a proactive stance and lead the proposed action plan, to revitalize and lead the energy and water sectors towards financial sustainability
Noruzi and Yazdandoost (2019)	International Journal of Optimization in Civil Engineering	Investigated the WE Nexus' approach for the Kashan city, Iran, as being an arid area and, thus, recommended unconventional water resources (e.g., desalinated saltwater and treated wastewater) to be considered as alternative water resources. Showed that alternative water resources must be exploited, while taking into account energy costs and environmental impacts. Used WEAP (Water Evaluation and Planning software program) to model the allocation of water demand and supply. Also used LEAP (Long-range Energy Alternatives Planning software program) to model the energy required to obtain water from unconventional resources. Accordingly, estimated the desired volume of unconventional water, using the optimization method
Simpson and Jewitt (2019a)	Current Opinion in Environmental Sustainability	Argued that the call for activating the Nexus' concept has been publicized in several recent publications, and the common theme is that "Nexus' Thinking" must evolve into "Nexus Action". Indicated that Nexus' policies were enabled at different spatial scales from regional and national levels to city level, and appropriate mechanisms and decision support tools were evolved to achieve integrated and coherent planning to practically implement the Nexus' concept
Simpson and Jewitt (2019b)	Frontiers in Environmental Science	Examined the evolution of the WEF Nexus' concept since its rise to prominence in policy and development discourses. Presented various interpretations of the Nexus' concept, while considering its novelty. Examined the challenges of integrating and optimizing components of the Nexus' concept, with case studies in South Africa and South Asia. Reviewed the WEF Nexus, as a contribution potential to the achievement of the United Nations' Sustainable Development Goals (UN's SDGs)

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Zhang et al. (2019a)	Resources, Conservation and Recycling	Presented a comprehensive literature review to discuss current concepts and methods of the WEF Nexus at different levels, with the goal of developing a conceptual knowledge base framework for scientific analysis and policy-making associated with urban interdependence of the WEF Nexus. Concluded that, although the Nexus' concept of correlative thinking has been widely accepted, a coherent and explicit realization of it is still lacking and, hence, a sophisticated, systematic modeling framework is urgently needed at various levels
Zhang et al. (2019b)	Journal of Cleaner Production	Investigated the WEF Nexus with particular end-demand-driven internal linkages of the Beijing city, China. This was at various points along the city's supply chains, by combining structural path analysis with the China 2010 multiregional input–output WEF Nexus' model, with the focus on the least developed regions and energy-related sectors in the city. Besides, critical supply chains showed divergent trends for the flows of the WEF Nexus, driven by the food supply, construction, and agricultural industries. Recommended that the results obtained are very useful for targeting the efforts to address the WEF Nexus' problems of under-developed urban connectivity from both supply-side and demand-side perspectives
Abdi et al. (2020)	Inventions	Attempted to review some of the recent research on the WEF Nexus' topic. First described some facts about the exponential growth of demand and consumption in the three areas (water, energy, and food) of the Nexus, focusing on their statistical dimensions. Next, the most important research works published in the field were reviewed. Also, the most important policy-making events of this emerging concept were discussed, including committees and conferences. Finally, some significant challenges and opportunities for implementation of the WEF Nexus, along with future visions, were presented

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Abou Farhat et al. (2020)	Book Chapter	Attempted to help overcome energy sustainability challenges in Lebanon, while minimizing impacts on the country's natural, economic, and value-added social resources, taking into account the climate, land, energy, and water (CLEW) Nexus. Proposed such a Nexus to increase the capacity of renewable electricity generation, as well as conventional power stations that run on imported fuels to ensure energy security. This is due to the fact that Lebanon has been facing long-standing energy challenges, resulting from the lack of comprehensive assessment of the decision-making. However, this approach does not necessarily take into account Lebanon's most pressing energy challenges and potential impacts of selected technologies on Lebanon's scarce land and water resources. Recommended that offshore wind, solar PV, natural gas, geothermal, nuclear, and hydropower technologies are the most desirable electricity generation options in Lebanon, based on the assumptions and values used
Avgoustaki and Xydis (2020)	Food Security	Carried out a comprehensive review of scientific papers of the WEF Nexus, to analyze the different applications of urban farming on the basis of three different dimensions, which are: (i) manufacturing techniques and equipment used to produce food; (ii) the energy required, energy distribution, and methods of energy-related cost reduction; and (iii) technological innovations applied to improve the possibilities of water consumption for urban farming
Connor et al. (2020)	Technical Report	Pointed out that water-use efficiency measures in agriculture can increase water availability and reduce the energy needed for pumping, and further reduce the water needed for energy production. This lower energy demand can also result in lower greenhouse gas emissions; thus mitigating the effects of climate change. This way of cross-benefits can lead to positive reinforcements. Also, increased use of renewable energy sources and technologies in agriculture and other sectors could increase energy efficiency and provide additional opportunities to reduce GHG emissions. Furthermore, in addition to energy savings and efficiency, improved approaches to wastewater treatment can provide a broader range of climate change's mitigation measures. This report presented a better understanding of the WEF–Climate Nexus

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Do et al. (2020)	Science of The Total Environment	Highlighted three major trade-offs that occur amongst hydropower and irrigation, hydropower and fisheries, and irrigation and fisheries, representing the WEF Nexus' approach for the Lancang–Mekong River Basin, China. Quantified the effects of reservoir operation on hydroelectric generation, irrigated crop production, and fisheries productivity in the Tonle Sap Lake through a new basin-wide hydro-economic model. Indicated that trade-offs can be turned into synergistic opportunities. Concluded that this alternative narrative can enhance the dialogue, regarding fair and efficient water use amongst the Mekong River's riparian countries
El Youssfi et al. (2020)	E3S Web of Conferences	Reviewed the WEF Nexus' adoption in two typical African countries—namely Morocco and South Africa. Compared the water, energy, and food sectors and relevant national policies, plans, and frameworks in both countries. Explored the importance of technology-supported frameworks for the WEF Nexus, and also analyzed the risks facing the agriculture and food security in both countries. Data on the WEF Nexus revealed major difficulties, regarding WEF availability in both countries. Revealed policy differences, regarding the Nexus across the water, energy, and agriculture sectors
Endo et al. (2020)	Current Opinion in Environmental Science & Health	Reviewed published research to understand the current state of the WEF Nexus, focusing on methodologies and the process by which it expands the Nexus as an interdisciplinary and integrated approach, academically and geographically. Highlighted various indicators for evaluating the Nexus' methods and tools. Also, discussed WEF Nexus' initiatives that apply mixed methods for replicability and reproducibility of specific case studies, based on findings
Katz et al. (2020)	Water	Examined the growing importance of the WEF Nexus to critically evaluate the features necessary to identify it. Indicated that the WEF interdependent relationship differs from sector-focused natural resources or sustainability problems, in terms of complexity and challenges. Stimulated two new focus areas of research—namely the identification of low-dimensional indices of the state of the WEF Nexus, and the approaches to determining the WEF Nexus' bounds

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Kirchem et al. (2020)	Applied Energy	Discussed the wastewater treatment process as a single industrial end user within the energy–water Nexus, where the lack of appropriate modeling tools affects the accurate assessment of the potential of the demand response (DR) within energy systems. Indicated that case studies suggested the potential for wastewater treatment plants to provide DR, but no study recognized the homogeneity of energy prices that arise from the widespread use of DR. Proposed an integrated modeling approach that combines energy system optimization with the level of operational detail in process simulation models. Recommended that such approach can yield a higher level of accuracy, regarding the assessment of DR potential from a specific process, such as wastewater treatment
Mahlknecht et al. (2020)	Energy	Examined baseline and resource security trends, based on the concept of the WEF Nexus in Latin America and the Caribbean. Developed a performance indicator to assess progress in the WEF Nexus' security in the regions studied. Also developed a correlation-based indicator to assess the interdependence of the three resources (WEF). Addressed issues and challenges that are critical to sustainable development. Showed that an unprecedented amount of infrastructure is needed to counteract the increasing energy consumption. Suggested that emphasis should be placed on the gradual replacement of high carbon sources of electricity with low carbon and clean energy production systems. Showed that the water scarcity will be exacerbated by the changing climatic conditions. Recommended that improvements are urgently needed in water management, water provision, and sanitation. Also recommended that it is important to promote new agricultural practices and sustainable food systems, by enhancing and implementing the WEF Nexus' approach
Norouzi and Kalantari (2020)	Water–Energy Nexus	Pointed out that the WEF Nexus' approach can bring about change and balance in various sectors, depending on the needs and participation of all stakeholders, taking into account the environmental and water crises that threaten Iran's food and energy security. Developed a model of the WEF Nexus' governance approach, using a multi-layered view of Iranian regions, regarding the water and food crises which the country is currently facing

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Norouzi and Soori (2020)	Water–Energy Nexus	Investigated the criteria and standards for evaluating different buildings, considering green building as a primary goal. Indicated that evaluation methods and mechanisms rely on the energy, environment, water, and land-use Nexus' approach, as one of the primary evaluation metrics. Compared the methods of obtaining sustainability assessment in three criteria dimensions—namely environmental, social, and economic
Putra et al. (2020)	Science of The Total Environment	Performed a systematic analysis of the WEF Nexus in South Asia, using open country-wide data sources. Statistically analyzed interactions amongst the WEF Nexus sectors. Identified positive and negative correlations between WEF safety indicators as synergies and trade-offs. Observed a greater share of trade-offs compared to synergies within the water and energy sectors, and a greater share of synergies compared to trade-offs amongst the WEF Nexus' sectors. Encouraged the strategies related to promoting sustainable energy sources (renewables), and discouraged the use of fossil energy sources that can have negative overall effects on the WEF Nexus' security. Provided evidence that WEF Nexus' security is viewed as an integrated system rather than just a combination of the three different sectors (WEF)
Sadegh et al. (2020)	Sustainable Cities and Society	Pointed out that agricultural irrigation accounts for 84% of global fresh water consumption, the food supply chain requires up to 30% of global primary energy use, and nearly 80% of global electricity generation depends on water for cooling. Thus, suggested a better understanding of the complex interactions of the WEF Nexus, as top priority for human well-being, sustainable development, and policy-making. Presented an interactive analysis toolkit of the WEF Nexus that brings together available data to enable modeling, analysis, and interrelationships of the WEF resources at the local and global levels. The samples analyzed included country-specific estimates of the water resources required to produce energy and different types of food, the energy required per amount of water or agricultural product, and the equivalent GHG emissions associated with the provision of water and energy, within the WEF Nexus' framework

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Shannak and Vittorio (2020)	Book Chapter	Described a spatio-temporal decision support tool that analyzes the energy requirements of the food sector based on the water demand in Saudi Arabia. The tool can provide policy-makers with background information for assessing greater energy inputs into food production and the factors that may influence increased energy use over space and time. The tool was developed using a web-based Geographical Information System (GIS) application, in such a way that it allows the user to navigate through different spatial locations, select an important point to grow a certain amount of a particular crop, and calculate the land, water, and energy requirements, representing a land–water–energy–food Nexus' approach
Sharma and Kumar (2020)	International Environmental Agreements: Politics, Law and Economics	Pointed out that, globally, 3 billion people do not have access to modern fuels or cooking/heating technologies; 900 million people lack safe drinking water; 2.6 billion people lack improved sanitation; 2 billion people lack intermittent food security; and more than 820 million people suffer from chronic hunger due to extreme poverty. Developed a model on the allocation and access of the WEF Nexus, based on the "Rawlsian Concept" of distributive justice for human security and the competing demands of WEF sources. Indicated that "policy coordination" amongst all actors that govern the WEF Nexus is a key to promoting fair allocation of, and access to, the WEF resources. Concluded that the findings can advance the objectives of mitigating trade-offs and enhancing synergies between WEF Nexus' resources, as well as preserving the environment in the context of the UN's SDGs. (Note: The Rawlsian Concept refers to John Rawls (1921–2002), who was an American political philosopher in the liberal tradition, and whose "Theory of Justice as Fairness" describes a society of free citizens holding equal basic rights and cooperating within an egalitarian economic system (SEP 2021)

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Zhang et al. (2020)		Pointed out that the WEF Nexus' security is a prerequisite for achieving the 2030 UN's SDGs. Indicated that the increasing restrictions and conflicts around the world, due to water scarcity, energy shortages, and food insufficiency, have forced people, globally, to think about the security and interdependence of each of the WEF Nexus' subsystems. Performed a bibliometric analysis of the literature on the WEF Nexus over the 1995–2018 period, and applied the CiteSpace technique for data visualization. Indicated that Nexus' research has not become a stable and independent system and is still suffering from great uncertainties, in terms of the mechanisms and driving forces of multi-system interactions. Concluded that synthesis and trade-offs amongst water, food, and energy sectors must be analyzed more systematically to gain insights into sustainable development
Al-Saidi and Hussein (2021)	Science of The Total Environment	Indicated that the COVID-19 pandemic provides an opportunity to study the effects of system-wide crises on key supply sectors, such as water, energy, and food (WEF Nexus). Highlighted the main long-term impact categories of medicalization/hygienization, (re)localization of production, and demand fluctuations. Indicated that analysis of the impacts of COVID-19 on the WEF Nexus reflects heterogeneous experiences of short-term adaptations and reassessment of the WF-Trade Nexus. Indicated that food adequacy can take advantage of green applications to reduce expected trade-offs. Regarding resource' security issues in the WEF Nexus, concluded that the globally wide-spread of COVID-19 reinforces discussions of the adequacy of production value chains (e.g., contingency and storage, diversification, and self-sufficiency) and the value of cross-border integration (e.g., trade, globalization, aid, etc.)

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Carmona-Moreno et al. (2021)	Book	Pointed out that the European Commission's Joint Research Center (EC' JRC) in partnership with the UNESCO's Intergovernmental Hydrological Program (IHP) launched, in 2018, the Water–Energy–Food–Ecosystems Nexus' (WEFE Nexus) project. The project, supported by the European Union Dialogue Program NEXUS and co-financed by the European Union (EU) and the German Federal Ministry for Economic Cooperation and Development, aimed to analyze security supply solutions. The project addresses the effective implementation of measures for sustainable growth by contributing to EU policy objectives and conducting analyses of the water, energy, and food security resilience of societies, without compromising ecosystem services. The project's components are present in 14 of the 17 UN's Sustainable Development Goals (UN's SDGs), whereas those components are closely related to be implemented

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
European Commission (2021)	EU's Research and Innovation Programme, Horizon 2020 (2014–2020)	Pointed out that water, energy, and food resources are essential to human well-being, poverty reduction, and sustainable development. Indicated that projections suggest that demand for fresh water, energy, and food will rise due to demographic changes, economic development, and international trade, amongst other things. Indicated that climate change imposes additional pressures on water availability and quality, and causes extreme events (floods/droughts) with severe social, economic, and environmental consequences. Suggested that mitigation and adaptation actions to climate change and variability can have powerful impacts on the surface water and groundwater systems and users. Also, changes in energy use and types of energy production (for example, fossil fuels replaced by hydroelectric or biofuels) can considerably affect water use and agricultural production. Concluded that the resulting conflicts in water distribution amongst the water, energy, and food sectors or subsystems cause additional concerns about the sustainable management of water resources, particularly transboundary water bodies, where a very large proportion of the world's population lives. Within this framework, the EU's Horizon 2020 Programme funded several projects to investigate the strong relationship amongst the water, energy, and food subsystems (WEF Nexus), in relation to the climate change impacts, as being essential mechanisms in achieving the goals of the European Green Deal. This deal aims to make the EU's economy sustainable by making the WEF Nexus an effective tool in sustainable development, and by turning climate and environmental challenges into opportunities in all policy areas

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Fontana et al. (2021)	Frontiers in Water	Presented “Five W Questions” (FWQ) as an iterative guide to the concept of WEF Nexus to encourage reflexivity and interdisciplinary dialogue, while aiming to produce actionable knowledge. The FWQ are: (i) ‘why’, in which the purpose of correlative research for actionable knowledge can be explored; (ii) ‘what’, in which the physical aspect of the interdependence and interactions amongst water, energy, and food subsystems (WEF Nexus) can be understood; (iii) ‘where’, in which issues of scale, interactions between scales, and the geographic context of the WEF Nexus or interdependence can be discussed; (iv) ‘when’, in which the temporal dimensions of interconnected research with a particular focus on intergenerational trade-offs can be considered; and (v) ‘who’ which focuses on relevant stakeholders and the importance of understanding justice and equity issues
Heal et al. (2021)	Hydrological Science Journal	Pointed out that the role of water quality and, in particular, its impact on health, the environment, and the broader well-being of the water–energy–food (WEF) Nexus, is rarely acknowledged. Demonstrated the necessity of including water quality in the water dimension of the WEF Nexus, to address the complex and multidisciplinary challenges facing humanity. Explained the impact of water quality on the energy and food dimensions of the WEF Nexus and vice versa at multiple scales, from households to cities, regions, and transboundary basins. Used examples to show how including water quality would increase and improve the WEF analyses and applications. Encouraged hydrologists and other scientists to promote relevant water quality research to address the associated challenges of the WEF Nexus. To make tangible progress, suggested that analyses of water quality interactions initially focus on interconnected WEF “hotspots,” such as cities, semi-arid regions, and regions dependent on groundwater or meltwater threatened by climate change

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Kondash et al. 2021	Environmental Science & Policy	Explored the state of WEF Nexus research in Guatemala to highlight progress, while also noting future research needs. Found that only a limited number of studies have inducted the correlation amongst WEF subsystems; 26% of articles (36 out of 138) focused on two aspects of the WEF, while 20% (27 out of 138) focused on all three aspects (WEF). Found that water issues were the most common to study, with drinking water, hydropower, and wastewater management frequently discussed. Pointed out that WEF Nexus in Guatemala revolves primarily around three separate but related areas: clean water and sanitation, climate change and renewable energy, and urbanization and modernization. Concluded that the inter-related roles of the WEF Nexus can improve the resilience of natural resources and reduce the multi-dimensional poverty in the country
Purwanto et al. (2021)	Sustainability	Presented knowledge gaps and criticisms, regarding the relationship amongst water, energy, and food (WEF Nexus) that have emerged since the WEF Nexus' concept was proposed by the World Economic Forum at the 2011 Bonn Conference. Analyzed current innovations around the WEF Nexus' concept and its applications and implications during 2012–2020. Proposed improvements to the interconnected frameworks that have been identified to narrow the gaps and put the WEF Nexus' concept into practices of management and governance. Proposed four principles and the 'local-to- global' perspective for development of a future WEF Nexus' framework to ensure sustainable water, energy, and food resources' security, which can improve the impacts of national and global ambitions regarding the WEF Nexus' security

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Tayal and Singh (2021)	Book Chapter	Indicated that the recent outbreak of COVID-19 has created a widespread impact on the economy, and disrupted the normal livelihoods of people around the world. Also indicated that COVID-19 has provided an opportunity for the integrated management of already stressed natural resources, such as water, energy, and food. Reviewed various aspects of the WEF city-wide interdependence with reference to two major cities in India (Navi Mumbai (Maharashtra) and Gurugram Haryana), under both pre-COVID-19 and in current scenarios. Examined the possibility of implementing mitigation measures integrated to ensure optimal WEF consumption levels and sustainable environmental benefits. Recommended that it is necessary to resume economic activities, but an integrated approach around the management of WEF resources has the potential to ensure sustainability from the environmental benefits achieved during COVID-19
Wang et al. (2021)	Renewable and Sustainable Energy Reviews	Explored the extended links amongst the water, energy, and food resources, such as GHG emissions, waste, pollution, land, etc. from a relationship and practical perspectives in mitigating challenges towards the environment-related UN's SDGs. Recommended that the term "Nexus" is generally more attractive to replace specific expressions, such as multi-criteria optimization, trade-offs, correlation, relationship, input–output evaluation, material flow analysis, and integrated design. Indicated that methodologies, such as input–output analysis and life-cycle assessment, necessitate the need to adequately integrate the WEF Nexus' diversity. Recommended that necessary assessment of resource flows in multiple regions and sectors, as well as the associated environmental and socioeconomic impacts, should be taken into account within the WEF Nexus

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Yuan et al. (2021)	Science of The Total Environment	Used a qualitative approach to form priority strategies in four selected cities—namely Amsterdam and Eindhoven (The Netherlands), and Taipei and Tainan (Taiwan), in order to study the WEF Nexus. Developed a system of indicators to guide implementation and improve urban sustainability, to illustrate the policy mechanisms and heterogeneity of sustainability issues related to the WEF Nexus at the city level. Concluded that renewable energy plays a fundamental role in the WEF Nexus' framework, while future Nexus' work should focus on technological innovation. Suggested that the unique combination of factors affecting water, energy, and food Nexus' sustainability provides a comprehensive view of the broad and complex challenges that cities face due to resource constraints, which can help guide future practices of governance
Yue et al. (2021)	Journal of Hydrology	Proposed an imprecise optimization's approach from the perspective of a new Nexus that links water–food–energy–climate change–land (WORLD), which has the potential to promote socioeconomic development, ensure livelihood security, and achieve a low-carbon target. Pointed out that WORLD subsystems are closely intertwined, and play notable roles in the regional and global resource management's systems. Recommended that there is a need to quantify the connections, synergies, and trade-offs across the WORLD subsystems in a more integrated and holistic manner, which is a challenging approach due to the complexities and uncertainties involved amongst the WORLD components
D'Amore et al. (2022)	Sustainability	Analyzed the role of Artificial Intelligence Technique in the WEF Nexus under the perspective of enterprise and stakeholder's theories and innovation. Particularly focused on AIT as a technology that companies adopt to promote sustainable development, with respect to the UN's SDGs. Developed an in-depth review of the literature that discusses the investigated main issues. Highlighted the importance of AIT in relation to the WEF Nexus' industries and the UN's SDGs, and concluded that the WEF Nexus and AIT are still needed to be deeply researched and investigated. Also concluded that it is highly important that AIT and other digital technologies should play a remarkable role in addressing the interconnected challenges of the WEF Nexus

Table 1 (continued)

Study by	Journal/book chapter/technical report/conference/action plan	Study areas/approaches/objectives/methodologies/tools/results/suggestions/recommendations
Feng et al. (2022)	Frontiers in Environmental Science, Frontiers in Ecology and Evolution, and Frontiers in Earth Science	Indicated that the booming development of advanced Artificial Intelligence Technique' methods could provide new possibilities for dealing with many practical engineering problems. Indicated that using well-designed mathematical models and a block of desired datasets, AIT methods can offer the advantages of high response speed, strong generalization's ability, and high data processing's ability. Pointed out that AIT is beneficial in promoting applied sciences involved in the linkages amongst water, energy, and food (WEF Nexus), as well as the environment, and, thus, contributing to the implementation of sound policies and sustainable solutions under a rapidly changing global environment
Yuan and Lo (2022)	Renewable and Sustainable Energy Reviews	Developed three special themes, which are assessment, awareness, and accessibility, regarding the WEF Nexus. Described interconnected governance that promotes integrated evaluation into cross-sectional and sectoral coherence of the WEF Nexus. The framework of the WEF Nexus governance is based on a cohesive set of nine principles, including: connectivity, innovation, equitability, participation, coordination, sharing, legitimacy, empowerment, and strategy. Taking Taiwan as an example, the results showed that effective Nexus' management requires a range of combined integration options

Water–food (WF) Nexus in five different regions of the world

The WF Nexus' thinking is approached in this paper from the perspective of equitable and sustainable growth and the multi- and inter-disciplinary relationship amongst population's growth, environment, climate change, society, economy (including green economy), finance, governance, innovation, urbanization, infrastructure, green cities, policy, synergies, trade-offs, governability, and, to some extent, water as a basic human right, international law, and regional geopolitics (Fig. 1).

To understand the interlinkages between the water and food subsystems (or elements), the following five regions were investigated in the present work, considering the variations amongst the different regions, concerning, for instance, climate, population, culture, socioeconomic conditions, and so forth.

a. Gulf Cooperation Council's (GCC) Countries: The six Gulf Cooperation Council's (GCC) countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates—UAE) constitute together an area of approximately 2.6 million km^2 (more than a million square miles). The population estimates indicate that more than 60 million people live in all GCC countries, and their total GDP is USD 3.464 trillion (WPR 2022a, b).

More money will come to the coffers of the Gulf Cooperation Council countries as a result of the recent war between Russia and Ukraine. This is due to oil and gas prices that have skyrocketed to over USD 100. If this war would continue for an extended period of time, it will have dire implications and consequences for the global economy, stability, and security (see, for instance, Jones 2022; Power 2022; Whalen and Bogage 2022).

The GCC countries are considered some of the driest and most freshwater-stressed countries globally. Accordingly, reasonable water management has become a challenge to the GCC countries, separately and collectively, as being considered one of the most difficult assignments confronting them. Water in the GCC countries is made available through three resources: (1) Groundwater, which is usually replenished by seasonal rains that are decreasing year after year due to climate change impacts and large, ungoverned water consumption; (2) Desalinated seawater, which is supplied via modern, high-tech desalination plants; and (3) Wastewater treatment and reuse, which has been introduced relatively recently, and is obtained via wastewater and sewage treatment plants that supply water for agricultural purposes at limited scales only (Saif et al. 2014; Aleisa and Al-Zubari 2017; Yihdego and Salem 2017; Qureshi 2020; Salem 2021).

By expanding the areas used for agriculture and, thus, the water consumption to satisfy irrigation and population's growth needs, the groundwater resources will dry out in the Gulf countries (Novo 2019; Al-Saidi and Hussein 2021). Estimates of the groundwater resources below the Saudi deserts have a range between 252 and 870 billion cubic meters (BCM) of "fossil groundwater" (NASA EO 2012a). On average, the Saudi deserts sit atop 500 BCM of fossil groundwater.

By 2008, 21 BCM of fossil groundwater were extracted annually to support modern intensive agriculture in Saudi Arabia (FAO 2008), whereas 87% of the water resources in Saudi Arabia go to the agriculture sector (Napoli et al. 2016; Ghanim 2019). By 2012, the consumption for human, industrial, and agricultural usages was 23.7 BCM/year (NASA EO 2012a). This fossil groundwater is used much faster than it can regenerate or replenish itself. The enormous imbalance between the current (as for 2020) groundwater discharge or consumption (currently 27.8 BCM/year) and fossil groundwater recharge (currently 5.3 BCM/year) causes the excessive lowering of groundwater levels in the aquifer systems in Saudi Arabia (Qureshi 2020). Accordingly, the discharge is approximately 5.25 (i.e., 27.8/5.3) times the replenishment rate of renewable groundwater resources. Other GCC countries have already reached a drawdown ratio of around 3:1, except for the UAE, where this ratio is much higher. Experts, accordingly, have estimated that 80% of the Saudi fossil groundwater has been gone (National Geographic 2012; DeNicola et al. 2015; Chandrasekharam 2018; Sultan et al. 2019; Bafarasat and Oliveira 2021). Over the past three decades (1990–2020), Saudi Arabia has been exploring and exploiting groundwater (fossil and replenished) at extremely severe rates, which is considered a resource that is more precious than hydrocarbons (oil and natural gas), especially Saudi Arabia and the other GCC countries have enormous sources of renewable energy, particularly solar energy (Basha et al. 2021).

Engineers and farmers have tapped into hidden water reserves to grow grains, fruits, and vegetables in the extremely hot deserts of Saudi Arabia. Figure 2 shows satellite images illustrating the evolution of agricultural operations in the Wadi As-Sirhan Basin, Saudi Arabia (NASA EO 2012b), as viewed by satellites over a period of a quarter a century (i.e., in 1987, 1991, 2000, and 2012).

The average precipitation is only 100–200 mm/year, and it usually does not recharge the aquifer systems in Saudi Arabia and other GCC countries. On the other hand, about 17,300 km^2 of irrigated areas will shrink in the foreseeable future due to water shortages; thus, resulting in a sharp reduction in the GDP contribution below 3%, which ascertains the groundwater as a non-renewable resource (Aboud et al. 2014; Chandrasekharam 2018; Pester and Zimmermann 2022). As for 2006, Saudi Arabia had 2.4 BCM of renewable freshwater resources on the surface, according to the Food and Agriculture Organization (FAO) (FAO 2008).

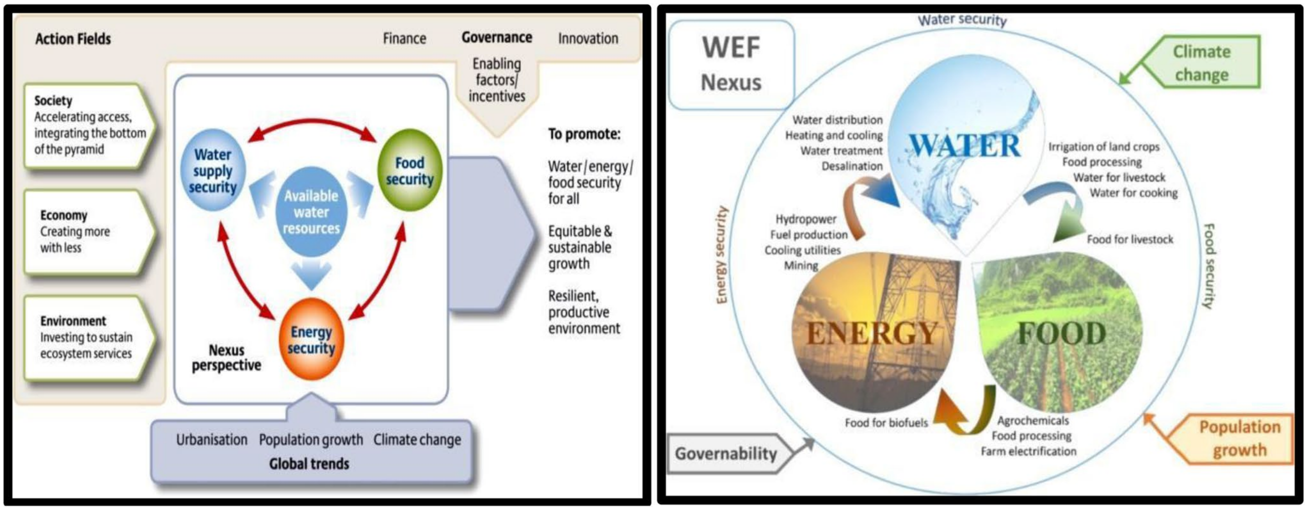

Fig. 1 Summary of the water–energy–food (WEF) Nexus (after Hoff (2011) and Albrecht et al. (2018) (left), and after Mahlknecht et al. (2020) (right))

Fossil groundwater in Saudi Arabia gave the nation hope of achieving its long-awaited goal of feeding itself rather than importing food from other countries. Saudi Arabia increased wheat imports from 1.92 million tons (MT) in 2013 to 3.03 MT in mid-2014, which was a short-term solution to circumvent water scarcity (Chandrasekharam 2018). In 2019/2020, Saudi Arabia imported 3.7 MT of wheat; 93.1% of the latter was imported from the European Union (EU) (Mousa 2021). However, as the war between Russia and Ukraine is currently going on, many countries worldwide, including Arab countries, will be badly affected regarding the wheat, corn, and cooking oils imported from Russia and Ukraine. This is due to the fact that Russia and Ukraine are primary exporters of these food products, worldwide (see, for instance, Arab News 2022; Quinn and Durisin 2022; TAW 2022).

Water management's efficiency or good governance of water resources in the GCC countries, on the supply–demand side, is very low. On the supply side, the fraction of the physical spillage of non-revenue generating water in urban systems ranges from 30% to over 40% (Al-Saidi and Saliba 2019). This contrasts with the expense of desalinated water, which is somewhere in the range of USD 0.5–1.0 per cubic meter (Ghaffour et al. 2013; Al-Saidi and Saliba 2019). Currently, 439 desalination plants produce 5.75 BCM/year of desalinated water in the GCC countries (Qureshi 2020). The WF Nexus indicates how important seawater desalination is in the GCC countries and how it plays a major role in increasing drinking water supply and meeting water demands in the food and agricultural sectors—considering that the GCC countries collectively bear about 60% of the global production of desalinated water (Al-Farra 2015; Qureshi 2020).

b. Central Asia Countries and the Caucasus: The Central Asia and Caucasus region comprises five Central Asia

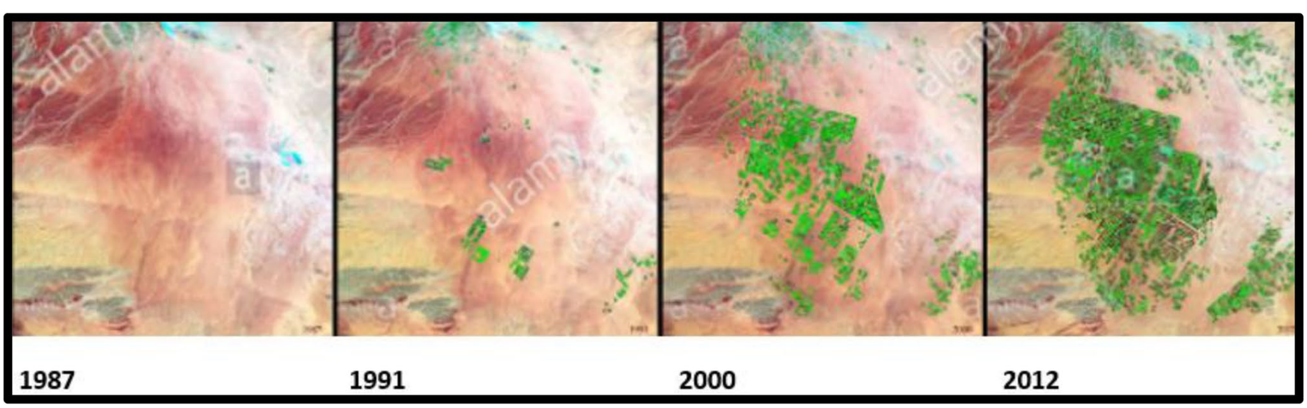

Fig. 2 Irrigation in Saudi Arabian deserts as seen from space (Image ID: DW64EE) for years—from left to right—1987, 1991, 2000, and 2012 (modified after Grist 2012)

countries—Uzbekistan, Kazakhstan, the Kyrgyz Republic, Tajikistan, and Turkmenistan—lying east of the Caspian Sea, and their three neighbors to the west of the Caspian sea, namely Azerbaijan, Armenia, and Georgia. The region is located near the center of the Eurasian continent, and its close proximity to Russia, China, the Middle East, Afghanistan, and Pakistan makes it vulnerable to geopolitical unstable regional conditions (Fig. 3). All countries in the region gained their independence after the collapse of the former Soviet Union in 1991. While they all seek to follow market economy systems, there are significant disparities in economic development due to each country's natural resources and other factors such as pace of reforms (JICA 2010).

In recent years, many Central Asian countries are striving to use water to generate hydropower from the Rogun Dam on the Vakhsh River, which is a branch of the Amu Darya River Basin (ADRB), representing Afghanistan's northern border with Tajikistan, Uzbekistan, and Turkmenistan (Fig. 3). The Dam will provide hydropower to the upstream country—Tajikistan, while the downstream countries fear the opposite effect when flooding of the River will affect their horticulture in a very negative way. Despite some recent evaluations of the water assets' management in ADRB, nothing to date tends to adversely negate the framework of the WF Nexus in the region of the Rogun Dam. To this connection, two basic methods of servicing the Dam were examined: (1) The energy situation, which ensures the hydropower needs of Tajikistan (WE Nexus); and (2) The deluge method, which guarantees water for agriculture for the downstream countries of the River (WF Nexus).

The outcomes that address the Rogun Dam (as aforementioned) show that the lifestyle can ensure a doubled vitality to Tajikistan, yet it will reduce access to water during the developing period, resulting in a 37% natural reduction in rural advantages in the downstream countries (Jalilov et al. 2016). In Central Asia, specifically, natural sciences and engineering professionals do not hold a prominent function in water assets' management. Moreover, Georgia, Tajikistan, Turkmenistan, and Uzbekistan (Fig. 3) are the central notable countries that did not agree to the Espoo Conference. Armenia only confirmed the Protocol on Strategic Environmental Assessment (SEA Protocol), while Georgia and Moldova have marked the SEA Protocol but have not yet approved it (UNECE 2013).

Fig. 3 Map of the Central Asia Countries and the Caucasus (modified after Maps Owje 2022)

In Moldova and Turkmenistan, national techniques for modifying environmental changes include water issues. An adjustment procedure for water supply and sanitation has also been drawn up in Moldova with the help of the Organization for Economic Cooperation and Development (OECD) and the European Union (EU). Kyrgyzstan has already built up a national methodology to adjust water assets' management to face the impacts of environmental changes (UN OECD 2014).

c. China: In China, the total annual preserved water assets are around 2800–2841 BCM (Xie et al. 2009; MWR 2011). Even though the full water preserved has increased, making it the sixth-largest proportion of other nations on the Earth, the per-capita water assets were 2040 m^3/ca/year in 2008, forming about a quarter of the global average (Liu et al. 2012). It is, in any case, an extraordinary share of water (2040 m^3/ca/year) compared with other nations in different regions of the world. For example, in the Occupied Palestinian Territories—OPT), the per-capita water supply per year reaches, in some localities of the OPT, as low as 7.3 m^3/ca/year (about 20 l/ca/day) (Salem and Isaac 2007; Isaac and Salem 2007; B'Tselem 2014; Hass 2014; Corradin 2016; Salem et al. 2021). However, this is not a result of water shortage but rather the geopolitics dominating the region. Israel (the occupation authority) is in almost total control of the Palestinian water assets (Corradin 2016; Salem et al. 2021).

Other than the generally few per-capita water assets in China, space allocation of water exacerbates the water shortage problem (Fig. 4). Ruled by the mainland rainstorm climate, 60–70% of annual rainfall in many regions of China is collected in summer times, whereas this rate is much higher in the northern parts of China (Cheng et al. 2009; Fang et al. 2021; Kondash et al. 2021; Yuan et al. 2021). Annual precipitation in China decreases little by little from the largest scale, over 2000 mm/year, to the lowest scale below 100 mm/year (Zhai et al. 2005; Ding et al. 2021). Also, the decrease in the annual precipitation in China has resulted in a clear increase of soil loss with precipitation up to mean annual precipitation of approximately 700 mm/year (Zhao et al. 2022). Water accessibility demonstrates a greater variation of space, whereas access to water assets is lower in northern China than in other regions of the country.

The Huaihe, Haihe, and Huanghe (3H) waterways' basins (ponds), mainly located in the North China Plain, account for 33% of China's water, 35% of the water yield, 40% of the developed land in China, and 50% of the general grain production. However, this area forms only 7.6% of the country's

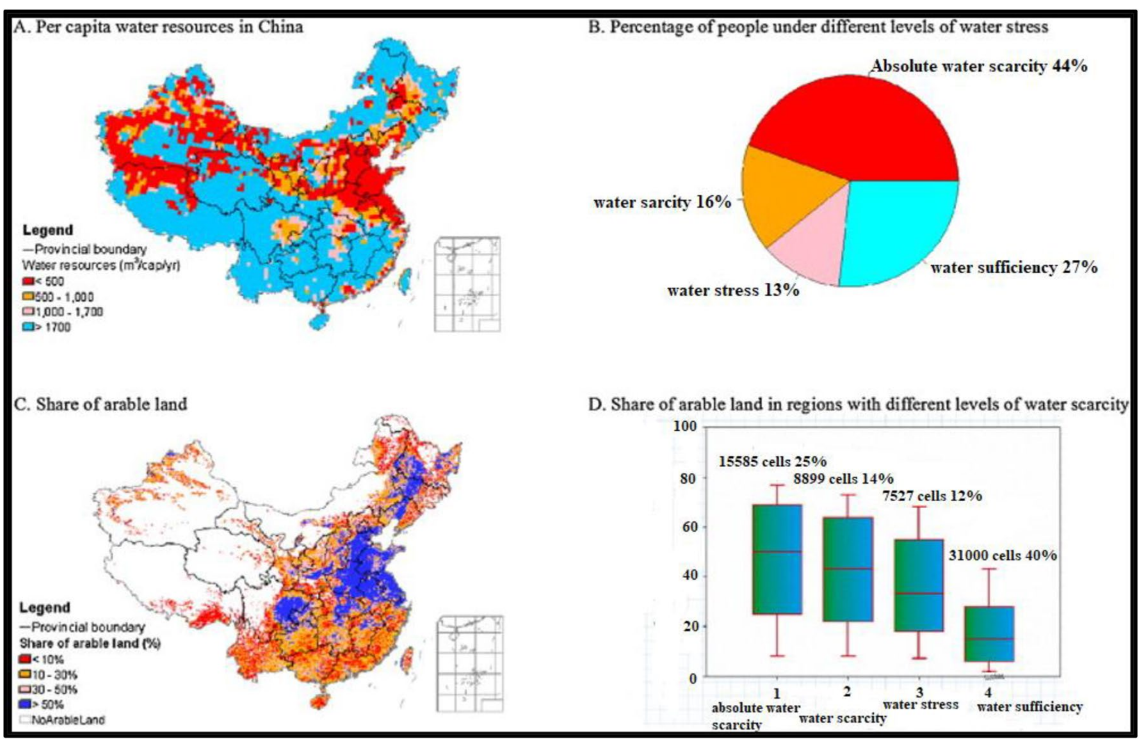

Fig. 4 Spatial dissemination of the Chinese water and arable land assets: **A** spatial example of water usage assets. All information depends on heave normal run-away evaluation and populace for the time of the year 2000 (CIESIN 2010) with a spatial goal of 30 circular segments; **B** the number of people below the various amount of water pressure; **C** portion of developed terra territory. Developed land information is from Fischer et al. (2008) with spatial goals of 5 circular segment minutes; and **D** portion of viable land with water shortages (modified after Liu et al. 2013)

water assets (Guoyuan and Jiongxin 1987; FAO 2011; Liu et al. 2013; Yu and Wu 2018). The 3H-ponds are amongst the Chinese regions with severe water shortages. In contrast, the management of water assets is of critical importance to maintain water and sustenance provision, societal resilience, financial development, and natural well-being at the provincial and federal levels to a large extent. This is because of the uneven distribution of water assets and population, and due to the fact that 44% of China's population lives in areas with severe water shortage (< 500 m^3/ca/year) and 16% of the population lives in areas suffering from water shortages (500–1700 m^3/ca/year) (Fig. 4A) (Liu et al. 2013).

Significant irregularities between water assets and arable land increase the water shortage problem. Arable land in China was only 0.08 ha/ca in 2008 and is still almost the same until recently (World Bank 2021), less than 40% of the average global level (FAO/WHO 2001; FAO 2021). The largest fertile land offerings are located in the North China Plain, the Northeast Plain, and the Sichuan Basin (Fig. 4C), yet these areas often suffer from real water shortages (Fig. 4A). Most of the developed arable land is located in deserted areas (Fig. 4D), including, for example, the North China Plain, which is known as "China's Bread Box" or Bin. Rainfall is insufficient to help generate expanded yields; however, the well-managed water system is expected to achieve a highly efficient yield, or in other words, to accomplish high harvest efficiency (Liu et al. 2013), representing a good achievement towards the WF Nexus in China.

d. Africa*:* Africa is a unique mainland, but it harbors several traits and problems regarding societal structures, monetary systems, and common assets, among others. Africa's multi-faceted ecology and natural resources require effective official responses to some formative measures (such as quality practices and their impacts on regional development), national assets, and security issues (Yihdego and Kwadwo 2017). Because of the mismanagement and high levels of corruption in many African countries, their governments are losing the financial revenues of their natural resources, including, for instance, the large revenues of energy (fossil and renewable) sources, considerably (Yihdego et al. 2017b, 2018a, b). Africa enjoys several renewable energy sources, including solar power, wind power, and hydro-power, which all have considerable values of the capacity factor (CF). The CF of a power plant is defined as the ratio of the actual energy produced in a given period to the hypothetical maximum possible (Yihdego et al. 2017b).

This also applies to issues related to water which, apart from its more considerable natural resources (surface and underground), are the heterogeneity of African landscapes and surroundings. Despite the efforts made by some African countries and the global network to advance, including, for instance, the achievements of the UN's Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs), many countries in Africa have missed the targets, particularly concerning integrating water supply and sanitation (Daniel et al. 2014; EABW News 2019). This is despite the fact that Africa, in general, enjoys considerable amounts of annual precipitation, recharging the surface water and groundwater bodies in the continent (Fig. 5).

Settlements in Africa, either urban or semi-urban, have contradicting access to water assets and use and management. These contradictions must be evaluated and taken into account when determining specific strategies for water advancement and management (Yihdego et al. 2017a). For example, the Africa Water Vision 2025 (AWV 2025) promotes that Africa, where an unbiased and maintainable use and management of water assets exist, should alleviate poverty, improve financial revenues, encourage regional participation, and preserve nature (UN Water/Africa 2004).

Rapid population's growth, improper water management, insufficient institutional plans, high rates of water consumption, pollution of water assets, climate change impacts, environmental degradation, deforestation, and low and unsustainable financing of interests in water supply and sanitation are all part of the significant risks that pose difficulties to manage water assets on the mainland Africa (Anelich 2014; Daniel et al. 2014).

Population's growth is one of the major problems Africa has been facing. By 2020, Africa had over 1.36 billion inhabitants with a population's growth rate of 2.49%, and the continent's population will continue to increase significantly in the coming years, reaching nearly 2.5 billion people by 2050 (Saleh 2022). It is generally envisioned that risks cannot be dealt with effectively by adhering to the same age-old things in water assets' management at the local, national, and regional levels. Attention to risk calls for appropriating good governance, community agreement and involvement, creative progress, and all the structures created for beneficial activities, guided by the AWV 2025, the UN's MDGs, and the UN's SDGs, urge African governments to deal with all water improvement issues, plus vitality improvement issues (Yihdego and Salem 2017).

One of the most severe difficulties that must be addressed if the AWV 2025 and the UN's MDGs and the UN's SDGs are to be achieved is the lack of trained personnel (specialized and administrative) and monetary and material assets. It is specifically important with what has been identified concerning the management and implementation of water and sanitation administrative issues and projects (Pietersen et al. 2006; Yihdego and Kwadwo 2017). Other than the labor shortage in the water assets' management, there is a need for more qualified personnel in parts of water laws and regulations and financial matters for quantitative water assets. The low rate of retention of qualified staff, the lack of adequate preparation and underfunding, and generally the lack of research institutions affect, primarily, the water assets

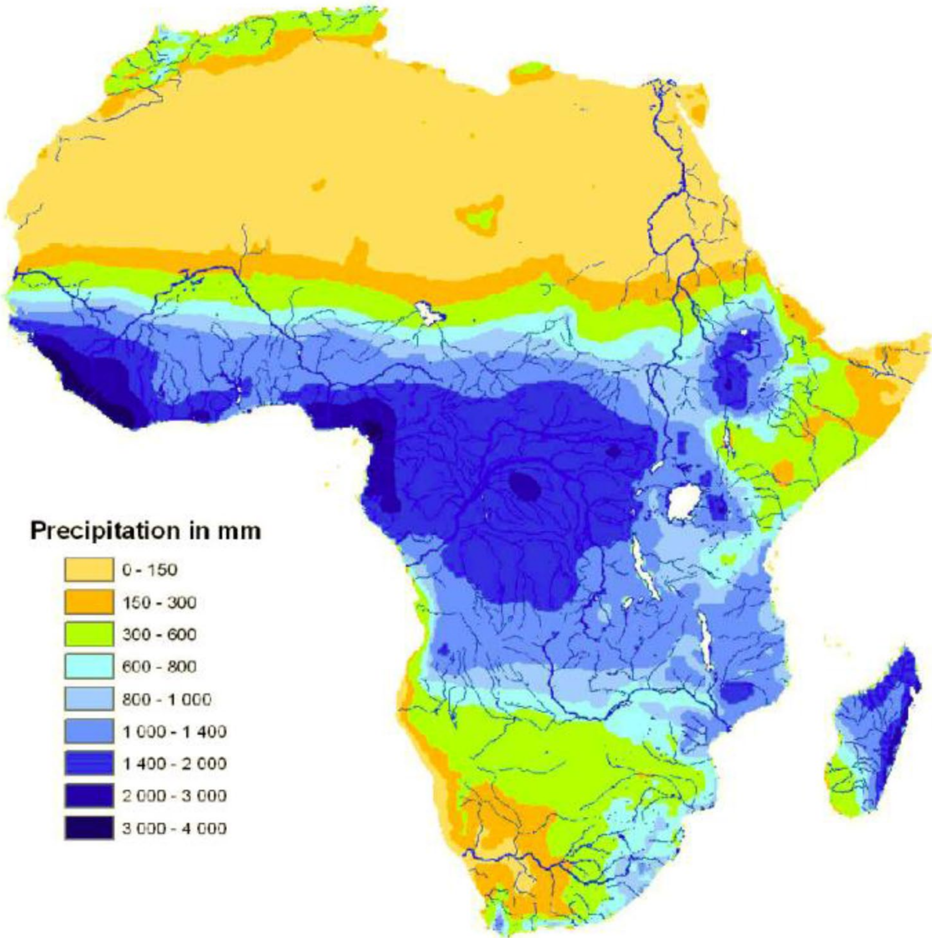

Fig. 5 Map of the mean annual precipitation in Africa (modified after Al-Gamal and Hamed 2014)

in Africa, though they are plenty. Likewise, there is a need to set a societal limit about WASH (USAID's Water, Sanitation, and Hygiene projects) and the assets to be effectively used through instructions, institutional good management, and data correctness and availability.

There is primarily a lack of technical know-how and institutional quality, especially in Integrated Water Resources Management (IWRM), where delivery of good management of water assets is limited (Pietersen et al. 2006). Strengthening indicative boundaries, preparing limits at all levels, advancing harmonization, and enhancing information collection and sharing are all advantageous elements for IWRM in Africa (Daniel et al. 2014). The good news is that the United Nations has recently indicated that there is some progress taking place regarding IWRM in Africa (UNEP 2021).

e. Canada: It is easy for Canadians to assume that they have an almost endless supply of clean freshwater, as Canada harbors 7% of the world's renewable freshwater (GoC 2018) (Fig. 6), with a total population of approximately 38.4 million as of July 2022—equivalent to only 0.48% of the total world population (Worldometer 2022b). In addition, Canada is the second-largest country in the area after Russia. Russia occupies 17.1 million km^2 and Canada, 9.985 million km^2—followed by the USA (9.857 million km^2) and China (9.597 million km^2) (CoW 2022).

Approximately 60% of Canada's freshwater drains to the north, while 85% of the total population lives close to Canada's southern borders with the USA. This makes harnessing and managing the Canadian water resources a considerable challenge, both nationally and within individual provinces and territories. In 2013, 37 BCM of freshwater was withdrawn from Canada's lakes, rivers, and underground aquifers (Pope 2019). Most of this water was used for industrial purposes, especially power generation, manufacturing, and agriculture (OMECC 2010; Loomer and Cooke 2011; McPhie and Post 2014; Roth and de Loë 2017).

Canada displays the following water characteristics (Fig. 6): Approximately 9% (891,163 km^2) of Canada's total area is covered by fresh surface water (rivers, lakes, and wetlands); Canada's rivers drain 105,000 m^3/s; The Mackenzie River is the longest river in Canada, with a total length of 4241 km; Canada has 563 lakes, covering an area of more than 100 km^2; Wetlands in Canada cover an area of more than 1.2 million km^2 (14% of the size of Canada's land),

Fig. 6 Canada's waterways map (modified after Maps Canada 2022)

forming approximately 25% of the world's wetlands, and making Canada the largest wetland's area in the world; Glacial ice, over 100,000 years old, has been found at the base of several ice caps in the Canadian Arctic; Glacial erosion created a number of lakes on the Canadian Shield, including the Great Lakes; It is estimated that about 2% (200,000 km^2) of Canada's area is covered by glaciers and icefields; There are currently 2921 active water level and stream flow stations, operating in Canada; and Canada's longest inland waterway runs 3700 km from the Gulf of St. Lawrence to Lake Superior (AWPS 2012; Freeman 2016; Pomeroy et al. 2019).

To face the escalating water problems in Canada, including those naturally caused or manufactured (man-made), the following strategies are recommended to be taken by the Canadian Federal Government: (1) Creating a "Canada Water Security Centre" that measures, investigates, monitors, predicts, stores, and disseminates comprehensive data and information about all water resources in the country. Such data would enable the center to respond to all water problems that are resulted naturally and anthropogenic, including floods, droughts, pollution, shortages, etc.; (2) Establishing a "National Water Committee" that promotes transboundary water management, prioritizes the protection of intact basins of the lakes and rivers, and directs water management and climate change mitigation and adaptation measures and strategies; (3) Improving cooperative planning of lakes and rivers' basins, by building enduring partnerships for water management and decision-making with provinces, territories, and Indigenous governments. It is to be with a clear outcome for building resilience in the face of extreme events, identifying priority areas for restoration of lakes and rivers' basins, and ensuring that ecosystem requirements are met across levels of jurisdiction and authority; and (4) Promoting reconciliation with the First Nations' Indigenous (FNI) communities, by ensuring that the Canadian Water Law is consistent with the United Nations Declaration on the Rights of Indigenous Peoples (UN DESA IP 2007; HRW 2016), and adopting a consent-based, co-drafting approach to law renewal in partnership with local Indigenous governments (Schraeder 2009; OMAFRA 2016; Roth and de Loë 2017; Pomeroy et al. 2019; TCC 2021).

The access to sufficient, affordable, and safe drinking water and adequate sanitation is easy for most Canadians. However, this is not the case for many First Nations Indigenous communities. In stark contrast, the water supplied to many FNI's communities on the lands, known as "Reserves," is polluted, difficult to access, and endangered due to defective treatment systems. The Canadian Federal Government regulates water quality for Canadian communities, but has no binding water regulations on the Canadian FNI's Reserves. A recent investigation carried out by the

Canadian Broadcasting Corporation (CBC) revealed that 180 homes in Garden Hill First Nation, Manitoba, Canada, lack running water and indoor plumbing, and some residents do not have central heating or electricity (CBC 2019; Palmater 2019). "We found that the Canadian government has violated its international human rights obligations toward First Nations persons and communities by failing to remedy the severe water crisis" (HRW 2016, 2019). According to Palmater (2019), "The First Nations water problems [are] a crisis of Canada's own making. How many Canadians would settle for water infected with fecal matter, sewers backing up into their bathtubs or being able to bathe only once a week due to lack of access to water? In all likelihood, if this were happening in any Canadian municipality on the same scale as in First Nations, a state of emergency would be declared and all resources would be brought to bear to address the crisis."

The quality of drinking water's supplies in rural and FNI's communities has dramatically deteriorated in recent decades, resulting in more than 100 drinking water's warnings for Reserves in Canada as of 2015, which have enforced some FNI' Reserves to boil water, and pay for water delivery and transportation costs. Accordingly, since 2015, the Canadian Federal Government has spent CD (Canadian Dollar) 2 billion to improve access to safe, clean drinking water in FNI's communities (Pomeroy et al. 2019). This laudable goal is to address the symptoms, but not the basic water problems that are facing the Indigenous population in Canada, according to Pomeroy et al. (2019). The inherent rights, laws, and jurisdiction of the Canadian Indigenous population in waters, as well as negotiated treaties, land claims, and governance agreements, all point to their role as full partners in decision-making, regarding water and other natural resources, as well as land use.

On another point regarding water in Canada, the big fear for groups like the "Council of Canadians" is that it will end up treating water as a commodity and that huge quantities of water will be funneled south to dry regions like California in the USA, through wholesales or water diversion projects. Successive Canadian governments, however, have pledged to never allow such sales and no deals have yet been struck. For instance, attempts to sell large quantities of water from Lake Superior and Newfoundland were only banned due to public pressures (Freeman 2016). Nevertheless, the Canadian Federal Government has firmly expressed that it will not allow exports of water to foreign countries (AWPS 2012).

Water conservation modeling and development strategies

In the twenty-first century, modern water management modeling provides an excellent opportunity for an astonishing scale to investigate and manage water utilization. Water management modeling mitigates the continuous financial wastes resulting from development in the water sector. Traditional water conservation projects aimed to boost financial attributes, such as GDP. Future water conservation modeling needs to be emphasized by amplifying the overall estimates of economic, social, agricultural, and environmental benefits.

A system should be built that includes both financial and ordinary capital (i.e., estimates of biological system's administrations in nature) (Carpenter et al. 2011) to assess biological community administrations of the oceans, seas, rivers, lakes, wetlands, and other water bodies; competition uses of conserved water; and actions that support the whole conserved water security bargains.

Water conservation in China, for instance, has put great attention to the foundations and primary goals of restricting waterways. The benefits of putting resources into premium protection are largely overlooked. For example, only about 3.3% of concerns in conserving water safety will be devoted to ensuring soils and waters' well-being and extending natural recovery in 2010. Hence, water conservation in the future needs to revitalize environmentally friendly projects (Tortajada 2001; Shucheng 2006; Jiao 2009; WBDG 2021), whereas many of the projects carried out nowadays use various strategies, including smart growth, compact development, green building, green economy, and green infrastructure that all aim at water and environmental sustainability (EPA 2021).

Likewise, it is important to move from mere "boom repulsion" to "give the increase method" (Yin and Li 2001; Opperman et al. 2009). To this end, giving water bodies (rivers, lakes, etc.) a chance to recover, introduced by former Chinese President Hu Jintao in mid-2008, can be an option. However, future water conservation projects need to look unambiguously at moving examples of environmental evolution. Water bodies in China were regulated and largely operated without thinking of environmental changes. Such a firm plan of projects is flawed at the elementary level (Milly et al. 2008; Matthews et al. 2011; Pittock and Hartmann 2011). Environmental changes in previous years have just caused noteworthy adjustments in water assets in China (Piao et al. 2010; Xie 2020; Xia et al. 2021).

One model is a strong evidence of the drying pattern in the Hanjiang River Basin (which is a tributary of the Yangzte River), China. If such a pattern continued, the Hanjiang River would have no additional waters to occupy unless it gets water from elsewhere first. Therefore, the Chinse Government built the South-to-North Water Transfer Project (SNWTP)—also known as the South-to-North Water Diversion Project (SNWDP) (Liu and Zheng 2002; Chen et al. 2007; News & Focus 2016; Zhang and Donnellon-May 2021) (Fig. 7).

The SNWTP comprises three water transfer or diversion routes in the Eastern, Central, and Western China, diverting water from the lower, middle, and upper reaches of the Yangtze River, respectively (Fig. 7). It also connects four major rivers—the Yangtze River, Huai River, Yellow River, and Hai River. Thus, the SNWTP establishes a pattern of water resources' allocation in China that regulates three south–north water routes and connects four west–east rivers. The SNWTP will supply a total of 6.15 BCM/year of water to the Jingjinji region in 2020 through the Middle Route (Phase I) and the East Route (Phase II), and also 8.58 BCM/year in 2030 through the Middle Route (Phases I and II) and the East Route (Phases II and III) (Fig. 7). The total water diversion's capacities of the SNWTP have already reached, just recently, 7.4 MCM/year, and are expected to reach 12 BCM/year soon (Falkenmark and Rockström 2006; Liu et al. 2009; Kobayashi and Porter 2012; Li et al. 2019; Yuan et al. 2021).

In view of the above, the SNWTP is a mega project, representing a key strategic infrastructure, aiming at improving the allocation of water resources in China. It plays a vital role in alleviating the severe water shortage in northern China, ensuring water supply, promoting sustainable social and economic development, and improving the ecological environment. Given the importance of green water projects, such as the SNWTP in China, the future focal point for water conservation should be shifted from the viewpoint of the blue-water projects towards considering water security as "reasonable," including green-water streams (Falkenmark and Rockström 2006).

Challenges of carrying water conservation goal

Water management and water use should be collaborative between the communities and respective governments. In northern China, for example, with the ultimate goal of relieving water shortage, the SNWTP (mentioned above)

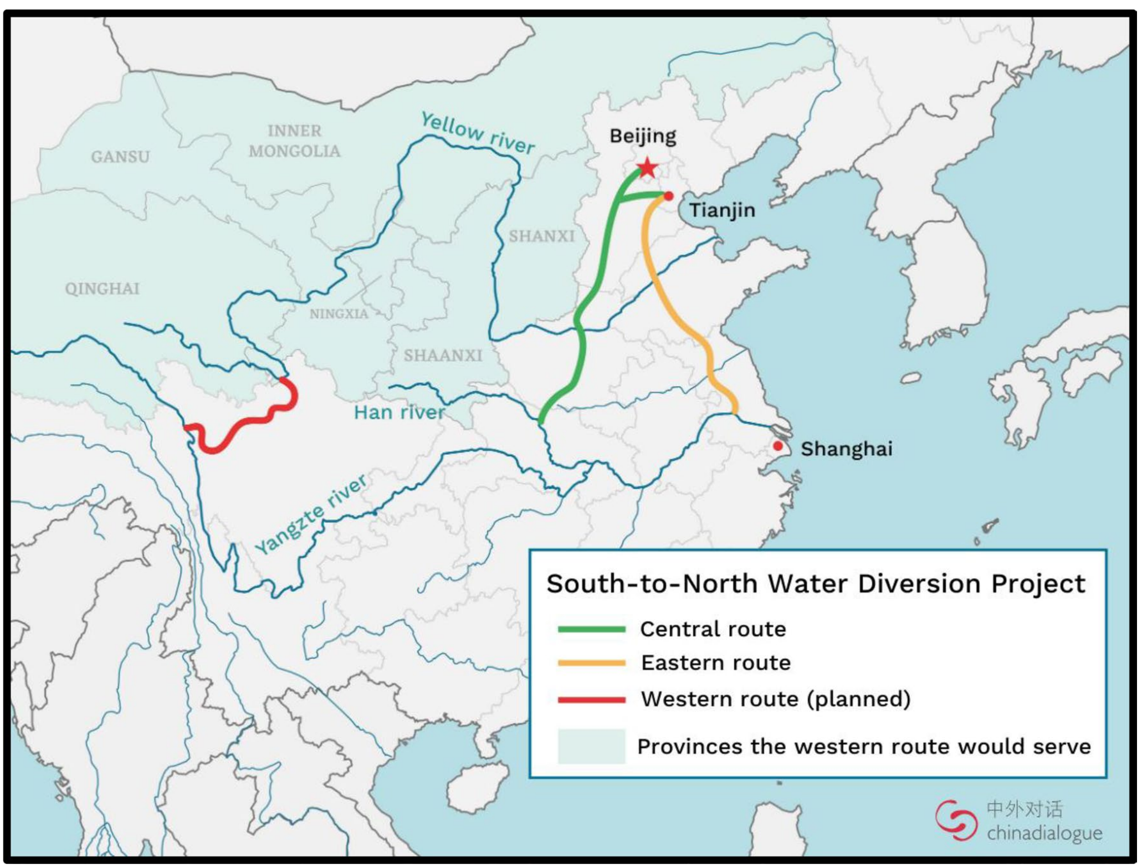

Fig. 7 South-to-North Water Transfer (Diversion) Project (SNWTP or SNWDP), China (modified after Zhang and Donnellon-May 2021)

has been activated with a planned total exchanged volume of 12–43 BCM/year in the next few decades (Ma et al. 2006; Liu and Savenije 2008; Li et al. 2019). Along these lines, the scarce-water regions in northern China provide much sustenance to the water-rich areas of southern China each season. Thus, the effective water movement installed by a reciprocal vessel is identical to 52 BCM/year (Ma et al. 2006; Liu and Savenije 2008), which is greater than the real level of the exchange project (Shao et al. 2003).

In the same manner, leaders and policy-makers must be highly conscious and environmentally knowledgeable regarding the building of water-exchange projects. In water-scarce regions, the effectiveness of water-exchange projects is generally restricted by adjacent water uses and water-saving incentives between different water-customer divisions. For example, water disturbances of the Tarim River in China reduced the distance of the far-stream path from about 850 km in 2001 to about 400 km in 2002 and 2003, meaning a more than 47% reduction of the length of the far-stream way (Liu et al. 2013). It also shortened the water-scarce season from 185 days in 2001 to 46 days in 2003, meaning more than 75% shortening of the water-scarce season only within three years (Liu et al. 2013). However, in 2009 the distance expanded to about 1200 km, while the period that had become visibly scarce grew to 302 days. Being preoccupied with water scarcity would not be beneficial for reducing the distance and time over the entire range. One crucial reason is that neighborhood residents use more water than currently for residential, industrial, and agricultural purposes. With no change in monetary composition and first-ranked water use, the water preoccupation alone cannot address the water shortage problems (Salem 2011, 2019a; NAE 2017; Stephenson 2018; PSE 2017; Salem et al. 2021).

Advantages and disadvantages of sustainable water conservation and applications for food

One of the direct advantages of the water reorientation or redirection projects, such as the cases of many projects in China, including, for instance, the SNWTP (mentioned above), is the exchange of water from areas of surplus water to areas of water shortages, to alleviate water shortages in certain regions. This water preoccupation extends to larger sizes and is expected to provide water for domestic and other uses, especially those areas that have lower amounts of water or those that suffer from water shortages, such as the Tianjin city (Fig. 7, above), which has the most insufficient per-capita water assets in China (180 m^3/ca/year). The Beijing-Tianjin-Hebei district—Jingjinji—is China's most densely populated region. Problems arise from the acute shortages of water resources, with the emergence of water issues for landowners, such as establishing water diversion projects, regional synergies development, and the impacts of climate change (Li et al. 2019). Water shortages in some regions of China, such as the North China Plain, particularly due to climate change, have led to extreme droughts affecting wheat production (Yang et al. 2020). Therefore, water transfer or diversion projects in China are of particular importance.

The Yin Luan Ru Jin water project began in 1982 to relieve the water shortage in Tianjin. By 2009, this project had redirected 19.2 BCM of water to Tianjin, primarily residential and industrial. Another example is the Yin Huang Ru Jin project in China, which aimed to deliver water from the Yellow River to Shanxi province (Fig. 7, above), which possesses a quarter of the total coal preserved in the country. Each year, the project offers 0.56 BCM to the cities of Datong and Shuozhou and 0.64 BCM to the city of Taiyuan, as well as to three noteworthy coal mines in that region of China.

The Yin Jiang Ji Tai project aimed to improve the water transport from the Yangtze River to Taihu Lake. As the third-largest freshwater lake in China, Taihu Lake is a noteworthy water hotspot for drinking, aquaculture, and industrial needs and is a popular vacation destination. The region of the Taihu Lake represents 0.4% of the total area of China, 2.9% of the world's population, and 14% of China's real GDP (Yang and Liu 2010; Hu et al. 2022).

Sustainable water conservation achievements models

At present, China, for example, has more than 20 noteworthy projects amongst the waterways with a total length of more than 7200 km. The main feature of allocating space for those projects is mainly in northern China. As indicated in China Vision 2006, the projects to redirect water between various water bodies represent 2.5% of the Chinese total surface water assets. This proportion may increase to 10% upon completion of the SNWTP (mentioned above) in 2050 (Cheng et al. 2009). The SNWTP, with a total length of 3187 km, is the most extended water running project on the planet Earth. This project, the largest of its kind globally, has benefited over 100 million people in the country's parched north by transferring water from the water-rich Yangtze River basins in the south (CISION 2019). The SNWTP, began in 2002, consists of three lines or routs (as mentioned above): Western, Central, and Eastern (Fig. 7, above). The water on the Central Route traverses more than 1400 km in its 15-day trip, starting from Danjiangkou Reservoir in the Hubei province, travels across the Henan and Hebei provinces before arriving in Beijing and Tianjin. The Eastern Route starts from Yangzhou in the Jiangsu province and ends in Shandong province and Tianjin. Estimates of the project's cost differ enormously (Lin 2017). Approximately USD 43 billion (equivalent to around Chinese Yuan 288.15 billion, as of July 2022) were invested in this mega project by the Central Government of China, and over 400,000 people living in water-source areas along the three routes have been resettled (CISION 2019). The areas fed by the project produce 1/3 of China's GDP. So far, with its three routes, the SNWTP project has transferred approximately 60 BCM since it was launched in 2013 (CISION 2019).

Challenges of securing water for food (water-food Nexus)

The water-for-nutrition challenge (in terms of WF Nexus) is a showcase for moving forward with a promise to reinvigorate science, innovation, development, and commercial enterprise (Table 1, above). By understanding the WF Nexus, distinct factors accelerate the advancement of science, innovation, synergies, trade-offs, and market-driven methodologies (Table 1, above). These factors are essential for reducing water shortages in the food-assessment chain and enhancing water management to support food security and alleviate and ease destitution, especially with the consideration of global warming and climate change impacts. These factors are:

(1) Improving water efficiency and wastewater reuse: These two goals can fundamentally expand the profitability of restricted water assets, especially in the food supply chain, where water assets can have multiplier impacts at different levels of the economy; (2) Effective water capture and storage systems: These two procedures are essential for expanding rapid access to water supply in areas where rainfall is regular. With projected increases in rainfall variability, due to environmental changes and climate change impacts, as well as due to expanded food generation demands, capacity frameworks at different levels are expected to anchor water supplies and build strength for droughts consistently; and (3) Salinity of the water supply: Increasing water salinity is a considerable risk to water resources, mainly due to climate change impacts and other causes. Thus, increased water salinity poses an induced risk to food production. For instance, in groundwater aquifers and coastal areas, overpumping and rising sea levels cause a considerable increase in freshwater salt content (Salem 2011; Liu and Liu 2014; Llovel et al. 2019; Said et al. 2021). However, in many regions around the world, people are witnessing sea-water rise due to climate change. There are some reasons for long-term sea-level changes, including, among others, astronomical, meteorological, and steric, such as water salinity and temperature (Boateng 2010; IPCC 2019).

Future needs for securing water for food (water–food Nexus)

Water shortages across the globe represent one of the most difficult challenges facing development in the twenty-first century; nearly 3 billion people, over 38% of the world's total population (7.96 billion as of July 2022) (Worldometer 2022c), live in watercourse regions affected by water shortages as well as water pollution and geopolitical instabilities. These 3 billion of the world's population can be divided into almost two halves. The first half (≈ 1.5 billion) lives in areas significantly affected by severe water shortages, where demand is more prominent than supply. The other half (≈ 1.5 billion) faces cash shortages of water and restrictions in access to water, despite its availability and, in some cases, its abundance. The second kind of water shortage is attributed to institutional, budget, human, and geopolitical variables and conditions, at the expense of locations affected by wars or under military occupation, similar to the conditions in the Occupied Palestinian Territories (Salem 2011; Salem et al. 2021). Water shortages in the second case are defined by physical, financial, political, and geopolitical effects, such as water control and hegemony by powerful governments (Zeitoun and Allan 2008; Wessels 2015; al-Shalalfeh et al. 2017; Salem 2019b; Gebrehiwet 2020; Putra et al. 2020; Salem et al. 2021).

However, both kinds of water shortages can lead to specific negative consequences in terms of welfare, the profitability of agriculture, military confrontation, terrorism, environmental degradation, business deterioration, and lack of sectoral and socioeconomic development. Between 2000 and 2050, overall water demand is expected to increase by 55%, as indicated above. Three activities will contribute to the overall 55% increase in water demand: (1) Manufacturing, with a 400% increase; (2) Thermal electricity generation, with a 140% increase; and (3) Domestic use, with a 130% increase (UN OECD 2012; Day 2019). Accordingly, the rapidly growing water demand for several purposes, such as urbanization, industrialization, energization, and development, in general, will be a great challenge facing the water supply for irrigation by 2050. It is particularly important if we are aware that more than 70% of the water use worldwide occurs in the Food Value Chain (FVC) (Fig. 8). Therefore, the number of individuals affected by water shortages and water stress will continue to rise, especially amongst poor people in developing countries worldwide.

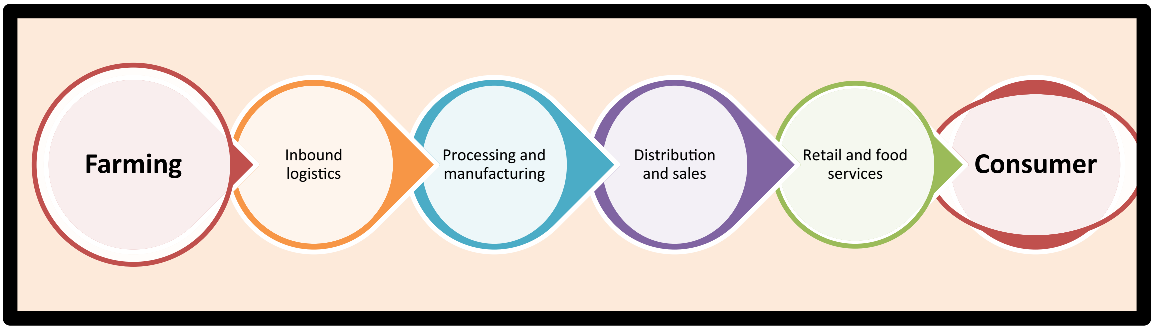

Fig. 8 Food value chain (FVC) from farm to fork (modified after, and adapted from, SWF 2017)

Securing water-for-food systems (water–food Nexus)

As already mentioned, countries across the globe are presently facing water shortage problems, some of which are severe and others are moderate. Such problems will be even more complicated in the presence of climate change impacts and population's growth. Thus, the countries will constantly be confronting such problems, given the way to 2050. Accordingly, country researchers, approach builders, system builders, policy- and strategy-makers, and so forth must move away from discovering short- and long-term measures to efficiently manage the water shortage issues (SWF 2017). Therefore, understanding the conditions for enabling neighborhoods for innovation and commercial advancement is a crucial issue to explain the social, environmental, institutional, legal, and administrative difficulties facing development and how to overcome those barriers, considering nearby economic conditions. The proximity of the "establishing water for food" program (WF Nexus) in developing countries is essential. It is also essential to identify the neighborhood with which it cooperates to establish the projects needed.

Conclusion and recommendations

While there are clear indications that water and food emergencies are approaching worldwide, as confirmed by more current events and challenges, including dry seasons and resulting droughts, long-term pollution of water resources, and the impacts of climate change, as well as geopolitical instabilities and military conformations, it is noteworthy to mention that strategy- and policy-makers have not made enough efforts to deal with such events and challenges and the consequences resulting from. With the focus on changes and advances in water and food resources' strategies and management, in the presence of these extraordinary challenges and frequently happening events, it is needed to surmount these events and challenges—one of the mechanisms to deal with them in implementing the Nexus' approach or framework.

Demands on water (W), energy (E), and food (F) are growing worldwide, driven by a growing global population, rapid urbanization, changing diets, and economic growth. Agriculture is the world's largest consumer of freshwater resources, and more than a quarter of the energy used globally is consumed during food production and supply. Accordingly, this paper can help managers effectively manage water resources and conceptualize a comprehensive WEF Nexus' policy or just a WF Nexus' policy, considering that the energy subsystem is not investigated in this work for the reasons mentioned above.

The present evaluation's results could be used as tools to strengthen the WF Nexus management and governance. Each country has unique economic and social characteristics that directly or indirectly affect the WF Nexus. Therefore, it is almost sure that the stewardship of water assets will be a vital issue in building an efficient WF Nexus' framework that will enable socioeconomic development and progress. It is suggested that socioeconomic indicators and their interactions with the WF Nexus (or WEF Nexus) are analyzed regarding the various regions investigated.

The outcomes of this work can guide managers and decision-makers to develop possible solutions, ensuring water-management tools are applied successfully according to the visions of multiple perspectives, which can help the relevant ministries and institutions improve plans and policy- and strategy-making related to WF Nexus. This means that before essentially 'giving more water' (i.e., the supply–demand management's approach), which often refers to developing new and costly foundations and infrastructures, the first and wisest things to do are the enhancement of water effectiveness within the framework of water–food Nexus' management, and also paying attention to issues at the exciting side. Such approach should be undertaken without seriously harming or altering the well-being of humans and the environment.

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