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Review

Water Footprint Study Review for Understanding and Resolving Water Issues in China

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Abstract: The water footprint (WF) is a widely recognised and comprehensive indicator of both the direct and indirect appropriation of freshwater. It has been utilised for diverse functions, including as a key indicator of the planetary boundaries and United Nations Sustainable Development Goals. Focusing on the nation with the greatest WF, i.e., China, this study reviews journal articles both in English and Chinese published from January 2003 to June 2020. Using CiteSpace and bibliometric analysis of papers, journals, and keywords, we explore state-of-the-art WF accounting, driving forces, and effects. Visible differences in WF accounting keywords and spatial scales between English and Chinese literature are identified. Reported WF values for the same product varied across studies, and there was a lack of information regarding uncertainties. Key driving factors have been largely investigated for agricultural WFs but not for other sectors. The WF impact analyses primarily assess the environmental effects, ignoring the associated social and economic impacts. The development of WF studies has improved our understanding of water issues in China. However, there are still existing knowledge gaps to be filled to find solutions to WF-related issues.

Keywords: water footprint; China; water footprint accounting; driving forces; impact analysis

1. Introduction

The water footprint (WF) measures the consumptive and degradative freshwater appropriations of human activities, which can be attributed to production, consumption, and trade [1]. As a comprehensive water consumption indicator, WF has played increasingly diverse roles in the fields of hydrology, environmental science, and sustainability. Green (rainwater consumption) and blue (surface and groundwater consumption) WF accounting enable the identification and mapping of green and blue water scarcity in time and space [2–6]. The grey WF (the water required for water pollutant dilution) assessment has inspired the creation of new water scarcity indicators, such as the blue water scarcity index as the ratio of sectoral water withdrawals of acceptable water quality to the overall water availability proposed by Van Vliet et al. [7]. The environmental impact analysis of water consumption has been improved by incorporating WF indicators in multiregional input–output (IO) modelling [8,9] and life cycle assessments (LCAs) [10]. As a part of the "footprint family" [11], the WF has become one of the key indicators for planetary boundaries [12] and for measuring the United Nations Sustainable Development Goals (SDGs) at various scales [13,14]. Therefore, it is not surprising that the cumulative number of published articles on WFs expanded from 80 by December 2010 to 1775 by August 2020 in the Web of Science (WoS) database.

Most WF studies have been conducted at the country or regional scale [15]. China has the largest total WF for national production [16], and it ranks fourth in the groundwater footprint for food production [17]. One in four people facing moderate to severe water scarcity for at least one month in a year live in China [3]. Given the spatial and temporal heterogeneities of water resource endowments, the climate, the soil, economic structures, production, and consumption patterns within China, studying the Chinese WF at various intranational geographical scales has been a popular undertaking. Searching for the keyword "water footprint" in journal article titles in the WoS, 31% (i.e., 215 of 702) concern China. Additionally, there are approximately 100 articles (in Chinese) in the China National Knowledge Infrastructure (CNKI) database on WFs. Several review papers [18–21] focused on WF studies in China. Wu et al. [18] and Qian et al. [20] summarised the primary methodologies and algorithms used in the WF assessment for Chinese products. Sun and Shen [19] reviewed Chinese literature on ecological, carbon, water, and energy footprints and concluded that research on WFs was less developed than that on ecological and carbon footprints. Zhu et al. [21] provided a systematic bibliometric review on WFs in China regarding trends in research region distributions, keywords, and methods. However, aside from the conventional bibliometric analysis, an in-depth summary of Chinese WF research is lacking in terms of study content and achievable implementations for practical water resource management.

Based on the bibliometric analysis of articles published from January 2003 to June 2020 in English (WoS) and Chinese (CNKI), this study explores state-of-the-art WF accounting, driving force analyses, and environmental impact assessments. The implementations and limitations of Chinese water management strategies and possible future study directions are also discussed.

2. Literature Searching and Selection

Publications in English and Chinese on Chinese WFs from January 2003 to June 2020 were selected in the WoS and CNKI datasets, respectively. This analysis selected 209 journal papers in the WoS and 368 articles in the CNKI, including papers focused on China with "water footprint" in the title, excluding review papers. CiteSpace [22,23] is a freely accessible Java application for progressive knowledge domain trend visualisation. The trends in paper numbers, journals, and keywords were bibliometrically analysed using CiteSpace version 5.6 R5.

In order to visualise the trends in keywords, the function of cluster analysis and mapping in CiteSpace software were applied by setting the number of the most cited articles (N) as 50 and time slicing = 1. Here, we show the method behind. The modularity (Q) and silhouette value (S) indicated the mapping efficiency in CiteSpace. Modularity is a commonly used indicator to measure the results of community division in a network [24]. The higher the value, the better the results of community division. Silhouette is an indicator to evaluate the clustering effect [25]. The value is between −1~1. The higher the value, the better the clustering effect. If Q > 0.5 and S > 0.3, then the mapping exhibits sufficient reliability and validity of the keywords cluster analysis, respectively. The Q calculation was introduced by Clauset et al. [24].

$$Q = \frac{1}{2\,\mathrm{m}}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2\,\mathrm{m}}\right]\delta(c_i, c_j) \quad (1)$$

where c_i refers to the community node i, k_i is the degree of node i, m represents the number of edges in the community, and A_{ij} represents the elements of the adjacency matrix. $A_{ij} = 1$ if i and j are connected; otherwise, $A_{ij} = 0$. When nodes i and j are in the same community, then $\delta(c_i, c_j) = 1$; otherwise, $\delta(c_i, c_j) = 0$. The S estimation was introduced by Rousseeuw [25].

$$S = \frac{b_i - a_i}{\max\{a_i, b_i\}} \quad (2)$$

where a_i is the average distance between node i and the other nodes within the cluster to which it belongs, and b_i is the minimum average distance between node i and the nodes in the nearest clusters.

3. Results

3.1. Trends in Publication Numbers, Journals, and Keywords

The number of studies on Chinese WFs rapidly increased over time in both datasets (Figure 1). The Chinese scholars gradually showed interest in WF two years after the first Chinese paper on this topic was published by Long et al. [26]. The first English journal paper on WFs in China by Zhao et al. [27] was published six years later in 2009. Overall, through local case studies, the number of Chinese papers has been larger than those in English. The rise in publications since 2016 indicates that WF studies are becoming a popular research topic among Chinese scholars for understanding and explaining water issues in China.

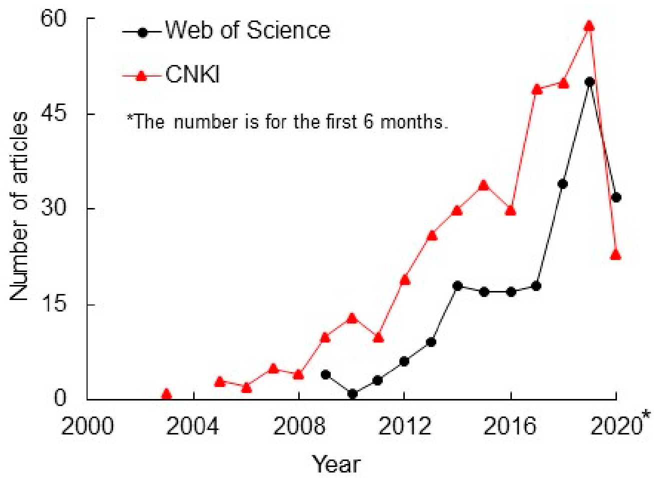


Figure 1. Annual developments in number of studies on water footprint for China's cases. Period: January 2003 to June 2020.

Table 1 lists the top ten journals in terms of publication numbers on Chinese WF case studies in WoS and CNKI. Sixty-one percent of the considered English articles and thirty percent of the Chinese papers were published in the listed journals. The top four English journals in terms of publication numbers, including the Journal of Cleaner Production, Science of the Total Environment, Ecological Economics, and Sustainability, each published over 10 papers on WFs. For the Chinese papers, six journals, led by Resources Science, published over 10 articles on WFs.

Table 1. The top 10 most productive journals on water footprint studies for China's cases.

Rank	Web of Science		China National Knowledge Infrastructure (CNKI)	
		n		n
1	Journal of Cleaner Production	38	Resources Science	16
2	Science of the Total Environment	22	Journal of Natural Resources	14
3	Ecological Economics	19	Agricultural Research in the Arid Areas	13
4	Sustainability	16	Acta Ecologica Sinica	12
5	Hydrology and Earth System Sciences	7	China Rural Water and Hydropower	11
6	Environmental Science & Technology	5	Yellow River	10
7	Water	5	Water Resources and Power	9
8	Ecological Modelling	5	Journal of Irrigation and Drainage	8
9	Water Science and Technology-Water Supply	5	China Population, Resources and Environment	7
10	Journal of the Science of Food and Agriculture	5	Journal of Glaciology and Geocryology	7

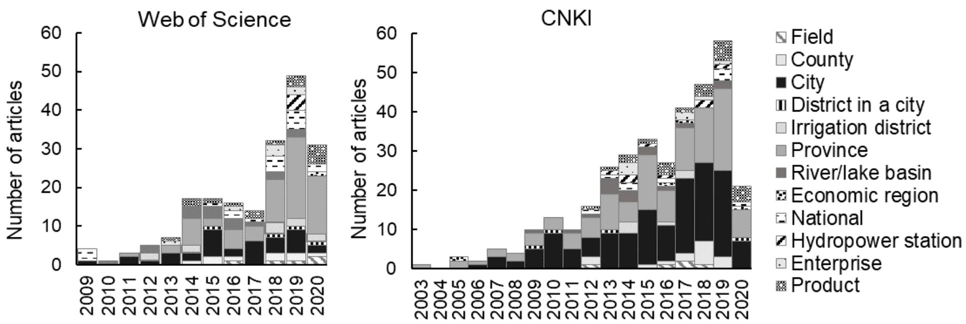
Keywords varied significantly between studies. However, the clustering characteristics of the keywords demonstrate the trends in research interest to a certain extent. Comparing the keyword clustering networks in WoS and CNKI (Figure 2), differences in scale, method, and/or research focus can be observed. The drier "North China Plain", where there were higher WFs and water scarcities, was the keyword with the greatest number of links to other keywords in the English papers, followed by "life cycle assessment", i.e., the most commonly used approach for industrial WF assessments (Figure 2a). With the recent focus on WF for energy production, "water-energy nexus" was also a popular keyword for Chinese WF studies. Additionally, in Chinese papers (Figure 2b), the keyword "crop" demonstrated an interest in using WF assessments in agriculture research. The keyword "dietary consumption" demonstrates the awareness in the studies regarding the close relationship between diet and WF.

Figure 2. Keywords clustering network in (**a**) Web of Science and (**b**) CNKI database. Period: January 2003 to June 2020. The figure is generated by the CiteSpace. Each colour block means a cluster of keywords. The smaller the pound sign number, the more keywords clustered. The name of the cluster is given by the keywords with the closest links to the others within the cluster.

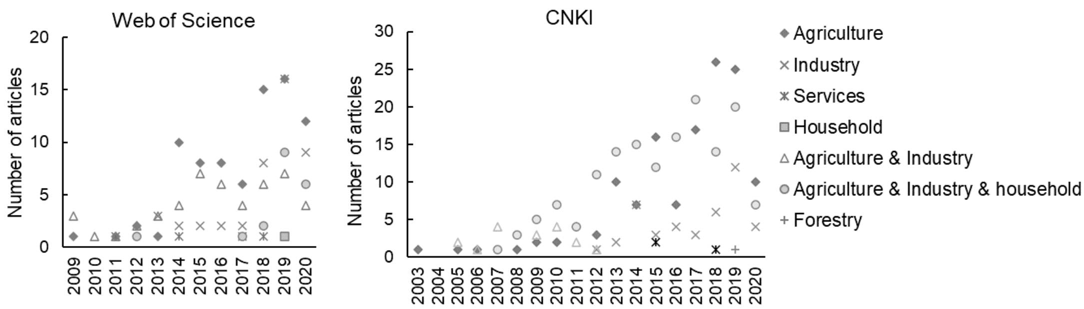
3.2. WF Accounting for China

The first English journal paper on WF accounting in China was by Zhao et al. [27], who estimated the direct and indirect blue national consumption WFs of 23 sectors for 2002 via an IO analysis. WF accounting based on an IO analysis was introduced in a Chinese paper in the same year by Cai et al. [28] for the nine provinces across the Yellow River Basin. Although the first Chinese paper [26] on WF accounting was published six years earlier than the English one, most of the Chinese papers until 2009 were based on a brief calculation framework for regional WF that involved multiplying the WF per product by the sum of local production and net imports. The WF per unit of agricultural products in the early papers was only for one product, and it did not consider temporal variations [29]. In English publications, for the agricultural sector, Yang et al. [30] first reported the Chinese national total of green and blue WFs for biofuel crop production, followed by Zeng et al. [31], who separately calculated the green and blue WFs of growing major crops in the Heihe River Basin. Among the Chinese papers, Deng et al. [32] were the first to estimate the green, blue, and grey WFs for cotton and its derivatives at the city level in the southern Xinjiang Province. For the industrial sector, Shao and Chen [33] reported the first accounting of the direct and indirect WFs of a sewage treatment plant in Beijing in an English paper. Wang et al. [34] reported the first blue WF inventory for seven typical textile products in a Chinese paper; and Li and Chen [35] calculated the WFs of operating inputs, labour, commission, and goods purchased in the gaming industry in Macao in an English paper. Ma et al. [36], a Chinese paper, calculated the WF of hotels in Zhangye City. The hybrid LCA model was a common method for service WF accounting. For households, only one English paper exists on blue and grey WF calculations for urban China at the national level for the period of 1992–2012 [37].

WF accounting publications on China have exhibited varying trends between the WoS and CNKI over time according to the spatial scale (Figure 3a). The provincial scale dominates WF accounting for China in the English articles (35% of the total considered papers), due to the accessibility and comprehensiveness of the input data for analysis. City WF estimates accounted for the second-largest portion (18%) of the English papers. Interestingly, we found that Beijing was the most popular case study in the WoS, with 39% of the city-level studies focusing on rapid changes in both water resource conditions and industrial structures [38]. Among the Chinese publications, WF calculations at the city level accounted for the greatest number of papers (40%), followed by those at the provincial level (32%). More local and accessible information for water authorities were displayed in the CNKI than the WoS. As the greatest water consumer, the agricultural sector was reported most frequently in both datasets, followed by the industrial sector (Figure 3b). With increasing attention paid to the industrial sector, WF assessments for a variety of industrial products are increasing. Recent studies have focused on agricultural or forestry-based industrial production, such as textiles [34,39], dairy [40], and papers [41]; and energy production, including coal [42] and gas [43].



(**a**)



(**b**)

Figure 3. Number of articles on water footprint accounting for China's cases (**a**) by spatial scale of analysis and (**b**) for different water use sectors in Web of Science and China National Knowledge Infrastructure (CNKI) database. Period: 2003–June 2020.

Although there are hundreds of articles on WF computations for Chinese cases, the reported WF values for the production or consumption of the same product in the same region typically differ across various studies because different algorithms, models, or input data sources are used. For example, WFs for crop and energy production are shown in Tables 2 and 3, respectively. Comparing the published green–blue WFs using diverse models for growing three staple crops in China at the national and provincial levels, the values at the provincial level exhibited higher coefficients of variation (CVs) (Table 2) [44]. There were higher variations in the recorded WFs for wheat production than those for the other two crops. Based on available estimates of the national average WF for energy production, the greatest differences were observed among four natural-gas-related accounts, with 65%, 154%, and 88% CVs for blue, grey, and indirect WFs, respectively (Table 3). Large variations in WF values for natural gas were due to different system boundary settings. The larger the reported WF, the longer the upstream supply chain was considered to be. Few studies have quantified the embedded uncertainties in crop WF accounting. Zhuo et al. [45] quantified the uncertainties as ±20% in WF for major crops within the Yellow River Basin, which was propagated by uncertainties in the input data and parameters when applying the grid-based daily water balance model. Tuninetti et al. [46] demonstrated that, based on a global estimate, the fast-track approach for crop WF calculation that only considers changes in crop yields generates uncertainty of approximately ±10%.

Table 2. Statistical variations of water footprint (WF) among different studies with different methodologies or data sources in the same area.

Scale	Maize		Wheat		Rice	
	WF (m^3 kg^{-1})	CV (%)	WF (m^3 kg^{-1})	CV (%)	WF (m^3 kg^{-1})	CV (%)
China	0.663	8	0.848	26	1.224	22
Provinces		16 (5–40)		32 (18–49)		27 (8–43)

Sources: Feng et al. [44]. In the Table, CV refers to the coefficient of variation measuring the range of deviation of WF quantification results within the same region.

Table 3. National average water footprint (WF) of energy production in publication (unit: m^3/GJ).

	Coal	Oil	Nature Gas	Thermal Power	References
Blue WF	0.021	0.224	0.083	0.744	[47]
Grey WF	0.164	0.016	0.013	0.470	
Blue WF				0.411	[48]
Grey WF				0.200	
Blue WF	0.021				[49]
Grey WF	0.164				
Indirect WF					
Blue WF				0.494	[50]
Grey WF				0.375	
Blue WF	0.021	0.189	0.081	1.083	[51]
Grey WF	0.157	0.057	0.000	0.107	
Indirect WF	0.015	0.035	0.030		
Blue WF			0.154		[43]
Grey WF			0.822		
Indirect WF			0.462		
Blue WF			0.005		[52]
Grey WF			0.063		
Blue WF				0.642	[53]
Grey WF				1.117	
Blue WF				0.455	[54]
Grey WF				1.379	
CV (Blue WF)	0.21	8%	65%	36%	
CV (Grey WF)	1.9%	56%	154%	78%	
CV (Indirect WF)			88%		

3.3. Drivers and Factors Affecting Chinese WFs

The driving factor analysis is an efficient path to understand the mechanisms behind changing WFs and identify possible key measures to reduce high WFs. Unsurprisingly, many Chinese case studies analysed key multiobjective WF-impacting factors. Table 4 summarises the existing representative publications on the driving factors of WFs in China. Scholars tended to identify the key socioeconomic driving factors of WFs. For regional WFs, including both direct and indirect WFs, population and affluence (i.e., per capita GDP) were reported as the leading positive forces, always compensating for the negative effects of technical development [55–57]. The total crop production WF (in m^3/year) for a particular geographic region, local rural population, and overall harvested area—i.e., the production scale—was defined as the growth in total WF [58–63]. In Xinjiang Province, Zhang et al. [64] identified that the technical irrigation levels, which were commonly viewed as a tool for reducing irrigation water use and enhancing water use efficiency, increased total crop production and led to an increase in total WF for crop fields—i.e., the irrigation paradox phenomenon—in other words, the higher efficiency of water use rarely reduces water consumption [65]. Increased fertilisation and irrigation efficiencies were demonstrated to be key management factors in declining the crop WF (in m^3/t) [66–70]. Of the climatic variables, the degree of growth and wind speed were the most critical ones [67]. For the agricultural consumption WF, the effects of diet changes were substantial [70,71]. Information on industrial sector impact factors was rare; only two examples of these factors were found. Shi et al. [72] discussed the key factors of the blue WF of a hydropower station; and Li et al. [39] analysed the impact factors of regional WFs in the textile industry.

Table 4. Summary of representative publications on driving factors of water footprints (WFs) in China.

	Unit	Key Driving Factors	References
Regional WF *	m^3/year	Population (+), Affluence (+); Technical development (−)	[55–57]
WF of crop production	m^3/year	Rural population (+); multiple-crop index (+); irrigated area (+); water-intensive cropping area (+); technical level (+); precipitation (+); irrigation project (+)	[58–63]
	m^3/t	Fertilizer (−); irrigation water use efficiency (−); growing day degree (−); wind speed (+);	[66–69]
WF of agricultural consumption	m^3/year	Population (+), Affluence (+); Diet change; Technical development (−)	[70,71]
WF of hydropower station	m^3/GJ	Climate; reservoir area (+); installed capacity; temporal resolution	[72]
WF of textile	m^3/year	Production scale (+); technical level (−)	[39]

* Regional WF means the total direct and indirect WF by agriculture, industry and household sectors for an administrative region.

3.4. Multiperspective WF Impacts

The WF impact assessment refers to the “sustainability assessment” and “environmental impact assessment” phases of Water Footprint Network [73] and LCA-based ISO14046 [74] frameworks, respectively. The two commonly used WF assessment frameworks both measure water consumption and inventory, but they differ in their impact assessment functions and methodologies [75–77]. The former places WF in the context of local water availability to inform regional water managers on where and how the WF can impact water endowments. The latter quantifies impacting indicators in terms of their effects on human health, ecosystems, and resource depletion, which are typically more critical to industrial water managers [75].

These framework differences are demonstrated in Chinese WF studies. Based on WF accounting in Chinese administrative regions, there are 59, 14, and 14 considered papers evaluating the blue water scarcity (i.e., the ratio of regional total blue WF to water availability), virtual water import dependency (i.e., the ratio of the external to the total WF of the regional consumption), and water self-sufficiency (i.e., the ratio of the internal WF to the total WF the regional consumption), respectively—all these concepts were introduced by Hoekstra et al. [73]. High, blue water scarcity due to spatial and temporal mismatches between water consumption and availability occurred in the northern China basins [6,29,31] and provinces [78]. Additionally, high water stress with a blue water scarcity value of 0.99, which was due to intensive demands by the large population and high agricultural water requirements, occurred in the water-rich southern city Wuhan [79]. Yu et al. [80] found that the wet Yalong River Basin, with 19 hydropower stations, exhibited low blue water scarcity throughout the year. In contrast, Zhuo et al. [81] demonstrated that environmental flow requirements have been largely appropriated by large amounts of reservoir water storage along the water-scarce Yellow River. Comparing the regional grey WF to local water resources made assessing water scarcity from both the quantity and quality perspectives possible [82], such as the Chinese case studies for Beijing [82], the Haihe River Basin [83], and the Qian-tang River Basin [84]. Following the ISO 14046 framework, the environmental impacts of WFs were also assessed for the dairy industry [85], energy production [86], electricity production [53], silk products [87], textile products [88], and viscose staple fibres [89]. The water scarcity and water degradative footprints were the most commonly evaluated WF impact indicators in these studies.

4. Discussion

4.1. Implementations and Limitations

Implementations of WF concepts in practical water resources management strategies and policies depend on robust measurements, comprehensive impact assessments, feasible reflections, and widespread awareness. All these are subject to the spatial resolution of analysis and the quality of data. Adding information to WF figures by comparing WFs to benchmarks or local environmental or economic conditions helps to display their grades and impacts [90]. According to the current analysis in terms of keywords in considered publications as well as trends in WF accounting for China, existing WF estimations and research for China were primarily on WF magnitudes, components in terms of water colours, and variation in time and space, while little information was available for WF benchmarks and viable action manuals. The WF spatial and temporal heterogeneities in agricultural production under varied climatic conditions and crop yield levels have been largely reported in [21]. Industrial WF datasets, especially for the textile industry and energy production, have been developed. Blue and green water scarcity levels from agricultural production and consumption in northern China have been revealed in finer spatial and temporal units [6]. According to the driving factor assessment, utilising water-saving technologies in crop fields, industrial restructuring, trade network optimisation, consumption pattern (diet) adjustments, and water price reformation have largely been recommended theoretically in the reviewed literature for reducing WFs in China. However, as previously mentioned, there is little information on the robustness of these WF values based on the algorithm used, and the spatial-temporal resolutions lack sufficient quantitative uncertainty analyses. Additionally, operable measures for reducing WFs were not found. Therefore, it is not surprising that WF research has not been widely incorporated by local water policies in China. Only 23 projects have been funded with "water footprint" in their titles, as compared to the over-1600 projects with words "water resources consumption" and to the over 2300 projects with words "water productivity", by the National Natural Science Foundation of China at the end of August 2020 [91]. The only two existing governmental actions related to the WF include the issue of the Chinese version of ISO 14046 as a national standard (GB/T 33859-2017/ISO 14046:2014) [92] and the Water Supplies Department of Hong Kong introduction of global average WF values, using term "virtual water", of common food and industrial products on their website [93].

4.2. Future Directions

Due to its ability to measure different water consumption sources at any spatial or temporal scale and be integrated with other environmental impact indicators [90], the WF has been widely highlighted as an effective metric for constructing evaluation frameworks for the water–food–energy nexus [94,95], determining the water planetary boundary [96], and measuring the progress of SDGs related to water security [13,14]. However, four primary knowledge gaps must be remedied before using WF assessments to identify and resolve the increasingly complex water issues in China. First, as shown in current results, multiple methodologies exist for WF accounting and impact analysis.

In choosing one or multiple proper methodologies and taking advantages of each, the most important step is clarifying the purposes of the WF accounting or impact analysis. Each kind of methodology has its own unique advantages and scope of application. Regarding WF accounting, the Water Footprint Network bottom-up approach, especially for agricultural products, can directly record the WF of producing a specific kind of product, whereas the multiregional IO-based WF modelling is able to show the appropriation of water resources by the entire supply-chain of a sector [97]. Regarding WF impact analysis, the Water Footprint Network framework shows WF inventory and tends to assess its impacts on local water resources physically; whereas the LCA-based ISO framework focused on the level of impacts on human health, ecosystems, and resource depletions by using indexes in unit of H_2O equivalent [75]. Second, for each water-use sector, WF accounting standards with unified measurements of uncertainties by verified algorithms are urgently needed. There is only one study currently available on the quantification of uncertainties in WF accounting for crops in the Yellow River Basin [45], and it is limited to certain tested crops, models, and scales. Although there is information in ISO 14046 on the principles of uncertainty analysis (see Section 3.6.3 in the ISO 14046 standard), case studies are scarce. Validations of existing WF algorithms and modelling in field experiments for the agricultural sector, enterprise monitoring for the industrial sector, and large sampling social surveys for households should be performed. At the same time, we should always keep in mind and try to answer the questions of how representative the field trials are, and of what level/scale—having in mind that water use/requirements can be very diverse from one field to the other. Of course, the balance between the complexity and efficiency in dealing with the abovementioned knowledge gaps should be taken into account. Third, widely valid and tested methodologies for setting WF benchmarks must still be developed. For industrial sectors, WF benchmarks can be set according to the optimal production techniques and supply chains [98]. Finally, assessments of the social and economic effects of WFs must be developed as WFs are generated by social and economic activities. Many studies have demonstrated how regional WFs affect local water resources or water quality; however, they lack information on the social and economic effects of the WFs. The next step is to distinguish between the green and blue water economic values to determine the associated economic effects (e.g., [99]).

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