Assessing blue-green water utilization in wheat production of China from the perspectives of water footprint and total water use

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Abstract

The aim of this study is to estimate the green and blue water footprint (WF) and total water use (TWU) of wheat crop in China, both in irrigated and rain-fed productions. Crop evapotranspiration and water evaporation loss are both considered in calculating water footprint in irrigated fields. We have also compared the water use for per unit product between irrigated and rain-fed crops and analyzed the relationship between promoting yield and saving water resources. The national total and the WF of per unit product of wheat production for the year 2010 are about 111.5 G m^3 (64.2% green and 35.8% blue) and 0.968 $m^3 kg^{-1}$, respectively. There exists a big difference in WFP among different provinces: the WFP is low in the provinces in and around the Huang-Huai-Hai Plain, whereas it is relatively high in the provinces located in the south of the Yangtze River and northwest China. The major portion of WF (80.9%) comes from the irrigated farmland and the remaining 19.1% falls into the rain-fed. Green water dominates the south of the Yangtze River, whereas low green water proportions relate themselves to the provinces located in north China, especially northwest China. National TWU and total water use of per kg wheat product (TWUP) are 142.5 G m^3 and 1.237 $m^3 kg^{-1}$, containing about 21.7% of blue water percolation (BW_p). The values of WFP for irrigated (WFP_I) and rain-fed (WFP_R) crops are 0.911 and 1.202 $m^3 kg^{-1}$, respectively. Irrigation has played an important role in food production and promoted the wheat yield by 170% and reduced WFP by 24% when comparing to rain-fed wheat production. Due to the low irrigation efficiency, more water is needed in irrigated farmland for each kilogram of wheat produced in many arid regions such as Xinjiang, Ningxia and Gansu provinces. We have divided the 30 provinces of China into three categories according to the relationship between $TWUP_I$ (TWU for per unit product in irrigated farmland) and $TWUP_R$ (TWU for per unit product in rain-fed farmland): (Ⅰ) $TWUP_I < TWUP_R$, (Ⅱ) $TWUP_I = TWUP_R$, and (Ⅲ) $TWUP_I > TWUP_R$. Category Ⅱ, which contains major wheat producing areas in the North China Plain, contributes nearly 75% of wheat production to the country. Double benefits of saving water and promoting production can be achieved substantially by irrigating wheat in Category Ⅰ provinces. Nevertheless, provinces in this category produce only 1.1% of the national wheat yield.

1. Introduction

China is not only the most populous and the largest food consuming country, but also one of the countries poorest in individual water resources, which is only 2100 m^3 per capita in 2010 (MWR, 2011) or less than a quarter of water resources per capita in the world (Ge et al., 2011). With the population surge and socioeconomic development, water crisis has become a hot spot all over the nation since the gap between increased demands and limited water resources has been increasingly widening. Meanwhile, agriculture is the largest water user in China, accounting for more than 60% of the total water (blue water) withdrawals (MWR, 2011). At present, due to bottlenecks in technology and management, agricultural irrigation water is low-efficiently used and wasted seriously. It is meaningful to reduce the water use in agriculture for meeting the freshwater challenges facing China in the future (Wu et al., 2010).

The concept of “water footprint” introduced by Hoekstra (2003), offers a new approach to assessing water resources utilization in agricultural productions. The water footprint of crop product is defined as the volume of freshwater consumed during the crop production process. Normally it has three components: blue, green and gray water footprints. The blue water footprint refers to the consumption of blue water resources (surface and groundwater) along the supply chain of a product; the green water footprint refers to the consumption of rainwater insofar as it does not become run-off; and grey water footprint is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011). Water footprint of crop product is usually measured in two ways: total water footprint in a specific region (in m^3) and water footprint of unit mass of product (in $m^3 kg^{-1}$ or $m^3 t^{-1}$). The total water footprint links itself directly to water resources availability, and the green and blue water footprints of unit production reflect regional water productivity.

Wheat is one of the three most important grain crops in China. The sown area of wheat was about 24.26 million ha and the yield was 115.18 million t in 2010, contributing about 17.8% of world production (NBSC, 2011). Wheat includes spring wheat and winter wheat based on their growing period. Winter wheat is planted in most provinces of China while spring wheat mainly in Heilongjiang, Neimenggu, Qinghai, Ningxia, and Xinjiang. A number of studies have already been conducted over the past decade on water footprint of wheat production. Hoekstra et al. (2005, 2007) and Chapagain et al. (2006) made a global evaluation of the water use in wheat production during the periods of 1995–1999 and 1997–2001 yet without distinguishing green and blue water consumptions. Liu et al. (2007a, 2009) made a global estimate of water consumption and its green-blue water distinction in wheat production in 2000 using a GIS-based EPIC model. Aldaya et al. (2010) have estimated the WF of wheat and analyzed the green and blue water components for major wheat producing countries of the world. Siebert and Döll (2010) quantified the blue and green water consumed in global crop production as well as potential production losses without irrigation by applying a grid-based approach for the period 1998-2002. Aldaya and Hoekstra (2010) made an assessment of the water footprint of wheat in Italy, for the first time specifying the green, blue and grey water footprint. And Mekonnen and Hoekstra (2010, 2011) made a global and high-resolution assessment of the green, blue and grey water footprint of wheat by taking a high-resolution approach.

Meanwhile, quite a few scholars have studied on water footprint of China’s wheat production. Liu et al. (2007b) simulated the national blue and green water evapotranspiration of winter wheat with the aid of GEPIC model. Zhang (2009) and Sun et al. (2012) calculated the provincial water footprint of each kilogram of wheat product for the periods of 1997-2007 and the year 2009, respectively. Ge et al. (2010) estimated the water footprint of wheat in the North China Plain and further drew distinctions between green, blue and gray water footprints. Xu, et al (2013) studied the water footprint of wheat product in four basins by taking the life cycle assessment (LCA) approach. Based on the evapotranspiration (ET) calculated with CROPWAT model. Tian et al. (2013) analyzed the temporal variation of water footprint of China’s major food crops from 1978 to 2010. Taking the loss of irrigation water (irrigation water consumed not by field crop ET during the transmission and distribution processes of water sources to field) into blue water footprint calculation, Sun et al. (2013) assessed the water footprint of grain crops, including wheat, in typical irrigation districts of China using a modified method.

These studies have promoted the development of the water footprint theory. However, almost all of them only calculated water consumption at field scale and on the assumption that crop planted in farmland with irrigation suffered no water stress. Their estimation methods have yet to take into account the irrigation water loss through evaporation from the water surface during the water transport from source to cropland. Consequently, they failed to reflect the actual water consumption in irrigation system (Perry, 2014). In addition, rare studies contrasted WF with traditional agricultural water utilization assessment indicators.

In this study, we focused on the water footprint of wheat. The objective is to estimate the green and blue water footprint of wheat from a production perspective, distinguishing between crops cultivated in irrigated and rain-fed farmland. Herein, we quantify the green and blue water footprint of wheat by adopting an approach that takes into account the actual water use by agricultural production at regional scale. The water evaporated from the water surface (E) is included in water footprint calculation and the blue water footprint is obtained by mutual check between the crop irrigation water requirement (IWR) and actual irrigation water capacity (IWC). The effects of irrigation on crop yield, water footprint, and total water use in each province of China are explored in this study as well.

2. Data Description

The water footprints of wheat in irrigated and rain-fed farmlands of China are calculated using a crop-model-coupled-statistics approach, where the elements needed are consolidated, including the CROPWAT model, agricultural data in irrigated land, and provincial agricultural data in total crop land.

2.1 FAO CROPWAT 8.0 Model

CROPWAT is a decision support tool developed by the Land and Water Development Division of UN Food and Agriculture Organization FAO (FAO, 2009). The computer program can be used to calculate crop water requirements (CWR) and irrigation water requirements (IWR) based on soil, climate and crop data. In addition, the program allows the development of irrigation schedules under different management conditions and the calculation of water supply schemes for various crop patterns (FAO, 2009). It is recommended by the Water Footprint Network to calculate crop water footprint. All calculation procedures used in CROPWAT 8.0 are based on the two FAO publications of the Irrigation and Drainage Series: No. 56 "Crop evapotranspiration – Guidelines for computing crop water requirements" (Allen et al., 1998) and No. 33, "Yield response to water" (Doorenbos and Kassam, 1979).

2.2 Agricultural data in irrigated land

The statistical data including actual irrigation water capacity (IWC, the gross irrigation water diversion), crop yield, irrigation water utilization coefficient (η) and irrigated area from the administration bureaus of 442 irrigation districts in 30 provinces (Fig.1) are collected for this study. The actual measurement of η was conducted by engineers work for administration bureau of irrigation district.

2.3 Agricultural data in total crop land

The climate data from 517 weather stations in 30 provinces of China used here are acquired from the China Meteorological Data Sharing Service System (CMA 2011), and include monthly average maximum temperature, monthly average minimum temperature, relative humidity, wind speed, sunshine hours and precipitation. Provincial agricultural data used including crop yield, crop-sowing area, agricultural acreage and irrigation area can be referenced to the China statistical yearbook 2011 (NBSC 2011). Crop planting and harvesting dates of 180 agricultural observation stations are obtained from the Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences (FIRI, CAAS). The crop coefficient (K_c) of wheat can be referenced to Chen, et al. (1995) and Duan, et al. (2004). K_c values listed in these references are the test results collected from irrigation experimental station located in different regions of China.

3. Methods

Blue and green water footprints of wheat are evaluated in this study. Both of the blue water and green water play a key role in crop growth in irrigated farmland, but in rain-fed cropland no blue water is consumed. The water footprints of per kg wheat product in irrigated and rain-fed croplands are estimated separately, and then each provincial total water footprint of wheat is calculated in this paper.

3.1 Water footprint of per kg wheat product (WFP) in irrigated farmland

Due to the fact that the irrigated farmland within a province appears as scattered pieces, the provincial water footprint of per kg wheat product (WFP) of the irrigated farmland should be the average of water footprints from every piece of irrigated land. By this, 442 typical irrigation districts in 30 provinces (Hainan Province excluded for having no wheat planting) are chosen as the calculation units (see Fig.1), and water footprint of per kg wheat product (WFP) for each irrigation district is calculated, and then, the WFP in irrigated farmlands of each province is estimated by using the weighted average method.

3.1.1 Green water footprint (GWF)

The GWF during crop growth period, normally, is equal to the effective precipitation in both rain-fed and irrigated cropland. The effective precipitation during crop growth period can be calculated with Eq. (1), which is recommended by FAO CROPWAT8.0 Model.

$$P_e = \begin{cases} P\times(4.17-0.02P)/4.17, & P<83 \\ 41.7+0.1P, & P>83 \end{cases} \tag{1}$$

Where, P and P_e are ten-day precipitation and effective precipitation, in mm.
In order to prevent the results of P_e exceed the crop water requirement of wheat (ET_c), the GWF is determined as:

$$GWF=A_p \times Min(ET_c, P_e) \tag{2}$$

And

$$ET_c = K_c \times ET_0 \tag{3}$$

Where, A_p is the crop planting area, in ha; K_c the crop coefficient, dimensionless; ET_0 the reference crop evapotranspiration calculated by CROPWAT 8.0 Model, in mm.

3.1.2 Blue water footprint (BWF)

The blue water of wheat in irrigation system is the sum of irrigation water evaporated from the water surface during the transmission and distribution process from the water sources to field (BWF_e) and the field evapotranspiration (BWF_f):

$$BWF=BWF_f + BWF_e \tag{4}$$

The BWF_f is obtained by mutual check between the crop irrigation water requirement (IWR) calculated by Eq. (5) and irrigation water capacity (IWC) surveyed by the administration bureaus of the studied irrigation districts.

$$IWR= \begin{cases} 0, & ET_c \leq P_e \\ ET_c - P_e, & ET_c > P_e \end{cases} \tag{5}$$

The calculation process of BWF_f in an irrigation district is as follows:
If $\eta \times IWC > IWR$, then:

$$BWF_f = IWR \tag{6}$$

Otherwise:

$$BWF_f = \eta \times IWC \tag{7}$$

Where, η is the irrigation water utilization coefficient (irrigation efficiency), dimensionless.

The amount of BWF_e is estimated as follows:

$$BWF_e = \alpha \times IWC \tag{8}$$

Where, α is the evaporation loss coefficient, dimensionless.

Referencing to the “Code for Design of Irrigation and Drainage Engineering” (WMR, 1999), the value of α could be: 1) $A_I < 20 \times 10^3$ ha, α=3%; 2) 20×10^3 ha $< A_I < 100 \times 10^3$ ha, α=5%; and 3) $A_I > 100 \times 10^3$ ha, α=8%. A_I is area of the irrigation district. The value of α recommended by the reference is consulted by irrigation engineering designers in China and it is widely considered accords with the actual conditions basically (Li, 2006).

The water footprint of per kg wheat product in an irrigation district (WFP_{ID}) is calculated as:

$$WFP_{ID} = \frac{GW+BW}{Y_{ID}} = GWFP_{ID} + BWFP_{ID} \tag{9}$$

$$BWFP_{ID} = BWFP_{ID,ET} + BWFP_{ID,CL} \tag{10}$$

Where, Y_{ID} is the crop yield of the irrigation district, $t\,ha^{-1}$; $GWFP_{ID}$ and $BWFP_{ID}$, the green and blue water footprints of per kg wheat product in an irrigation district, $m^3\,kg^{-1}$; $BWFP_{ID,\,ET}$ and $BWFP_{ID,\,CL}$, the blue water footprints of per kg wheat product for evapotranspiration and for conveyance loss, $m^3\,kg^{-1}$.

3.1.3 Water footprint of per kg wheat product in irrigated farmland (WFP_I) of every province

The water footprint of per kg wheat product in irrigated farmland (WFP_I) is estimated by the weighted average method:

$$WFP_I = \frac{\sum (WFP_{ID}^i \times A^i)}{\sum A^i} \tag{11}$$

Where, WFP_{ID}^i is the water footprint of per kg wheat product in ith irrigation district, in $m^3\,kg^{-1}$; A^i is the irrigation area of the ith irrigation district; in ha.

The green water footprint and blue water footprint of per kg wheat product, and the crop yield in irrigated farmland (GWF_I, $BWFP_I$, and Y_I) can also be calculated by using a method similar to Eq. (11).

3.2 Water footprint of per kg wheat product in rain-fed farmland (WFP_R) of every province

For rain-fed crops, WF is derived all from green water. The calculation of green water footprint (GWF) in rain-fed cropland of a province can reference to Eqs. (1) ~ (5). Then the water footprint of per kg wheat product in rain-fed farmland (WFP_R) of a province is calculated as follows:

$$WFP_R = \frac{GWF}{Y_R} \tag{12}$$

Y_R is the crop yield in rain-fed farmland, $t\,ha^{-1}$. Y_R is hard to get due to a lack of surveyed data from management institutions, thus different from the calculation of crop yield of irrigated land in China. It can be calculated by Eq. (13):

$$Y_R = \frac{O_T - Y_I \times A_I}{A_R} \tag{13}$$

$$A_R = A - A_I \tag{14}$$

Where, O_T is the provincial total output of wheat product, in t; Y_I the crop yield in irrigated farmland, tha^{-1}; A_I the area of irrigated farmland, ha; and A_R the area of rain-fed farmland, ha.

3.3 Provincial water footprint of wheat in total crop land

Water footprint of wheat (WF) in total crop land of a province is the sum of water footprint in irrigated land and rain-fed land:

$$WF = WF_I + WF_R \tag{15}$$

$$WF_I = WFP_I \times Y_I \times A_I \tag{16}$$

$$WF_R = WFP_R \times Y_R \times A_R \tag{17}$$

Where, WF_I and WF_R is the water footprint of wheat in irrigated farmland and rain-fed farmland respectively, in $10^6 m^3$; Y_I and Y_R the crop yield in irrigated and rain-fed farmland, tha^{-1}; A_I and A_R the sown area of irrigated and rain-fed wheat, in ha. The green water footprint (GWF) and blue water footprint (BWF) in total crop land of a province can be calculated as similar to Eq. (15) ~ (17). Provincial water footprint, green water footprint and the blue water footprint of per kg wheat (WFP, GWFP and BWFP) in total farmland can be calculated based on results of WF, GWF and BWF.

3.4 Total water use (TWU)

The total water use (TWU) is a common and useful index in agricultural water utilization evaluation, especially for irrigation agriculture. TWU refers to the total amount of water invested in agricultural production consumed in terms of evapotranspiration and percolation (BW_p). BW_p, which can be calculated by Eq. (18), is the part of irrigation water infiltration into deep soil or groundwater mass that can neither be reused by crops during their growth stages, nor sever departments of social economy.

$$BW_p = IWC - BWF \tag{18}$$

Blue water footprint (BWF) of crop could not be satisfied if some more water withdrawal for percolation has not been supplied by the reservoir or the headwork of irrigation district. It is important for regional could be reduced by improving the quality of irrigation works. The TWU of wheat production in cropland of China can also be estimated by this study:

$$TWU = WF + BW_p \tag{19}$$

TWU, which reflects both the water productivity and irrigation efficiency, is the amount of water needed to produce wheat at the regional scale. It is associated with climate, crop variety and water diversion ability and the condition of irrigation engineering. WF is a part and also the most important part of TWU normally. The proportion of consumption water use in the TWU as a whole reflects the condition of agricultural water utilization and the regional water saving potential (Playan and Mateos, 2006; Cao et al. 2012, 2014). So it is meaningful to analyze the relationship between WF and TWU for the areas facing water scarcity.

4 Results and discussions

4.1 Water footprint (WF) and total water use (TWU)

4.1.1 From the total cropland perspective

The national WF and TWU of wheat production is about 111548.2 and 142520.3 Mm^3 respectively. Data and the spatial distribution of water use are shown in Table 1 and Fig.2 for the 30 provinces in Mainland China. The spatial difference of water footprint is obvious among all provinces of China in 2010. Provinces which hold large WF values are concentrated in the Huang-Huai-Hai Plain while the ones with low WF values mostly aggregate in the south of Yangtze River. Approximately 75.3% of wheat product and 70.0% of WF are contributed by the sub-region North China, contrastively 0.85% and 1.05% by Northeast. At provincial level, large WFs are estimated for Henan (25036.8 Mm^3), Shandong (18577.1 Mm^3), Anhui (12357.8 Mm^3), Hebei (10731.8 Mm^3), Jiangsu (10419.5 Mm^3) and Xinjiang (8913.7 Mm^3). These six provinces together contribute to 69.4% of the national total sown area, 80.0% of wheat production, and 77.1% of wheat production-related WF. Provinces with WF below 50 Mm^3 are Guangdong (3.2 Mm^3), Gaungxi (8.4 Mm^3), Jilin (15.4 Mm^3), Fujian (18.5 Mm^3), Jiangxi (27.1 Mm^3) and Liaoning (49.2 Mm^3), only 0.1% of the national when added together.

The national green water footprint (GWF) in wheat cultivation in 2010 is calculated to be 71629.7 Mm^3. The largest green water GWF is observed for Henan (16511.4 Mm^3), Shandong (11499.6 Mm^3), Anhui (8489.1 Mm^3), Jiangsu (6883.0 Mm^3) and Hebei (6867.3 Mm^3). These five provinces together account for 70.2% of the total blue water footprint related to wheat production. At sub-regional level, the largest and least blue water footprints can be found in North China (50735.2 Mm^3) and Northeast (894.4 Mm^3), respectively. The blue water footprint (BWF) related to wheat production is 39918.6 Mm^3 in the studied year. The largest blue water footprint in wheat cultivation process can also be found in Henan (8525.4 Mm^3), Shandong (7077.5 Mm^3), Xinjiang (5988.2 Mm^3), Anhui (3868.6 Mm^3), Hebei (3864.5 Mm^3) and Jiangsu (3536.5 Mm^3). These six provinces alone account for about 82.3% of the national blue water footprint related to wheat production. Provinces holding small amounts of green and blue water footprint in wheat production are Hunan, Liaoning, Jilin, Fujian, Jiangxi, Guangxi and Guangdong.

The estimated α in irrigation system of China is about 5.86%, and the provincial value ranges from about 3.00% in Xizang and Qinghai to 7.57% in Anhui (Table 1). China's blue water percolation (BW_p) is 30972.1 Mm^3, accounting about 43.7% of the total irrigation water (70890.7 Mm^3) invested in wheat production. Adding WF and BW_p together, the total water use (TWU) in the studied year is estimated to be 142520.3 Mm^3. Same to WF, large TWUs are found in Henan (32974.2 Mm^3), Shandong (2923.7 Mm^3), Anhui (15418.1 Mm^3), Hebei (14059.4Mm^3), Xinjiang (13527.1 Mm^3) and Jiangsu (10419.5 Mm^3). These six provinces alone account for about 78.2% of the national TWU related to wheat production. WF occupies the main part of TWU and the national WF proportion in TWU as a whole (P_w) is 78.3%. Provinces with a high P_w are located in southwest while ones with low P_w are concentrated in northwest of China (Fig. 2).

4.1.2 Distinguishing between irrigated and rain-fed crop

The irrigated farmland produces 80.4% of China's wheat in 2010. Table 2 demonstrates provincial and sub-regional wheat outputs, water footprint (WF) and total water use (TWU) in irrigated and rain-fed farmland. Fig.3 shows provincial WF-TWU relationship between irrigated farmland and total cropland. The irrigated and rain-fed WFs are 84365.1 and 27183.2 Mm^3, accounting for 75.6% and 24.4% respectively of the national WF. Irrigated land produces 84.3%, 73.4%, 62.6%, 58.4% and 53.7% wheat in North China, Northwest, Southeast, Southwest and Northeast, and contributes to 79.7%, 74.2%, 55.7%, 48.2% and 62.5% of WF respectively.

The provinces with large water footprint in irrigated land (WF_I) are Henan (19652.9 Mm^3), Shandong (14781.6 Mm^3), Anhui (9134.6Mm^3), Jiangsu (8975.7 Mm^3), Hebei (8822.0 Mm^3) and Xinjiang (8586.7 Mm^3). The sum of WF_I in these six provinces is up to 69953.5 Mm^3, accounting for 82.9% of the national WF of irrigated wheat. Large water footprint in rain-fed land (WF_R) can be found in Henan (5383.8 Mm^3), Shandong (3795.5 Mm^3), Anhui (3223.2 Mm^3), Shaanxi (2058.0 Mm^3), Hebei (1909.8 Mm^3), Sichuan (1830.7 Mm^3) and

Hubei (1785.7Mm^3). These seven provinces together account for 73.5% of the total water footprint related to rain-fed wheat. It is illustrated in Fig.3a that the proportions of WF_I (or WFR) in water footprint of total cropland are significantly different to each other between provinces. In general, the proportion of WF_I in WF in a province that has a large water footprint in total cropland is high. The proportions of WF_I in 6 provinces (including Henan, Shandong, Hebei, Beijing, Jiangsu, Tianjin and Xinjiang) all exceed the national level, with highest percentages up to 96.3% in Xinjiang. In contrast, the proportion is no more than 30.0% in the provinces, such as Guizhou (29.6%), Chongqing (29.0%) and Yunnan (19.3%).

The TWU is equal to WF for rain-fed crops; however, it is not the case for irrigated farmland. TWU for irrigated wheat (TWU_I) in 2010 is 115337.1 Mm^3, accounting for about 80.9% of TWU. The distribution pattern of provincial proportion of TWU_I in TWU as a whole in Fig.3b is quite similar to the proportion of WF_I in WF shown in Fig.3a. The gap of percentage of WF in TWU for the irrigated crop (Fig.3c) among provinces is very small. Most provinces (20) hold values ranging from 70.0% to 80.0% in Fig.3c.

4.2 Blue and green water composition of water footprint (WF) and total water use (TWU)

From the perspective of source of water resources, the provincial proportion of green water footprint (GWF) in WF in total cropland and the composition of TWU in irrigated land are shown in Fig.3. The spatial distribution pattern of green water proportions in both total cropland and irrigated farmland (not shown in figure) agrees with that of precipitation. GWF proportions go low for provinces in the North China Plain and northwest China, whereas they exceed 70.0% in most provinces in the south of the Yangtze River. The proportions of green and blue water footprints for wheat production in total cropland in 2010 are 64.2% and 35.8% respectively. The GWF proportion in Yunnan is 92.8%, ranking the highest among the 30 provinces as for the ratio of GWF to the WF. Other regions above 80.0% are Chongqing, Guizhou, Guangxi, Jiangxi and Hubei, with a value of 88.3, 88.1, 84.9, 84.6, and 82.3% respectively. The GWF proportions of Gansu, Tianjin, Xizang (Tibet), Ningxia and Xinjiang rank the lowest in China and the proportion in Xinjiang is only 32.8%.

The national proportion of green water footprint (GWF), blue water footprint (BWF) and blue water percolation (BW_p) in TWU for irrigated land is 38.5%, 34.6% and 26.9% respectively. GWF proportions in most (21) provinces are above national average and exceed 50.0% in 6 provinces, namely Yunnan (50.2%), Hubei (52.0%), Zhejiang (53.2%), Jiangxi (55.0%), Guangdong (55.6%) and Guangxi (55.7%). In contrast, provinces with low GWF proportions for irrigated wheat are Gansu (19.9%), Xinjiang (19.7%) and Ningxia (15.0%), none of the three greater than 20.0%. The irrigation water utilization coefficient (η) is 0.503 in irrigation system of China in the studied year, and the provincial values range from 0.424 (in Ningxia) to 0.678 (in Beijing). Several provinces that are characterized by the WF which contains a large share of BW_p in irrigated land are such as Ningxia (42.5%), Neimenggu (36.3%) and Xinjiang (34.9%). BWF_{CL} proportions of 21 provinces fall between 20.0% ~ 30.0%. With the highest irrigation efficiency, Beijing has a water wasting proportion for irrigated wheat that is lower than all studied provinces, only 16.7%.

4.3 Water footprint per kg of wheat (WFP)

4.3.1 WFP in total cropland

National average water footprint for per kg of wheat (WFP) in the year 2010 is estimated to be 0.968 $m^3 \cdot kg^{-1}$. The results (in Fig.5) show a great variation among provinces. Provinces in and around the Huang-Huai-Hai Plain are lower in WFP, while the provinces in the south of the Yangtze River and northwest China have lower water use efficiency. Only three provinces have their own WFPs below the national average, namely Shandong (0.902 $m^3 \cdot kg^{-1}$), Hebei (0.872 $m^3 \cdot kg^{-1}$), and Henan (0.812 $m^3 \cdot kg^{-1}$). These four provinces together produce 63.7 M t wheat, accumulatively contributing to 55.3% of the total output of China. Then rising harvest from the regions with low WFP is conducive to improving the water productivity (WP) of the country. On the other side of the spectrum, there are also provinces like Fujian, Yunnan and Xinjiang with WFP more than 1.500 $m^3 kg^{-1}$. Xinjiang is the 6th largest wheat producer of China in 2010, as well as one of the most promising and pressing regions demanding reduce in water footprint.

Apart from WFP variation, the spatial distribution of green water footprint for per kg of wheat (GWFP) and blue water footprint for per kg of wheat (BWFP) is also displayed in Fig. 5. Broadly speaking, the distribution patterns of GWFP and BWFP are opposite. In the sunny, hot and resources-adequate northwestern provinces, wheat is planted extensively in some areas despite the poor precipitation there. But still, a large amount of irrigation water diversion is needed for crops growth in these areas. In another case, some provinces in the Southwest (including Yunnan, Guizhou and Chongqing), with an average annual precipitation over 1500 mm, need almost no irrigation for wheat production. The climatic conditions in southeastern provinces, such as Hunan, Fujian and Guangdong, are similar to southwestern provinces. This mismatch of rainy seasons and growth period of wheat and the low yield lead to a relatively low GWFP and a high BWFP. The North China Plain is the winter wheat-intensive center of the country. Precipitation during the growth period of wheat in North China is around 300 mm and hence a substantial amount of irrigation water is demanded, so the BWFP is higher than those of southern provinces. Crop yield in provinces located in the plain is higher than any other regions, which mainly result in low WFPs in these provinces.

The calculated national WFP value in this study is compared with those reported in the literatures (Table 3). Since the WFP in the previous literatures is calculated at the field scale by assuming a sufficient irrigation, the water footprint (WF) and consumptive water use (ET) for per kg of wheat in circumstances of actual irrigation and sufficient irrigation are listed in the table. Hoekstra and Hung (2005) got a WFP about 0.690 $m^3 kg^{-1}$, which is much lower than the result in any other literatures. WFP of wheat in the period 1995-1999 should be higher because of low actual crop yield. WFP in this report is 0.968 $m^3 kg^{-1}$, which is lower than the value 1.266 $m^3 kg^{-1}$ in Liu et al. (2007a), 1.190 $m^3 kg^{-1}$ calculated by Zhang (2009) and 1.286 $m^3 kg^{-1}$ estimated by Mekonnen and Hoekstra (2010) while is approximate to the water footprint of wheat product estimated by Sun et al. (2013) and Liu et al. (2007c).

The national crop yield and field evapotranspiration (ET) for each study are also enumerated in Table 3 so as to make comparison clearly. National crop yield of wheat increased over time during the last two decades and reached up to 4748 tha^{-1} in our study year 2010. National crop water requirement (ET under sufficient irrigation) of wheat ranges between 430 ~ 510 mm except a value of 262 mm in Hoekstra and Hung (2005). It is quite normal that the calculated ET varies from year to year due to the different climatic conditions. The crop water requirement and actual ET of this study is about 461 and 443 mm, which are very close to Liu et al. (2007a), Liu et al. (2007c), and Zhang (2009). Distinguishing between crop cultivated in irrigated and rain-fed farmlands, Liu et al. (2007a) estimates the ET by using the grid-based GEPIC model. Liu et al. (2007c) reference a crop water requirement of average for many years before 1995 from Chen et al. (1995), and Zhang (2009) also references crop water requirement of average for many years from Liao (2005). In addition, the crop yield 4110 t ha^{-1} in Liu et al. (2007c) is the value average of Henan, Shandong, Hebei, Anhui and Jiangsu provinces, instead of the national average. Sun et al. (2012) and Mekonnen and Hoekstra (2010) get an ET exceeding 500 mm adopting a different approach. Similar to our study, Sun et al. (2012) also apply the CROPWAT model and climate data from the China Meteorological Data Sharing Service System (CMA), but are yet to distinguish between irrigated and rain-fed crops. Among these previous, only three studies have distinguished between green and blue water footprints. Proportions of green water at field scale in both this paper and Mekonnen and Hoekstra (2010) are around 65.0%. Our green water proportion in field ET, in both sufficient irrigation and actual irrigation conditions, are above 51.0% and 63.8%, the value from Sun et al. (2013) and Mekonnen and Hoekstra (2010). It is essential to discuss that the crops cultivated in the land equipped irrigation may not be irrigated crop. Many reasons, such as there is not enough water in the source and the irrigation facilities are deficient, may cause the insufficiency in irrigation. The gap between ET actual and potential ET without water stress of this study is around 18 mm, accounting for about 3.9% of the crop water requirement. The 18 mm could equate to 4474 M m^3 of consumption water use on the field scale. The national average of irrigation efficiency in study year is about 0.503. Meaning China's irrigation water deficit in the year 2010 is about 8900 Mm^3. On the other hand, the percolation loss of irrigation water during the transmission and distribution process is about 30972 M m^3, which is 3.5 times the irrigation water deficit. Irrigation water requirement could be totally met if the efficiency in irrigation system of China is enhanced by 13.0% (to 0.566). Raising irrigation efficiency is of great importance for the utilization of water resources.

A significant difference between our report and the literatures is the irrigation water sources. And based on the actual irrigation from typical irrigation districts, we estimate the gap between crop water requirement and actual field evapotranspiration. However, because of the actual agricultural data in irrigated land is affected by human factors, artificially influenced we estimate water use in crop production based on finite sample points. So the agricultural production data and weather data couldn't be processed by gridding or spatial interpolation but by weighted averaging. Our estimates of the water consumption and water footprint of wheat production are better than the earlier estimates as provided by Hoekstra and Hung (2005), Zhang (2009) and Sun et al. (2012), but it is also arguable to claim that they are more accurate than the results from the grid-based estimates as presented by Liu et al. (2007a,) and Mekonnen and Hoekstra (2010, 2011).

4.3.2 Comparison between rain-fed and irrigated WFPs and TWUPs

The calculated national average water footprint per kg of rain-fed wheat (WFP_R) is 1.202 $m^3 kg^{-1}$. The results (in Fig.6) show a great variation among 30 provinces. The highest WFP_R is found for Zhejiang, Fujian and Yunnan, with WFP_R values of 2.210, 2.374 and 2.623 $m^3 kg^{-1}$ respectively. On the other side of the spectrum, there are also provinces like Gansu, Ningxia, Jiangsu and Henan with wheat water footprint values around 0.900–1.100 $m^3 kg^{-1}$ in rain-fed farmland. The national average water footprint per kg of wheat in irrigated land (WFP_I) is 0.911 $m^3 kg^{-1}$, a little lower than WFP_R. WFP_I in Fujian is 1.658 $m^3 kg^{-1}$, ranking the highest among all provinces. Qinghai and Xinjiang also hold a value surpassing 1.400 $m^3 kg^{-1}$. WFP_I in other 22 provinces are above the national average. The lowest WFP_I is found in Henan (0.759 $m^3 kg^{-1}$), Hebei (0.818 $m^3 kg^{-1}$), Shanxi (0.842 $m^3 kg^{-1}$), Shandong (0.857 $m^3 kg^{-1}$), and Shaanxi (0.889 $m^3 kg^{-1}$), all of which are major wheat producing areas of China. The total water use per kg of wheat in rain-fed land ($TWUP_R$) is equal to WFP_R. Total water use for per kg of irrigated wheat ($TWUP_I$) of China is about 1.237 $m^3 kg^{-1}$, and provincial value ranges from 1.065 $m^3 kg^{-1}$ in Henan to 2.214 $m^3 kg^{-1}$ in Fujian.

As we know, crop yield under rain-fed situations will be enhanced if given irrigation, which is in particular the case for water-deficient areas. The calculated result based on statistical data shows that crop yield in irrigated land is 2.76 times the rain-fed wheat. While, irrigation does not always achieve both the water saving and production increasing goals. It is illustrated in Fig.6 that $TWUP_I$ and WFP_I are not equal to those in rain-fed land. $TWUP_I$ is higher than WFP_R in most provinces located in northern China, while it is the opposite in the south. In order to compare the crop yield and water footprint per kg of wheat between irrigated and rain-fed farmlands, four indexes QW, QF, QU and QY are defined as follows:

$$QW=ETP_I/ETP_R \tag{20}$$

$$QF=WFP_I/WFP_R \tag{21}$$

$$QU=TWUP_I/TWUP_R \tag{22}$$

$$QY=Y_I/Y_R \tag{23}$$

ETP_I, ETP_R are field evapotranspiration (ET) for per kg wheat product in irrigated and rain-fed lands, ETP_R= WFP_R. The meaning of other parameters in Eq. (20) ~ (23) has been explained in Section 3 and above. Calculated provincial results of QW, QF, QU and QY in 2010 are shown in Fig.7. The national QW, QF, QU and QY are 0.72, 0.76, 1.04, and 2.76, meaning that crop yield, field water productivity (WP_f), and total water use can be promoted by 176%, 39% and 4% while water footprint (WF) can be reduced by about 28.0% when wheat is irrigated. Irrigation helps achieve the dual benefit in yield-increasing and water-saving respects at the field scale in almost all of the provinces of China. Nevertheless, the estimated results from the water footprint perspective and based on regional scale show that, an extra 0.044 m^3 amount of water resources needs to be invested in irrigated land compared to water amount in rain-fed land for producing 1 kg of wheat product. Irrigation helps promote crop yield and reduce water footprint for per kg of product while increase total water use for China's wheat production. QW and QF in most of the 30 studied provinces are lower than 1, but it is not the case for QW. The provinces can be divided into three categories according to QU value: Ⅰ) QU < 0.900; Ⅱ) 0.900 < QU < 1.100 and Ⅲ) QU > 1.100. Provinces with low QU values, including Yunnan, Hunan, Jiangxi, Zhejiang, Shanghai and Guizhou, belong to Category Ⅰ; with QU values around 1.000, the 10 provinces, including Hebei, Shanxi, Chongqing, Fujian, Anhui, Guangxi, Henan Shandong, Hubei, and Shaanxi, belong to Category Ⅱ; and the remaining 14 fall into Category Ⅲ. QW and QF in all of the three categories are below 1.00, while QU in reaches up to 1.42 in Category Ⅲ.

The contributions to the country of the three categories for wheat output, sown area, WF, TWU and IWC are shown in Fig. 7. In addition, crop yield and TWU of per kg of wheat product for the three categories as well as QU and QY (including the values in total cropland, irrigated land and rain-fed land) are listed in Table 4.

Total water uses of per kg of product in irrigated ($TWUP_I$) and rain-fed ($TWUP_R$, WFP_R) farmlands of Category Ⅰ are 1.492 and 2.099 $m^3 kg^{-1}$ respectively, and the value of QU is 0.71. Irrigation saves water resources by 29% while promotes crop yield by 64% in this category. Water saving and production increasing targets can be achieved simultaneously through irrigation in these provinces. Category Ⅰ provinces should expand wheat acreage and irrigation area as far as water use efficiency is concerned. However, all the provinces of Category Ⅰ are located in southern China, where climatic conditions are not suitable for the cultivation of wheat but of rice. It is illustrated in Fig. 8 that wheat planting area and output of Category Ⅰ account for only 3.5% and 1.1% of the amounts nationally. This category contributes to 1.8% of water footprint, 1.6% of total water use and only 0.8% of irrigation water capacity to the whole country. So, reducing water investment of wheat production makes no sense in increasing the wheat yield or relieving the water resources pressure in China. Moreover, crop yield of this category is only 2.4 tha^{-1}, significantly lower than those of other regions. In a word, it is unrealistic to depend on these areas to produce more wheat product in China.

The calculated QY and QU are 2.83 and 0.96 in Category Ⅱ. Irrigation brings about a conspicuous increase in yield yet hardly reduces water footprint. This category which encompasses all of the major wheat-producing areas in North China Plain safeguards China's food security. In the year 2010, 68.7% of sown area, 74.7% of total output, and 69.4% of water footprint, 68.6% of total water use and 64.8% of irrigation water capacity of wheat production across the country are contributed by Category Ⅱ. WFP and TWUP in the category are 0.899 and 1.165 $m^3 kg^{-1}$, which are less than the national average. For this, producing more wheat in this category is instrumental to promoting the country's water use efficiency. In reality, however, with an annual per capita water resources volume at about 400 m^3, the North China Plain is one of the most water-deficient regions of China; plus water pollution is also a serious issue facing these provinces. Effective measures, such as adopting water-saving irrigation technology so as to promoting irrigation efficiency should be taken to protect agricultural production from the impact of water crisis.

QY in Category Ⅲ is 2.57, meaning crop yield could be promoted by 157% if wheat receives irrigation. The value of QU reaches up to 1.42 at the same time, indicating a plenty of water waste in the process of wheat production. This category contributes to 24.4% of output, 28.8% of water footprint, 29.8% of total water use and takes 34.4% of the irrigation water to China's total. Provinces with high QY and QU values belong to Category Ⅲ and are located in droughty northwest China, whereby massive irrigation water is demanded to withdraw due to scarce rainfall. In the meantime, the irrigation efficiency is low (no more than 0.500), resulting in a large amount of water wastage in irrigated farmland. With these two drawbacks, this category is not suitable for producing irrigated wheat as far as water efficiency is concerned. In spite of that, it is still essential for China's food security since a few advantages are noticeable. The climatic condition with sufficient sunlight and heat is conducive to crop growth, and the provinces in Category Ⅲ sum up to produce nearly 1/4 (24.2%) of the national wheat production. On the other hand, figures of total water use per kg of wheat in total farmland and irrigated farmland are 1.522 and 1.618 $m^3 kg^{-1}$ (Table 4), both being much higher than those of Category Ⅱ and the national average. Proportions of blue water use for percolation in some provinces of Category Ⅱ, are very high, such as in Ningxia (42.5%), Neimenggu (36.3%), Xinjiang (34.9%), and Qinghai (31.7%). These high WPF and BW_p proportions signify a great water saving potential. In this regard, irrigation efficiency should be improved further and blue water footprints be reduced, so as to achieve water-saving and production promoting objectives simultaneously.

5 Conclusions

Studies on crop water footprint at a macroscale (global or national) suffer from the limitations in terms of data availability and quality frequently. By distinguishing between the irrigated and rain-fed crop, the contribution of this work is the utilization of the actual statistical data from typical irrigation districts, and also the calculation of crop water footprint and total water use at regional scale. The major findings of the current study are that: (i) the green water related to China's wheat production plays a dominant role in water footprint while it is roughly equal to the blue in total water use, (ii) a large amount of water footprint is depleted in delivery process and could not be reused during the crop growth period, and (iii) irrigation promotes crop yield and reduces water footprint for per kg of wheat product dramatically, yet it also means more water resources needs to be invested into crop production, which leads to that total water for per unit of irrigated wheat becomes higher than that of rain-fed crop. It is meaningful to compare water productivity (water use for per unit product) between irrigated and rain-fed farmlands only when the water utilization is assessed at regional scale.

The study agrees with earlier studies in the importance of green water in China's wheat production, especially for the field evapotranspiration (consumption water use). It is observed that, compared to rain-fed crop, obtaining the double benefits of promoting yield and saving water in irrigated land is an unattainable objective for some arid provinces. The calculated result is compared with measured water productivity and virtual water values introduced in the literature of previous studies. It appears difficult to attribute difference in estimates from various studies to specific factors and it is also difficult to assess the quality of our new estimates relative to the quality of earlier estimates. The authenticity of data defines the accuracy of the water footprint calculation result. In this study, we have collected a large amount of data about agricultural production and tried to work out a water footprint value as closest to the actual situation as possible. An unavoidable drawback of this report is that the water footprint we have estimated is just for the representative year. Decision making needs long-term serial historic data sets of reality and high quality. Database about agricultural production should be built by the government in cooperation with scientific and technological workers in future.

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Table 1. Water use of wheat production for the 30 provinces of China in 2010.

Sub-region	Province	Contribution (%)	Yield (kgha^{-1})	α (%)	BWF (Mm^{3}yr^{-1})	GWF (Mm^{3}yr^{-1})	WF (Mm^{3}yr^{-1})	BW_p (Mm^{3}yr^{-1})	TWU (Mm^{3}yr^{-1})
North China	Henan	26.760	5838	5.34	8525.4	16511.4	25036.8	7937.4	32974.2
	Shandong	17.873	5780	6.02	7077.5	11499.6	18577.1	4346.6	22923.7
	Anhui	10.476	5101	7.57	3868.6	8489.1	12357.8	3060.4	15418.1
	Hebei	10.684	5085	6.09	3864.5	6867.3	10731.8	3327.6	14059.4
	Jiangsu	8.752	4816	4.87	3536.5	6883.0	10419.5	2195.0	12614.5
	Tianjin	0.462	4814	5.00	305.1	301.0	606.0	171.7	777.8
	Beijing	0.246	4610	5.00	152.5	183.8	336.3	57.1	393.4
Northeast	Heilongjiang	0.803	3303	3.85	250.2	852.1	1102.2	195.2	1297.4
	Liaoning	0.032	4933	4.89	17.4	31.8	49.2	10.1	59.3
	Jilin	0.011	3473	3.77	4.9	10.5	15.4	3.1	18.4
Northwest	Xinjiang	5.413	5567	6.59	5988.2	2925.5	8913.7	4613.4	13527.1
	Shaanxi	3.506	3515	5.66	825.5	3162.1	3987.6	558.0	4545.7
	Gansu	2.178	2852	4.34	1333.3	1484.8	2818.1	745.8	3563.9
	Shanxi	2.016	3188	4.79	636.8	1701.3	2338.1	593.3	2931.4
	Neimenggu	1.435	2918	6.65	564.3	1377.1	1941.5	685.3	2626.8
	Ningxia	0.611	3327	7.54	361.8	340.3	702.0	362.6	1064.6
	Qinghai	0.324	3693	3.00	244.4	288.8	533.2	184.7	717.9
Southeast	Hubei	2.979	3430	5.79	665.0	3094.2	3759.2	543.1	4302.3
	Zhejiang	0.214	3730	4.79	74.1	247.5	321.6	58.2	379.9
	Shanghai	0.167	3897	5.00	88.1	135.1	223.2	56.5	279.7
	Hunan	0.086	2526	4.13	28.4	87.5	115.9	28.2	144.1
	Jiangxi	0.018	2031	4.06	4.2	23.0	27.1	4.7	31.8
	Fujain	0.009	2840	3.85	4.7	13.9	18.5	4.4	22.9
	Guangdong	0.002	2826	5.00	0.7	2.5	3.2	0.7	3.9
Southwest	Sichuan	3.713	3379	4.88	1192.4	3236.9	4429.3	999.2	5428.5
	Yunnan	0.399	1072	4.77	69.5	890.6	960.1	45.8	1005.8
	Chongqing	0.399	3051	4.55	66.1	497.7	563.8	55.6	619.4
	Guizhou	0.216	952	3.53	48.8	361.8	410.6	43.0	453.6
	Xizang	0.211	5160	3.00	118.5	122.4	240.9	84.1	325.0
	Guangxi	0.005	1357	4.29	1.3	7.1	8.4	1.3	9.7
China		100	4748	5.86	39918.6	71629.7	111548.2	30972.1	142520.3

Table 2. Provincial water footprint of wheat production in irrigated and rain-fed farmlands.

Sub-region	province	Irrigated					Rain-fed	
		Output (10^3t)	BWF_e ($Mm^3 yr^{-1}$)	BWF_f ($Mm^3 yr^{-1}$)	GWF_I ($Mm^3 yr^{-1}$)	WF_I ($Mm^3 yr^{-1}$)	Output (10^3t)	WF_R ($Mm^3 yr^{-1}$)
North China	Henan	2590.8	878.4	7647.0	11127.5	19652.9	491.5	5383.8
	Shandong	1725.6	688.2	6389.3	7704.1	14781.6	333.0	3795.5
	Anhui	965.2	524.4	3344.2	5266.0	9134.6	241.5	3223.2
	Hebei	1077.9	437.9	3426.6	4957.5	8822.0	152.8	1909.8
	Jiangsu	873.4	279.1	3257.4	5439.2	8975.7	134.7	1443.8
	Tianjin	49.7	23.8	281.2	256.3	561.4	3.5	44.6
	Beijing	24.3	10.5	142.0	132.8	285.3	4.1	51.0
Northeast	Heilongjiang	49.0	17.2	233.0	334.2	584.4	43.5	517.8
	Liaoning	2.6	1.3	16.0	17.9	35.3	1.1	13.9
	Jilin	0.7	0.3	4.6	4.7	9.6	0.5	5.8
Northwest	Xinjiang	605.3	698.9	5289.3	2598.5	8586.7	18.1	327.0
	Shaanxi	217.0	78.3	747.3	1104.1	1929.6	186.8	2058.0
	Gansu	150.0	90.2	1243.1	515.5	1848.9	100.9	969.2
	Shanxi	156.8	58.9	577.9	682.6	1319.4	75.5	1018.8
	Neimenggu	108.7	83.1	481.3	637.4	1201.8	56.6	739.7
	Ningxia	50.3	54.6	307.2	127.8	489.6	20.0	212.5
	Qinghai	27.1	12.9	231.5	153.9	398.2	10.1	134.9
Southeast	Hubei	202.3	70.0	595.0	1308.5	1973.5	140.8	1785.7
	Zhejiang	20.3	6.3	67.8	150.7	224.8	4.4	96.8
	Shanghai	17.5	7.2	80.9	99.8	187.9	1.7	35.3
	Hunan	8.0	2.3	26.1	46.4	74.8	1.9	41.1
	Jiangxi	1.5	0.4	3.8	10.9	15.0	0.6	12.1
	Fujain	0.8	0.3	4.3	8.5	13.1	0.2	5.4
	Guangdong	0.2	0.1	0.7	1.8	2.5	0.1	0.8
Southwest	Sichuan	269.1	107.0	1085.4	1406.1	2598.5	158.6	1830.7
	Yunnan	16.5	5.5	64.0	116.2	185.7	29.5	774.4
	Chongqing	17.0	5.5	60.6	97.4	163.5	28.9	400.3
	Guizhou	10.3	3.2	45.6	72.8	121.6	14.5	289.0
	Xizang	19.0	6.1	112.4	64.0	182.5	5.3	58.4
	Guangxi	0.3	0.1	1.2	3.2	4.5	0.2	3.9
China		9257.3	4152.1	35766.5	44446.5	84365.1	2260.8	27183.2

Table 3. Documented results for WFP of wheat production in China.

Reference	Year/period	WFP ($m^3 kg^{-1}$)	Crop yield (tha^{-1})	Field ET (mm)	Proportion of green water
This study	2010	0.968	4748	-	64.2%
		1.007[1]		-	-
		0.932 (ETP)		443	66.7%
		0.971 (ETP[1])		461	64.1%
Sun et al. (2012)	2009	1.071	4739	508	51.0%
Liu et al. (2007a)	2000	1.266	3738	473	-
Liu et al. (2007c)	1999-2001	0.975	4110	430	-
Zhang (2009)	1997-2007	1.190	4065	484	-
Mekonnen and Hoekstra (2010)	1996-2005	1.286	3925	505	63.8%
Hoekstra and Hung (2005)	1995-1999	0.690	3802	262	-

[1]: Assumed a sufficient irrigation

Table 4. Crop yield and total water use of per kg wheat product for three categories.

Category	Crop yield ($t ha^{-1}$)			QY	Total water use of per kg product ($m^3 kg^{-1}$)			QU
	Total cropland (Y)	Irrigated (Y_I)	Rain-fed (Y_R)		Total cropland (TWUP)	Irrigated ($TWUP_I$)	Rain-fed (TWU_R)	
Category Ⅰ	2.4	2.8	1.7	1.64	1.762	1.492	2.099	0.71
Category Ⅱ	4.9	6.8	2.4	2.83	1.165	1.155	1.208	0.96
Category Ⅲ	4.1	5.4	2.1	2.57	1.522	1.618	1.140	1.42
China	4.7	6.4	2.3	2.76	1.237	1.246	1.202	1.04

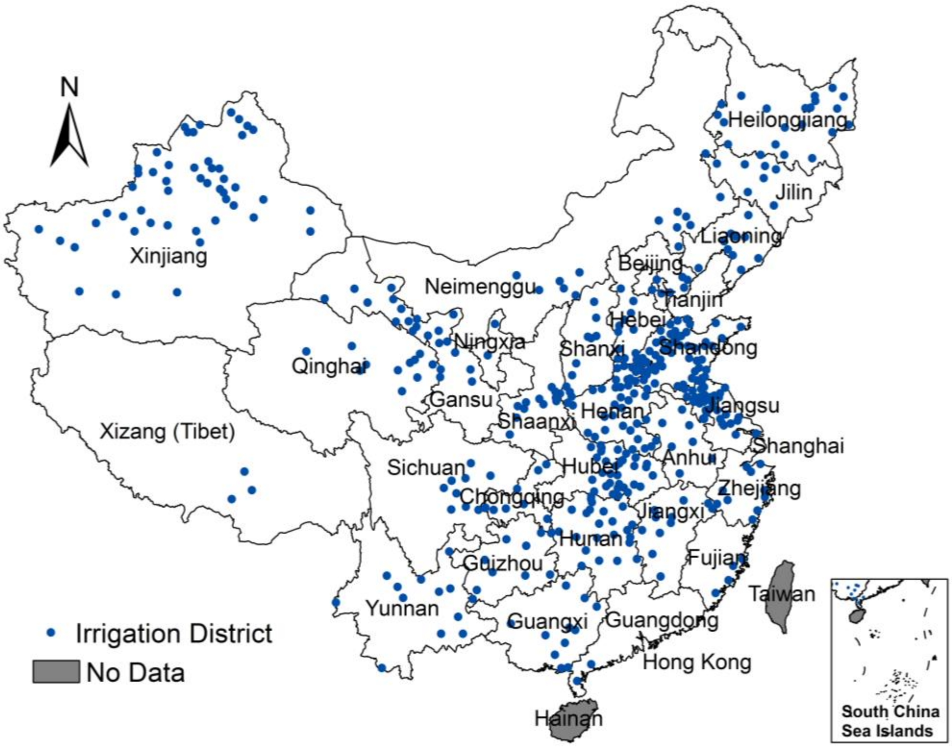

Fig. 1. Distribution of 442 irrigation districts in 30 provinces investigated in China.

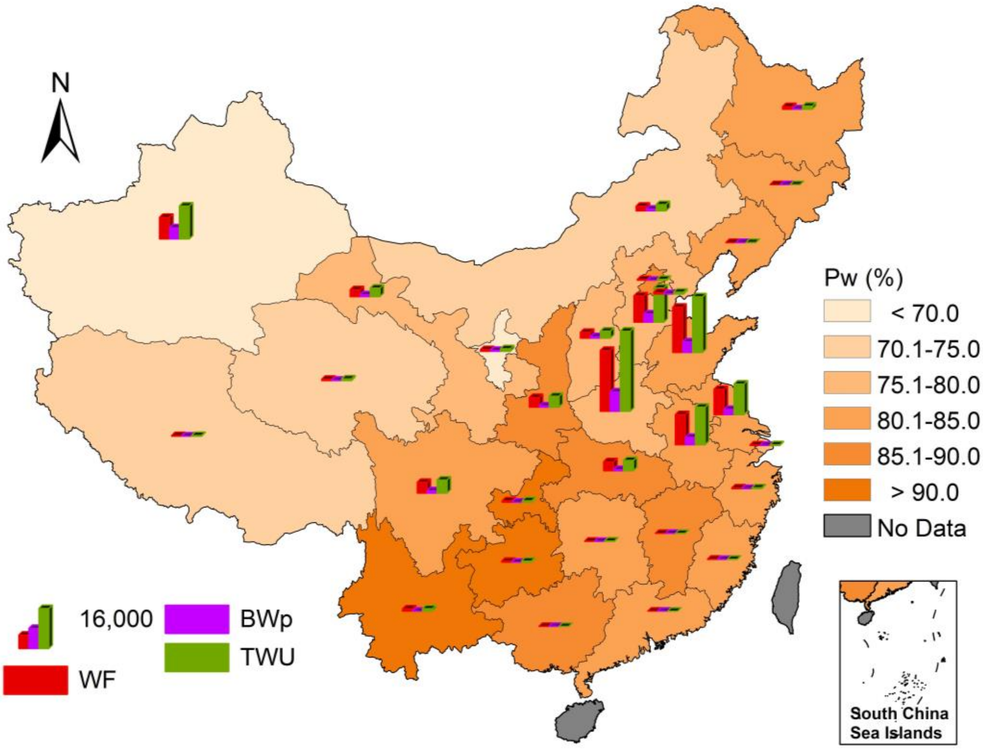

Fig. 2. Provincial amount of water use for wheat production in China in 2010.

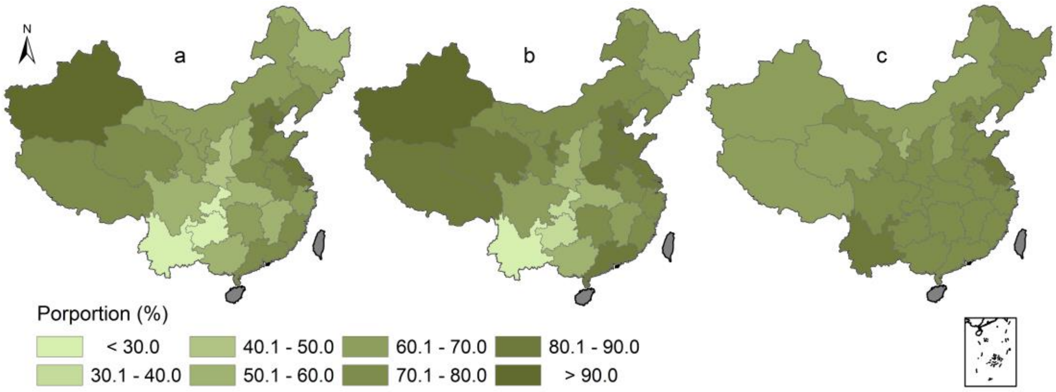

Fig. 3. Proportions of water use in in irrigated land in China, including (a) proportion of WFI in WF, (b) proportion of TWUI in TWU, and (c) proportion of WF in TWU for irrigated crop (WFI/TWUI).

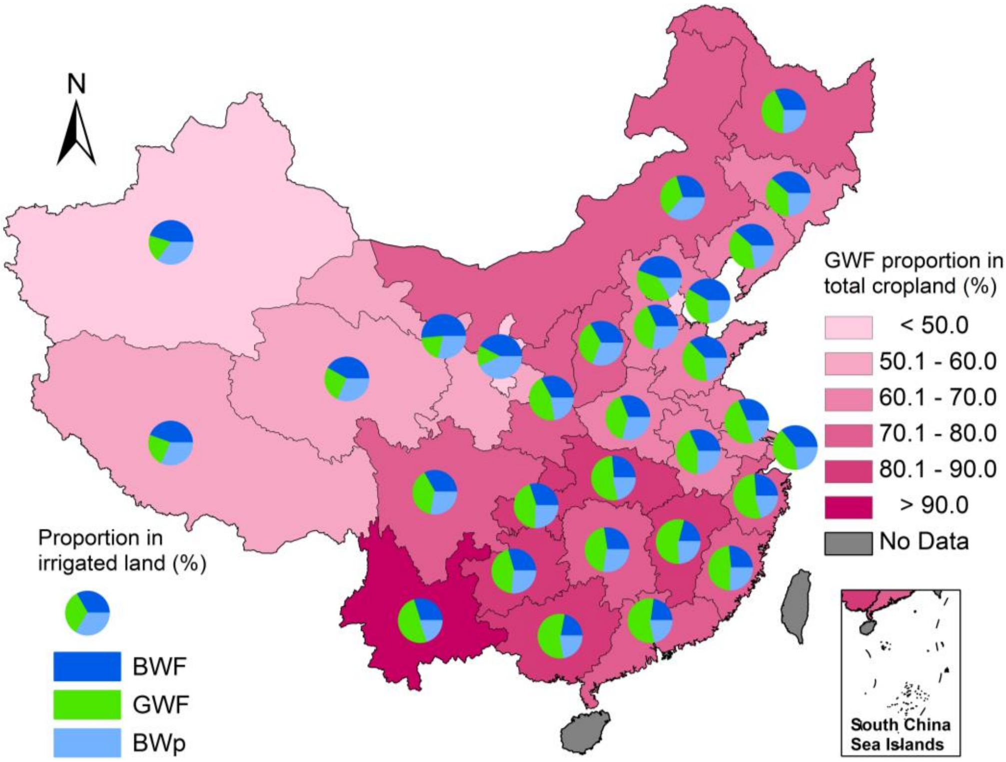

Fig. 4. Proportion of GWF (Green water footprint) in total crop land and composition of TWU (Total water use) in irrigated land in China.

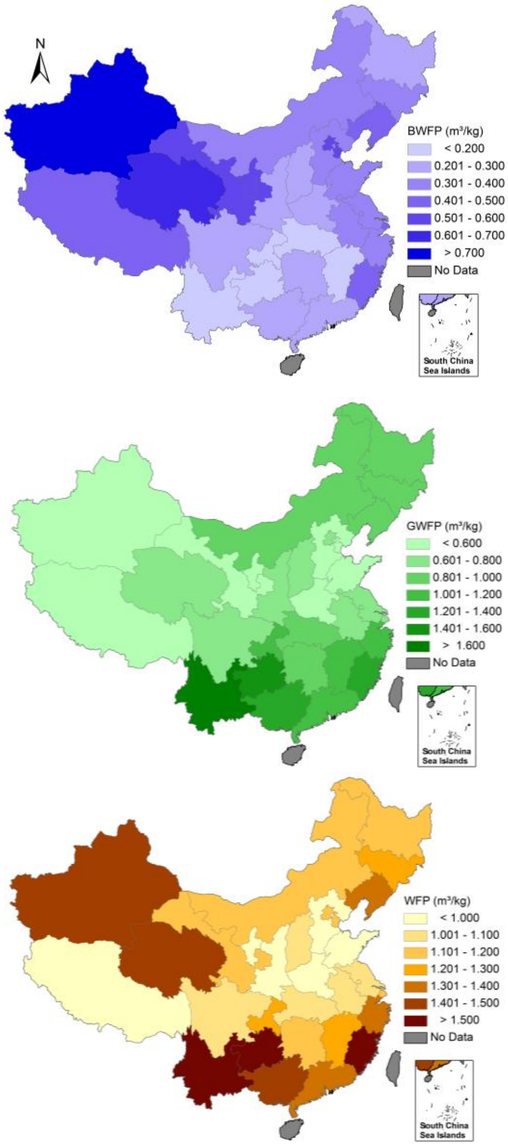

Fig.5. The blue, green, and total water footprint for per kg of wheat product in China.

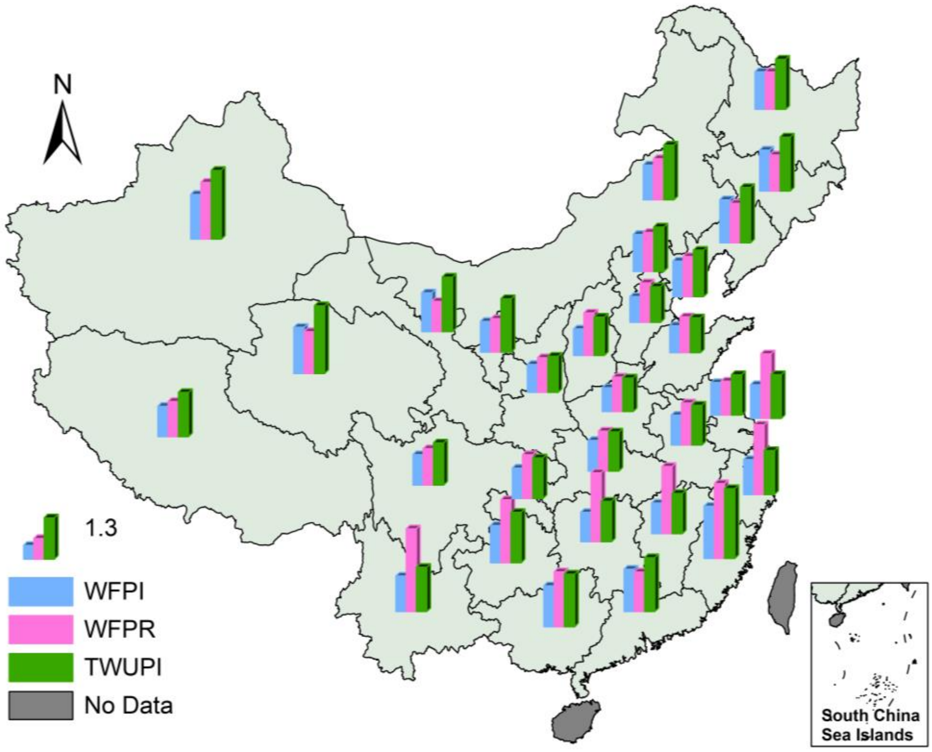

Fig.6. Water footprint and total water use per kg of wheat product in irrigated and rain-fed lands in China.

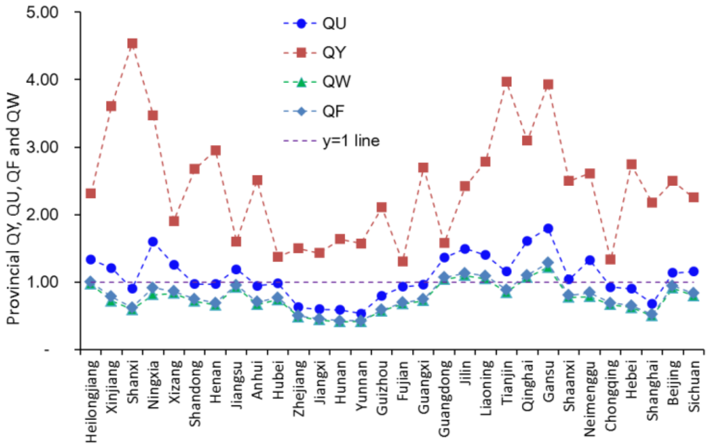

Fig.7 Provincial value of QU, QW, QY and QF in 2010

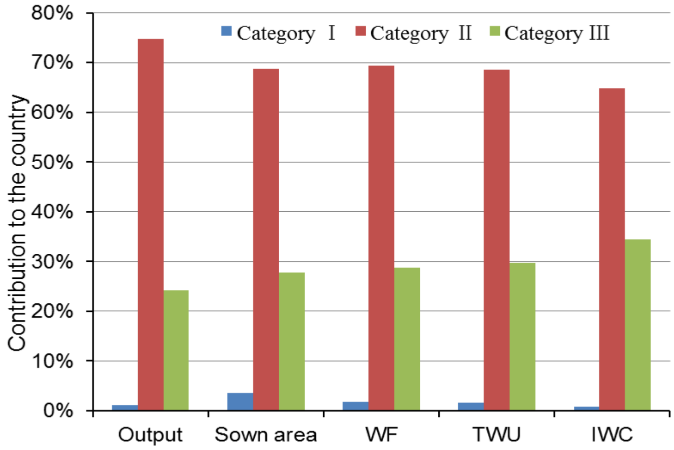

Fig.8. Contributions of three categories to wheat production indicators.