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Review

Water Footprint and Water Resources Sustainability: A Review

Mahmoud Said Rashed[a], Shaimaa Fakhry[b], Radwa Satour[b], Mabrouk Sobhy[a], A.K. Haghi[c]

[a] Food Science and Technology Department, Faculty of Agriculture, Alexandria University, Alexandria, 21545, Egypt

Email: mahmoudsaidrashed88@gmail.com

Email: mabrouk-sobhy@alexu.edu.eg

[b] Department of Pomology, Faculty of Agriculture, Alexandria University, Alexandria, 21545, Egypt

Email: shaimaa.fakhry@alexu.edu.eg

Email: radwasatour@alexu.edu.eg

[c] Department of Chemistry, Institute of Molecular Sciences, University of Coimbra, Coimbra, Portugal

Email:akhaghi@gmail.com

A. K. Haghi

https://orcid.org/0000-0002-7259-6718

Abstract

This review provides an overview of recent progress in water footprint research in terms of theoretical development, methodological improvement and practical implementation at different levels. In addition, the development of the concept of the water footprint is analysed, existing calculation methods are reviewed, and strengths and limitations are discussed. Particular attention is paid to the complex interactions within the food, energy and water Nexus by showing how analysing the water footprint can shed light on the interdependencies of resources and trade-offs. It also highlights the great progress that has been made in integrating the assessment of the water footprint with other environmental indicators, particularly within the "environmental footprint family": water, environment, energy, carbon, land, nitrogen and phosphorus footprints. This review contributes to the growing literature in the field of water resource management and provides policy makers and researchers with some useful insights into strategies for sustainable resource use.

Keywords: **w**ater footprint; water resources sustainability; environmental footprint; water resource management; food-energy-water nexus

Highlights

- Evolution of the Water Footprint Concept
- Methodological Advances in Water Footprint Calculation
- Role in the Food-Energy-Water (FEW) Nexus
- Assessment of Water Resources Sustainability
- Challenges in Water Footprint Research

1. Introduction

The main challenge facing sustainable development in the Anthropocene is the global water crisis, characterized by rising freshwater scarcity and pollution; it is a time when human beings have made more changes to the earth's systems [1]. The combination of urbanisation and economic development with the relative growth in population as outlined by United Nations rapid population growth, which estimates the population to grow by 8.2 billion in the year 2022 to 10.9 billion in the year 2100, has resulted in a rise in the demand of water in the domestic, industrial and agricultural sectors of the population. Approximately 70 percent of the freshwater withdrawals worldwide are due to agriculture [2], and in some dry and semi-arid regions, including sub-Saharan Africa, the ratio of internal renewable water resources per capita has been reduced by 20 percent between 2000 and 2018 [3]. The pressure is heightened by climate change, which affects rainfall patterns and the frequency of extreme weather events, disrupting the water cycle and putting water resources under strain [4]. A global food system is in a state of considerable transformation caused by a variety of factors, among which the most important are population growth, urbanisation and the increase in living standards, thus resulting in a rather noticeable change in the eating habits towards more water-absorbing products, namely, animal proteins and processed foods [5]. This has been observed mainly in China, with the level of food demand on water rising to 860 m 3 per capita in 2003, compared with the demand of 255 m 3 per capita in 1961. The biggest change in water usage in China has been an increase in food consumption, especially the consumption of animal food products. These observable shift in diet is the cause of adding pressure on the water resources and by 2030, total water demand in China in producing food will be immense [6]. The increase in water consumption has also been a result of economic growth and consumer preference shift towards high water-intensive food stuffs including processed foods and animal protein although recent studies have indicated that there is an equilibrium between water consumption and economic growth in economies over an extended period [7].Hoekstra and Chapagain [8] suggest that water footprint is an extensive method used to estimate how much fresh water is directly and indirectly used in the production and consumption of goods and services. This measure enables the researcher and the policy makers to determine the sustainability of water use in various industries and supply chains by differentiating between the green (rainwater) and blue (surface and groundwater) and grey (polluted water) footprints. The water footprint is especially applicable to the agriculture and energy industries that are important to the global water use and are under threat of water shortage. It is projected that the areas that already have water shortages will witness a further reduction in the supply of water as a result of the shifting climate patterns [9]. Recent advancement in water footprint accounting has recognized various ways in which water can be used more efficiently. Guo et al. [10] state that there remain several issues with regional water supply inequalities and environmental consequences of the increased water demand.

The purpose of the review is to provide a summary of the existing body of knowledge regarding the accounting of water footprint in achieving water resources sustainability, particularly in the agriculture and energy industries. We start with the genesis and development of the idea of water footprint, and proceed to a review of the methodologies of measuring the water footprint in production and consumption processes. After that we consider the methods involved to evaluate the sustainability of water resources in respect of sustainable development with more focus on the interaction of water use, economic growth and environmental impacts. Lastly, we indicate areas of research gaps towards future research, including the fact that there is very little incorporation of water footprint information in policy formulation and recommend areas of future research to enhance sustainable water management. These problems will bring the paper to the scientific and policy debate on how to alleviate the water crisis in the world.

2. The concept and origin of the water footprint

The concept of the water footprint was developed from the theory of virtual water. Virtual water was proposed by Allan [11] in 1993 and refers to the amount of water needed to produce products and services. It is the "invisible" form of water contained in the product. For example, if the production of 1,000 kg of wheat requires 1,000 m^3 of water, then 1,000 m^3 is the virtual water content of the 1,000 kg of wheat. In 2002, Dutch scientists first clearly formulated the concept of water footprint, which refers to the amount of water resources required for all products and services in a given time and space, figuratively expressed as water in the production and consumption of the footprint (water footprint). This idea comes from the theory of "ecological footprint" [12]. The concept of water footprint has attracted the attention of governments and scientists around the world since the first publication of the Water Footprint Assessment Handbook by Aldaya et al., [13].

The water footprint and the concept of virtual water are both related and different in their analytical scope and purpose. What they have in common is that they can be used to analyse the relationships between human production and consumption, water use and management [14]. The difference between the two concepts is that from a conceptual perspective, virtual water focuses on describing the water resources used in the production of a product, i.e. you look at a product and see the water consumption behind it, which is different from physical water, while the water footprint can be used to characterize the amount of water used in the two processes of production and consumption [15]. From the perspective of accounting objects, virtual water focuses on the accounting of blue and green water, while the water footprint adds the accounting of grey water. In terms of scope, the virtual water approach is mainly used for agricultural products and is a useful tool to balance water scarcity and food security; the water footprint covers a wide range of products and services at individual, household, sectoral, regional and national levels. The water footprint is more advanced than virtual water because virtual water accounts for blue and green water, lacking the comprehensive scope of the water footprint, while the water footprint can characterize the time, place and type of water use in addition to the amount of water consumed, offering a more advanced analysis compared to virtual water [16] and can also measure the impact of human activities on the region's ecosystems.

Consider the example of wheat growing in Egypt and the Netherlands to better highlight these distinctions. Egypt, a nation with limited water resources, relies heavily on irrigation. One tonne of wheat requires about 1,600 m^3 of water. Only 10% of this is green water because of the drought, with 90% being blue water from the Nile River [17]. In contrast, wheat production in the Netherlands, a water-rich country, is more dependent on rainfall and has more efficient irrigation systems (a mix of green and blue water) with green water (80 %, ~1,200 m^3/tonne) and less blue water (20 %, ~300 m^3/tonne). The increased irrigation demand (1600 m^3/tonne for Egypt against 1500 m^3/tonne for the Netherlands) makes Egyptian wheat more water-intensive from a virtual water perspective. However, the water footprint analysis would additionally consider virtual water imports (e.g. from water-rich countries) and grey water reflecting pollution from fertiliser run-off on Egyptian farms (estimated at 200 m^3/tonne), which is higher due to lower regulation and higher input use per hectare. The Dutch water footprint, on the other hand, considers consumption patterns, including exported wheat and minimal grey water (~50 m^3/tonne) due to efficient agricultural practises.

This case study thus shows that while the water footprint provides a more thorough and policy-relevant assessment of water consumption and its impact on sustainability in all production and consumption systems across different scales, the trade analysis of virtual water focuses on water consumption in production [16].

While virtual water and water footprint serve different purposes, they are both vital for sustainable water management. Virtual water helps address water scarcity through trade analysis, whereas the water footprint offers a holistic view of water use impacts, aiding in comprehensive environmental assessments. This not only opens up a new way of thinking about the integrated management of water resources but also offers a completely new perspective for realizing the sustainable use of water resources [18], [19].

3. Water footprint components and accounting methods

3.1. Composition of the water footprint

Water footprint is a multidimensional indicator of water use, including blue water, green water and grey water in terms of water use types [8], [20], of which: blue water refers to liquid water in rivers, lakes, wetlands and aquifers, which is the most widely used in traditional water resources related studies; green water includes green water flow, which refers to the vapour flow evaporated from the ground, water bodies and vegetation; and green water storage, which refers to soil water maintained in the unsaturated zone, formed by precipitation and available for plant use. Grey water is a measure of the extent of water contamination and is defined as the amount of freshwater needed to absorb pollutants to meet existing environmental water quality standards [12]. In terms of water use boundaries, the water footprint includes an internal water footprint and an external water footprint [8], where the internal water footprint of a region is the amount of water used excluding imported products and services, and the external water footprint is the amount of water included in imported products and services in the form of virtual water. Water footprints are characterized by different temporal and spatial scales, such as global, national, provincial, municipal, or watershed, and temporal scales such as years, months, or days.

3.2. Accounting for the water footprint

The extent to which humans have reached or even exceeded the planetary boundaries of freshwater resources is an important issue for global sustainable development [21]. As illustrated in Figure 1, balancing food, energy and water are all important resources that are essential for human survival. These three are interdependent and interact with each other, forming the Food-Energy-Water (FEW) system [22]. In the context of climate change and societal transformation, maintaining the health of the ecosystem and providing sufficient food, energy and water resources for the growing population and managing the resulting water footprint are of great importance to ensure people's water, food and energy security.

3.2.1. Method for calculating the water footprint of food production in the agricultural production process:

As defined the agricultural water footprint includes green, blue and grey components. According to Allen et al. [23], the agricultural water footprint is usually calculated as follows:

1) Green water footprint: if evapotranspiration (ET) exceeds effective precipitation (P) during the growing season, the green water footprint equals the effective P; if ET is less than effective P, the green water footprint equals the actual ET.

2) Blue water footprint: This depends on the crop's tolerance to water scarcity, irrigation efficiency, and the availability of green water. If evapotranspiration (ET) exceeds precipitation (P), the blue water footprint equals ET minus P; otherwise, the blue water footprint is zero. Complete information on irrigation, soil, and cultivation is required to calculate the blue water footprint.

3) The grey water footprint: This quantifies the freshwater needed to dilute pollutants from agricultural activities to meet environmental quality standards. Nitrogen fertilisers are considered as one of the major contributors to grey WF [24]. Phosphorus, also from fertilisers, has a significant impact on water bodies as it causes eutrophication and requires significant dilution [25]. Two examples of emerging pollutants that are becoming more significant but are

challenging to quantify because of their complex interactions and lack of data are pharmaceuticals from manure or wastewater irrigation and microplastics from mulch films [16]. Sophisticated modelling tools (e.g. SPARE: WATER) are required to capture the persistence of these pollutants in the environment [26]. Together, these components make up the overall water footprint. Traditionally based on nitrate leaching, but now increasingly takes multiple pollutants into account. The grey water footprint is calculated using the formula:

$$GWF = \frac{L}{C_{max} - C_{nat}}$$

Where Cmax is the permissible concentration in the receiving water body, Cnat is the natural background concentration and L is the pollutant load (e.g. nitrogen or phosphorus). The robustness of the assessment is considerably increased by the inclusion of several pollutant loads and region-specific water quality criteria.

According to different researchers, there are different models to simulate the water footprint of crop production. These models include the CROPWAT model [27], [28], the GEPIC model [29] (GIS-based environmental policy integrated climate model), the Environmental Policy Integrated Climate (EPIC) and the AquaCrop model [30]. The most widely used model for calculating the water footprint of crops is the CROPWAT model [31], [32]. The main advantage of the CROPWAT model is above all its flexibility and the possibility to adapt it for application to a large number of crops and in almost any location in the world, taking into account the localization of the model and modifying the accuracy of the calculation results. Table 1 summarises the main tools for assessing the water footprint of agricultural production. At the international level, water footprint studies are usually conducted either at the global or country level. The work of Tuninetti et al. [33], for example, projects the global consumption of green and blue water for wheat, rice, maize and soybeans. These assessments reveal that crop production primarily relies on green water, with blue water becoming more efficient when irrigation is applied [33]. WF estimates are sensitive to various input parameters, particularly reference evapotranspiration (ET_0) and crop coefficients (K_c). Blue WFs tend to be more sensitive to input variability than green WFs. The sensitivity of WFs varies across crop types, water supply methods, and regional climates. Uncertainties in WF estimates due to combined input uncertainties can be around ±26% at a 95% confidence level [34], [35]. Figure 2 illustrates agriculture water footprint calculations.

Table 1: Summary of Water Footprint Assessment Tools for Agricultural and Energy Sectors [18, 27-30, 36-38].

Model/Tool	**Developer / Source**	**Main Features**	**Strengths**	**Limitations**	**References**
CROPWAT	FAO	Calculates crop water requirements and irrigation needs based on climatic and crop data	Widely used, easy to operate, adaptable to various locations, supports multiple crops	Limited pollutant modelling; requires accurate local climate and soil data	[27], [28]
GEPIC	IIASA & CAU	Integrates GIS data with crop models and environmental data to estimate crop production and water use	Spatially explicit; considers land use, hydrology, and environmental impacts	Complex setup; limited access to input data in data-scarce regions	[29]
EPIC	USDA	Simulates crop growth and environmental impacts including nutrient runoff and sediment transport	Includes nutrient and pesticide leaching; suited for policy assessment	Requires detailed input data; complex calibration	[36]
AquaCrop	FAO	Focuses on the relationship between water and yield in response to different water conditions	Simple interface; water productivity-focused; suitable for scenario analysis	Limited pollutant tracking; does not account for grey water components directly	[30]
SPARE: WATER	ZALF, Germany	Integrative tool for analysing WF and water productivity at farm level using systems approach	Holistic integration of social-ecological dynamics; suitable for comparative studies	Still under limited use, high data and calibration demands	[37]
WaterStat / WF Assessment Tool	Water Footprint Network	Online tool following Hoekstra's methodology for calculating green, blue, and grey WF	Transparent methodology; consistent with global WF standards	Limited crop-specific detail; primarily used for awareness/policy rather than detailed farm management	[18]

WaNuLCAS	ICRAF	Simulates nutrient and water dynamics in agroforestry systems	Good for mixed cropping/agroforestry; nutrient and water flow dynamics	Limited to agroforestry systems; not standardised for WF estimation	[38]

Research on water footprints spans global and regional scales, addressing different policy objectives. Global studies aim to identify countries with high agricultural water consumption to reduce the overall water footprint [39]. For instance, in China, a modified water footprint assessment framework revealed that 24.9% of water consumed by grain crops is transferred to animal products through feed grain [40]. Regional studies, such as that of the Chinese province of Liaoning, use input-output analysis to compare the water footprint from both a production and consumption perspective. They help identify sectors with high water footprints and provide policy suggestions, such as changes in industrial structure and trade, water-saving technologies and capacity building to reduce the stress of water scarcity [41].

3.2.2. Method for calculating the water footprint of energy production

The International Energy Agency has also conceptualized energy security as "uninterrupted access to energy supply at an affordable price". Energy and water are complementary and valuable resources, and the "water-energy Nexus" has always been the subject of study. The energy industry is an energy-consuming sector, and the degradation of water quality, quantity and availability poses a threat to the sustainability of energy supply [42]. In addition, greenhouse gas emissions from the energy sector have caused changes in the hydrological cycle on a global scale, the interaction of which jeopardizes the energy-water Nexus [43]. The water footprint of energy is determined by pollution intensity during the extraction, processing, and purification phases [44], specifically the blue and grey water footprint. Water consumption and pollution in energy production, and energy development planning based on water resources, are useful indices for achieving maximum efficiency in water resource use. For example, Peña et al. [45] used a life cycle approach to estimate the blue water footprint of ore mining and processing in the Atacama Desert in northern Chile.

The water footprint of energy production should be considered using tools such as life cycle assessment (LCA) and input-output analysis (IO), which are inseparably important for explaining the water-energy nexus clearly. These approaches allow for optimizing resource flows, especially on a small scale, where attentive evaluation can facilitate sustainable practices. As an example, in the calculation of the water footprint of energy production, it is considered to weigh the small and large scales equally without preference; the small scale is allocated to the flows of the respective departments. This approach is essential for describing the multidimensional interactions in the water-energy nexus and for optimizing resource use. Small-scale studies usually employ models and methods to examine and optimize flows to manage resources effectively.

Input-output (IO) models have been extensively applied to measure the virtual water content of economic activities and to depict water footprint of different sectors in terms of environmental impact, the energy sector being included. The importance of input-output models is that they help assess the flow of water resources in energy production and assist in evaluating and managing the environment. These models, which comprise both demand- and supply-side components, help predict sectoral outputs and inputs using cross-sectoral transactions and final demand forecasts. These models help understand the flow of resources among sectors and assist in identifying inefficiencies and potential areas for improvement. These models are specifically applicable to the water-energy nexus; optimizing water use in energy generation is crucial for sustainability [46]. Input-output models help determine how water resources move through the energy production process and are central to environmental assessment. Atheistic approaches, such as mathematical modeling and decision-support systems, enhance water resource management through real-time monitoring and prediction. These instruments enable adaptive management and real-time monitoring to make better-informed decisions [47]. A decentralized structure for the optimization of micro water-energy nexus (MWEN) systems is proposed to enhance resource supply and enable separate management of the water and energy sectors. Silva-Rodriguez & Li [48] offer a decentralized co-optimization model based on a goal-centered alternating direction method of multipliers (OB-ADMM) to optimize operations where the privacy of resource providers is preserved.

Life cycle assessment (LCA) models evaluate the environmental impact of energy products throughout their life cycle, including water consumption. These models examine and optimise the water-energy nexus by minimising the water footprint and maximising the economic and energy outcomes per unit of water consumed. These models help to identify trade-offs between energy production and water resource consumption and to promote synergies within the water-energy-food nexus. These models provide a comprehensive representation of resource flows and optimise their impact within the value chain [49]. According to different authors, LCA models are primarily used to link the water and food systems to the energy system by simulating different types of linkages and resource transfers between them. Consequently, they can capture broader impacts of resource consumption [50]. For example, research by Kock et al. [51] developed a novel framework for the Water-Energy-Food Nexus of energy products that considers food footprint and water scarcity indicators and was applied to biodiesel production in Argentina to highlight the potential impacts on land use and water, and the need for integrated assessment.

While the research examines individual industrial resource chains on a smaller scale, larger models incorporate broader interdependencies, including the Nexus between energy, water and food. The models and frameworks are needed to develop sustainable resource management practises that address both local and international problems. This is mainly because the fact that the entire production chain needs to be considered in order to calculate the energy-water footprint. With the impact of energy types, manufacturing processes and information for each link, it is difficult to find the production chain. In addition, industrial and energy products make up only a small part of the virtual water business, so much less effort is put into studying the topic.

3.3.Food-Energy-Water (FEW) Relevance

The water footprint method aims to manage water resources in an integrated way. The Harvard Water Resources Project Milliman, (1962) was the first to propose an interdisciplinary, integrated social and environmental approach to water resources management. However, the implementation of many water resources management plans, including this project, Integrated Water Resources Management (IWRM), has not been ideal. There are three main reasons for this: 1) The IWRM project attempts to integrate all seemingly water-related resource elements, but their scope is not clearly defined; 2) The IWRM project focuses only on water resources and has a single accounting purpose; 3) The problem of scope. In the past, water resource accounting methods were mostly limited to the river basin scale. For resources such as energy and food, which are statistically based on administrative units, accounting methods are limited. FEW also follows a cross-sectoral integration approach, but its more advanced features are: 1) FEW has a clearer accounting object, namely food, energy and water resources; 2) FEW does not need to focus only on water, and stakeholders from the agriculture and energy sectors are more likely to participate; 3) The choice of scale is more flexible and free, both river basins and administrative units can be used as units of analysis. It was emphasized during the 2011 World Conference on Green Economic Development that the food, energy and water resources are major pillars for human sustainable development and that water resources are central within the FEW Nexus [52]. The inclusion of WF in the FEW models is important to enable effective management of resources because it quantifies the consumption of water by sectors and points out trade-offs and synergies. One such significant real-world example is the Sponge City Initiative of China, launched in 2014 to fight urban flooding, water pollution and shortage with the help of low impact development (LID) and green infrastructure. In Shenzhen, a pilot Sponge City, urban planning was informed by optimising rainwater retention, reducing the blue WF for urban water supply by 15% (from 1.2 billion m^3 to 1.02 billion m^3 annually) and the need for energy-intensive water treatment by 10% [53]. These water savings supported urban agriculture by reallocating the saved water for irrigation, improving local food security and reducing the virtual WF of food imports by 8%. By integrating permeable pavements, green roofs and wetlands, the initiative minimised runoff, reduced energy consumption for drainage systems and increased food production, demonstrating the policy relevance of the FEW Nexus [54]. Such examples highlight the importance of WF metrics in operationalising the FEW frameworks for sustainable urban planning, even if scaling these practises in different hydrological contexts remains a challenge [55].

In the past, most studies have focused on the relationship between the two, especially the application of the water footprint to the study of the "water-food" Nexus and the "water-energy" Nexus. After the World Conference on Greening the Economy in 2011, the study of the FEW has greatly increased, and the research contents include three aspects: 1) the concept of the

FEW Nexus; 2) the modelling and simulation of the FEW Nexus; 3) the study of use cases, the identification of trade-offs and synergies of the FEW Nexus, and the formulation of cross-sectoral strategies for sustainable regional development. In the literature, there are 4 main categories to which the most commonly used methods to study the FEW belong: 1) the ecological footprint method by Vanham [56], who studied the applicability of the water footprint to the FEW nexuses; 2) economic methods, such as the Computable General Equilibrium (CGE) method. Computable general equilibrium (CGE) models are particularly well suited to analysing environmental policy and the FEW nexus, as they can assess both the costs and benefits of policy changes at multiple economic levels [57], [58]. Integrated modelling methods, such as that described by Dale et al. [59], the authors systematically analysed the water and energy use of the electricity generation system in California, USA, in the context of climate change, combining this with a hydrological model and long-term energy substitution planning; 4) online modelling platforms specifically that used to assess the FEW Nexus include the "FEW Nexus Assessment Tool 2.0" [60]. There are more studies at the global, national and cross-regional levels, but fewer studies at the city level. Ramaswami et al., [61] analysed the relationship between food, energy and water in New Delhi, India, from the perspective of urban systems. Domestic FEW correlation research started late but is receiving increasing attention. Figure 3 illustrate the integration of water Footprint into FEW nexuses.

In a series of System Dynamics Models (SDM), different frameworks have been applied to investigate the sustainability of the food-energy-water (FEW) Nexus in different contexts. Aquaponics systems in peri-urban food production systems research [62] aquaponics systems [63] and urban areas have also been used for systemic modelling to study sustainable practices [31], [64]. SDM can reveal different interactions in FEW systems and thus becomes a tool for decision making and informing policy processes with regard to sustainability [62], [63]. This has been used to describe the imbalanced relationships between supply and demand, evaluate certain policies or conduct scenario analysis to optimally secure the resources of megacities [31]. At the same time, SDM has also been used in considering the sustainability transition for urban FEW infrastructures, with particular attention to climate, policy drivers and land use context [64]. Documented examples increasingly demonstrate the generalizability of SDM in addressing the challenges of the FEW Nexus in terms of sustainable management of resources at different scales and in different environments.

In summary, while there is a consensus on the need to include blue, green and grey water in the water footprint assessment, there are differences in the choice of accounting methods, with CROPWAT preferred for agriculture and LCA for the energy sector, reflecting sectoral differences in data availability and complexity.

4. Assessing the sustainability of water resources

Water is an important resource provided by natural ecosystems for human survival. Its sustainable use is an important guarantee for sustainable regional development. Building on the understanding of water footprint calculation methods discussed in Section 3, this section examines how these methods are used to assess the sustainability of water resources. The sustainability of water resources refers to ensuring the stability of the ecosystem structure and supporting sustainable social and economic development based on the theory of sustainable development. Its core task is the orderly development of the economy under the premise of protecting the environment and meeting the water needs of present and future generations [65]. The sustainability of water resources is assessed based on three dimensions: Environmental, social and economic. The assessment of the sustainability of water resources was originally referred to as "impact assessment" and is divided into primary and secondary impact [12]. Primary impact refers to changes in water quality and quantity and are characterized by relevant indicators of water resource shortage. Figure 4 illustrate a representation of water resource sustainability assessment. Early methods for assessing the scarcity of water resources focused mainly on blue water, ignored green and grey water, and did not consider spatial and temporal changes in water resources. The most widely used methods are the Falkenmark Index [66], the ratio of water footprint to available water [67] and the Water Poverty Index (WPI) [68]. In terms of application, Karabulut et al. [69] used the Falkenmark Index to assess water shortage in the Danube River Basin. These assessments typically involve calculating the ratio of water consumption to water availability, known as the water stress index or water scarcity [70], [71]. Results consistently show that agriculture is the largest water consumer, often accounting for over 90% of total water use. These analyses shed light on water management and how unsustainable water consumption can be avoided [72]. Rockström et al. [21] made the first progress in quantifying green water deficits by formulating a so-called Green Water-Blue Water Index. This index assesses the extent of water scarcity based on the ratio of blue and green water footprint in relation to the local blue and green water supply and characterises the water deficit caused by pollution through the ratio of grey water footprint to water resources. This is an improvement of the water footprint theory-based water resource supply and demand index. Zeng et al., [73] comprehensively considered the indicators of water quality and quantity and analysed the water supply and use of Beijing by calculating the ratio of water footprint and water resources in the basin. The Quantity-Quality-Environment (QQE) index comprehensively considers water quality, water quantity and ecological water demand [74].

The secondary impact of water shortage refers to the loss of ecological, social and economic products and services caused by the primary impact of water shortage and water quality degradation, such as the degradation of ecosystem services, food and energy security, human health and water-dependent economic activities due to water scarcity. Most methods for assessing water resource sustainability of water resources integrate indicators from different fields, of which Life Cycle Assessment (LCA) is widely used. Boulay et al., [75] combined the water stress index, LCA and human development index to assess the combined impact of water quality degradation and food production reduction due to water resource depletion on human well-being.

According to Aldaya et al., [13] the Water Footprint Manual changed the term "impact assessment" to "sustainability assessment of water resources", which better reflects the connotation of water resource management. The assessment methods are mainly divided into three categories: 1) the indicator assessment method; 2) the product sustainability assessment method related to the life cycle of water; 3) the comprehensive assessment method. In the indicator assessment methods, the Environmental Performance Index (EPI) integrates different areas such as water resources, forest resources and waste; the gross domestic product and net gross national product measure social and economic sustainability [76]; the well-being index consists of two parts: the Human Well-being Index (HWI) and the Ecosystem Well-being Index (EWI) [77]. The HWI covers the areas of population, prosperity, knowledge, culture and fairness, while the EWI summarizes indicators of resource use such as water and land. The method for assessing product sustainability in relation to the life cycle of water focuses on measuring the energy and material flow of production and services as well as assessing the use and environmental impact of water resources throughout their life cycle. The environmental impact of water resources are not as important, and the social and economic dimension plays a lesser role. Commonly used methods include Life Cycle Assessment (LCA) (Christiansen et al., 1995, Life Cycle Costing (LCC) [78], material flow analysis of products [79] and energy flow analysis of products [80]. Comprehensive assessment methods are usually interdisciplinary, such as system dynamic models in complex problem scenarios [81]. IEEE, pressure-state response models covering social, economic, environmental and political aspects [79], etc. In addition, there are various methods for assessing water resource vulnerability of water resources which combine social, economic and ecological dimensions and aim to determine the sensitivity and resilience of human and ecological systems to changes in driving forces [82].

There are various indicators and methods for assessing the sustainability of water resources, each offering different perspectives on water scarcity, quality and socio-economic impacts. Researchers agree that it is important to integrate the environmental, social and economic dimensions, but there is no standard methodology, which leads to different approaches depending on the context.

5. Challenges and future perspectives in research on the water footprint

5.1. Current challenges

1) Data limitations are one of the biggest challenges in calculating the water footprint. They affect accuracy both in agriculture (data on grey water pollution from pesticides, nitrogen, phosphorus and microplastics) [16] and in the energy sector (data on production and the supply chain obscure the distinction between water demand and actual consumption) [44]. The complexity of the estimation method and the deviation caused by the overlap of several departments affect the accuracy of the water footprint calculation [83]. Insufficient data on water conservation facilities, for example, make it impossible to assess whether it is "physical water scarcity" or "economic water scarcity" that influences policy decisions. The timeliness of WF assessments for dynamic resource management is limited and substantial delays result from the conventional dependence on product input-output tables, which are updated every five years [84]. On the other hand, recent developments have greatly increased the water data's temporal resolution. To monitor the water balance in real time, the GRWNOD platform, launched in 2023, provides high-frequency, open-access, and near real-time data on water consumption in urban, industrial and agricultural areas [83]. In areas where traditional monitoring is infrequent or delayed, it allows for the dynamic tracking of grey water

contamination and offers reliable data for water footprint modeling. Complementary tools such as IoT-based smart metering supported by Low-Power Wide-Area Networks provide granular data for urban and industrial WF calculations and improve the accuracy of consumption tracking [85]. Remote sensing platforms such as OpenET utilise satellite data to provide field-scale estimates of evapotranspiration. According to Thaler et al. [84], there are three areas where the accuracy of water footprint models needs to be improved: (i) data acquisition and pre-processing, (ii) calibration of model parameters, and (iii) methodological innovations tailored to sectoral and regional conditions. These limitations need to be addressed for WF sustainability studies to be optimally utilised for decision-making, as highlighted in Section 4 [83]. To provide context to the challenges, Table 2 summarises the main water footprint research studies and highlights their methods, results and identified gaps to improve the accuracy of agricultural WF [86]. Even when environmental water demand was included in the calculation, most calculations assume that environmental water demand is a fixed percentage of water flow. Ecological water demand varies due to regional and seasonal differences, and methods for measuring or simulating regional ecological water demand still need to be improved. The reliability and accuracy of the water footprint calculation results are the basis for the sustainability assessment (Section 3.1) and the formulation of policy measures.

Table 2: Summary of key studies in water footprint research [8, 11,17, 21, 41, 66, 68, 87-101].

Study	Year	Focus Area	Methods	Main Findings	Gaps	Ref.
Water scarcity in semi-arid climate countries	1989	Falkenmark Index	Water scarcity assessment	Defined water stress based on per capita water availability	Does not account for water quality and temporal variability	[66]
Virtual water and global solutions to regional deficits	1998	Concept of virtual water.	Conceptual development.	Introduced virtual water as a strategic resource to address regional deficits.	Lacked quantification and application to specific sectors.	[11]
Green and grey water footprint for crop production	1998	Water footprint components	Water footprint accounting	Defined blue, green, and grey water footprints.	Needed more detailed accounting methods for different sectors.	[11]
Integrated assessment of water stress and scarcity	2002	Water Poverty Index	Composite index	Integrated social, economic, and environmental dimensions	Complex to calculate, needs validation in different contexts	[68]

Water consumption for food production	2005	Green and blue water resources	Hydrological assessment	Distinguished between green and blue water, emphasizing green water's role.	Limited focus on grey water and pollution aspects.	[87]
Consumption patterns across nations	2007	Water footprint of nations	Water footprint accounting	Quantified water use by people as a function of their consumption pattern.	Did not fully integrate grey water footprint.	[8]
Spatial quantification of water footprint	2008	Global water footprint for crops	Lund-Potsdam-Jena managed Land model	Analysed green and blue water consumption for major crops globally.	Sensitivity to input parameters and regional variability.	[88]
Analysing the availability of Green-blue water	2009	Green Water-Blue Water Index	Hydrological modelling	Assessed water scarcity considering both green and blue water.	Requires detailed data on water use and availability	[21]
Analysing impact assessment	2011	Combined water stress index and LCA	Life cycle impact assessment	Linked water footprint to human well-being.	Needs standardization and broader application	[89]
Analysing of water footprint	2011	Water supply and use in Beijing	Water footprint accounting	Analysed water use in Beijing considering water footprint.	Focused on one city, needs comparison with other regions	[90]
Quantification of water footprint for global crop production	2011	Green, blue, and grey water footprint of crops	Global assessment	Provided comprehensive data on water footprints of various crops	Data limitations for some regions and crops	[17]
Analysing water scarcity problems	2013	Regional water footprint	Input-output analysis	Assessed water footprint in Liaoning, China, from production and consumption perspectives	Limited to regional scale, needs global comparison	[41]
Evolvement of water footprint assessment	2013	Water footprint in energy production	Life cycle assessment	Quantified water footprint in the energy sector.	Data gaps in supply chain water use.	[91]
Assessment of water scarcity	2017	QQE index	Integrated assessment	Considered quantity, quality, and environment in water assessment.	Complex model, needs simplification for practical use	[92]
Analysing the nexus between economic growth and water usage	2017	Water consumption and economic development	Empirical analysis	Linked water footprint to economic growth	Needs to consider social equity and sustainability	[93]
Assessment of Water footprint in EU energy sector	2019	Green and blue water footprint components of energy sector	Thress-stage assessment (Production, Construction, Operation)	Provided a comparative analysis between the water footprints of various energy production systems in EU.	Needed more detailed accounting for the impact of climate change.	[94]
Accounting grey water footprint	2020	Data availability for grey water	Data analysis	Highlighted data gaps in grey water footprint assessment.	Requires better data collection and sharing	[95]
Application of advanced techniques to ensure the environment sustainability and freshwater ecosystem conservation	2021	Green, blue and grey water footprints	Review	Emphasized the need for improved grey water accounting	Requires standardized methods and data	[96]

Determining the effect of climatic condition on water scarcity	2022	Agricultural water footprint	Crop water requirement calculation	Provided methods for calculating evapotranspiration in agriculture.	Focused primarily on blue water, less on green and grey	[97]
Determining the effect of climatic condition on water scarcity	2022	Agricultural water footprint	Crop water requirement calculation	Provided methods for calculating evapotranspiration in agriculture.	Focused primarily on blue water, less on green and grey	[97]
Regional water footprint assessment	2022	Water footprint in large basins	Case study	Mapped water footprint in large semi-arid basins	Limited to specific basins, needs global perspective	[98]
FEW Nexus and circular economy	2024	FEW Nexus and sustainable development	Integrated assessment	Integrated Framework for WEF Nexus Management.	The predominantly qualitative nature of some socio-anthropologic models.	[99]
Regional water footprint assessment	2024	FEW Nexus and sustainable development	Integrated assessment	Highlighted the importance of FEW Nexus for sustainability	Requires more case studies and policy integration	[100]
Water, energy, food and environment nexus	2024	Sustainable transition	Integrated assessment	Interventions in one sector (e.g., water use) significantly impact others (e.g., food production, energy generation, and ecosystem health)	Lack robust methods to handle uncertainty, Data and Tool limitations	[101]

Therefore, improved methods for simulating regional ecological water demand in combination with high-frequency data are needed to increase the reliability of the water footprint.

1) One of the main difficulties in the successful estimation and management of water resources is the spatial and temporal mismatch between the spatial and temporal scale of water resource management and the spatial and temporal scale. Song et al. [102] in their research found that the spatial mismatch is greater than the temporal mismatch, especially in regions of high urbanisation. Temporal scales are unable to distinguish between the different changes of seasons, while geographical scales are unable to account for the movement of water and its different forms, like virtual water. In order to manage water effectively, the right scale must be chosen since different scales can initiate different management practices [103]. Seasonal shortage of water is commonly underrated in interannual studies and therefore produces false predictions of water supply and demand [104]. For example, for India's Indo-Gangetic Plain, seasonal WF assessments for rice

revealed 28% higher green WF during the monsoon months (July–September) compared with interannual averages (2,500 m^3/tonne vs. 1,950 m^3/tonne) due to great variability in rainfall [105]. In sub-Saharan Africa, the estimated water demand for sorghum varied by 22% between the wet and dry seasons (1,600 m^3/tonne vs. 2,050 m^3/tonne), with interannual models underestimating water stress in the dry season by 12% [106]. These examples underscore the need for an adaptive timescale for WF research because both short- and long-term climatic variability play a dominant role in water supply [107]. Water footprint accounting can play a role in supporting sustainable water management in large, semi-arid catchments by mapping the spatial and temporal patterns of sectoral water use [108]. Recent findings emphasise the links between climate variability, water resources and socio-economic status. Short-term climatic fluctuation, especially heavy rainfall, plays an important role in drinking water quality in developing countries [109]. High/low temperature and drought in farming regions negatively impact farmers' psychological status, especially drought [110]. Prolonged hydrological extremes have persistent impacts on Sub-Saharan African wealth disparities, and dryness and wetness reduces regional GDP per capita [111]. Rainfall regimes are being altered by climate change, leading to shorter and more intense rainy seasons that threaten water and food security in marginal areas [112]. These results show that adaptation measures and investments are needed to prevent future impacts on water resources and socio-economic well-being. Effective water resource management and policy decisions therefore depend on the careful selection of appropriate spatial and temporal scales for specific research objectives. In this context, the length of the study changes the results. For example, China's changing agricultural water footprint between 2000 and 2019 was influenced by significant route dependence and geographical dependence [113].

Calculation of the water footprint at the selected spatial level is complicated by the flow of water resources and the virtual availability of water [108]. This complication arises because both direct and indirect water consumption and the multiple impacts of human management and weather conditions in different locations, must be considered. For example, Mao et al. [114] state that the water footprint is distributed differently across spatial scales (e.g. crop field, county, river basin) and is influenced by local management practices and climatic conditions. These are in agreement with the findings of Zhuo et al. [115], who found that different spatial scales result in different responses to water use in agriculture. Virtual water trade, that is, water embedded in exported and imported goods, must be updated to estimate regional water dependence [116]. Accurate calculation of virtual water is often hindered by a lack of data and methodological sophistication, making national water resources planning challenging [47]. Effective water management therefore requires a nuanced understanding of both local and global water flows, highlighting the need for spatially explicit assessments. Consequently, the precise choice of spatial scale is often independent of regulatory decisions, which in turn could alter the perceived upper limits of water resource use [107].

Matching spatio-temporal scales to the characteristics and objectives of specific research topics enables a better understanding of water distribution and use and ultimately supports the formulation of sound response strategies. Spatio-temporally disaggregated information can provide opportunities for water saving and offer strategic planning insights for further sustainable water management policies in large basins [108].

While choosing the right spatial and temporal scale is crucial, it is equally important to consider the broader context of water resources management. This requires a good understanding of the socio-economic and environmental factors that affect water use and availability, in the broader context of how policy decisions affect the sustainability of water management. However, these issues require more global solutions as they evolve, i.e. bringing together different data and methodologies to look at the dynamics of water resources holistically.

2) Grey and green water footprint assessments are essential for sustainable water management under favourable conditions in urban landscapes and agriculture. The water footprint of crops has mostly been analysed in the green domain, often overlooking the transcendence of trees, pastures and urban greenery. The analysis of grey water also needs improvement, especially with regard to the self-purifying power of water bodies and the increasingly complicated nature of pollutants. These topics are described in more detail in the following sections.

The green water footprint is the amount of rainwater consumed during plant growth, especially in agriculture. However, it is important to know that urban green spaces within the urban area also contribute to the water footprint. Unfortunately, these contributions are not always taken into account when calculations are made to value such areas [16]. Extending the green water footprint to recreational areas and forests could be one way to address the failure of urban water management systems [117].

On the other hand, the grey water footprint quantifies the amount of water used to dissolve pollutants. Current methods are simple and do not capture the complex interaction of different pollutants [37]. Complex models such as SPARE: WATER provide extensive calculations due to the factor of the environment in which it exists combined with the complexity of the pollutants [17]. Future studies would need to focus on integrating the multivariate variables into the assessment of the grey water footprint to ensure a better expression of the environmental impact [16].

Conversely, there are also those who argue that too much emphasis on the water footprint would undermine other large-scale approaches to optimising the economical and efficient use of water. One school of thought suggests that there needs to be a holistic approach to the efficient use and management of water resources.

3) The unequal distribution of water resources is reflected in the differences in per capita water consumption across countries worldwide, which presents an additional challenge. Political dynamics, socio-economic development, and geographical conditions contribute to these differences. In this context, the work carried out by Yalew et al. [118] highlighted that regions with higher levels of economic development have a higher water footprint. The authors attributed this to the increased consumption and industrial activity. Furthermore, the relocation of production to less developed regions lead to greater pollution and resource degradation, which perpetuating inequalities [119]. A study of 27 countries covering the period from 1960 to 2010 found an N-shaped relationship between urban water use and GDP, known as the cubic water Kuznets curve [120]. In China, the urban water footprint was found to be 1.6 to 3.7 times higher than the rural footprint, with consumption levels accounting for the differences between provinces [121]. Globally, around 70% of countries show an inverted U-shaped trend in water consumption due to technological progress and optimization of production structure. The Organisation for Economic Co-operation and Development (OECD) is a 36-member intergovernmental economic organization established in 1961 with the objective of economic growth and international trade [35]. OECD nations have abolished competition-restricting regulations and harmonized their product market policies to a greater extent [122]. The OECD countries with the highest water consumption typically generate over 60% of their GDP in the service sector, have an urbanization rate of 70% and a GDP per capita of over $20,000 [108]. The above results show the complex nature of the relationship between economic growth, urbanization and water use patterns.

Current studies focus on the implementation of distributive justice principles to manage water resources in a way that maximizes equity and considers hydrological efficiency. Traditional models have a tendency to overlook socio-economic impacts, thereby further aggravating inequalities [118]. The inclusion of morality and distributive justice into the IWRM context could ensure fair and sustainable distribution, especially in regions of water scarcity [123]. Equity principles in running water systems can reconcile equity and efficiency, expand the space for solutions and indirectly benefit poor people [124]. Equity in water distribution is considered central to a more equal future, and equity takes precedence over efficiency and markets in water policy [108]. This research pointed out the necessity of interdisciplinary and strong policy support in developing models that are technically robust and incorporate social equity provisions, aligning water resources management with higher social values of equity and sustainability.

Indices of equality, such as the Gini coefficient and Theil index, have been used in recent studies to quantify fair access to water sources across provinces and to provide numerical data on spatial and population inequality [125]. The Gini coefficient, a standard economic measure of income inequality, is a statistical indicator of dispersion ranging from 0 (equality) to 1 (maximum inequality). In the context of water resource distribution, it is determined by plotting the Lorenz curve of cumulative water supply against cumulative population or supply area and calculating the ratio of the area between the equality line and the Lorenz curve to the total area under the equality line.

Similarly, the Theil Index is an entropy-based measure of inequality that breaks down overall inequality into within-group and between-group components. For this reason, it is particularly suitable for analyzing nested spatial scales, such as municipal, provincial, and national levels. The following formula is used for the calculation:

$$T = \sum_{i=1}^{n} (\frac{x_i}{X} . \ln(\frac{x_i/_X}{p_i/_P}))$$

Where xi is the water resource allocated to region i, X is the total water resource, p_i is the population of region i, and P is the total population. A higher Theil index indicates greater inequality in the distribution of water per capita.

These indices are useful for identifying areas experiencing oversupply (i.e., uneven water supply to a population or region) or undersupply (i.e., uneven allocation). For example, Yu et al. [125] used the Gini coefficient to highlight significant inequalities in the water supply systems of rapidly growing Chinese provinces. Li et al. [31] advanced this approach by developing a composite framework for evaluating water resource sustainability, which includes security (measured by resilience indicators), efficiency (measured by water productivity indicators), and equity (measured by the Gini coefficient) to assess the multi-layered sustainability of water resource systems. In the context of water movement towards water sustainability, this holistic perspective encompasses not only availability and use efficiency but also equitable and just access for all population segments.

All these interventions have promoted a more equitable distribution of water. However, the management of the international water regime and a mechanism for international co-operation remain significant challenges. Addressing these concerns therefore requires an approach that effectively balances local needs and international sustainability requirements.

5.2.Future research perspectives

Future research must focus on exploring the FEW Nexus by integrating ecosystem services and developing effective, comprehensive management practices. The Food-Energy-Water (FEW) Nexus is identified as a significant driver of sustainable development, considering the intricate interdependencies between these imperative resources[99]. Integrated management practices should be implemented to enhance resource efficiency and minimize inefficiencies [126]. Analysts have applied predictive mathematical modeling tools and techniques to support FEW Nexus planning, including advanced multi-criteria optimization methods and aggregate decision-making indices [126], [127]. These techniques enable the identification of Nexus synergies and trade-offs, leading to improved resource management, policy planning, and formulation. The coupling, links, and efficiency within the FEW Nexus have been described and addressed in most fields, with gaps and opportunities for future improvement identified [128]. Stakeholders adopting a Nexus perspective can drive resource efficiency and sustainable action, thereby facilitating the achievement of the Sustainable Development Goals [99].

The Nexus approach to FEW specifically addresses the interconnections between these sectors and recognises that a shift in one sector significantly affects the other two drivers [129]. This holistic approach is necessary for sustainable resource management and for achieving the Sustainable Development Goals [99]. Various studies have suggested different quantitative models to characterise the FEW Nexus, such as input-output models to analyse interlinkages among sectors [130] and multi-criteria decision-making models to optimise production and resource use [131]. These help to identify synergies and trade-offs in agricultural land use systems [126]. Agricultural crops such as alfalfa are highly sensitive to energy and water use [130]. For example, according to Nie et al. [126], Pareto solutions could maximise food production, save water and energy, and function efficiently under a wide range of climatic conditions.

There must be the political will and commitment to develop synergies between actors working towards complementary goals in the basin. Ideally, cross-sectoral stakeholder engagement ensures the representation of different perspectives that would improve the coherence and efficiency of resource management strategies [132]. The concept of the FEW Nexus seems promising to address some of the sustainability challenges. However, there are still some critical bottlenecks in its operationalization and much more research needs to be done to conceptualize and effectively use these linkages. Linking theories and methods for food, energy, water and ecosystem services is still at an early stage of research; there is little literature to date that integrates ecological services into a somewhat broader system. There is a need for multidisciplinary and interdisciplinary comprehensive studies and breakthroughs from many case studies. There is also a great need for cooperation and coordination at transboundary and regional levels and the need to pursue compensation mechanisms to make water resources sustainable.

1) Use the "environmental footprint family" indicator to assess the environmental sustainability dimension of the human-environment system. The sustainability of the human-environment system includes social, economic and environmental dimensions, with environmental sustainability being the foundation of social and economic sustainability. The family of ecological footprints includes the ecological footprint, the water footprint, the carbon footprint, the nitrogen footprint, the phosphorus footprint, the land footprint, the energy footprint, etc. [133]. Their common feature is that they can quantify the use and utilization of natural resources by humans and comprehensively assess the ecological sustainability dimension of the coupled human-environment system. The ecological footprint family concept is suitable for solving the problem of ignoring other resources while focusing on a single resource and considering the environmental impacts of different resource uses, which is particularly important for achieving sustainable regional development. Therefore, including the environmental impacts of social and economic development in the assessment of the "footprint family" [134] is a new research idea and direction that considers sustainable development, the comprehensive development of society, economy and environment.

The main challenges in researching the water footprint include data limitations, methodological inconsistencies and problems with spatial and temporal scale. While there is a consensus on the need for improved data and methods, future research should focus on developing standardised protocols and integrated models to fill these gaps.

In summary, despite several problems and challenges in existing research, water footprint accounting, particularly the theory and method of linking food, energy, water and other ecosystem services, can provide important scientific and technological support for fulfilling human well-being, reducing trade-offs in resource use, promoting mutual synergies and fostering sustainable regional development.

6. Conclusion

The WF has become a key analytical concept to comprehend and manage water resources amidst mounting global pressures such as population growth, urbanization, climate change and economic development. The review outlines the principal developments within WF research, from its theoretical development based on virtual water to its sophisticated use in agriculture, energy and urban systems. Combination of blue, green and grey WF components, supported by tools such as CROPWAT and LCA, has enabled advanced water consumption quantification and revealed inherent interdependencies within the FEW Nexus. Operational applications such as the China Sponge City program illustrate how WF metrics can contribute towards integrated urban planning by reducing blue WF by 15% and improving food security through water redistribution. Similarly, quantitative insights into seasonal versus interannual WF variability, such as the 28% higher green WF for rice in India and the 22% variability for sorghum in Sub-Saharan Africa, emphasise the importance of adaptive temporal scales for precision water management.

There are limitations despite this progress. Very scarce data, particularly for grey WF pollutants such as microplastics and pharmaceuticals, and methodological heterogeneity constrain WF analysis accuracy. Disparities in the spatio-temporal patterns, i.e., asymmetrical seasonal water scarcity, obstruct resource planning, while uneven dispersion of water, as reflected through the Gini index value of 0.42 and Theil index value of 0.35, depicts the need for an equity policy. The integration of WF into sustainability analysis using indicators such as the Quantity-Quality-Environment (QQE) index and the ecological footprint family provides an integrated approach to the integration of environmental, social and economic concerns. Future research will require to prioritize standardised processes for increasing the reliability and comparability of WF and the inclusion of high frequency data from platforms such as GRWNOD and OpenET. The extension of the FEW Nexus framework by including ecosystem services and cross-boundary collaboration will be crucial in addressing global water challenges. By promoting interdisciplinary models and cross-sectoral stakeholder engagement, WF research can drive sustainable resource management that is in line with the Sustainable Development Goals. Ultimately, the WF paradigm provides us with a firm foundation for evidence-informed policy-making that acknowledges means by which water scarcity can be avoided, equity can be increased and the human-environmental system resilience ensured in a water-scarce future.

List of Abbreviations:

EPIC – Environmental Policy Integrated Climate

FEW – Food–Energy–Water

Gini Coefficient – Indicator of inequality in water distribution

GRWNOD – Global Real-time Water Network Observation Database

IO – Input–Output (Analysis/Model)

IoT – Internet of Things

IWRM – Integrated Water Resources Management

Kc – Crop Coefficient

LCA – Life Cycle Assessment

OpenET – Open Evapotranspiration (Satellite Remote Sensing Platform)

QQE – Quantity–Quality–Environment Index

Theil Index – Indicator of inequality and spatial disparity

WF – Water Footprint

Author Contributions:

Mahmoud Said Rashed: Conceptualization, Writing – original draft & editing, Data curation, Visualization. Shaimaa Fakhry: Writing – original draft & editing, Software, Conceptualization. Radwa Satour: Writing – review & editing, Formal analysis, Visualization. Mabrouk Sobhy: Writing – original draft & editing, Software, Data curation. A. K. Haghi: Conceptualization, Writing – original draft & editing. All authors have read and agreed to the published version of the manuscript.

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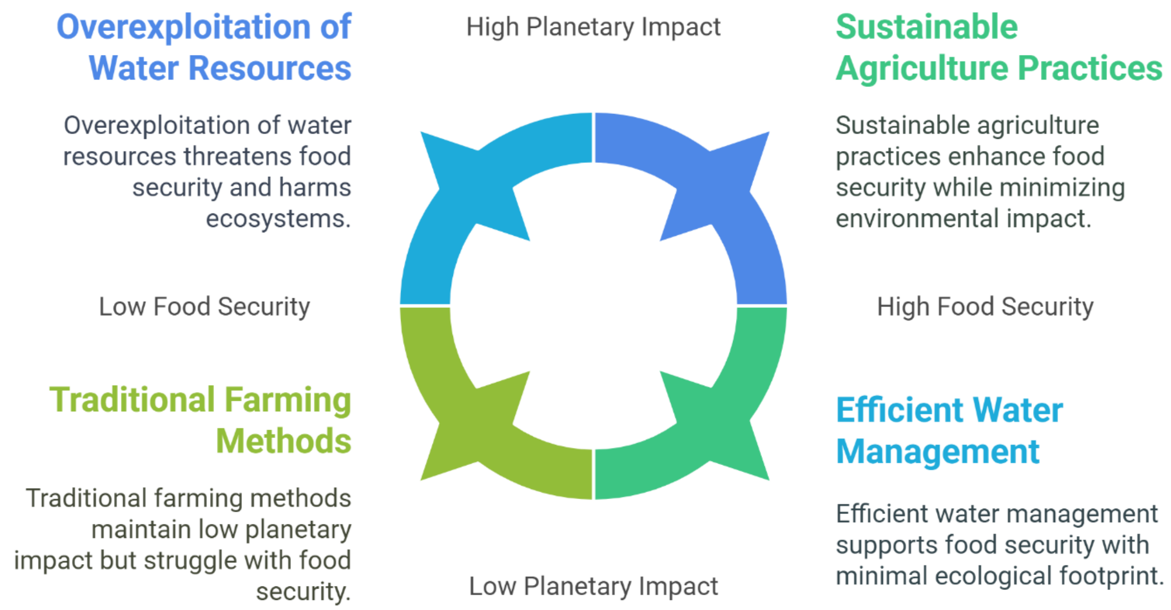

Figure 1: Balancing Food-Energy-Water (FEW) system and planetary Impact

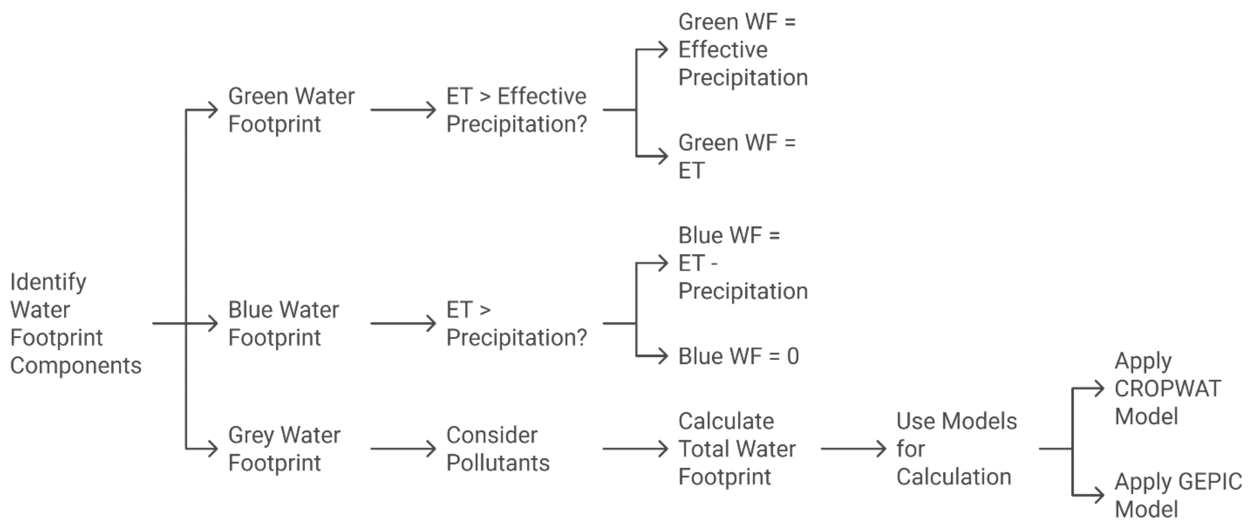

Figure 2: Agriculture Water foot Print Calculations

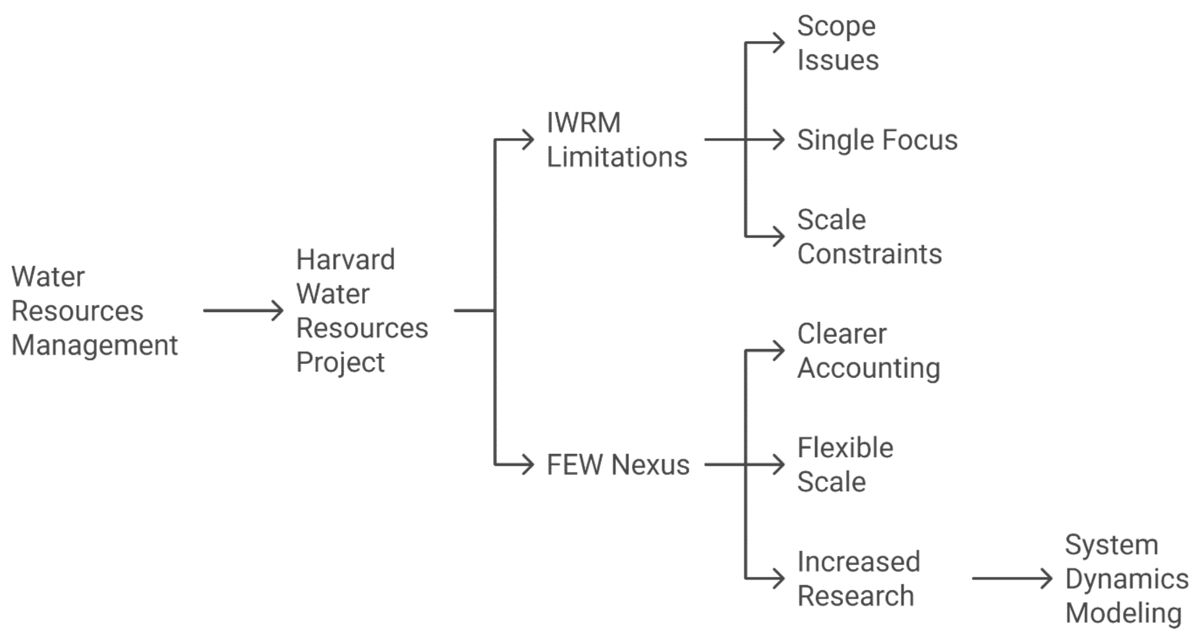

Figure 3: Integrating Water Footprint into FEW Nexus.

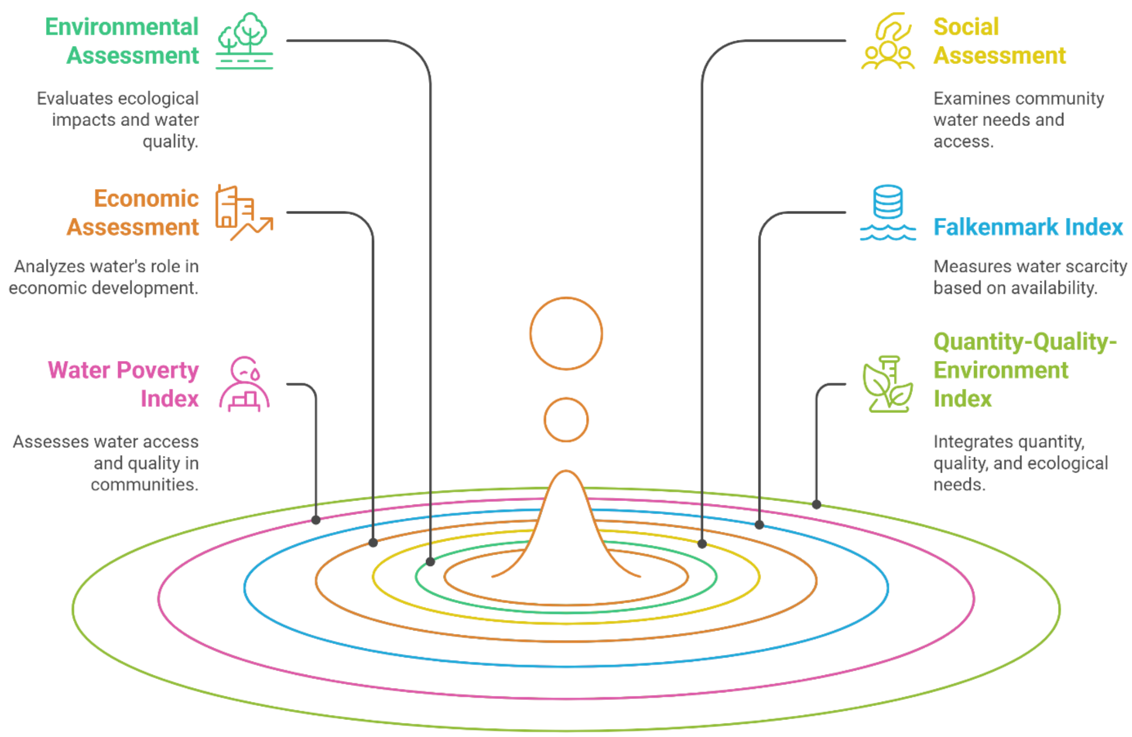

Figure 4: Water Resource Sustainability Assessment