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Article

Environmental Sustainability of Water Footprint in Mainland China

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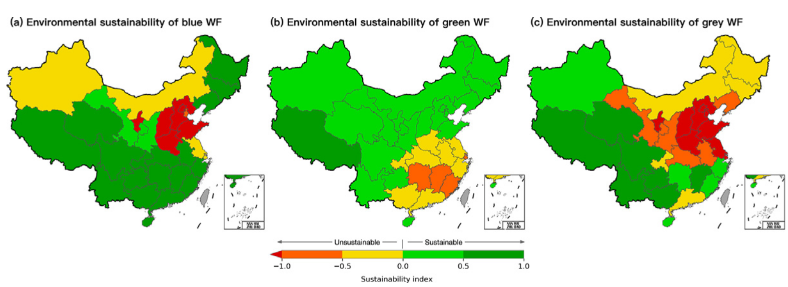
HIGHLIGHTS

- Total water footprint (WF) increased by 30% from 2002 to 2012 in mainland China
- Growth of WF was mainly attributed to the increase of grey WF
- Blue, green and grey WFs were not sustainable in 35%, 39% and 61% of provinces
- Sustainability index of blue (green) WF enhanced in 58% (71%) provinces over time
- Sustainability index of grey WF decreased in almost two third of provinces

GRAPHICAL ABSTRACT



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ABSTRACT

Water footprint (WF) measures human appropriation of water resources for consumptive use of surface and ground water (blue WF) and soil water (green WF) and for assimilating polluted water (grey WF). Questions have been often asked about the exact meaning behind the numbers from WF accounting. However, to date environmental sustainability of WF has never been assessed at the sub-national level over time. This study evaluated the environmental sustainability of blue, green and grey WF for China's 31 mainland provinces in 2002, 2007 and 2012, and identified the unsustainable hotspots. Overall, the total WF increased by 30% between 2002 and 2012. The growth can be attributed to the increase of grey WF because the green and blue WF showed only a slight rise. Among all provinces investigated in 2012, eleven showed unsustainable blue WF (sustainability index SI<0), which were mainly located in the North China Plain. There were 12 provinces that displayed unsustainable green WF, and they were distributed in China's southern and southeastern areas. The grey WF was not sustainable in approximately two third of provinces (19), which were mainly located in China's middle and northern regions and Guangdong province. More than half of China's provinces showed trends of improved SI of green and blue WF from 2002 to 2012. However, the SI of grey WF decreased in almost two third of provinces. Poor levels of WF sustainability were due to water scarcity and pollution, which intensify the degradation of local rivers and ecosystems and make restoration more difficult. The results shed light on the policy making needed to improve sustainable water management, and ecological restoration of hotspot regions.

1. Introduction

Freshwater is essential for human beings and ecosystems, and is closely linked with many of the Sustainable Development Goals adopted by the UN (UN, 2015). Due to rapid population and economic growth, human water consumption has increased from ~1,200 km^3 in 1980 to ~1,700 km^3 in 2016 (Qin et al., 2019). Increasing water demand has become a challenge for sustainability at both the regional and global scales (Vörösmarty et al., 2010). Unsustainable water use has resulted in many environmental problems including: drops in groundwater levels (Scanlon et al., 2012), water pollution (Mekonnen and Hoekstra, 2015)

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and declines in river flows (Steward et al., 2018), which together are resulting in the degradation of ecosystems (Davidson, 2014).

Water footprint (WF) is the amount of water consumed to produce goods and services, and is a measure of human appropriation of global water resources as measured by the volume of water consumed and/or polluted (Hoekstra, 2011). Since the introduction of the concept in 2002 (Hoekstra and Hung, 2002), WF has gained popularity among scientists, policy makers and the public due to its strength in communicating water problems to a variety of audiences. Early studies focused mainly on WF accounting (Hoekstra and Chapagain, 2007; Orr and Chapagain, 2008) across three components: green, blue and grey. The blue WF is the use of surface and ground water; the green water footprint is the use of soil moisture (Hoekstra et al., 2011); and the grey WF is the use of freshwater required to dilute polluted water in order to meet existing water quality standards (Hoekstra, 2011).

With the progress of WF accounting, scholars began to explore the linkage between WF and environmental sustainability. Hoekstra (2009) was among the first to examine WF from the sustainability perspective by comparing it with the freshwater availability. He argues that WF analysis provides a broader way to assess the sustainability of human use of freshwater resources. Moreover, Hoekstra et al. (2011) suggested a four-step approach to assess WF sustainability by identifying: (1) sustainability criteria; (2) WF sustainability hotspots; (3) quantifying the primary impacts of the hotspots; and (4) the secondary impacts of the hotspots. Following Hoekstra, a few studies assessed the environmental sustainability of WF at different spatial scales. For example, Zeng et al. (2012) found that environmental sustainability of the blue WF in the Heihe River Basin (located in the arid and semi-arid regions of Northwest China) was compromised as the blue WF had exceeded blue water availability in the basin for eight months of the year. Lathuillière et al. (2018) evaluated the agricultural sustainability in Southern Amazonia with respect to the green and blue water scarcity. Mekonnen and Hoekstra (2016) assessed the environmental sustainability of blue WF for the world's major river basins and found that four billion people were suffering from severe water scarcity for at least one month a year. Other studies assessed the environmental sustainability of grey WF by comparing it with the assimilative capacity of water bodies (Aldaya et al., 2020; Karandish, 2019; Liu et al., 2012; Mekonnen and Hoekstra, 2018). However, to our knowledge, environmental sustainability has never been assessed in an integrated way considering blue, green and grey WF at the sub-national level over space and time.

This study aims to assess the environmental sustainability of WF (i.e. blue, green and grey WF) for 31 provinces in China for 2002, 2007 and 2012. Because China suffers from serious water quantity and quality issues (Liu et al., 2017) it is an excellent place to demonstrate environmental sustainability of WF. This study develops novel approaches and provides the first assessment of environmental sustainability of blue, green and grey WF over space and time at the provincial scale. The results will facilitate policy making on sustainable water resource management.

2. Material and Methods

2.1. WF Accounting

A GIS-based Environmental Policy Integrated Climate model (GEPIC) (Liu, 2009) was selected to estimate the blue and green WF for the major crops (i.e., wheat, maize, rice, soybean, millet and sorghum) in China for 2002, 2007 and 2012. The GEPIC model has been applied to assess the water consumption of agriculture at global, national and regional scales, and has performed well in China (Liu and Yang, 2010; Liu et al., 2007; Zhao et al., 2014). Model parameters adopted in this study were the same as those used by Liu et al. (2007). The detailed simulation processes could be found in Liu (2009) and Liu and Yang (2010). The six major crops accounted for 60% of the total cultivated area in China in 2012 (National Bureau of Statistics of China, 2013). Since the agricultural areas include other crops, the ratio of the areas of the six studied crops to the total cultivated area for each province was calculated. The blue and green WF in the agricultural sector was derived by dividing the blue and green WF for the six major crops by the area ratio above. Regarding the blue WF in forestry, livestock, fishery, industry and domestic sectors, it is often reported as the surface water and groundwater consumption in official statistics. Since green water is only consumed by agricultural-related commodities, the green WF in forest and rangeland was neglected because their water uses are not directly related to human economic activities.

Grey WF (GWF) is an indicator of water pollution produced by human activities. Hoekstra et al. (2011) defined it as the volume of freshwater that is required to assimilate the load of pollutants (L, kg/yr) based on natural background concentrations (C_{nat}, mg/l) and existing ambient water quality standards (C_{max}, mg/l).

$$GWF = \frac{L}{C_{max} - C_{nat}} \tag{1}$$

Agricultural, industrial and domestic sectors contribute to the *GWF*. Ammonia nitrogen (NH_3-N) and chemical oxygen demand (COD) were included in the calculation (Eq. 1) for each sector. Regarding the agriculture sector, two additional pollutants (i.e. total nitrogen (TN) and total phosphorus (TP)), were also considered because of the non-source pollution from fertilizer utilization. The following equation is used to estimate L for TN and TP:

$$L_j = \alpha_j \times M_j \tag{2}$$

Where α_j is the leaching rate of pollutant j, with a value of 7% for TN and 2% for TP according to previous studies (Chukalla et al., 2018; Hoekstra et al., 2011); M_j represents the application of fertilizer containing pollutants.

After quantifying GWF for each pollutant, the GWF for the same water pollutant in different sectors was summed up and the total GWF in provincial i ($TGWF_i$) is estimated as the maximum of GWF for the individual water pollutant (Eq. 3):

$$TGWF_i = \max\left(GWF_{i,NH_3-N},\ GWF_{i,COD}, GWF_{i,TN}, GWF_{i,TP}\right) \tag{3}$$

Where $GWF_{i,\,NH_3-N}$, $GWF_{i,COD}$ $GWF_{i,TN}$, $G_{i,TP}$ are the GWF of province i calculated for *NH_3-N*, *COD*, *TN* and *TP*, respectively.

We calculated blue, green and GWF for 2002, 2007 and 2012 for each province in China. While there are 34 provinces in China, data were not available for Taiwan, Hong Kong and Macau, thus this study only considered the 31 provinces of mainland China.

2.2. Water Availability Accounting

Water availability is defined as the quantity of water that can be used for human purposes without significant harm to ecosystems or other users (Liu and Yang, 2010). Blue water availability is equivalent to the quantity of blue water resources minus the amount of blue water that should be used to maintain healthy ecosystems. We followed Hoekstra et al. (2011) and assumed that environmental flows required 80% of natural blue water resources. Green water availability is defined as the available soil water for cropland evapo-transpiration (Rockström et al., 2009), which has been applied in many studies (Schuol et al., 2008; Zang and Mao, 2019; Zuo et al., 2015). Green water availability is simulated using the Water And ecosYstem Simulator (WAYS) (Mao and Liu, 2019) which considers the impacts induced by the spatial heterogeneity of plant rooting system in hydrological cycling. Green water availability is computed by multiplying the actual evapotranspiration in cropland. The formula for the green water availability is expressed as:

$$rWA = c \times AET \times A \tag{4}$$

Where, $GrWA$ is the green water availability (m^3/yr), AET represents the actual evapotranspiration in cropland (mm/yr), and A is the cropland area (m^2). The constant c is used to convert unit.

The GrWA was firstly calculated by the WAYS model simulation at 0.5-degree spatial resolution and daily scale, then was summed up to the province level.

2.3. WF Environmental Stainability

To indicate the environmental sustainability, a sustainability index (SI) was developed which compare specific WF to the corresponding water availability or resources, as shown in the equations below:

$$SI_{blue}^{i,j} = 1 - \frac{WF_{blue}^{i,j}}{WA_{blue}^{i,j}} \tag{5}$$

$$SI_{green}^{i,j} = 1 - \frac{WF_{green}^{i,j}}{WA_{green}^{i,j}} \tag{6}$$

$$SI_{grey}^{i,j} = 1 - \frac{WF_{grey}^{i,j}}{WR_{blue}^{i,j}} \tag{7}$$

Here SI_{blue}, SI_{green} and SI_{grey} represent environmental sustainability of blue, green and grey WF in province *i* at year *j*; WF_{blue}, WF_{green} and WF_{grey} represent blue, green and grey WF; WA_{blue} and WA_{green}, represents blue and green water availability, and WR_{blue} is the blue water resources required to dilute the pollutant.

When blue WF exceeds blue water availability ($SI_{blue}^{i,j} < 0$), the blue WF is environmentally unsustainable because human blue water use violates environmental flow requirement (Hoekstra et al., 2011). Similarly, when $SI_{green}^{i,j}$ and $SI_{grey}^{i,j}$ are smaller than 0, the corresponding WF is environmentally unsustainable.

2.4. Data Sources

The land use and climate data to drive the GEPIC model were obtained from the Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) from the Agricultural Model Intercomparison and Improvement Project (AgMIP) group (Ruane et al., 2015). The annual data associated with harvested land areas were retrieved from the *China Statistic Yearbook* (National Bureau of Statistics of China, 2003; 2008; 2013). Data related to blue water consumption in different sectors excluding the agriculture sector were obtained from the *China's Provincial Water Resource Bulletin* (Ministry of Water Resources of China, 2003; 2008; 2013). Annual data related to blue freshwater resources were also obtained from provincial water resource bulletin (Ministry of Water Resources of China, 2003; 2008; 2013).

To quantify green water resources, the climate data set from the Global Soil Wetness Project 3 (Kim, 2017), GSWP3, was used to drive the WAYS model. The GSWP3 data set was selected because it has been proven to be able to represent realistic temporal variability and has been used in several studies for water resources simulation (Tangdamrongsub et al., 2018; Veldkamp et al., 2017). The climate data used in WAYS includes precipitation, minimum temperature, maximum temperature, relative humidity, surface downwelling longwave radiation, surface downwelling shortwave radiation and wind speed at 10m. In addition, we used the MODIS land cover data product (MCD12Q1) derived from the International Geosphere–Biosphere Programme (IGBP) land cover type classification (17 classes) (Friedl et al., 2010), as well as the root zone storage capacity data from Wang-Erlandsson et al.(2016). The croplands data used for green water availability computation is taken from a global dataset, i.e. Global Agricultural Lands: Croplands 2000, which is downloaded from Socioeconomic Data and Applications Center (SEDAC https://sedac.ciesin.columbia.edu/data/set/aglands-croplands-2000). The global croplands data are created based on the satellite data of MODIS (Moderate Resolution Imaging Spectroradiometer) and SPOT (Satellite Pour I'Observation de la Terre) and agricultural inventory data, which represents the proportion of land area used as cropland (land used for the cultivation of food) in the year 2000 at 5 arc-second grid cells (Ramankutty et al. 2010).

The loads of NH_3-N and COD in the industrial and domestic sectors were obtained from *China Environmental Statistical Yearbooks* (National Bureau of Statistics of China, 2003; 2008; 2013). The loads of NH_3-N and COD in the agricultural sector in years of 2002 and 2007 based on the statistical load data in 2012 and the ratio of agricultural GDP in target year and agricultural GDP in 2012. The data associated with TN and TP in the agriculture sector was also taken from *China Statistic Yearbook* (National Bureau of Statistics of China, 2003; 2008; 2013). According to the *Environmental Quality Standards for Surface Water of China* (Ministry of Environmental Protection of China, 2003), water quality of Grade III indicates the water is suitable for fish, aquaculture and swimming while levels below Grade III mean poor water quality. Therefore, Grade III was selected as the ambient water quality standard in this study and the C_{max} of NH3-N, COD, TN, TP is estimated as 1 mg/L, 20 mg/L, 1 mg/L and 0.2 mg/L, respectively. Because there were no specific values for the above four pollutants in nature we followed Hoekstra et al. (2011), and assumed the C_{nat} to be 0.

3. Results

3.1. Spatial Variations of the Water Footprint in 2012

Overall, the total WF (sum of blue, green and grey) for China was 3,370 Gm^3/y in 2012 (1 Gm^3=10^9 m^3) with the grey WF of China being much larger than the green and blue WF. The grey WF accounted for 77% of the total WF, while green and blue WF accounted for 17% and 6%, respectively, indicating that water pollution is the primary influencing factor for water appropriation. As shown in Fig. 1a, the distribution of WF through China was uneven. High WFs were located in the North China Plain (i.e. Shandong, Henan and Jiangsu), as well as some southern provinces (i.e. Guangdong, Hunan and Sichuan), which could be associated with the large grey WF in these regions. For example, in the four provinces where total WF exceeded 200 Gm^3/y (Guangdong, Henan, Hunan and Shandong), the grey WF was also the highest. The largest WF was found in the Guangdong province, with a value of 257 Gm^3/y, while the smallest WF was in Tibet, with 5 Gm^3/y (Fig. 1a). These two provinces also had the largest and smallest grey WF in China. Moreover, the percent of grey WF in the total WF ranged from a high of 95% in Shanghai to a low of 64% in Tibet (Fig. 1a).

Green and blue WF had quite different spatial patterns. At the national level, green WF was almost three times that of blue WF. The ratio of green WF to blue WF ranged from 10.8 in the humid Hunan province to 0.18 in the arid Xinjiang province (Fig. 1a). The low ratios were generally found in arid or semi-arid provinces where the agriculture is highly dependent on the irrigation. Blue WF ranged from 26 Gm^3/y in Xinjiang to 0.8 Gm^3/y in Shanghai (Fig. 1b) and green WF ranged from 47 Gm^3/y in Hunan and 0.7 Gm^3/y in Beijing (Fig. 1c). The high blue WF was mainly found in arid and semi-arid northern provinces in China, where irrigation is necessary for crop growth. The low blue WFs were mainly found in regions where agriculture was not the main economic sector or in humid regions. The high values of green WF were found in the provinces with large areas of rice production such as Hunan, Sichuan, and Heilongjiang.

3.2. Temporal Variations in WF

Overall, the total WF increased by 30% from 2002 to 2012 with the growth of grey WF larger than that of green and blue WF (Fig. 2a). The total WF in most provinces increased from 2002 to 2012, with the highest increases in Hainan (119%) and Guangdong (82%). Only three provinces had decreasing trends: Beijing (-2%), Qinghai (-57%), and Tibet (-76%). This implies that human appropriation of water increased and put more pressure on water resources most of China's provinces.

The increases in total WF was caused by the change in grey WF. The provinces with the highest increase of total WF (Hainan and Guangdong)

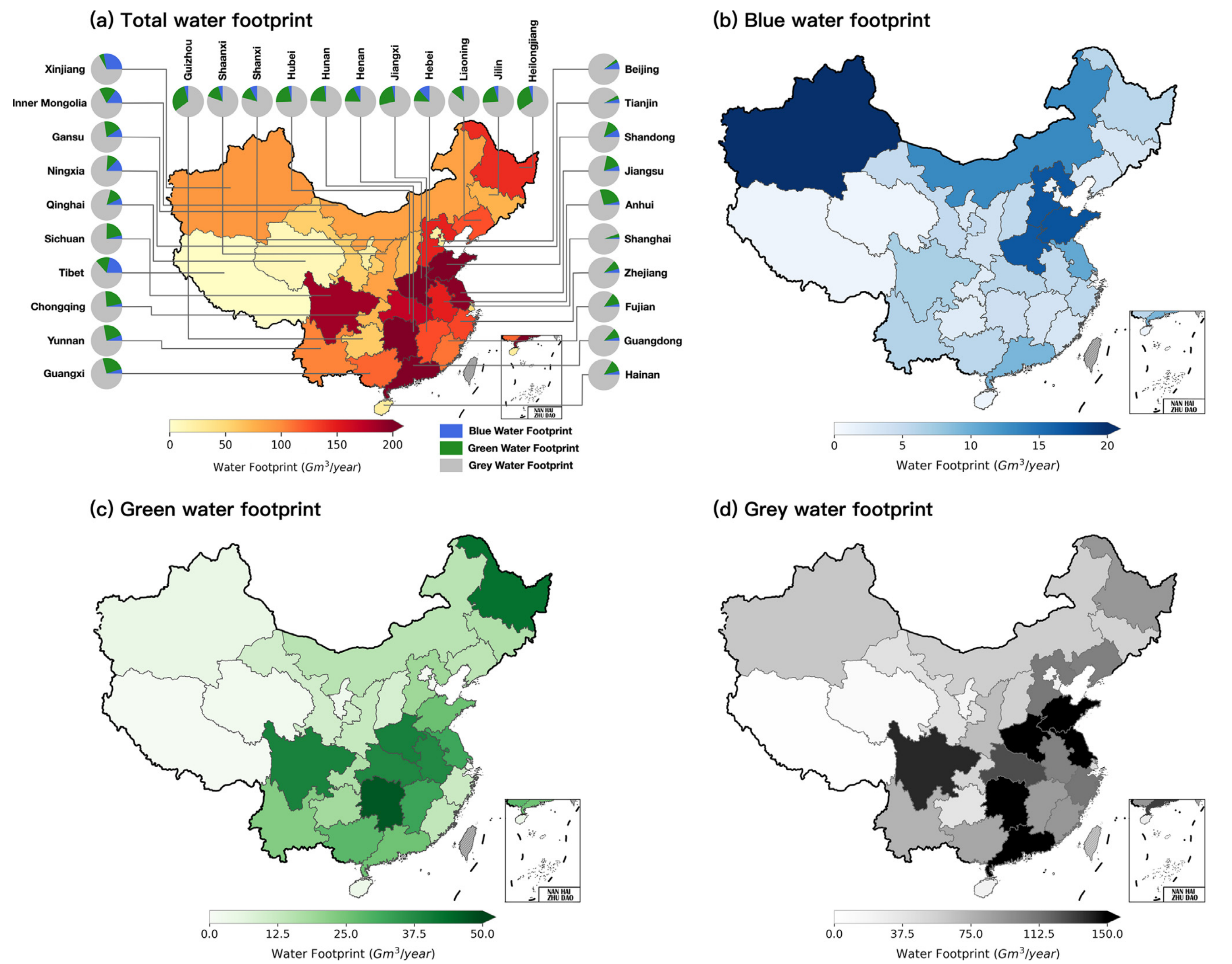

Fig. 1. Water footprint (WF) in China. (a): Total WF that is the sum of blue, green and grey WF; (b): Blue WF; (c): Green WF; (d): Grey WF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

also suffered from the highest growth of grey WF (Hainan at 184% and Guangdong at 109%).

The temporal changes in blue, green and grey WF were not consistent. Overall blue WF increased by 17% in China between 2002 and 2012. At the provincial level, blue WF increased in 22 provinces ranging from 1% in Jilin to 83% in Chongqing and decreased in 9 provinces ranging from 2% in both Shanxi and Heilongjiang to 38% in Tibet (Fig. 2b). Overall green WF decreased by 2% in China between 2002 and 2012. Green WF decreased in 20 provinces, ranging from almost 0% in Ningxia to 35% in Shanghai and increased in 11 provinces ranging from 1% in Yunnan to 54% in Xinjiang (Fig. 2c). The total green and blue WF increased slightly by 2%. Grey WF increased by 41% at the national level, and except for Beijing, Qinghai and Tibet, it experienced increasing trends in all provinces (Fig. 2d).

3.3. Spatial Variations of WF Sustainability in 2012

At the national level, blue WF accounted for only 1/3 of blue water availability in 2012, however the environmental sustainability of blue WF differed across China (Fig. 3a). Blue WF was sustainable (SI>0)in 20 provinces and unstainable (SI<0)in the remaining 11 provinces, many of which are located in the North China Plain. Ningxia had the most unsustainable blue WF with a sustainability index (SI) of -12.6, followed by Hebei (-2.6), Henan (-2.2) and Shandong (-2.1).

At the national level, green WF was 4% lower than green water availability in 2012. Unsustainable green WF occurred primarily in south and southeastern China (Fig. 3b). These are major rice production areas, and because rice consumes large amounts of soil water it results in deficiencies of green water for natural ecosystems. Twelve provinces had unsustainable levels of green WF, while 19 provinces had sustainable levels. The most unsustainable green WF occurred in Hunan with a SI of -0.65, followed by Shanghai (-0.57), Fujian (-0.56) and Jiangxi (-0.55).

At the national level, grey WF was 88% of the blue water resources in 2012. However, the environmental sustainability of grey WF differed widely across China (Fig. 3c) with 12 provinces being classified as sustainable and 19 provinces with an unstainable classification. Many of those unsustainable provinces are located in the northern part of China, as well as Guangdong. The most unsustainable grey WF was Ningxia with a SI of -15.1, followed by Shanghai (-12.9) and Tianjin (-6.7).

3.4. Temporal Variations of WF Environmental Sustainability

From 2002 to 2012, the Chinese population exposed to unsustainable blue and green WF similar trends, i.e. a slight decrease is found between 2002 and 2007 then it increased in 2012 (Fig. 4a). However, the environmental sustainability of grey WF shows a different pattern with the exposed population in China with unsustainable grey WF found to be continuously increasing between 2002 to 2012, especially in the

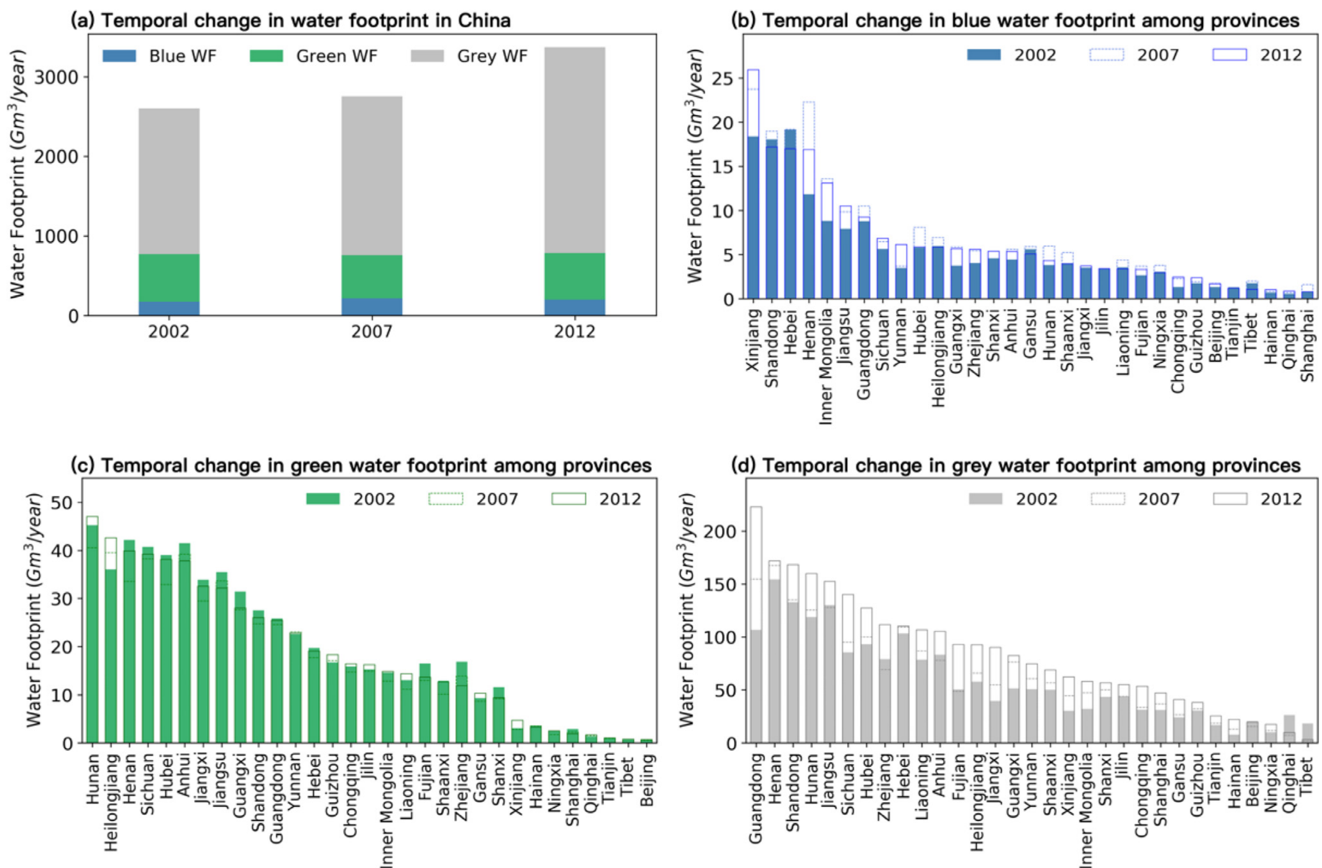

Fig. 2. Temporal change in water footprint (WF) in China. (a): National WF; (b): Provincial Blue WF; (c): Provincial Green WF; (d): Provincial Grey WF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

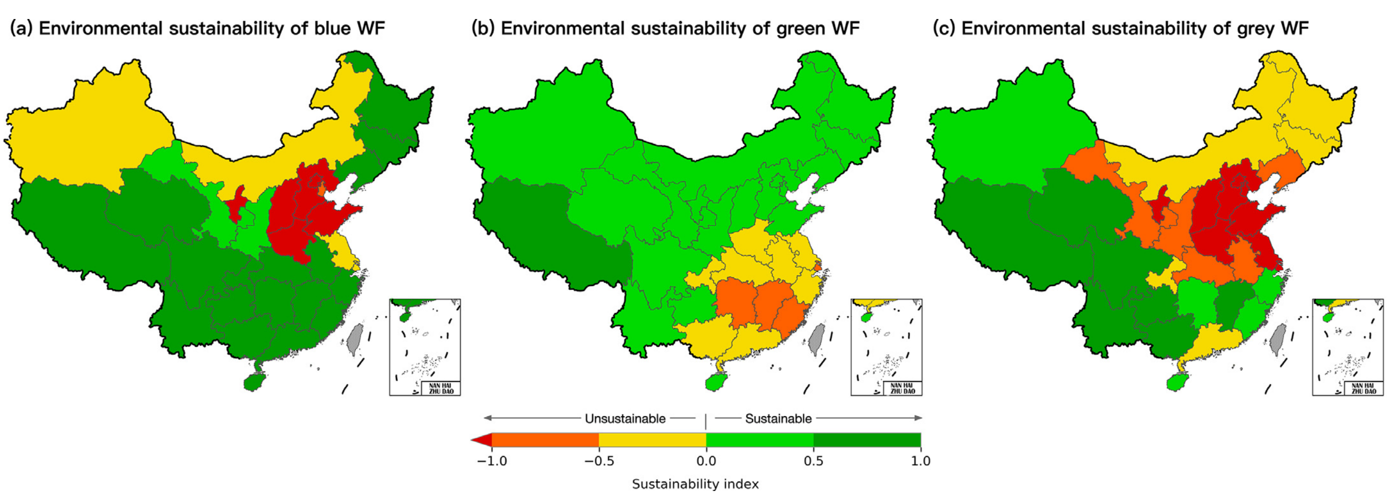

Fig. 3. Environmental sustainability of water footprint (WF). (a): Blue WF; (b): Green WF; (c): Grey WF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

five years between 2007–2012, where 200 million more people were exposed in unsustainable grey WF regions.

Between 2002 and 2012, the overall SI of blue WF showed a 5% decline; but the SI of green WF increased from -0.03 to 0.04, indicating a slight sustainability improvement. The SI of Grey WF declined sharply from 0.39 to 0.12, indicating degraded levels of sustainability. The SI of blue WF decreased in 13 provinces with the most significant change in Yunnan, Chongqing and Guangxi; while it increased in 18 provinces with the highest percentages in Tianjin, Liaoning and Hebei (Fig. 4b). The SI of green WF declined in 9 provinces and increased in 22 provinces. The largest declines occurred in Xinjiang, Qinghai and Heilongjiang; and the largest increases were in Shanghai, Shanxi and Zhejiang (Fig. 4c). The SI of grey WF found that almost 2/3 of provinces had a declining SI trend with the largest decreases in Hainan, Xinjiang and Jiangxi; while the SI increased in 1/3 of provinces with the largest increased in Tianjin, Tibet and Qinghai (Fig. 4d).

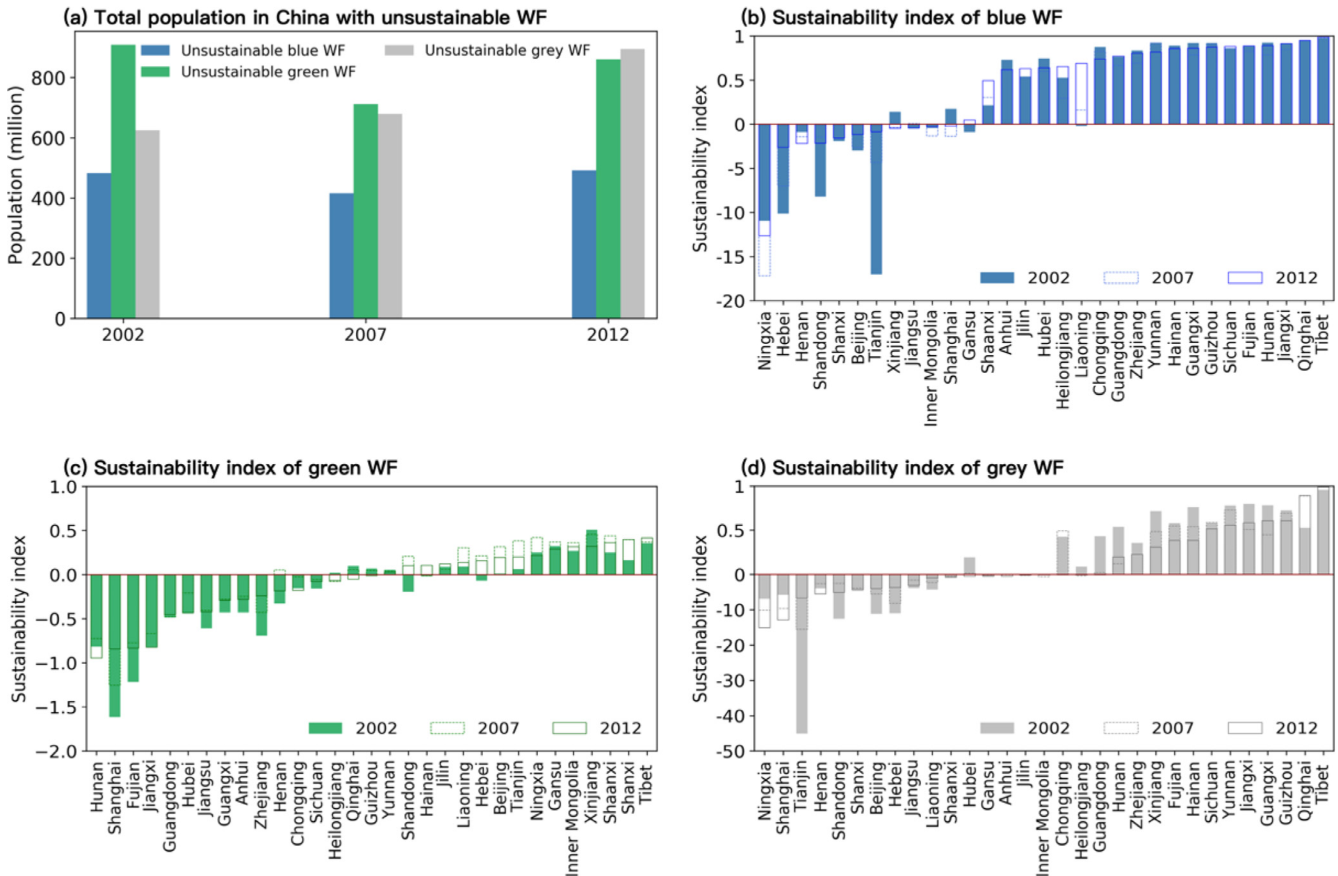

Fig. 4. Temporal change in environmental sustainability of water footprint (WF) in China. (a): Total population with unsustainable WF in China; (b) Temporal change in environmental sustainability of blue WF in each province; (c) Temporal change in environmental sustainability of green WF in each province; (d) Temporal change in environmental sustainability of grey WF in each province. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Comparison with the Literature

The robustness and accuracy of our results depends on the calculation of WF. Blue WF in this study was calculated using the GEPIC model (blue WF for agriculture), and official statistics. Mekonnen and Hoekstra (2011) estimated the blue WF of China to be 142 Gm^3/y during 1996–2005. This was 17% higher than the blue WF of 170 Gm^3/y we estimated for 2002. Mekonnen and Hoekstra (2011) estimated the green WF of China to be 706 Gm^3/y during 1996–2005. This was 18% higher than the green WF of 600 Gm^3/y in 2002 we estimated in this study. We found Mekonnen and Hoekstra (2011) provided systematically higher estimates for both green and blue WF compared to our results. There are many reasons for these differences including different estimation methods and study periods. Another reason is that our calculations were focused on the cultivated land and excluded the green WF in the grazing system. Mekonnen and Hoekstra (2011) calculated green WF for both cropland and grazing systems. The green WF for crop production was 624 Gm^3/y from Mekonnen and Hoekstra (2011), which was very close to our estimate of 600 Gm^3/y in 2002.

At the provincial level, Zhang et al. (2014) assessed blue WF for 30 provinces in 2007 (Table 1). For these provinces, Zhang et al. (2014) estimated the total blue WF to be 336 Gm^3/y. Our estimate of 212 Gm^3/y for the same year and the same provinces was 63% of the Zhang et al (2014) estimate. The reason for the difference is partly because Zhang et al. (2014) assumed WF was equal to water withdrawal. This assumption leads to overestimate of blue WF, because water withdrawal is the sum of blue WF and the amount of return flow. According to the Ministry of Water Resources, in China, water consumption was 52% of water withdrawal on average in 2012 (Ministry of Water Resources of China, 2013). Another reason is that Zhang et al. (2014) calculated the consumption-based blue WF, while our estimates were production-based blue WF. This difference will lead to the redistribution of WF among regions. For example, Hebei was a typical exporter of grains and a net virtual water exporting province (Zhao et al., 2015). Hence, our estimate of production-based blue WF was much bigger than that of consumption-based blue WF from Zhang et al. (2014).

Mekonnen and Hoekstra (2011) estimated the grey WF of China to be 360 Gm^3/y during 1996-2005. This was 20% of our grey WF of 1,832 Gm^3/y in 2002. Zhang et al. (2019) estimated the grey WF to be 1,816 Gm^3/y in 2012. This estimate was also much larger than the estimate from Mekonnen and Hoekstra (2011), but at a comparable magnitude as ours. Both our study and Zhang et al. (2019) selected four pollutants (TN, TP, NH_3-N, COD), and calculated the grey WF for each pollutant. Mekonnen and Hoekstra (2011) used the part of the return flow which is disposed into the environment without prior treatment as a measure of the grey WF. Thus, they assume a dilution factor of one which can lead to a conservative estimate, as stated by Hoekstra and Mekonnen (2012).

4.2. Impacts of WF on River and Groundwater Degradation

To maintain healthy aquatic ecosystems, sufficient environmental flows need to be maintained in rivers and groundwater. When blue WF exceeds the availability of blue water, human water use is met by using

Table 1
Comparison of blue WF at national and provincial levels

Province	Consumption-based blue WF for the year of 2007 estimated by Zhang et al. (2014) (Gm^3/y) [1]	Production-based blue WF for the year of 2007 estimated by this study (Gm^3/y) [2]	[2]/[1] (%)
Beijing	7.2	1.7	2
Tianjin	6.1	1.2	20
Hebei	9.5	19.2	202
Shanxi	5.0	5.4	108
Innter Mongolia	3.8	13.6	358
Liaoning	8.4	4.4	52
Jilin	5.4	3.3	61
Heilongjiang	8.5	6.9	81
Shanghai	13.0	1.6	12
Jiangsu	23.1	9.8	42
Zhejiang	14.9	5.5	37
Anhui	7.3	5.6	77
Fujian	8.6	3.7	43
Jiangxi	8.4	3.3	39
Shandong	22.0	19.0	86
Henan	11.2	22.3	199
Hubei	9.1	8.1	89
Hunan	8.4	6.0	71
Guangdong	21.8	10.5	48
Guangxi	7.2	5.9	82
Hainan	1.9	0.8	42
Chongqing	3.0	2.3	77
Sichuan	7.4	6.5	88
Guizhou	3.3	1.9	58
Yunnan	7.3	3.7	51
Shaanxi	5.3	5.3	100
Gansu	6.8	5.9	87
Qinghai	1.8	0.7	39
Ningxia	3.1	3.8	123
Xinjiang	87.3	23.8	27
China	336.1	211.6	63

environmental flows, leading to river and groundwater degradation. Our results show that the SI of the blue WF was negative in most of China's northern regions which means the blue WF had exceeded blue water availability in these regions. The unsustainable WF is one reason that many river systems in northern China have reduced water flows and are drying up. For example, Wang et al. (2019) found that reduced flows and or drying happened in 267 rivers of the 345 rivers monitored in Beijing, Tianjin and Hebei. Dry river sections accounted for 25% of total river length. Even in the rainy season, 13% of the total length of river channels were dry in 2015 in Beijing (Wang et al., 2016). In Xinjiang, 300,000 metres of the Tarim River were dried out (Chen et al., 2017). For the Yellow River, during the 28 years between 1972 and 1999, drying occurred in 22 years; in particular during 1990 and 1999 when it occurred every year (Wang et al., 2011). Since the 1990s, many measures have been taken to reduce water use in provinces in the Yellow River basin. For example, in Shandong, the downstream province where the Yellow River flows to the sea, blue WF in 2012 was even lower than that in 2002 and 2007. Recent efforts at water management have been successful as drying has not occurred in the Yellow River since 2000 (Huang, 2019). Thus in order to avoid the drying situations in many northern provinces, blue WF needs to be reduced to levels that are below blue water availability.

Moreover, unsustainable blue WF is closely associated with the exploitation of groundwater in these regions. According to the Asia Development Bank (2018), the average annual groundwater resources are 60 and 164 Gm^3/y in the north and southeast coasts, respectively, during 1956–2000. However, the groundwater supply was 40.8 and 4.7 Gm^3/y in the two regions, accounting for 67% and 2.8% of groundwater availability, respectively. In the north, groundwater has been exploited. Groundwater is an important water source for river, lake and wetland ecosystems, and it provides fundamental living conditions for the terrestrial vegetation. Once the groundwater level declines, it leads to the degradation of its dependent ecosystems. For example, Wang et al. (2012) found that the shrinkage of wetland in Yellow River Delta was closely related to groundwater exploitation and pollution. Chen et al. (2019) pointed out the large extractions of groundwater for agriculture irrigation and industrial manufacture is the main reason behind the lake degradation in Inner Mongolia. To achieve the sustainable use of blue water in the north and northwest of China, the protection and regulation on the groundwater withdraws must be strengthened.

4.3. Impacts of WF on Water Quality

Grey WF is an indicator of water pollution. In China, it was much larger than the green and blue WFs and accounted for a major part of total WF. The highest grey WF was found in the eastern and southern areas of China, which could be associated with more active industrial and domestic production. For example, the Yangtze River provides freshwater for 400 million people and supports one of the largest economies in China. Wastewater discharges have increased from 20% in the beginning of the 2000s to more than 30% in 2010 and have resulted in Yangtze River water not meeting the drinking water quality standards (Chen et al. 2016). Water quality in the upper and middle Yangtze River has dramatically deteriorated. Moreover, the building of dams on the eastern and southern rivers caused the serious river fragmentation, shrinkage of lakes and wetlands, as resulted in severe water quality problems (Zhang et al., 2012; Xia et al., 2015). Zhai et al. (2017) found that the Huai River Basin suffered from water pollution aggravated by both intensive dam construction and wastewater discharges, especially in the middle and lower sections of the river. The grey WF could be effectively reduced by treating wastewater prior to discharging it into rivers, lakes and coastal water bodies. All the above facts alarm the local government to strengthen the regulation of wastewater discharges and the use and placement of dams.

From the perspective of WF environmental sustainability (e.g. Fig. 3), grey WF was not sustainable in the eastern, southern and northern parts of China, because the water volumes needed to dilute pollution were insufficient and capacity to treat wastewater were inadequate. Bu et al. (2019) identified that the direct release of domestic sewage and industrial wastes were the main causes of river pollution impacting Liaodong Bay in northeast China.

4.4. Impacts of WF on Ecological Restoration

According to the Asia Development Bank (2018), more than half of China's land is considered as ecologically fragile. Some regions might have been beyond the tipping point, which will make restoration much more difficult (Asia Development Bank, 2018). This study identified the fragile ecosystem hotspots and provided insights into ecological restoration. The WF environment sustainability map (Fig. 3) shows that water resources and related ecosystems (e.g. river and wetland) in the middle northern regions of China would not only be threatened by reduced water availability (Fig. 3a) but also by water pollution (Fig. 3c). The western parts of China (e.g. Xinjiang province) were susceptible to water shortages and the northeast China (e.g. Heilongjiang province) had unsustainable levels of grey WF. These regions are more sensitive to ecosystem perturbations, which increases the difficulty of ecological restoration.

To better maintain aquatic ecosystem functions and to improve ecological resilience, environmental water flows should be protected and the exploitation of groundwater should be controlled and monitored in the hotspots shown in Fig. 3a. For example, Chen et al. (2019) pointed out that adjusting industrial water use and reducing groundwater extraction were necessary to restore the lake ecology of Inner Mongolia. Cui et al. (2009) suggested that to alleviate the shrinkage of wetlands in the Yellow River Delta, the ecological water requirements should be maintained at the levels to support ecosystem services. Finally controlling water pollution sources and improving the treatment of wastewater should be a priority, particularly for the unsustainable regions shown in Fig. 3c.

4.5. Water and Environmental Policies and Management

In recent years, the Chinese government has been working to improve the regulation and management of water resources, as well as their dependent ecosystems. For example, the three "redlines" policy focuses on: control the exploitation of water resources; water use efficiency improvements; and preventing water pollution. The three redlines are currently applied at the national, regional, as well as the local level to restrict the anthropogenic activities within the redline standards (Liu et al., 2013; Zhang et al., 2017).

Another of China's management strategies is "sponge city" which seeks to address the flooding problem in urban areas and to reduce the nonpoint pollution with the appropriate practices of low impact development (Chan et al., 2018). When combined with the measures for improving the sustainability of grey WF mentioned above, these policies can provide guidelines for more efficient investments.

Furthermore, the implementation of "river chief system" from the local governments can improve the governance of blue water and control the water pollution more effectively. According to *The Opinion on Comprehensively Promoting the River Chief System* released in 2016, the major tasks of this system are to manage and protect rivers or lakes and water resources, to control water pollutions and to restore and protect aquatic ecosystems (MWR, 2016). A river chief is the chief local government officer who manages efforts within an administrative region and collaborates and coordinates with river chiefs in other local government areas.

In this study, the total blue and green WF declined in quite a few provinces (e.g. Shanghai, Zhejiang and Fujian), which is partly attributed to increased attention to protecting water resources and their dependent ecosystems, as well as the effective implementation of environmental policies in recent decade. The SI for blue, green and grey WF could shed light on the development of effective policies and regulation. Moreover, given the WF hotspots identified in this study, the appropriate reduction targets should be quantified as part of a future research effort to help improve water management efforts.

Compared to green water, blue water has high opportunity costs due to its potential as an input to the supply-chain of economic sectors rather than its use for water intensive agricultural products. As a result, blue water sustainability is often addressed by key water resource policies in China, like "the most stringent water resources management policy" (Liu et al., 2013), water-saving society plan, and many hydraulic infrastructures, e.g. South-North-Water-Transfer-Project and large dams. However, green water is usually ignored. Our sustainability results (Fig. 3) showed that some southern provinces with abundant blue water resource are facing sustainability problems in terms of green WF. Exploitation of green water may lead to degradation of the local environments, therefore guiding agricultural production and green water management is crucial to having sustainable water ecosystems. In addition, the sustainability problems of grey WF were found in China's north and central parts, and the deterioration of water quality was maily induced by economic and social activities. Effective measures, such as controlling wastewater discharges and reducing the consumption of fertilizer and pesticides, should be adopted to control water pollution.

5. Conclusions

This study assessed the environmental sustainability of WF (i.e. blue, green and grey WF) for 31 provinces in China for 2002, 2007 and 2012. At the national level, the total WF was 3,370 Gm^3/y in 2012 which represents an increase of 30% from 2002. This growth was primarily attributed to the increase of grey WF by 40% from 2002 to 2012 because green and blue WF showed a small rise by 2% between 2002 and 2012. This suggests that water pollution is the key factor for water appropriation in China. At the provincial level, the distribution of blue, green and grey WF were not consistent. However all the three components of WF were high in the North China Plain provinces, which is the result of water scarcity issue in the region.

Based on the SI, blue WF exceeded blue water availability in most of China's northern regions (e.g. Xinjiang, as well as most provinces in the North China Plain). The unsustainable blue WF is one important driver for river flows and groundwater degradation. Moreover, grey WF was not sustainable in the eastern and southern areas, nor in the northern part of China, where there were large flows of wastewater. The unsustainable blue and grey WF results in problems such as river fragmentation, shrinkage of lake and wetlands and deterioration of water quality, whereas unsustainable green WF has negative effects on rainfed agriculture. Blue and green WF showed a declining trend in Shanghai, Hebei and Shandong, reflecting the effectiveness of environmental policies over the past several years, focusing on water resources and their related ecosystems.

Because of the overuses of the water resources and the release of untreated pollutants, the resilient capacity of many water bodies and ecosystems has been exceeded, which makes the restoration much more challenging. The results of this study provide some insights into: policy making for sustainable water resources management; and effective strategies for the ecological restoration in hotspot areas.

Finally, we would like to note that in our study, the estimation of green WF was from the GEPIC crop model and the estimation of green water availability was derived from the WAYs model which is more hydrologically based. The estimated data from the two models may be not perfectly consistent and compatible, which is a common situation in multi-model applications (Zaherpour et al., 2018). This could lead to uncertainties in the assessment of the sustainability of green WF thus enhancing data consistency will be a key task in the next phase of our research.

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Conflict of Interest Statement

No potential conflict of interest was reported by the authors.

References

Aldaya, M.M., Rodriguez, C.I., Fernandez-Poulussen, A., Merchan, D., Beriain, M.J., Llamas, R., 2020. Grey water footprint as an indicator for diffuse nitrogen pollution: The case of Navarra, Spain. Sci. Total Environ. 698, 134338.
Asia Development Bank, 2018. Managing Water Resources for Sustainable Socioeconomic Development: A Country Water Assessment for the People's Republic of China.
Bu, H., Song, X., Zhang, Y., 2019. Using multivariate statistical analyses to identify and evaluate the main sources of contamination in a polluted river near to the Liaodong Bay in Northeast China. Environ. Pollut. 245, 1058–1070.
Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y., Xu, Y., Thorne, C.R., 2018. "Sponge City" in China—A breakthrough of planning and flood risk management in the urban context. Land Use Policy 76, 772–778.
Chen, J., Lv, J., Li, N., Wang, Q., Wang, J., 2019. External Groundwater Alleviates the Degradation of Closed Lakes in Semi-Arid Regions of China. Remote Sens. 12 (1), 45.
Chen, X., Bao, A., Wang, X., Japar, G., Huang, Y., 2017. Ecological Effect Evaluation of Comprehensive Control Project in Tarim River Basin. Bull. Chin. Acad. 32 (1), 20–28. (in Chinese)
Chen, Z., Kahn, M.E., Liu, Y., Wang, Z., 2016. The consequences of spatially differentiated water pollution regulation in China. J. Environ. Econ. Manag. 88, 468–485.
Chukalla, A.D., Krol, M.S., Hoekstra, A.Y., 2018. Grey water footprint reduction in irrigated crop production: Effect of nitrogen application rate, nitrogen form, tillage practice and irrigation strategy. Hydrol. Earth Syst. Sci. 22, 3245–3259.
Cui, B., Yang, Q., Yang, Z., Zhang, K., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. Ecol. Eng. 35 (7), 1090–1103.
Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshw. Res. 65 (10), 934–941.
Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114 (1), 168–182.
Hoekstra, A.Y., 2009. Human appropriation of natural capital: A comparison of ecological footprint and water footprint analysis. Ecol. Econ. 68 (7), 1963–1974.
Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resour. Manage. 21 (1), 35–48.
Hoekstra, A.Y., Chapagain, A.K., Aldaaya, M.M, Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.
Hoekstra, A.Y., Hung, P.Q., 2002. Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop. UNESCO-IHE Institute for Water Education 49 (11), 203–209.
Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U.S.A. 109 (9), 3232–3237.
Huang, F., 2019. The Yellow River has achieved continuous flow for 20 consecutive years China. Water Resour. 16. (in Chinese)
Karandish, F., 2019. Applying grey water footprint assessment to achieve environmental sustainability within a nation under intensive agriculture: a high-resolution assessment for common agrochemicals and crops. Environ. Earth Sci. 78, 200.
Kim, H., 2017. Global Soil Wetness Project Phase 3 Atmospheric Boundary Conditions (Experiment 1). Data Integr. Anal. Syst. doi:10.20783/DIAS.501.
Lathuillière, M.J., Coe, M.T., Castanho, A., Graesser, J., Johnson, M.S., 2018. Evaluating water use for agricultural intensification in Southern Amazonia using the Water Footprint Sustainability Assessment. Water 10 (4), 349.
Liu, C., Kroeze, C., Hoekstra, A.Y., Gerbens-Leenes, W., 2012. Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. Ecol. Indicat. 18, 42–49.
Liu, J., 2009. A GIS-based tool for modelling large-scale crop-water relations. Environ. Model. Softw. 24 (3), 411–422.
Liu, J., Wiberg, D., Zehnder, A.J.B., Yang, H., 2007. Modeling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrig. Sci. 26, 21–33.
Liu, J., Yang, H., 2010. Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water. J. Hydrol. 384 (3-4), 187–197.
Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, M., Hanasaki, N., Wada, Y., Zhang, X., Zheng, Y., Alcamo, J., Oki, T., 2017. Water scarcity assessments in the past, present, and future. Earth Future 5, 545–559.
Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., Zhang, M., 2013. Water conservancy projects in China: Achievements, challenges and way forward. Global Environ. Change 23 (3), 633–643.
Mao, G., Liu, J., 2019. WAYS v1 : A hydrological model for root zone water storage simulation on a global scale. Geosci. Model Dev. 12 (12), 5267–5289.
Mekonnen, M.M., Hoekstra, A.Y., 2018. Global Anthropogenic Phosphorus Loads to Freshwater and Associated Grey Water Footprints and Water Pollution Levels: A High-Resolution Global Study. Water Resour. Res. 54, 345–358.
Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity - Supplementary. Sci. Adv. 2 (2), e1500323.
Mekonnen, M.M., Hoekstra, A.Y., 2015. Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water. Environ. Sci. Technol. 49 (21), 12860–12868.
Mekonnen, M.m, Hoekstra, A.Y., 2011. National water footprint accounts: the green, blue and grey water footprint of production and consumption. Value of water research report 50. UNESCO-IHE Institute for Water Education, Delft.
Ministry of Environmental Protection of China, 2003. Environmental Quality Standard for Surface Water (GB3838-2002). China Environmental Science Press, Beijing, China. (in Chinese)
Ministry of Water Resources of China, 2003. Provincial Water Resource Bulletin in 2002. China Water & Power Press, Beijing. (in Chinese)
Ministry of Water Resources of China, 2008. Provincial Water Resource Bulletin in 2007. China Water & Power Press, Beijing. (in Chinese)
Ministry of Water Resources of China, 2013. Provincial Water Resource Bulletin in 2012. China Water & Power Press, Beijing. (in Chinese)
Ministry of Water Resources of China, 2016. The Opinion on Comprehensively Promoting the River Chief System. Ministry of Water Resources in China, Beijing. (in Chinese)
National Bureau of Statistics of China, 2003. China's Environmental Statistics Yearbook. China Statistics Press, Beijing. (in Chinese)
National Bureau of Statistics of China, 2008. China's Environmental Statistics Yearbook. China Statistics Press, Beijing. (in Chinese)
National Bureau of Statistics of China, 2013. China's Environmental Statistics Yearbook. China Statistics Press, Beijing. (in Chinese)
Orr, S., Chapagain, A.K., 2008. UK Water Footprint : the impact of the UK 's food and fibre consumption on global water resources, World Wildlife Fund-UK, Godalming.
Qin, Y., Mueller, N.D., Siebert, S., Jackson, R.B., AghaKouchak, A., Zimmerman, J.B., Tong, D., Hong, C., Davis, S.J., 2019. Flexibility and intensity of global water use. Nat. Sustain. 2, 515–523.
Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2010. Global Agricultural Lands: Croplands, 2000. NASA Socioeconomic Data and Applications Center (SEDAC) New York.
Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resour. Res. 45, W00A12.
Ruane, A.C., Goldberg, R., Chryssanthacopoulos, J., 2015. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agric. For. Meteorol. 200 (15), 233–248.
Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proc. Natl. Acad. Sci. U.S.A. 109 (24), 9320–9325.
Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R., Zehnder, A.J.B., 2008. Modeling blue and green water availability in Africa. Water Resour. Res. 44, W07406.
Steward, A.L., Negus, P., Marshall, J.C., Clifford, S.E., Dent, C., 2018. Assessing the ecological health of rivers when they are dry. Ecol. Indic. 85, 537–547.
Tangdamrongsub, N., Han, S.-C., Decker, M., Yeo, I.-Y., Kim, H., 2018. On the use of the GRACE normal equation of inter-satellite tracking data for estimation of soil moisture and groundwater in Australia. Hydrol. Earth Syst. Sci. 22, 1811–1829.
Veldkamp, T.I.E., Wada, Y., Aerts, J.C.J.H., Döll, P., Gosling, S.N., Liu, J., Masaki, Y., Oki, T., Ostberg, S., Pokhrel, Y., Satoh, Y., Kim, H., Ward, P.J., 2017. Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. Nat. Commun. 8, 15697.
Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.
Wang, C., Yao, Y., Gao, Y., Cao, F., 2016. Remote Sensing Monitoring and Analysis of River Drying up in Beijing. Environ. Dev. Sustain. 41, 170–173.
Wang, C., Zhi, X., Wu, C., Meng, B., Yin, S., Xu, D., Zhou, Y., Feng, A., Yang, Y., 2019. Spatial and Temporal Distribution of River Drying uo in Beijing-Tianjin-Hebei Region in Spring. In: Proceedings of the Annual Meeting of Science and Technology of the Chinese Society of Environmental Sciences, 2019, Volume 2, Chinese Society for Environmental Sciences, Xi'an, ShanXi, pp. 1520–1524. (in Chinese)
Wang-Erlandsson, L., Bastiaanssen, W.G.M., Gao, H., Jägermeyr, J., Senay, G.B., van Dijk, A.I.J.M., Guerschman, J.P., Keys, P.W., Gordon, L.J., Savenije, H.H.G., 2016. Global root zone storage capacity from satellite-based evaporation. Hydrol. Earth Syst. Sci. 20, 1459–1481.
Wang, H., Zhao, S., Zhang, J., Ji, J., 2011. Features of Runoff Changes in the Yellow River from 1950 to 2010. Yellow River 33, 16–18. (in Chinese)
Wang, M., Qi, S., Zhang, X., 2012. Wetland loss and degradation in the Yellow River Delta, Shandong Province of China. Environ. Earth Sci. 67, 185–188.
Xia, J., Zhang, Y.Y., Zhao, C.S., Bunn, S.E., 2015. Bioindicator assessment framework of river ecosystem health and the detection of factors influencing the health of the Huai River Basin, China. J. Hydrol. Eng. 1943–5584.
Zaherpour, J., Gosling, S.N., Mount, N., Schmied, H.M., Veldkamp, T.I.E., Dankers, R., Eis-

ner, S., Gerten, D., Gudmundsson, L., Haddeland, I., Hanasaki, N., Kim, H., Leng, G., Liu, J., Masaki, Y., Oki, T., Pokhrel, Y., Satoh, Y., Schewe, J., Wada, Y., 2018. Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. Environ. Rese. Lett. 13 (6), 065015.

Zang, C., Mao, G., 2019. A Spatial and Temporal Study of the Green and Blue Water Flow Distribution in Typical Ecosystems and its Ecosystem Services Function in an Arid Basin. Water 11 (1), 97.

Zeng, Z., Liu, J., Koeneman, P.H., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: A case study for the Heihe River Basin in northwest China. Hydrol. J. Earth Syst. Sci. 16, 2771–2781.

Zhai, X., Xia, J., Zhang, Y., 2017. Integrated approach of hydrological and water quality dynamic simulation for anthropogenic disturbance assessment in the Huai River Basin, China. Sci. Total Environ. 598 (15), 749–764.

Zhang, L., Dong, H., Geng, Y., Francisco, M.J., 2019. China's provincial grey water footprint characteristic and driving forces. Sci. Total Environ. 677, 427–435.

Zhang, Y., Chu, C., Liu, L., Xu, S., Ruan, X., Ju, M., 2017. Water environment assessment as an ecological red line management tool for marine wetland protection. Int. J. Environ. Res. Public Health. 14 (8), 870–875.

Zhang, Y., Arthington, A.H., Bunn, S.E., Mackay, S., Xia, J., Kennard, M., 2012. Classification of flow regimes for environmental flow assessment in regulated river: the Huai River Basin, China. River Res. Applic. 28 (7), 989–1005.

Zhao, Q., Liu, J., Khabarov, N., Obersteiner, M., Westphal, M., 2014. Impacts of climate change on virtual water content of crops in China. Ecol. Informatics 19, 26–34.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. U.S.A. 112 (4), 1031–1035.

Zuo, D., Xu, Z., Peng, D., Song, J., Cheng, L., Wei, S., Abbaspour, K.C., Yang, H., 2015. Simulating spatiotemporal variability of blue and green water resources availability with uncertainty analysis. Hydrol. Process. 29 (8), 1942–1955.