Original Research

A Single-Indicator Approach to Assessing the Water Footprint of Zhejiang's Textile Industry

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Abstract

Water footprint is an indicator to quantify the potential environmental impacts related to water. Current methods for the water footprint assessment can only obtain the results which are typically reported as a profile of impact category indicator results. Due to the diverse and incomparable results, the demand for a single indicator for water footprint assessment is highlighted in recent years. In this paper, an improved approach integrating water quantity and quality into a single indicator was proposed for water footprint assessment. Then, a case study for water footprint assessment of Zhejiang's textile industry was analyzed with this approach. The results revealed that the comprehensive assessment indicator of water footprint (CAI_{wf}) of Zhejiang's textile industry decreased more than 20% from 2008 to 2018. CAI_{wf} and endpoint indicator of water footprint (WF_{end}) obtained with volumetric water footprint approach depicted similar tendencies to the CAI_{wf} and WF_{end} obtained with impact-oriented water footprint approach. Among the three sub-sectors of Zhejiang's textile industry, the CAI_{wf} of textile manufacture sector was the largest, followed by chemical fiber manufacture sector and clothing manufacture sector.

Keywords: comprehensive assessment indicator, textile industry, water footprint, water degradation, water scarcity

Introduction

China is the world's largest producer and exporter of textiles and clothing. In 2019, China's exports of textiles and clothing were 272 billion dollars, accounting for 34.02% of the world's total textiles and clothing exports [1]. Zhejiang's textile industry is the largest contributor to China's textiles and apparel exports, occupied approximately 28.64% of China's textiles and apparel exports in 2019 [2, 3]. The textile manufacturing process is characterized by a large amount of water consumption and wastewater generation, which have a serious impact on the environment related to

water. In 2019, Zhejiang's textile industry discharged 0.50 billion tons of wastewater, accounting for 47.64% of the total wastewater discharge of the thirty-eight industrial sectors in Zhejiang province [4]. The large amount of water consumption and wastewater discharge has resulted in growing pressure on the textile industry. Therefore, a quantitative and evaluation tool is urgently needed to assess the potential environmental impacts related to water. It can be an important reference to the improvement of water saving and emission reduction in the textile industry.

The water footprint is a comprehensive indicator of freshwater resources appropriation considering water consumption and pollution [5]. According to Water Footprint Network (WFN), water footprint is composed of green water footprint, blue water footprint and grey water footprint [5]. The green water footprint is the rainwater that do not become run off or recharge the groundwater. The blue water footprint is the water taken from surface or ground water resources. The grey water footprint is the amount of fresh water required to assimilate a load of pollutants to meet specific water quality requirements. Different from WFN, the international standard ISO 14046: Environmental management - Water footprint - Principles, requirements and guidelines divided water footprint into two major categories: water scarcity footprint caused by water consumption and water degradation footprint caused by water pollution [6, 7]. WFN performed water footprint assessment at the volumetric level and ISO14046 at the impact-oriented level [8-10]. The former has focused on a volumetric measure of water consumption and pollution, while the latter has given greater emphasis to the potential environmental impacts related to water [11, 12].

Water footprint have been widely applied to assess the effects on water environment in many industries, such as wine-making industry [13-15], gaming industry [16], steel industry [17], brick-manufacturing industry [18], cement industry [19], dairy industry [6, 20], electric power industry [21], mining industry [22], plumbing Industry [23], gold industry [24], match industry [25], and bottled water model industry [26]. For textile industry, Chapagain et al. [27] studied the green water footprint, blue water footprint and grey water footprint of cotton growing around the world from 1997 to 2001. Wang et al. [28] introduced the theory of industrial water footprint into the textile and garment industry, so as to strengthen the management of water resources in the textile and garment industry. Chico et al. [29] calculated the water footprint of jeans and found that the fiber production is the stage with the highest water consumption. Hossain & Khan [30] calculated the water footprint of cotton cultivation, transportation and textile industry and showed possible means to reduce water consumption and pollution in cotton cultivation and textile industries. Yang et al. [31] evaluated the water footprint of silk crepe de chine dresses and silk brocade dresses based on the ISO 14046 standard and found

that the contribution of brocade dress to both water scarcity footprint and water degradation footprint is greater than that of crepe de chine dresses dress. Chen et al. [32] analyzed the water footprint of China's textile industry based on ISO 14046 and found that water scarcity footprint and water eutrophication footprint increased from 1996 to 2015. It can be seen that there are a variety of indicators such as blue water footprint, water scarcity footprint, water eutrophication footprint to quantify the environmental impacts related to water of textile industry. However, these results have also been questioned on grounds that the different units of impact category indicators are incomprehensible to non-professionals. In addition, these indicators are mostly indicated at the midpoint level. Up to now, far too little attention has been paid to environmental impact scores on endpoint level.

Water footprint can be indicated at the midpoint level and at the endpoint level [33]. The midpoint indicators of water footprint convert the extractions of water resources and emissions of hazardous substances into impact category indicators. The endpoint indicators of water footprint are typically assessed for three areas of protection which are human health, ecosystem quality and resource scarcity. The endpoint indicators can model the cause-effect chain up to the endpoint, identifying environmental impacts with fewer indicators. However, both of midpoint and endpoint indicators are difficult to interpret. Within a water footprint assessment, it is possible to determine the contribution to the acidification, eutrophication and other environmental effects while the total environmental impact related to water remains unknown. The midpoint and endpoint indicators have its standalone units resulting in incomparable and incomprehensive water footprint results [34]. It is necessary to normalize the results into a comprehensive metric [35-36].

To address this gap, this paper proposes a single-indicator approach to assess the environmental potential impacts related to water considering water quantity and quality. The approach provides a great contribution made in the direction of creating a comprehensive analytical framework for water footprint assessment and aggregating environmental effects related to water into a single score. The approach combines water consumption and water pollution into a composite single indicator, which achieves the goal of comparing water footprint results. To illustrate the approach, we applied the approach to estimate the water footprint of Zhejiang's textile industry during the period 2008-2018. The presented approach is useful for water management of water-intensive industry as well as for sustainable use of water resources.

Methods and Data

A defining feature of the new approach is a single stand-alone result calculated with volumetric water

footprint approach and impact-oriented water footprint approach. According to the volumetric water footprint approach, two midpoint indicators (blue water footprint and grey water footprint) and two endpoint indicators (damage to human health and damage to ecosystem quality) are applied. Meanwhile, there are also two midpoint indicators (water scarcity footprint and water eutrophication footprint) and two endpoint indicators (damage to human health and damage to ecosystem quality) which are taken into account based on the impact-oriented water footprint approach.

The comprehensive assessment indicator of water footprint(CAI_{wf}) metrics that quantifies the total environmental impacts related to water. The CAI_{wf} can be calculated as follows:

$$CAI_{wf} = f_{wei,hum} \times f_{nor,hum} \times WF_{end,hum}$$
$$+ f_{wei,eco} \times f_{nor,eco} \times WF_{end,eco} \quad (1)$$

where CAI_{wf} is the comprehensive assessment indicator of water footprint. $f_{wei,hum}$ is the weighting factor of damage to human health. $f_{nor,hum}$ is the normalized factor of damage to human health. $f_{wei,eco}$ is the weighting factor of damage to ecosystem quality. $f_{nor,eco}$ is the normalized factor of damage to ecosystem quality. $WF_{end,hum}$ and $WF_{end,eco}$ are the damage to human health and damage to ecosystem quality respectively. The $f_{nor,hum}$ and $f_{nor,eco}$ were determined by total emissions and resource consumption caused by the reference system. The $f_{wei,hum}$ and $f_{wei,eco}$ were obtained by the mixing triangle which can be used to graphically depict the weighting factor for all three damage categories. The $f_{nor,hum}$, $f_{nor,eco}$, $f_{wei,hum}$ and $f_{wei,eco}$ will not change due to processes, equipment and other factors. The $WF_{end,hum}$ and $WF_{end,eco}$ were endpoint indicators of water footprint, which changed with wastewater discharge and water consumption.

According to volumetric water footprint approach, $WF_{end,hum}$ and $WF_{end,eco}$ can be calculated as follows:

$$WF_{end,i} = CF_i \times (WF_{mid,blue} + WF_{mid,grey}) \quad (2)$$

where CF_i is the endpoint characterization factors of endpoint indicator i. $WF_{mid,blue}$ and $WF_{mid,grey}$ are blue water footprint and grey water footprint respectively.

In the process of textile, clothing and chemical fiber manufacturing, there is less water evaporated and less water incorporated into the product. The blue water footprint is approximately equal to the wastewater discharge [37]. Therefore, The $WF_{mid,blue}$ can be calculated as follows:

$$WF_{mid,blue} = V_{dis} \quad (3)$$

where V_{dis} is the industrial wastewater discharges.
The $WF_{mid,grey}$ can be calculated as follows [5]:

$$WF_{mid,grey} = \max \left(\frac{L_i}{c_{max,i} - c_{nat,i}} \right) \quad (4)$$

where L_i is the amount of pollutants i. $C_{max,i}$ is the maximum acceptable concentration of pollutant i in the receiving water body. $C_{nat,i}$ is the natural concentration of pollutant i in the receiving water body.

The comprehensive assessment indicator based on impact-oriented water footprint approach can also be calculated with Eq. (1). Water scarcity footprint addresses the potential environmental impacts associated with the quantity aspect of water consumption. Water eutrophication footprint addresses the potential eutrophication impact associated with wastewater pollutants on the water environment. The $WF_{end,i}$ based on the impact-oriented water footprint approach can be calculated as follows [38]:

$$WF_{end,i} = \sum_{j=1}^{n} CF_{i,j} \times M_j \quad (5)$$

where $CF_{i,j}$ is the endpoint characterization factors of pollutant or water consumption j. M_j is the quantity of water consumption or wastewater pollutant.

The damage to human health from water eutrophication footprint was excluded when calculating the endpoint indicator. That was because only chemical oxygen demand and ammonia nitrogen which caused water eutrophication were counted in the yearbook and there was no damage pathway of water eutrophication on human health. The data of wastewater discharge and wastewater pollutants in this paper were collected from Zhejiang natural resources and statistical yearbook on environment (2008-2018)and presented in Table 1. The endpoint characterization factors used in this paper, as shown in Table 2, were derived from ReCiPe 2016. Table 3 listed the normalized factor and the weighting factor extracted from Eco-indicator 99. The maximum acceptable concentration (C_{max}) of pollutants in the water environmental quality standards were based on the Environmental quality standards for surface water (GB 3838-2002). In general, the natural concentration of pollutants in the receiving water body was estimated to be low. For simplicity, the natural background concentration (C_{nat}) was assumed to be 0 mg/L. However, The grey water footprint will be underestimated when C_{nat} is not equal to zero. The C_{max} and C_{nat} were listed in Table 4.

Results and Discussion

Fig. 1 shows the CAI_{wf} of Zhejiang's textile industry calculated with volumetric water footprint approach and impact-oriented water footprint approach from 2008 to 2018. According to the results in Fig. 1, the CAI_{wf} of Zhejiang's textile industry showed a downward trend except for a slight increase from 2008 to 2011. The CAI_{wf} dropped from 6.12×10^6 in 2008 to 4.83×10^6

Table 1. The data for wastewater discharge and wastewater pollutants.

	Textile manufacture sector			Clothing manufacture sector			Chemical fiber manufacture sector		
	Water (m³)	Cod (t)	Ammonia nitrogen (t)	Water (m³)	Cod (t)	Ammonia nitrogen (t)	Water (m³)	Cod (t)	Ammonia nitrogen (t)
2008	628310000	76297.64	5575.28	6007000	461.09	54.54	10819000	1044.7	83.30
2009	664097000	71553.8	5393.60	5694000	536.30	36.20	9292000	3608	173.60
2010	662954700	67090.43	4862.51	8726900	673.06	64.58	18962500	5588.74	88.81
2011	647536900	61446.69	4932.17	25398000	1868.71	144.49	22303800	2735.15	133.39
2012	600509900	65927.22	5191.13	10538300	879.47	72.91	18107300	1592.53	76.88
2013	555092500	61572.1	4826.31	10951000	946.21	89.67	17826000	1330.06	61.46
2014	530302500	58648.46	4653.93	10997100	927.31	77.99	19436600	1100.94	48.12
2015	517103600	55279.47	4195.18	10336700	961.51	93.57	19888300	1333.43	62.92
2016	475456200	32947.93	2090.58	23974500	1125.55	77.85	21135700	1286.3	64.25
2017	488099400	28867.96	1017.55	16690100	882.95	47.02	19979200	1188.54	82.32
2018	473189700	23069.25	631.52	16315200	810.76	44.78	19214200	857.29	21.48

Table 2. Endpoint characterization factors from ReCiPe 2016.

	COD	Ammonia nitrogen	Water consumption
Human health (DALY/kg or DALY/m³)	-	-	0.000000758
Ecosystem quality (species·yr/kg or species·yr/m³)	1.73E-09	2.64E-08	3.91E-12
Resource (USD/kg or USD/m³)	-	-	-

in 2018 with a decrease of approximately 21.20 percent. The decrease of the CAI_{wf} of water footprint stemmed from the reduction in water consumption and wastewater discharge caused by the issuance of governmental policies such as the 12th Five-Year Plan of Textile Industry and the 13th Five-Year Plan of Textile Industry. During the "12th Five-Year Plan" period, the amount of fresh water used from 100 meters of printed and dyed cloth has dropped from 2.5 tons to less than 1.8 tons, and the water recycling rate has increased

Table 3. Normalized factor and weighting factor from Eco-indicator 99.

	Normalized factor	Weighting factor
Human health	41.7	400
Ecosystem quality	676	400
Resource	0.0000357	200

Table 4. The C_{max} and C_{nat}.

	COD	Ammonia nitrogen
C_{max} (mg/L)	20	1
C_{nat} (mg/L)	0	0

from 15% to more than 30%. During the "13th Five-Year Plan" period, water consumption per unit output value of textile industry decreased by 11.9%. The discharge of wastewater and major pollutants in the textile industry decreased by more than 10%. The implement of responsible practices around water consumption and wastewater discharge such as water reuse and wastewater treatment technologies also played a vital role in bringing about this result. As shown in Fig. 1, the CAI_{wf} of Zhejiang's textile industry increased slightly first and then decreased from 2008 to 2018. The recovery from the world financial crisis may have contributed to the increase of the CAI_{wf} from 2008 to 2011. Because investor and consumer confidence was restored and steady increased recorded in textile production and consumption. Water consumption and wastewater discharge of textile industry increased due to the increase of textile and garment production. So the CAI_{wf} increased despite the efforts at water saving and wastewater treatment. The CAI_{wf} calculated with volumetric water footprint approach and impact-oriented water footprint approach showed that the proportions of the CAI_{wf} of the three component sectors varied greatly. The textile manufacture sector was the most important contributor to CAI_{wf} (94.66%), followed by chemical fiber manufacture sector (3.06%) and clothing manufacture sector (2.28%). What could be
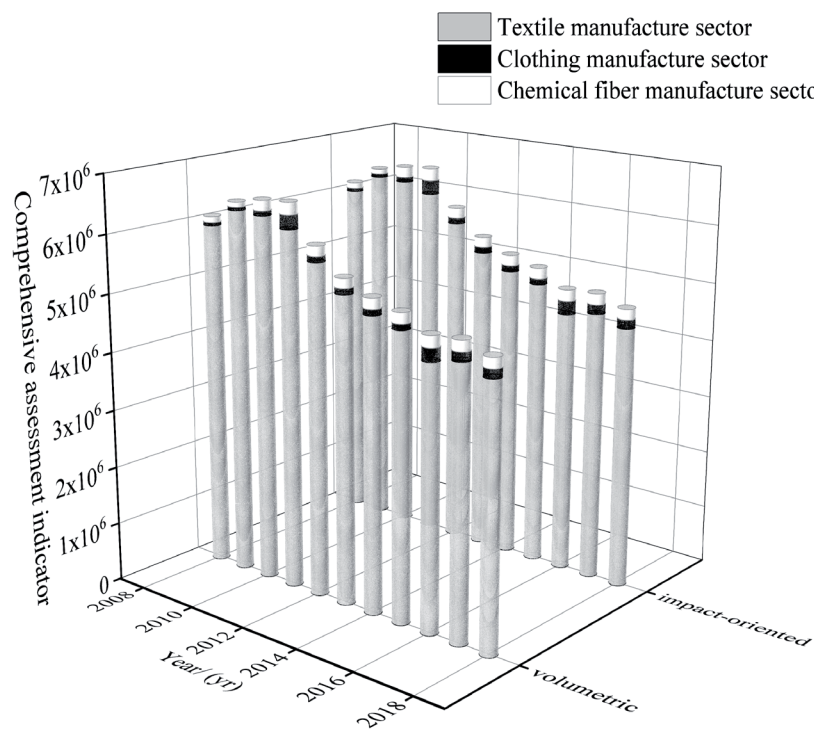
Fig. 1. The comprehensive assessment indicator for water footprint assessment of Zhejiang's textile industry from 2008 to 2018.
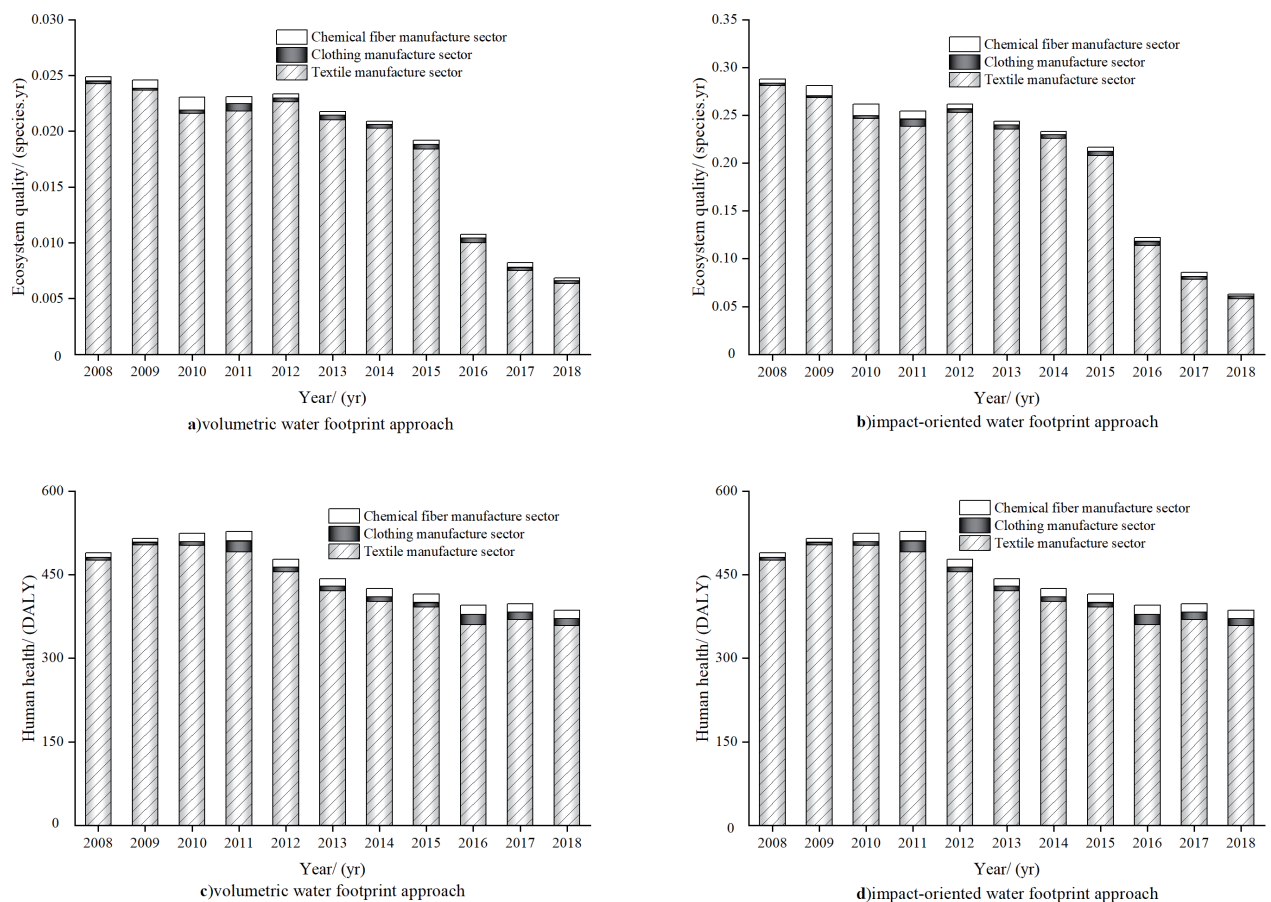

Fig. 2. The endpoint indicator for water footprint assessment of Zhejiang's textile industry from 2008 to 2018: a) $WF_{end,eco}$ of volumetric water footprint approach, b) $WF_{end,eco}$ of impact-oriented water footprint approach, c) $WF_{end,hum}$ of volumetric water footprint approach, d) $WF_{end,hum}$ of impact-oriented water footprint approach.

seen was that both results obtained by volumetric water footprint approach and impact-oriented water footprint approach are similar, with a concomitant variation trend.

The $WF_{end,eco}$ and $WF_{end,hum}$ of Zhejiang's textile industry calculated with volumetric water footprint approach and impact-oriented water footprint approach from 2008 to 2018 are presented in Fig. 2. What could be seen from Fig. 2a) and Fig. 2b) is that $WF_{end,eco}$ calculated with volumetric water footprint approach and impact-oriented water footprint approach gradually decreased from 2008 to 2018 with similar trends. But $WF_{end,eco}$ calculated with volumetric water footprint approach is smaller by an order of magnitude than $WF_{end,eco}$ calculated with impact-oriented water footprint approach due to their different endpoint characterization factors for grey water and water eutrophication. As shown in Fig. 2c) and Fig. 2d), $WF_{end,hum}$ calculated with volumetric water footprint approach and impact-oriented water footprint approach showed a decreasing trend from 2008 to 2018. The decrease of the endpoint indicator of water footprint stemmed from the issuance of governmental policies and the establishment of national standards on restrictions for water withdrawal and wastewater discharge. Driven by policies and standards, pollution-prevention techniques and optimization in process operation, design, and equipment have been implemented. With the understanding of the dangers from water security and water degradation, the attention to water saving and wastewater reduction was given to reduce the potential environmental impacts related to water and to increase adaptation efforts. It is obvious that whichever methodologies or endpoint indicators was applied, the textile manufacture sector had the largest environmental impacts. It is consistent with the largest market share of textile manufacture sector.

The water footprint of the textile manufacture sector was analyzed in detail due to its largest environmental impacts related to water. Fig. 3 illustrates the CAI_{wf} of Zhejiang's textile manufacture sector calculated with volumetric water footprint approach and impact-oriented water footprint approach from 2008 to 2018. According to the results in Fig. 3a), the CAI_{wf} of Zhejiang's textile manufacture sector calculated with volumetric water footprint approach showed a decreasing trend except for a slight increase from 2008 to 2010. It can be seen from Fig. 3b) that the results calculated with impact-oriented water footprint approach increased slightly first from 2008 to 2009 and then decreased from 2009 to 2018. During the study period from 2008 to 2018, the CAI_{wf} calculated with volumetric water footprint approach dropped from 5.96×10^6 in 2008 to 4.49×10^6 in 2018, by about 24.69 percent. The results calculated with impact-oriented water footprint approach fell from 6.03×10^6 in 2008 to 4.50×10^6 in 2018 with a decrease of approximately 25.38 percent. What could be seen was that the variation tendency of the results obtained with volumetric water footprint approach is consistent with those obtained with impact-oriented water footprint approach. For both approaches, it is obvious that the damage to human health in the process of textile and garment production is larger than the damage to ecosystem quality.

Fig. 4 reports the results for $WF_{end,eco}$ of Zhejiang's textile manufacture sector calculated with volumetric water footprint approach and impact-oriented water footprint approach from 2008 to 2018. It can be seen that $WF_{end,eco}$ calculated with volumetric water footprint approach had similar evolution trends to $WF_{end,eco}$ calculated with impact-oriented water footprint approach from 2008 to 2018. Grey water footprint and water eutrophication footprint were the most important factors contributing to $WF_{end,eco}$ calculated with volumetric water footprint approach and impact-oriented water footprint approach respectively. It can be seen that water pollution is more harmful to the ecosystem quality than water consumption. Wastewater treatment are the most important driving factors of the
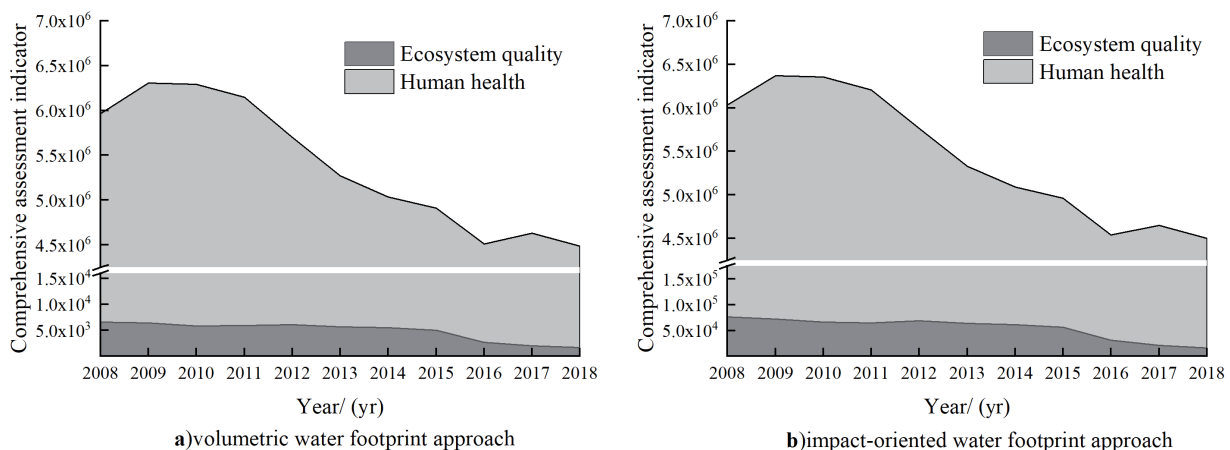

Fig. 3. The comprehensive assessment indicator for water footprint assessment of Zhejiang's textile manufacture sector from 2008 to 2018: a) CAI_{wf} of volumetric water footprint approach, b) CAI_{wf} of impact-oriented water footprint approach.

a)volumetric water footprint approach
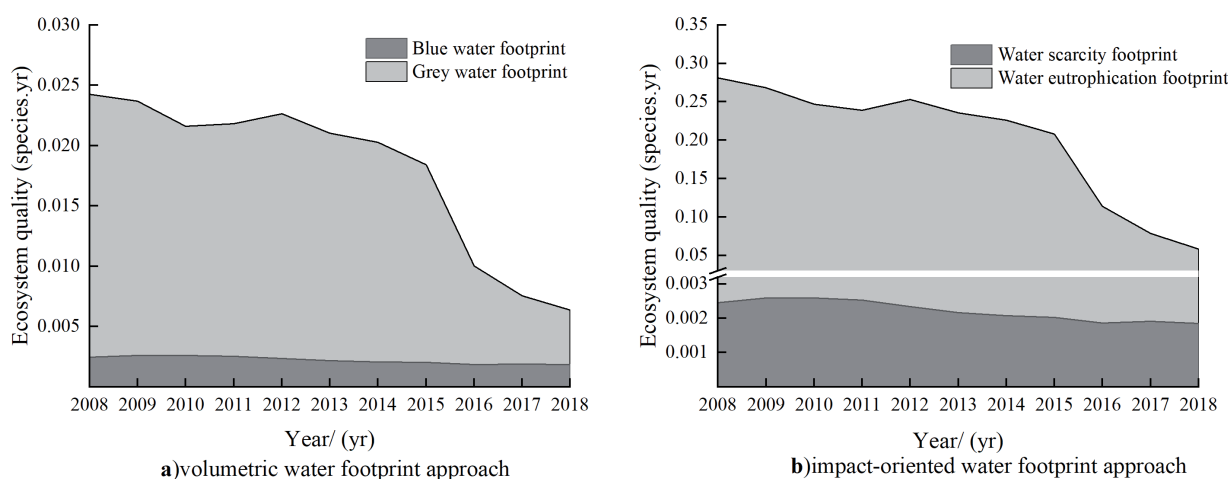

b)impact-oriented water footprint approach

Fig. 4. The damage to ecosystem quality for water footprint assessment of Zhejiang's textile manufacture sector from 2008 to 2018: a) WF$_{end,eco}$ of volumetric water footprint approach, b) WF$_{end,eco}$ of impact-oriented water footprint approach.

decrease of the damage to ecosystem quality from 2008 to 2011. Due to the fact that modern technologies related to pollution-prevention, wastewater reuse and recycle, and wastewater treatment have been developed and implemented from 2008 to 2018, guidance of national policies achieved remarkable results.

It can be seen from the above analysis that the variation tendency of CAI$_{wf}$, WF$_{end,eco}$ and WF$_{end,hum}$ obtained with volumetric water footprint approach is consistent with those obtained with impact-oriented water footprint approach. The approach that integrates water quantity and quality can be used to enable a reporting of water consumption and pollution, which is considered a means of informing the general public about the potential environmental impacts related to water. In the study of textile industry, only the damage to ecosystem quality was considered when it came to

grey water footprint. But damage to human health was also an important indicator to be taken into account. If added the damage to human health from grey water footprint, the results will make a huge difference. As shown in Fig. 5, the CAI$_{wf}$ calculated with volumetric water footprint approach is larger by an order of magnitude than CAI$_{wf}$ calculated with impact-oriented water footprint approach due to the lack of damage pathway of water eutrophication on human health. Therefore, the damage pathways considered to go from water eutrophication to human health remains to be studied.

As illustrated in Fig. 6, WF$_{end,hum}$ of Zhejiang's textile manufacture sector had similar evolution trends as WF$_{end,eco}$ from 2008 to 2018. The contributions to human health from the portion of grey water footprint were much larger than that of blue water footprint due to the
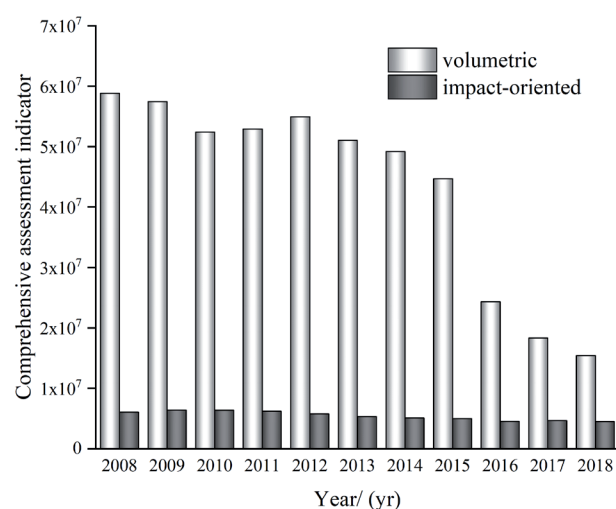

Fig. 5. The comprehensive assessment indicator for water footprint assessment of Zhejiang's textile manufacture sector from 2008 to 2018.
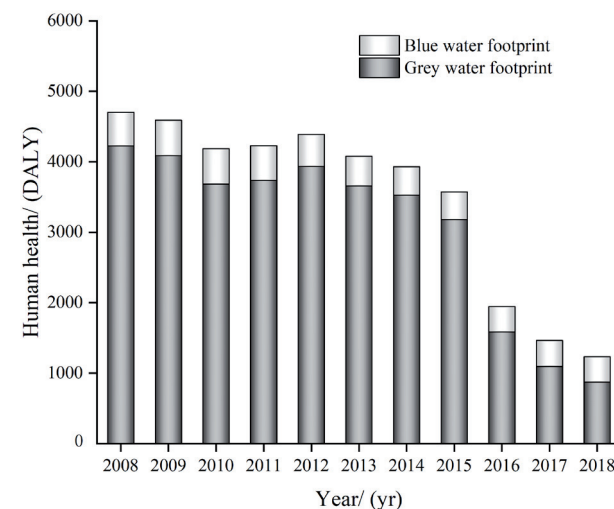

Fig. 6. The damage to human health for water footprint assessment of Zhejiang's textile manufacture sector from 2008 to 2018.

fact that water pollution had more serious environmental impacts than water consumption. Hence, especially when assessing the damage to human health, the water consumption need to be considered in combination with water pollution. This combined approach is needed as both water consumption and pollution have a significant impact on textile production. It is worth noting that only water eutrophication is considered in this study because only chemical oxygen demand and ammonia nitrogen are counted in wastewater during textile production in the yearbook.

Conclusion

The water footprint is a helpful indicator to measure and understand the pressure on water resources by impact category indicators. It can help policy makers and stakeholders develop effective water resource management strategies. However, the units of impact category indicators are dispersive which causes an inefficient communication to wider audience.

To address the weaknesses, this paper provided a single-indicator approach considering water quantity and quality to assess the environmental impacts related to water. The approach makes it possible to report a single stand-alone result of water footprint and to drive more efficient and sustainable industrial system related to water. The illustration of the proposed approach with Zhejiang's textile industry indicated that the CAI_{wf}, $WF_{end,eco}$ and $WF_{end,hum}$ of Zhejiang's textile industry calculated with volumetric water footprint approach and impact-oriented water footprint approach have shown clear declining trends from 2008 to 2018, implying the great progress in water saving and wastewater treatment of Zhejiang's textile industry. Despite the great progress, the impacts of water consumption and pollution on the water environment remain serious in Zhejiang's textile industry, especially water pollution. In particular, this study is specifically helpful for improving the use of water resource and reducing the emission of wastewater for mitigating the environmental impacts of textile industry.

The need for a more comprehensive water footprint approach has been highlighted in recent years. The new approach demonstrates superior capabilities of the single-indicator approach for water footprint assessment, but the uncertainties of this approach should continue to be noticed due to the normalized factor and the weighting factor. These indicators are subjective which should be determined with a more logical approach and warranted with a more extensive statistical validation.

Conflict of Interest

The authors declare no conflict of interest.

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