Quantifying the Inter- and Intra-Annual Variations in Regional Water Consumption and Scarcity Incorporating Water Quantity and Quality

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Abstract
Water stress due to poor water quality has been becoming severe in many places across the world. Comprehensive water utility and water scarcity assessments require information integrating both water quantity and quality. While massive attentions have been paid to water quantity scarcity evaluations, little effort has been made to assess inter-annual variations of regional water scarcity resulting from both water quantity and quality. The study, taking water-abundant while stressed Jiangsu province (JSP) in eastern China as the study area, investigated (i) the development in green, blue and grey water footprint (WFs) for crop production, over 1986–2016, (ii) the inter-annual evolutions in blue and grey WFs for industry and households over 2010–2016 and (iii) the associated inter- and intra-annual variations in water scarcities resulting from water quantity and quality. Results showed that the annual total WF of crop production in JSP increased by 18% between 1986 and 2016. Grey WF accounted for 77% of the total WF at an annual average level. Crop production occupied 61% and household accounted for 34% in the total grey WF related to N. The monthly blue water scarcity levels in JSP increased by 4 (October 2016) – 62 (February 2012) folders when water quality effects were taken into account. The wetter the year, the lower the blue water scarcity of water quality and quantity. As a sensitive and crucial region with both severe water pollution scarcity and the role of water source region in the huge South-to-North water transfer project, it is of great necessity to enhance the water pollution management and increase information transparency among water authorities and consumers.

Keywords Water footprint · Water quantity and quality · Water scarcity · Jiangsu province

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The increasingly limited and unevenly distributed freshwater availability resulted in that two thirds of global population have been consuming the amount of water more than two times the sustainable level (Oki and Kanae 2006; Mekonnen and Hoekstra 2016; Rodrigo et al. 2017). At the same time, water stress due to poor water quality has been becoming severe in many rivers across the world (Liu et al. 2012; Bayart et al. 2010; Pavlidis and Tsihrintzis 2018). Modern sustainable water resource management for different purposes should thus be undertaken to help meet the water quantity demand, and help improve water quality for the sustainable development of the human social stability, ecological health and sustainable biodiversity (Van Vilet et al. 2017; Liu et al. 2017). Apparently, comprehensive water utility and water scarcity assessments require information integrating both water quantity and quality. Water footprint (WF), proposed by Hoekstra in 2002 (Hoekstra 2002), has already been widely accepted as a comprehensive and powerful indicator of water consumption as well as water quality levels. The WF for a specific region consists of green WF (consumption of rain water), blue WF (consumption of surface and ground water) and grey WF (the water required to assimilate anthropogenic loads of pollutants to freshwater bodies) (Hoekstra et al. 2011). One of the contributions of the WF indicators is that the grey WF is able to measure the water quality by unit of water quantity (Liu et al. 2012).

Water scarcity level of a region is normally expressed by indicators as the ratio of water withdrawal or consumption to the water availability, most of available water scarcity indicators focus on the water quantity perspective and merely on the water quality aspects (Liu et al. 2017, 2016; Van Vilet et al. 2017). The widely used water scarcity indicators include the Falkenmark water stress indicator (~per capita blue water availability) (Falkenmark et al. 1989), the IWMI indicator (~proportion of water supply) (Seckler et al. 1998), the criticality ratio of water use to availability (Alcamo et al. 2000), and the water poverty index (~weighted average of water availability, access, capacity, use and environment) (Sullivan et al. 2003). Given the fact that only part of water withdrawal was finally consumed and contributed to the blue water scarcity, Hoekstra et al. (2012) developed the WF-based blue water scarcity indicator which is calculated as the ratio of blue WF to the blue water available for human society (equivalent to natural runoff minus environmental flow requirement). Zeng et al. (2013) firstly claimed the possibility of incorporating the water quality into water scarcity assessment through comparing total of blue and grey WF to natural runoff, but they ignored the environmental flow requirement. Nor did Liu et al. (2016) for water quality scarcity in the quantity-quality-environmental flow requirement indicator. Recently, Van Vilet et al. (2017) proposed a water scarcity index that includes relevant water quality requirements per sector and considered environmental flow requirements. More specifically, the index assesses water scarcity as the ratio of sectoral water withdrawals of acceptable water quality to the overall water availability. Van Vilet et al. (2017) found that the percentage of the world population under severe blue water scarcity increased from 34% to 37% through including water temperature in assessments of water scarcity. Nevertheless, the latest indicator ignores again the truth that return flows from withdrawal still can be treated as water availability (Perry 2007). Through indexing water pollution level by a water quantity unit, grey WF provides the possibility to evaluate simultaneously the water stress resulting from water pollution in a certain area (Liu et al. 2012, 2016), in addition to assess the water stress from the quantity perspective by comparing the blue WF to blue water availability (Hoekstra et al. 2012; Mekonnen and Hoekstra 2016). Temporal variations of regional blue water scarcity is also
crucial given the great inter and intra-variability of water availability and use (Liu et al. 2017). However, only one study by Zhuo et al. (2016a) was available on analyzing the inter-annual variability of blue water quantity scarcity in the Yellow River Basin. To our knowledge, it is hard to find any information on inter-annual variations in regional water quality scarcities.

Therefore, the study aimed to, taking Jiangsu Province (JSP) (Fig. 1) in eastern China as a study area, investigate (i) the development in green, blue and grey water footprint (WFs) for crop production, over 1986–2016, (ii) the inter-annual evolutions in blue and grey WFs for industry and households over 2010 and 2016 and (iii) the associated inter- and intra-annual variations in water scarcities in the JSP accounting for both water quantity and quality.

2 Methodology and Materials

2.1 Study Area

Jiangsu Province, located in eastern China (116.30°-121.95°E, 30.75°-35.33°N), was chosen as the study site because it is water abundant province and also suffers from considerable water stress. JSP is one of thirteen major food producing areas in China (Cao et al. 2018). Yangzhou, located in the central JSP, is the source of the “east line” in the world-famous South-to-North Water Transfer Project, currently transferring 889 billion m³ per year to the northern Chinese province Shandong through the project (Jiangsu Bureau of Statistics of 2017). Surface water accounted for 75% of the water resources within the province. There is severe pressure on local freshwater by the big population as well as the agricultural production activities. According to Jiangsu Bureau of Statistics of 2017, by 2016 the total water withdrawal was 46.59 billion m³, which equals 91% of the total annual inflow of the JSP. Agriculture is the biggest water user, accounting for 66% of the total withdrawal. Although the annual precipitation is higher than 1000 mm across the JSP, the per capita water resource is 490m³/cap, only one fifth of the national average level (NBSC 2018).
2.2 Water Footprint for Crop Production, Industry and Households

We calculated the annual and monthly green, blue and grey WFs in producing nine types of major crops in JSP during 1986–2016. The considered crops accounted for 78% of total harvested area in JSP by 2016 (NBSC 2018). The WF accounting work was conducted according to the WF accounting framework introduced by the Water Footprint Network (Hoekstra et al. 2011). Green and blue WFs per unit mass of crop (WF\(_{g,crop}\) and WF\(_{b,crop}\), m\(^3\)/kg), which equal to the actual green and blue evapotranspiration (ET\(_g\) and ET\(_b\), m\(^3\)/ha) over the cropping period (cgp, day) divided by the crop yield (Y, kg/ha), respectively, were simulated at a grid level at a 5 arc minute resolution, based on the same methodology and data sources as used in Sangam et al. (2013) and Zhuo et al. (2016b).

\[
WF_{g,crop} = \frac{\sum ET_g[t]}{Y} \quad (1)
\]

\[
WF_{b,crop} = \frac{\sum ET_b[t]}{Y} \quad (2)
\]

The daily ET\(_g\) and ET\(_b\) per crop per grid were simulated by the FAO crop productivity model AquaCrop through tracking the daily green and blue dynamic soil balances in the root zone (Sun et al. 2013; Chukalla et al. 2015; Zhuo et al. 2016b). The main assumption of the model is S\(_g[t]\), S\(_b[t]\), IRR\(_t\), and CR\(_t\), and its core algorithms are given below.

\[
S_{g[t]} = S_{g[t-1]} + \left( PR_{t} + IRR_{t} - RO_{t} \right) \times \frac{PR_{t} + IRR_{t}}{\left( PR_{t} + IRR_{t} \right) - \left( DP_{t} + ET_{t} \right)} \times \frac{S_{g[t-1]}}{S_{g[t-1]}} \quad (3)
\]

\[
S_{b[t]} = S_{b[t-1]} + \left( PR_{t} + IRR_{t} - RO_{t} \right) \times \frac{IRR_{t}}{\left( PR_{t} + IRR_{t} \right) - \left( DP_{t} + ET_{t} \right)} \times \frac{S_{b[t-1]}}{S_{b[t-1]}} \quad (4)
\]

where, S\(_{g[t-1]}\) and S\(_{b[t-1]}\) (mm) are the green and blue soil water content at the end of day t-1, respectively. PR\(_{t}\) (mm) is the precipitation on day t, IRR\(_{t}\) (mm) represents the irrigation water applied on day t, ET\(_{t}\) (mm) is the actual evapotranspiration, RO\(_{t}\) (mm) means daily surface runoff and DP\(_{t}\) (mm) is deep percolation.

As following Siebert and Doll (2010) and Zhuo et al. (2016a), the initial soil water moisture was simulated from the maximum soil water content through two years rain-fed fallow land prior to the planting date. The initial soil water moisture at the start of the growing period was assumed as green water, i.e. S\(_{g[1]} = S\), S\(_{b[1]} = 0\). The indicative values on the hydraulic characteristics for each type of soil were directly provided by AquaCrop. Data on total soil water capacity (in %vol) at a spatial resolution of 5 arc minute were obtained from Batjes (2012). Here the IRR\(_{t}\) refers to the irrigation required with the option of “Net irrigation” in the AquaCrop modelling. When the root zone depletion exceeds the default 50% of readily available soil water, a small amount of irrigation water will be stored in the soil profile to keep the root zone depletion just above the field capacity level so that the IRR\(_{t}\) excludes extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field (Raes et al. 2011). The CR\(_{t}\) is assumed to be zero.
because the ground water depth is considered to be much larger than 1 m (Allen et al. 1998). The above assumption and setting in AquaCrop modelling have been widely used in previous studies (i.e. Zhuo et al. 2016a, b; Chukalla et al. 2015).

The \( Y \) per crop per grid was simulated by AquaCrop as the harvestable portion of the total above-ground biomass at the end of the growing period. It was determined as the aboveground biomass of a product (\( B \)) and the harvest index (HI, %). Then the simulated outputs were calibrated to meet the provincial statistics on crop production.

\[
Y = HI \times B
\]  

(5)

In the study, we assumed the grey WF as a result of the nitrogen (N) fertilizer at the provincial level. For a unit mass of crop, the grey WF (\( WF_{\text{grey}} \) m\(^3\)/kg) related to N per year was calculated as:

\[
WF_{\text{grey}} = \frac{\alpha \times AR}{(c_{\text{max}} - c_{\text{nat}})} \times \frac{1}{Y}
\]

(6)

where, \( \alpha \) is the leaching-runoff fraction, which was set as 0.1 for N (Franke et al. 2013). AR (kg/ha) refers to the application rate of N fertilizer of the year, which is the ratio of total N fertilizer application (kg) to total cropping area (ha) of JSP, \( c_{\text{max}} \) (kg/m\(^3\)) is the maximum acceptable concentration of the nutrient in water body, and \( c_{\text{nat}} \) refers to the natural concentration of the nutrient in water body.

Given the limited data availability, we assessed annual and monthly blue and grey WFs of industry and household in JSP as a whole for 2010–2016. Annual blue WFs of industry and household were obtained from Jiangsu Bureau of Statistics of each year (available at: http://jswater.jiangsu.gov.cn/col/col51453/index.html). The annual grey WFs of industry and household in JSP for the same period were estimated as the amount of water needed for a dilution of \( \text{NH}_3\text{-N} \) pollution to an acceptable level, using eq. (6). Corresponding monthly blue and grey WFs of industry and households were assumed to distribute equally across twelve months of each year (Hoekstra et al. 2012; Schyns and Hoekstra 2014; Zeng et al. 2012; Zhuo et al. 2016b).

2.3 Blue Water Scarcity Assessment

We estimated the monthly blue water scarcity over 2010–2016 for the JSP considering both water quantity and water quality, as inspired by Liu et al. (2016), Zhao et al. (2016) and Van Vilet et al. (2017). The monthly blue water scarcity considering only water quantity can be assessed as the ratio of the blue WF to the difference between natural runoff and the environmental flow requirement (EFR) (Hoekstra et al. 2012). While considering both water quantity and quality, the water quality dimension in the blue water scarcity index (WSI) is indicated by the grey WF, i.e. the extra water consumption requirement to dilute and lower pollutants’ concentration below the threshold according to the water sectoral guidelines (Van et al. 2017).

\[
WSI = \frac{\sum_{j=1}^{3}(WF_{b,j} + WF_{\text{grey},j})}{Q - EFR}
\]

(7)

where, \( WF_{b,j} \) and \( WF_{\text{grey},j} \) (m\(^3\)/month) refer to the monthly total blue and grey WFs, respectively, of sector j, including agriculture, industry and household. The \( Q \) (m\(^3\)/month) refers to the blue water availability. Regarding the EFR (m\(^3\)/month), we used the presumptive standard
proposed by Richter et al. (1997), which considered the environmental flow as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and their well-beings (Brisbane Declaration 2007). The EFR standard allocates 80% of monthly natural runoff to the environment.

2.4 Data

Gridded monthly precipitation, ET_0 and temperature at a resolution of 30 × 30 arc minute were extracted from CRU-TS-3.10 and 3.10.01 (Harris et al. 2014). Gridded irrigated and rain-fed area for each crop at a 5 × 5 arc-minute resolution were obtained from the MIRCA2000 dataset (Portmann et al. 2010). Yearly areas and yields for each crop within JSP were scaled to fit the yearly provincial agriculture statistics (NBSC 2018). Crop calendar, maximum root depth and reference harvest index were obtained from Zhuo et al. (2016b). Soil texture data at a 10 × 10 km resolution were obtained from the ISRIC Soil and Terrain database for China (Dijkshoorn et al. 2008). Records on nitrogen fertilizer use statistics, blue WFs and the discharge load of NH3-N by industry and household sector for JSP over the study period 1986–2016 were obtained from NBSC (2018). The monthly blue water availability records were obtained from NBSC (2018) and Jiangsu water resources bulletin (Jiangsu Water Resources Department 2018). The values for c_max and c_nat for the calculation of grey WFs were taken from the national surface water quality standard of China (MEP 2002).

3 Results

3.1 Water Footprint of Crop Production

Annual total WF of crop production in JSP increased by 18% from 159.7 × 10^9 m^3 yr^{-1} in 1986 to 188.5 × 10^9 m^3 yr^{-1} in 2016 (Fig. 2). Grey WF accounted for 77% of the total WF at the annual average level. Such increase in the total WF in crop production was mainly a result of the increase of 26% in the total grey WF from 111.3 × 10^9 m^3 yr^{-1} in 1986 to 139.8 × 10^9 m^3 yr^{-1} in 2016. The increase in annual grey WF of crop production was in line with the increase in N fertilizer application of 28% (NBSC 2018). Whereas the magnitude of annual total green and blue WF changed slightly. In averaged, blue WF accounted for 6% of the total WF while 24% of the total green-blue WF.

Figure 3 compares the contributions of each crop to annual total green, blue and grey WFs of crop production in JSP in 1986 and 2016. Rice and wheat growth made majority of the WF of crop production in the province. By 2016, the contribution of the rice and wheat to the total green, blue, grey and total WF was 89%, 93%, 82% and 85%, respectively. Over 1986–2016, due to the changing cropping patterns in JSP, the contribution of each crop to total WF changed. The phenomenon could be reflected distinctly in the crops of barley, soybean, and cotton (Fig. 3). The relative contribution of the three crops to the total green-blue WF, blue WF, and green WF significantly decreased over the study period. The sharpest decrease in WFs (by 83% in total WF) occurred on cotton, of which the harvested area shrunk by 87%.

Spatial variations in the consumptive (green and blue) WFs of crop production in JSP are shown in Fig. 4. The total blue-green WF in JSP ranged from 7.5 × 10^6 m^3 yr^{-1} to 354.5 × 10^6 m^3 yr^{-1} with two high value areas (Nantong and Lianyungang city), where the agricultural district was most concentrated (Fig. 4a). The blue WF evidently increased eastern ward, with
the value ranging from $0.1 - 17.8 \times 10^6$ m$^3$ yr$^{-1}$ to $17.9 - 39.5 \times 10^6$ m$^3$ yr$^{-1}$ (Fig. 4b). The spatial distributions of the green WF was similar to the total blue-green WF, and also had two high value areas (i.e., the Nantong and Lianyungang city) (Fig. 4c).

Table 1 lists the provincial average green, blue and grey WFs per ton of considered crops and corresponding crop yields in JSP for 1986, 2001 and 2016. Total unit green-blue WFs for most of the crops reduced over the study period, although their yields increased. Given the doubled yield level, the WFs of tomato decreased more rapidly than other crops by 51%, 66% and 43% in green, blue and grey WFs, respectively. Among the crops, cotton had the largest WF while tomato had the smallest WF (Table 1).

The blue and green WF per ton of crops were negatively correlated with crop yields, as shown for cereals in Fig. 5. The blue and green WF reduced significantly, while the cereal yield increased significantly. Whereas with the decreasing total harvested area (of 12% less over the study period) and increasing fertilizer application rate (by 42%), the grey WF per ton of cereals showed increasing trend during 1986–2008, then decreased with faster improvements in crop yields.

### 3.2 Water Footprint of Industry and Households

Figure 6 shows the annual developments in blue and grey WFs of industry and households in JSP for 2010–2016. Annual blue WFs of industry were higher than blue WFs of households, while grey WFs of industry were much smaller than grey WF of households in JSP. During this period, the industry in JSP had a declining blue and grey WFs, with reductions of 39% and 34%, respectively. However, with the increasing urban population by 14% during 2010–2016, even though there is only 2% of increases in the total population of JSP, annual grey WF of households in JSP increased by 35% from $48 \times 10^9$ m$^3$ yr$^{-1}$ in 2010 to $64.8 \times 10^9$ m$^3$ yr$^{-1}$ in 2016. Meanwhile, overall blue WFs of households kept stable.

### 3.3 Monthly Blue Water Scarcity in JSP

Both the water quality and quantity were considered in the monthly water scarcity assessment for JSP over 2010–2016. The annual average total blue and grey (related to N) WF considering crop production, industry and household in JSP was $27 \times 10^9$ m$^3$ yr$^{-1}$ and $246 \times 10^9$ m$^3$ yr$^{-1}$,
In total blue WFs, crop production accounted for the most, 89%, followed by industry with 6%. Whereas crop production occupied 61% and household accounted for 34% of the total grey WF related to N.

Fig. 3 The contribution of each crop to total annual green, blue and grey WF for crop production in the JSP by the years 1986 and 2016

respectively. In total blue WFs, crop production accounted for the most, 89%, followed by industry with 6%. Whereas crop production occupied 61% and household accounted for 34% of the total grey WF related to N.
With regard to the water quality affects only, Fig. 7a compares the monthly blue WF to the blue WA. The blue WF peaked in June, one month earlier than the blue WA. The blue WF in JSP was mainly concentrated in the cropping period from April to December, which accounted for 94% of the yearly total. Over the study period, groundwater contributed 10% to 47% of monthly total blue WA in the province. In most cases, JSP faced severe blue water quantity scarcity (when the monthly blue WF was higher than 1.5 times of the blue WA) for May to November. The contribution of considered crop to the monthly blue WF was given in Fig. 7b, and the peak months of the blue WF were mainly made by rice and wheat.

Taking the extra pressure from water quality related to N into the blue water scarcity, as shown in Fig. 8, the monthly blue water scarcity levels in JSP increased by a factor of 4 (October 2016) – 62 (February 2012). The peak periods of the monthly blue water scarcity of quality and quantity during June–September were in line with that of the blue water scarcity of quantity. The considered crop production contributed 34–83% to the blue water scarcity related to water quality. The wetter the year, the lower the blue water scarcity of both water quality and quantity. For JSP, at an annual base, the blue water scarcity level in the dry year 2013 (~23) was 2.5 times the level in the wet year 2016 (~9).

4 Discussion

Our study derived the green, blue and grey WFs in crop production of JSP over 1986–2016, blue and grey WFs of industry and households and assessed the monthly blue water scarcities related to both water quantity and quality over the period 2010–2016. There are a few studies available on green and blue WF accounting for crop production of JSP (e.g. Gong et al. 2018; Gu et al. 2012) while little has drawn attention on grey WF assessment. Therefore, our study, compared to previous studies, completed a more comprehensive assessment of WFs in JSP, and our results could act as a useful reference for water resource management in JSP. In addition, the method employed in our study is capable of applying in other areas, and therefore meaningful for water resource management for wider places. The differences between our results on total of green and blue WFs and those from previous studies are within the acceptable uncertainties (±30%) (Table 1). Regarding the grey WF, our results on total annual grey WF (~221.9 × 10^8 m^3 yr^-1 by 2010) in JSP match well to the values (~213.5 ×
|       | 1986     | 2001     | 2016     |
|-------|----------|----------|----------|
|       | Green WF (m³ t⁻¹) | Blue WF (m³ t⁻¹) | Grey WF (m³ t⁻¹) | Yield (t ha⁻¹) | Green WF (m³ t⁻¹) | Blue WF (m³ t⁻¹) | Grey WF (m³ t⁻¹) | Yield (t ha⁻¹) | Green WF (m³ t⁻¹) | Blue WF (m³ t⁻¹) | Grey WF (m³ t⁻¹) | Yield (t ha⁻¹) |
| Wheat | 1539     | 172      | 4368     | 4.1       | 1453     | 267      | 7358     | 4.1       | 1605     | 176      | 5038     | 5.1 |
| Maize | 840      | 101      | 3614     | 5.0       | 761      | 106      | 5001     | 6.0       | 918      | 122      | 4891     | 5.3 |
| Rice  | 901      | 519      | 2573     | 7.0       | 887      | 512      | 3590     | 8.4       | 785      | 453      | 3060     | 8.4 |
| Barley| 347      | 49       | 6895     | 4.4       | 347      | 49       | 6895     | 4.4       | 330      | 51       | 4848     | 5.3 |
| Soybean | 1831   | 565      | 8802     | 2.1       | 1353     | 562      | 11,012   | 2.7       | 1825     | 605      | 11,029   | 2.3 |
| Cotton | 6867     | 400      | 22,405   | 0.8       | 4524     | 335      | 25,213   | 1.2       | 5125     | 293      | 22,107   | 1.2 |
| Sunflower | 456    | 310      | 7147     | 4.2       | 456      | 310      | 7147     | 4.2       | 248      | 129      | 3258     | 7.9 |
| Groundnuts | 1526  | 417      | 6756     | 2.7       | 1013     | 360      | 8277     | 3.7       | 1244     | 300      | 6587     | 3.9 |
| Tomato | 209      | 20       | 806      | 22.5      | 165      | 15       | 921      | 32.8      | 103      | 7        | 458      | 56.2 |
10^8 m^3 yr^{-1} for 2002–2010) in Mekonnen and Hoekstra (2015). Therefore, our estimations on WFs in crop production are solid and acceptable (Table 2).

JSP is an economically developed (~with the 4th highest GDP per capita among Chinese provinces) and highly urbanized (68% in 2016) province in China, demonstrating the importance and necessity of incorporation water pollution effects into studies on local water stress. With limited land for agriculture and high demand for food production, the annual total N fertilizer application in JSP ranked the 4th highest (~206 kg ha^{-1}) at the provincial level in mainland China (NBSC 2018). China contributed 45% to global grey WF related to N and JSP...
is located in the hot places with much higher water pollution levels (~7.55–12.98) than other places within China (Liu et al. 2012; Mekonnen and Hoekstra 2015). Our results demonstrated that the monthly grey WF generated blue water scarcities were much higher (by 4–62 times) than the blue WF generated blue water stress. It indicates that, in regions like JSP, it is important for water resource management to control and reduce water pollution instead of increasing water use efficiency. Hence, it is necessary for reducing the grey WF and the crisis of local water shortage to optimize planting structure, improve the production techniques, and reduce fertilizer use. In addition, facing such severe blue water quality scarcity, JSP is still transferring increasing amount of freshwater (~ 602 × 10^6 m^3 yr^{-1} by 2016) to its neighbor Shandong province through the South-to-North Water Transfer Project. It raises the critical issue on the quality control of the transferred water as well. Therefore, the key challenge in the local water authorities in JSP would be how to monitor and manage sustainably the water pollutants along the whole water use processes of all the water use sectors. As the very first step, transparent information and estimation on water quality should be given to all the relative water managers and users (Barnett et al. 2015).

Fig. 7  a The monthly blue water footprints (WFs) versus the blue water availability (WA) and b the contributions of considered crops to the monthly blue WFs for crop production over 2010–2016 in JSP

Fig. 8  Blue water scarcity in the JSP over 2010–2016
Our study focused on JSP, but the methods used, combining data from climate observations, hydrological models and national statistics, can be applied to other regions as well. However, there are some shortcomings in our study that should be pointed out. First, during the simulation of WFs for crops, not all the crops were taken into account, which may lead to underestimations in the WF. Second, the annual variation of the initial soil water content for each crop (at the beginning of the growing season) in each grid cell was not taken into consideration (Zhuo et al. 2016a). Third, we only assessed the water scarcity at the provincial scale due to the data limitations, more detailed information on spatial variations in grey WF and the blue water scarcity may be necessary for local implementation in water policy making.

5 Conclusion

In the study, we estimated the WF-based blue water scarcity indicators for JSP, a water-abundant while stressed province, through considering both water quantity and quality as well as environmental flow requirements. Based on the quantification of green, blue and grey WFs in crop production over 1986–2016 and WFs of industry and households for 2010–2016, the inter- and intra-annual variability of both water quality and quantity scarcities for 2010–2016 were analyzed. The results showed that the annual total WF of crop production in JSP increased by 18%. Grey WF accounted for 77% of the total WF at an annual average level. The monthly blue water scarcity levels in the JSP increased by 4 (October 2016) – 62 (February 2012) folders when water quality effects were considered. The peak periods of the monthly blue water scarcity of both quality and quantity during June–September were in line with that of the blue water scarcity of quantity. The wetter the year, the lower the blue water scarcity of both water quality and quantity. As a sensitive and crucial region with both severe water pollution scarcity as well as the role of water source region in the huge South-to-North water transfer project, it is of high necessity to enhance the water pollution management and increase information transparency among water authorities and consumers. The current WF-based water scarcity indicator provides possibilities to integrate and measure pressures from both water quantity consumption and pollution at various spatial and temporal scales.
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Compliance with Ethical Standards

Conflict of Interests The authors declare that there is no conflict of interests regarding the publication of this paper.

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