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Discussions

Assessing water footprint of wheat production in China using a crop-model-coupled-statistics approach

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Abstract

The aim of this study is to estimate the green and blue water footprint of wheat, distinguishing the irrigated and rain-fed crop, from a production perspective. The assessment herein focuses on China and improves upon earlier research by taking a crop-model-coupled-statistics approach to estimate the water footprint of the crop in 30 provinces. We have calculated the water footprint at regional scale based on the actual data collected from 442 typical irrigation districts. Crop evapotranspiration and the water conveyance loss are both considered in calculating irrigated water footprint at the regional scale. We have also compared water footprint of per unit product between irrigated and rain-fed crops and analyzed the relationship between promoting yield and saving water resources.

The national wheat production in the year 2010 takes about 142.5 billion cubic meters of water. The major portion of WF (80.9 %) comes from the irrigated farmland and the remaining 19.1 % falls into the rain-fed. Green water (50.3 %) and blue water (49.7 %) carry almost equal shares of water footprint (WF) in total cropland WF. Green water dominates the south of the Yangtze River, whereas low green water proportions relate themselves to the provinces located in the north China especially northwest China. Approximately 38.5 % of the water footprint related to the production of wheat is not consumed in the form of crop evapotranspiration but of conveyance loss during irrigation process. Proportions of blue water for conveyance loss (BW_{CL}) in the arid Xinjiang, Ningxia and Neimenggu (Inner Mongolia) exceed 40 % due to low irrigation efficiency.

The national average water footprint of wheat per unit of crop (WFP) is 1.237 $m^3\,kg^{-1}$ in 2010. There exists a big difference in WFP among provinces. Compared to the rain-fed cultivation (with no irrigation), irrigation has promoted crop yield, both provincially and up by about 170 % nationally. As a result, more water resources are demanded in irrigated farmland for per kg of wheat production. WFP for irrigated (WFP_I) and rain-fed (WFP_R) crops are 1.246 and 1.202 $m^3\,kg^{-1}$ respectively. We have divided the 30

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provinces into three categories according to the relation between WFP_I and WFP_R: (I) $WFP_I < WFP_R$, (II) WFP_I is equivalent to WFP_R, and (III) $WFP_I > WFP_R$. Category II, which contains major wheat producing areas in the North China Plain, contribute nearly 75 % of wheat production to the country. Provinces belonging to Category III have to invest 0.478 cubic meters of water in order to harvest 1 kg wheat product. Double benefits of saving water and promoting production can be achieved substantially by irrigating wheat in Category I provinces. Nevertheless, provinces in this category, which should have contributed more, are summed to produce only 1.1 % of the national wheat production.

1 Introduction

China is not only the most populous and the largest food consuming country, but also one of the countries poorest in water resources per capita, 2100 m^3 in 2010 (MWR, 2011), which is 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 above 60 % of the total water (blue water) withdrawals (MWR, 2011). At present, due to bottleneck in technology and management, agricultural irrigation water is used low-efficiently and wasted seriously. It is meaningful to reduce the water use in agriculture for meeting freshwater challenges facing China in the future (Wu et al., 2010).

The "water footprint" introduced by Hoekstra (2003), offers a new approach for assessing water resources utilization in the agricultural production process. The water footprint of a crop product is defined as the volume of freshwater consumed during the crop production process, and normally it has two components: green water footprint (the volume of rainwater consumed in crop production) and blue water footprint (the volume of surface or ground water consumed in crop production) (Hoekstra et al.,

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2011). Water footprint of crop product is measured in two ways usually: total water footprint in a specific region (in m^3) and water footprint of unit mass of product (in $m^3\,kg^{-1}$ or $m^3\,t^{-1}$) (Hoekstra et al., 2011). The total water footprint links itself directly to water resources availability, and the green and blue water footprint of unit production reflects regional water productivity and irrigation efficiency.

In this paper, we focus on the water footprint of wheat, which is one of the three most important grain crops in China. The sown area of wheat was about 24.26 million ha in 2010, and harvested 115.18 million t of product, contributing about 17.8 % to the world's production (NBSC, 2011). Wheat can be subdivided into spring and winter wheat based on the growing period. Winter wheat is planted in most provinces of China while spring wheat is mainly cultivated in Heilongjiang, Neimenggu, Qinghai, Ningxia and Xinjiang. A number of fruitful studies have already been conducted in 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 between 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 around 2000 by using a GIS-based EPIC model. Gerbens et al. (2009) and Aldaya et al. (2010) have estimated the WF of wheat and analyzed the green and blue water components for major 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 et al. (2010) made a global and high-resolution assessment of the green, blue and grey water footprint of wheat at a 5 by 5 arcmin grid by taking a high-resolution approach. Meanwhile, quite a few scholars have been dedicated to studies on water footprint of China's wheat production. Liu et al. (2007b, c) simulated the national blue and green water footprint of winter wheat with the aid of GEPIC model. Zhang (2009) and Sun et al. (2012)

calculated the provincial water footprint of per kg wheat product for the period 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 main breadbasket basins by taking the life cycle assessment (LCA) approach. Based on the evapotranspiration (ET) calculating by CROPWAT model, Tian et al. (2013) analyzed the temporal variation of water footprint of China's major food crops from 1978 to 2010. And Sun et al. (2013) assessed the water footprint of grain crops, including spring wheat, and also illustrated the temporal variation, for an irrigation district on a regional scale.

While these studies have promoted the development of the water footprint theory, however, almost all of them only calculated water use at field scale. Their quantization methods have yet to take into account the irrigation water losses during the transport process from water source to cropland. Consequently, they failed to reflect the actual water consumption and water use efficiency in irrigation system. The aim of this report 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 a crop-model-coupled-statistics approach that takes into account the actual water use by agricultural production at regional scale. The water conveyance loss (CL) is included in water footprint calculating 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 and water footprint in each province are explored in this study as well.

2 Data description

The water footprint of wheat in irrigated and rain-fed farmlands of China is calculated using a crop-model-coupled-statistics approach. The elements needed are

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consolidated, which include 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 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 actual irrigation water capacity (IWC, the gross irrigation water diversion), crop yield, irrigation water utilization coefficient (η) and irrigated area from the administration bureau of 442 irrigation districts in 30 provinces (Fig. 1) were collected in this study.

2.3 Agricultural data in total crop land

The climate data (2011) from 517 weather stations in 30 provinces of China were used here were 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 from the China statistical yearbook

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2011 (NBSC, 2011). Crop planting and harvesting dates of 180 agricultural observation stations were obtained from Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences (IFI, CAAS). The crop coefficient (K_c) of wheat can be referenced to Chen et al. (1995) and Duan et al. (2004).

3 Methods

Blue and green water footprint of wheat is evaluated in this study. Both of blue 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 cropland are estimated separately, and then the 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 as 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 are calculated, and then, the WFP in irrigated farmlands of every province is estimated by using the weighted average method.

3.1.1 Green water (GW)

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

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

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:

$$GW = Min(ET_c, P_e) \quad (2)$$

and

$$ET_c = K_c \times ET_0 \quad (3)$$

where, K_c is the crop coefficient, dimensionless; ET_0 the reference crop evapotranspiration calculated by FAO CROPWAT 8.0 Model, in mm.

3.1.2 Blue water (BW)

The amount of blue water of wheat in irrigated land is obtained by mutual check between the crop irrigation water requirement (IWR) calculated by Eq. (4) and irrigation water capacity (IWC) surveyed by the administration bureaus of the studied irrigation districts.

$$IWR = ET_c - P_e \quad (4)$$

There are two consumption pathways of IWC from the regional perspective, the field evapotranspiration (IWC_{ET}) and the conveyance loss (IWC_{CL}). So, the blue water (BW) and blue water footprint of per unit wheat product (BWFP) can be divided into two parts for each irrigation district: BW_{ET} (also called $ET_{irrigation}$), BW_{CL}; blue water footprint of per kg wheat product for evapotranspiration ($BWFP_{ET}$), blue water footprint of per kg

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wheat product for conveyance loss ($BWFP_{CL}$). BW_{CL} (or $BWFP_{CL}$) are not needed for the crop grown; in other words, it can be saved through the improvements in technology. The calculation process of BW in an irrigation district is as follows:

If $\eta \times IWC > IWR$, then:

$$BW_{ET} = IWR \tag{5}$$

$$BW = \frac{IWR}{\eta} \tag{6}$$

$$BW_{CL} = \frac{(1-\eta) \times IWR}{\eta}. \tag{7}$$

If $\eta \times IWC < IWR$, then:

$$BW_{ET} = \eta \times IWC \tag{8}$$

$$BW = IWC \tag{9}$$

$$BW_{CL} = (1-\eta) \times IWC \tag{10}$$

where, η is the irrigation water utilization coefficient, dimensionless.

It is important to note that some water lost in conveyance might be re-used by crop via groundwater well or consumed by natural vegetation in the arid area. So the calculated BW_{CL} may slightly higher than actual performance theoretically. While the re-used or vegetation consumed part is generally small and should not influence our research findings greatly due to the deep underground water level in most areas of China.

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

$$WFP_{ID} = \frac{GW + BW}{Y_{ID}} = GWFP_{ID} + BWFP_{ID} \tag{11}$$

$$BWFP_{ID} = BWFP_{ID,ET} + BWFP_{ID,CL} \tag{12}$$

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

$$WFP_I = \frac{\sum \left(WFP^i_{ID} \times A^i\right)}{\sum A^i} \quad (13)$$

where, WFP^i_{ID} 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, blue water footprint, blue water footprint for evapotranspiration, blue water footprint for conveyance loss of per kg wheat product, and the crop yield in irrigated farmland (GWF_I, $BWFP_I$, $BWF_{I,ET}$, $BWF_{I,CL}$ and Y_I) can also be calculated by using a method similar to Eq. (13).

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

For rain-fed crops, WF is derived all from green water. The calculation of green water (GW) in rain-fed cropland of a province can reference to Eqs. (1)–(4). Then the water footprint of per kg wheat product in rain-fed farmland (WFP_R) of a province is calculated as follows:

$$WFP_R = \frac{GW}{Y_R}. \quad (14)$$

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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. (15):

$$Y_R = \frac{O_T - Y_I \times A_I}{A_R} \quad (15)$$

$$A_R = A - A_I \quad (16)$$

where, O_T is the provincial total output of wheat product, in t; Y_I the crop yield in irrigated farmland, t ha^{-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:

$$\text{WF} = \text{WF}_I + \text{WF}_R \quad (17)$$

$$\text{WF}_I = \text{WF}_I \times Y_I \times A_I \quad (18)$$

$$\text{WF}_R = \text{WFP}_R \times Y_R \times A_R \quad (19)$$

where, WF_I and WF_R are the water footprint of wheat in irrigated farmland and rain-fed farmland respectively, in $10^6\,\text{m}^3$; Y_I and Y_R the crop yield in irrigated and rain-fed farmland, t ha^{-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 Eqs. (17)–(19).

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. The consumptive water use (CWU) refers to the total amount of water consumed by crop in terms of evapotranspiration (Liu and Yang, 2010). Then the CWU of wheat in total cropland of China can also be estimated by this study:

$$CWU = WF_R + BWF_{I,ET} + GWF_I. \quad (20)$$

CWU is the amount of water needed to produce wheat at the field scale. It is associated with climate, crop variety and water diversion ability and it is indispensable for crop growth (Liu and Yang, 2010; Liu et al., 2013). The proportion of CWU in the WF as a whole reflects the condition of agricultural water utilization and the regional water saving potential (Cao et al., 2012). So it is important to analyze the proportion of CWU for the areas facing water scarcity.

4 Results and discussions

4.1 Water footprint (WF) of wheat production

The national WF of wheat production is about 142 520.3 Mm^3. Data and the spatial distribution of WF is 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. 75.3 % of wheat product and 69.6 % of WF are contributed by the sub-region North China, contrastively 0.85 and 0.96 % by Northeast. At provincial level, large WFs are estimated for Henan (32 974.2 Mm^3), Shandong (22 923.7 Mm^3), Anhui (15 418.1 Mm^3), Hebei (14 059.4 Mm^3), Xinjiang (13 527.1 Mm^3) and Jiangsu (12 614.5 Mm^3). These six provinces accumulatively contribute to 69.4 % of the national total sown area, 80.0 % of wheat production, and 78.3 % of wheat production-related WF. Provinces with WF below 100 Mm^3 are Guangdong (3.9 Mm^3), Gaungxi (9.7 Mm^3), Jilin (18.4 Mm^3), Fujian (22.9 Mm^3), Jiangxi (31.8 Mm^3) and Liaoning (59.3 Mm^3), only 0.1 % of the national when added together.

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The national green water footprint (GWF) in wheat cultivation in 2010 is calculated to be 71 629.7 Mm^3. The largest green water GWF is observed for Henan (16 511.4 Mm^3), Shandong (11 499.6 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 green water footprint related to wheat production. At sub-regional level, the largest and least blue water footprints can be found in North China (50 735.2 Mm^3) and Northeast (894.4 Mm^3), respectively. The blue water footprint (BWF) related to wheat production is 70 890.6 Mm^3 in the studied year. The largest blue water withdrawals in wheat cultivation process can also be found in Henan (16 462.8 Mm^3), Shandong (11 424.1 Mm^3), Xinjiang (10 601.6 Mm^3), Hebei (7192.1 Mm^3), Anhui (6929.0 Mm^3) and Jiangsu (5731.5 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 Jilin, Liaoning, Guangxi, Jiangxi, Hunan, Guangdong, Shanghai and Fujian.

The irrigated farmland produces 80.4 % of China's wheat in 2010. Table 2 demonstrates provincial and sub-regional wheat output and water footprint (WF) in irrigated and rain-fed farmland. The irrigated and rain-fed WFs are 115 337.1 and 27 183.2 Mm^3, accounting for 80.9 and 19.1 % 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 84.0, 81.2, 61.7, 57.2 and 60.9 % to WF respectively.

The provinces with large water footprint in irrigated land (WF_I) are Henan (16 462.8 Mm^3), Shandong (11 424.1 Mm^3), Xinjiang (10 601.6 Mm^3), Hebei (7192.1 Mm^3), Anhui (6929.0 Mm^3) and Jiangsu (5731.5 Mm^3). The sum of WP_I in these six provinces accounts for 82.7 % 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 (1785.7 Mm^3). These seven provinces together

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account for 73.5 % of the total water footprint related to rain-fed wheat. It is illustrated in Fig. 2 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 a province that has a large water footprint in total cropland is high. The proportions of WF_I in 12 provinces (including Xinjiang, Tianjin, Jiangsu, Shanghai, Beijing, Hebei, Henan, Shandong, Xizang, Qinghai, Guangdong and Ningxia) all exceed 80.0 %, with highest percentages up to 94.3 and 97.6 % in Tianjin and Xinjiang. In contrast, the proportion is no more than 40.0 % in the provinces, such as Guizhou (36.3 %), Chongqing (35.4 %) and Yunnan (23.0 %).

4.2 Composition and spatial distribution of water footprint (WF)

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 WF in irrigated land are shown in Fig. 3. The spatial distribution pattern of green water proportions in both total cropland and irrigated farmland agrees with that of precipitation. Low GWF proportions go for provinces in the North China Plain and northwest China, whereas it exceeded 50.0 % in most provinces in the south of the Yangtze River. The proportions of green and blue water footprint for wheat production in total cropland in 2010 are 50.3 and 49.7 % respectively. The green water footprint (GWF) proportion in Yunnan is 88.5 %, ranking the highest among the 30 provinces as for the ratio of GWF to the WF. Another region above 80.0 % is Chongqing, with a value of 80.3 %. The GWF proportions of Gansu, Qinghai, Tianjin, Xizang (Tibet), Ningxia and Xinjiang rank the lowest in China and the proportion in Xinjiang is only 21.6 %.

The national proportion of green water footprint (GWF), blue water footprint for evapotranspiration (BWF for ET, BWF_{ET}), and blue water footprint for conveyance loss (BWF for CL, BWF_{CL}) irrigated land is 38.5, 31.0 and 30.5 % respectively. GWF proportions in most provinces (21) are above national average and exceed 50.0 % in 6 provinces, including 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

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for irrigated wheat are Gansu (19.9 %), Xinjiang (19.7 %) and Ningxia (15.0 %), none of the three greater than 20.0 %.

Obviously, the blue water footprint in rain-fed wheat production is zero. In irrigated wheat production, the blue water footprint makes up 61.5 % of the total water footprint. 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 BWF_{CL} in irrigated land are such as Ningxia (49.0 %), Neimenggu (40.7 %) and Xinjiang (40.2 %). BWF_{CL} proportions of 26 provinces fall between 20.0 ~ 35.0 %. With the highest irrigation water utilization coefficient, Beijing has a water wasting proportion for irrigated wheat that is lower than all studied provinces, only 19.7 %.

From the perspective of the ways of water usage we partition WF into consumptive water use (CWU) and conveyance water loss. China's CWU for wheat production in 2010 is 107 396.1 Mm^3, with 66.7 % green and 33.3 % blue water. CWU for per kg wheat of wheat product is 0.932 $m^3 kg^{-1}$. The CWU is so inevitable in agricultural production that the proportion of it in WF reflects the level of regional water resources utilization. Proportion of CWU for wheat production in total cropland for the year 2010 is estimated to be 75.4 % and its spatial distribution is shown in Fig. 4.

Spatial distribution pattern of CWU proportion in total cropland is similar to the GWF in Fig. 3. Large CWU proportions can be found in Guangxi (85.6 %), Hubei (85.8 %), Shaanxi (86.0 %), Guizhou (89.8 %), Chongqing (90.1 %) and Yunnan (94.9 %), whose figures all exceed 85.0 %. However, these six provinces together contributed only 7.5 % to the national total output of wheat. CWU proportions range from 70.0 to 80.0 % in 14 provinces but no more than 65.0 % in Xinjiang and Ningxia. The proportions in some major wheat-producing areas, such as Henan and Hebei, are below the national level.

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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 was estimated to be 1.237 $m^3 kg^{-1}$. The results (in Fig. 5) show a great variation among provinces. Provinces in and around the Huang-Huai-Hai Plain have lower WFP, while the provinces in the south of the Yangtze River and northwest China have lower water use efficiency. Only four provinces have their own WFPs below the national average, namely Hebei (1.142 $m^3 kg^{-1}$), Shaanxi (1.126 $m^3 kg^{-1}$), Shandong (1.114 $m^3 kg^{-1}$) and Henan (1.070 $m^3 kg^{-1}$). These four provinces together produced 67.8 M t wheat, accumulatively contributing 58.8 % to 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 2000 $m^3 kg^{-1}$. 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

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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 literature (Table 3).

WFP in this report is 1.237 $m^3 kg^{-1}$, which is close to the value 1.190 $m^3 kg^{-1}$ calculated by Zhang (2009) and 1.286 $m^3 kg^{-1}$ estimated by Mekonnen and Hoekstra (2010). We evaluate the crop water footprint at regional scale since the field scale has been discussed in previous studies. The water footprint for per kg of wheat at field scale (also called consumptive water use for per kg of wheat, CWUP) in our study is listed and compared to previous results. We get a CWUP about 0.932 $m^3 kg^{-1}$, which is approximate to the water footprint of wheat product estimated by Sun et al. (2013) and Liu et al. (2007c). Sun et al. (2013) also applied the CROPWAT model and studied the water footprint of wheat in the year 2009. Among the previous, only three studies distinguished between green and blue water footprint. Proportions of green water at field scale in this paper and Mekonnen and Hoekstra (2010) are around 65.0 %, both greater than 51.0 %, the value from Sun et al. (2013).

4.3.2 Comparison between rain-fed and irrigated WFPs at regional scale

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 1.246 $m^3 kg^{-1}$, a little higher than WFP_R. WFP_I in Fujian is 2.214 $m^3 kg^{-1}$, ranking the highest among all provinces. Qinghai and Xinjiang also hold a value surpassing

2.000 $m^3 kg^{-1}$. WFP_I in other 21 provinces are above the national average. The lowest WFP_I is found in Henan (1.065 $m^3 kg^{-1}$), Shandong (1.109 $m^3 kg^{-1}$), Hebei (1.127 $m^3 kg^{-1}$), Shaanxi (1.147 $m^3 kg^{-1}$) and Hubei (1.244 $m^3 kg^{-1}$), all of which are major wheat producing areas of China.

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 water footprint per kg of wheat in irrigated land is not equal to that in rain-fed land. WFP_I is higher than WFP_R in most provinces located in northern China, while it is opposite in the south. In order to compare the crop yield and water footprint per kg of wheat between irrigated and rain-fed farmlands, two indexes QW and QY are defined as follows:

$$QW = \frac{WFP_I}{WFP_R} \tag{21}$$

$$QY = \frac{Y_I}{Y_R}. \tag{22}$$

The meaning of parameters in Eqs. (21) and (22) has been explained in Sect. 3. The national QW and QY are 1.04 and 2.76, meaning that crop yield can be promoted by 176 % when wheat is irrigated. Normally, irrigation achieves the dual benefit in yield-increasing and water-saving respects at the field scale. 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 reaping 1 kg wheat product. Irrigation not only promotes crop yield but also increases water footprint for China's wheat production. Calculated provincial results of QW and QY in 2010 are shown in Fig. 7.

QY in each of the 30 studied provinces is greater than 1, but it is not the case for QW. The provinces can be divided into three categories according to QW value:

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(I) QW < 0.900; (II) 0.900 < QW < 1.100 and (III) QW > 1.100. Provinces with low QW values, including Yunnan, Hunan, Jiangxi, Zhejiang, Shanghai and Guizhou, belong to Category I; with QW 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. The contributions to the country of the three categories for wheat output, sown area, WF, GWF and BWF are shown in Fig. 7. In addition, crop yield and water footprint of per kg wheat product for the three categories as well as QY and QW (including the values in total cropland, irrigated land and rain-fed land) are listed in Table 4.

Water footprint of per kg product (WFP) in irrigated and rain-fed farmland of Category I are 1.492 and 2.099 $m^3 kg^{-1}$ respectively, and the value of QW was 0.71. Irrigation saves water resources by 29 % while prompted 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 1.6 % of water footprint (WF) to the whole country. So, reducing WF (or WFP) 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 $t ha^{-1}$, 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 QW 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. 68.7 % of sown area, 74.7 % of total output and 68.6 % of water footprint of wheat production across the country are contributed by Category II in the year 2010. WFP in the category is 1.165 $m^3 kg^{-1}$, which is 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 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 QW reaches up to 1.42 at the same time, indicating a plenty of water waste in the process of wheat production. This category contributes 29.8 % of water footprint to China's total, 25.2 % green water and 34.4 % blue water. Provinces with high QY and QW values belong to Category III and are located in droughty northwest China, whereby massive irrigation water is demanded to withdraw due to scarce rainfall. Simultaneously, 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. Despite 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 water footprint per kg of wheat in total 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 footprint for conveyance loss (BW_{CL}) in some provinces of Category II, are very high, such as in Neimenggu (40.7 %), Xinjiang (40.1 %), Ningxia (49.0 %), Qinghai (33.9 %) and Gansu (33.2 %). These high WPF and BW_{CL} proportions signify a great water saving potential. In this regard, irrigation efficiency should be improved further and blue water footprints reduced, so as to achieve water-saving and production promoting objectives simultaneously.

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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 the calculation of crop water footprint at regional scale. The major findings of the current study are that: (i) the green water footprint related to China's wheat production is roughly equal to the blue water footprint, (ii) a large amount of water footprint depleted in delivery process and could not be reused during the crop growth period, and (iii) irrigation promotes crop yield dramatically, yet it also means more water resources needed have to be invested into crop production, which results in that water footprint for per unit of irrigated wheat becomes higher than that of rain-fed crop. 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 provinces located in the arid area.

The study has showed that the national water footprint of wheat production for the year 2010 is 142.5 $\mathrm{G\,m^3}$ (50.3 % green and 49.7 % blue). The amount of water conveyance loss accounts for 30.5 % of the total water footprint due to low irrigation efficiency. About 78.3 % of the national water footprint comes from the six provinces Henan, Shandong, Anhui, Hebei, Xinjiang and Jiangsu. Irrigated farmland provides 80.4 % of China's wheat production and contributes 80.9 % of the water footprint to the country. National water footprint for per kg of wheat product (WFP) is 1.237 $\mathrm{m^3\,kg^{-1}}$. WFP in provinces in and around the Huang-Huai-Hai Plain is low, whereas in the provinces located in the south of the Yangtze River and northwest China it is relatively high. Irrigation has played an important role in increasing food production and promoted the wheat yield by 170 % compared to the role of the rain-fed case. We have also perceived that irrigation does not always save water resources in wheat production

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of China. WFP for irrigated wheat is 0.044 higher than that for rain-fed wheat. Yield promoting and water saving benefits are obvious in the six provinces, which however are summed to contribute to only 1.1 % of China's wheat production. WFP in irrigated farmland is higher than that in rain-fed land in many regions such as the arid Xinjiang, Ningxia and Gansu. Irrigation increases food production, and should reduce water footprint for the country facing an enormous population and a severe water crisis.

The calculated result is compared with measured water productivity and virtual water values introduced in the literature of previous studies. It appears some difficulty to attribute differences in estimates from the various studies to specific factors also it is difficult to assess the quality of our new estimates relative to the quality of earlier estimates. Our crop-model-coupled-statistics approach based estimates of the water consumption of wheat production are better than the earlier estimates as provided by Chapagain and Hoekstra (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. (2009, 2010), Siebert and Döll (2010) and Mekonnen and Hoekstra (2010, 2011). The authenticity of data defines the accuracy of the water footprint calculation result. It has been observed that it is meaningful to compare WFP between irrigated and rain-fed farmland only when the water footprint is calculated at regional scale. 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. A tiny shortcoming (tiny or 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 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 footprint of wheat production for the 30 provinces of China in 2010.

Sub-region	Province	Contribution to national wheat production (%)	Contribution to national sown ara (%)	Yield ($t\,ha^{-1}$)	GWF ($Mm^3\,yr^{-1}$)	BWF ($Mm^3\,yr^{-1}$)	WF ($Mm^3\,yr^{-1}$)
Northeast	Heilongjiang	0.803	1.154	3.3	852.1	445.3	1297.4
	Jilin	0.010	0.015	5.6	10.5	7.9	18.4
	Liaoning	0.032	0.031	3.2	31.8	27.5	59.3
North China	Jiangsu	8.752	8.625	3.3	6883.0	5731.5	12 614.5
	Anhui	10.477	9.749	5.2	8489.1	6929.0	15 418.1
	Shandong	17.873	14.678	5.8	11 499.6	11 424.1	22 923.7
	Henan	26.760	21.758	5.8	16 511.4	16 462.8	32 974.2
	Tianjin	0.462	0.455	4.8	301.0	476.8	777.8
	Heibei	10.684	9.974	5.1	6867.3	7192.1	14 059.4
	Beijing	0.247	0.254	3.4	183.8	209.5	393.4
Northwest	Neimenggu	1.434	2.333	3.7	1377.1	1249.7	2626.8
	Xinjiang	5.413	4.615	2.0	2925.5	10 601.6	13 527.1
	Ningxia	0.610	0.871	2.5	340.3	724.3	1064.6
	Qinghai	0.324	0.416	1.1	288.8	429.1	717.9
	Gansu	2.178	3.625	1.0	1484.8	2079.1	3563.9
	Shanxi	2.016	3.002	2.8	1701.3	1230.1	2931.4
	Shaanxi	3.506	4.735	1.4	3162.1	1383.6	4545.7
Southwest	Xizang	0.211	0.194	2.8	122.4	202.6	325.0
	Yunnan	0.399	1.767	3.5	890.6	115.3	1005.8
	Guizhou	0.215	1.075	4.9	361.8	91.8	453.6
	Guangxi	0.005	0.017	4.8	7.1	2.6	9.7
	Chongqing	0.399	0.620	3.7	497.7	121.7	619.4
	Sichuan	3.713	5.216	2.9	3236.9	2191.6	5428.5
Southeast	Hubei	2.979	4.121	3.5	3094.2	1208.1	4302.3
	Zhejiang	0.214	0.273	2.9	247.5	132.3	379.9
	Jiangxi	0.018	0.043	3.1	23.0	8.9	31.8
	Hunan	0.086	0.162	5.1	87.5	56.6	144.1
	Guangdong	0.003	0.004	3.9	2.5	1.4	3.9
	Shanghai	0.168	0.204	4.6	135.1	144.6	279.7
	Fujian	0.009	0.015	3.4	13.9	9.1	22.9
China		1	1	4.7	71 629.7	70 890.6	142 520.3

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

Sub region	Province	Irrigated				Rain-fed	
		Total output (10^3 t)	BWF_I (Mm^3)	GWF_I (Mm^3)	WF_I (Mm^3)	Total output (10^3 t)	WF_R (Mm^3)
Northeast	Heilongjiang	490	445.3	334.2	779.6	435	517.8
	Jilin	7	7.9	4.7	12.7	5	5.8
	Liaoning	26	27.5	17.9	45.4	11	13.9
North China	Jiangsu	8734	5731.5	5439.2	11 170.7	1347	1443.8
	Anhui	9652	6929.0	5266.0	12 195.0	2415	3223.2
	Shandong	17 256	11 424.1	7704.1	19 128.2	3330	3795.5
	Henan	25 908	16 462.8	11 127.5	27 590.3	4915	5383.8
	Tianjin	497	476.8	256.3	733.1	35	44.6
	Heibei	10 779	7192.1	4957.5	12 149.7	1528	1909.8
	Beijing	243	209.5	132.8	342.4	41	51.0
Northwest	Neimenggu	1087	1249.7	637.4	1887.1	566	739.7
	Xinjiang	6053	10 601.6	2598.5	13 200.1	181	327.0
	Ningxia	503	724.3	127.8	852.1	200	212.5
	Qinghai	271	429.1	153.9	583.0	101	134.9
	Gansu	1500	2079.1	515.5	2594.6	1009	969.2
	Shanxi	1568	1230.1	682.6	1912.7	755	1018.8
	Shaanxi	2170	1383.6	1104.1	2487.6	1868	2058.0
Southwest	Xizang	190	202.6	64.0	266.6	53	58.4
	Yunnan	165	115.3	116.2	231.4	295	774.4
	Guizhou	103	91.8	72.8	164.6	145	289.0
	Guangxi	3	2.6	3.2	5.8	2	3.9
	Chongqing	170	121.7	97.4	219.1	289	400.3
	Sichuan	2691	2191.6	1406.1	3597.7	1586	1830.7
Southeast	Hubei	2023	1208.1	1308.5	2516.6	1408	1785.7
	Zhejiang	203	132.3	150.7	283.0	44	96.8
	Jiangxi	15	8.9	10.9	19.7	6	12.1
	Hunan	80	56.6	46.4	103.1	19	41.1
	Guangdong	2	1.4	1.8	3.2	1	0.8
	Shanghai	175	144.6	99.8	244.5	17	35.3
	Fujian	8	9.1	8.5	17.5	2	5.4
China		92 573	70 890.6	44 446.5	115 337.1	22 608	27 183.2

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Table 3. Documented results of WFP in China.

Reference	Scale	Year (period)	WFP ($m^3 kg^{-1}$)	Proportion of green water
This study	Regional	2010	1.237	50.3 %
	Field		0.932	66.7 %
Sun et al. (2012)	Field	2009	1.071	51.0 %
Liu et al. (2007c)	Field	1998–2001	0.980	–
Zhang (2009)	Field	1997–2007	1.190	–
Chapagain et al. (2006)	Field	1997–2001	1.321	–
Mekonnen and Hoekstra (2010)	Field	1996–2005	1.286	63.8 %
Hoekstra and Hung (2005)	Field	1995–1999	0.690	–

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

Category	Crop yield ($t\,ha^{-1}$)				Water footprint of per kg product ($m^3\,kg^{-1}$)			
	Total cropland	Irrigated	Rain-fed		Total cropland	Irrigated	Rain-fed	QW
	(Y)	(Y_I)	(Y_R)	QY	(WFP)	(WFP_I)	(WFP_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

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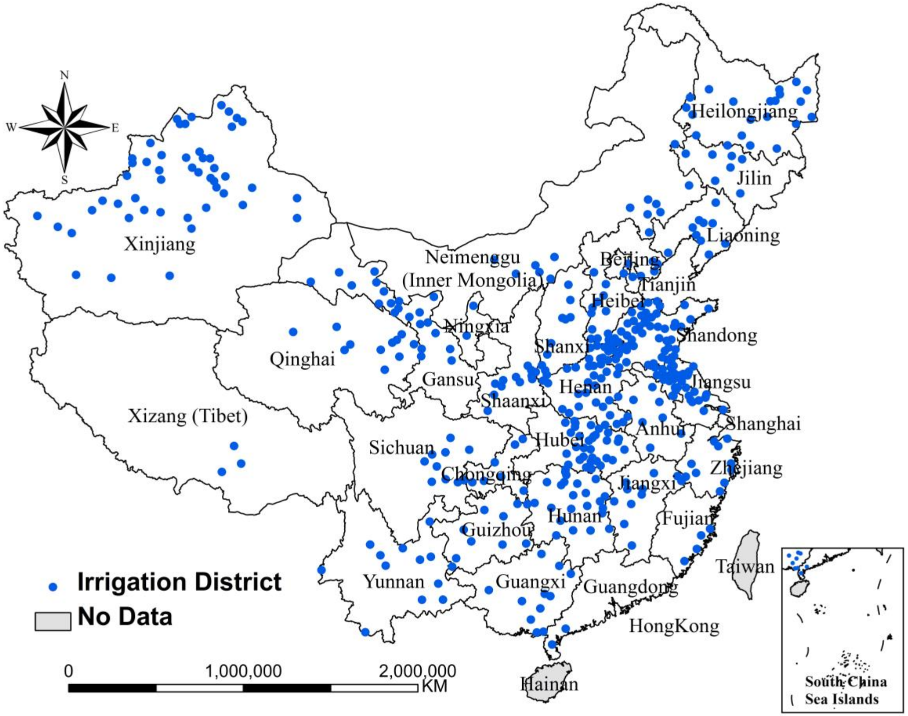

Fig. 1. Distribution map of 442 irrigation districts in 30 studied provinces.

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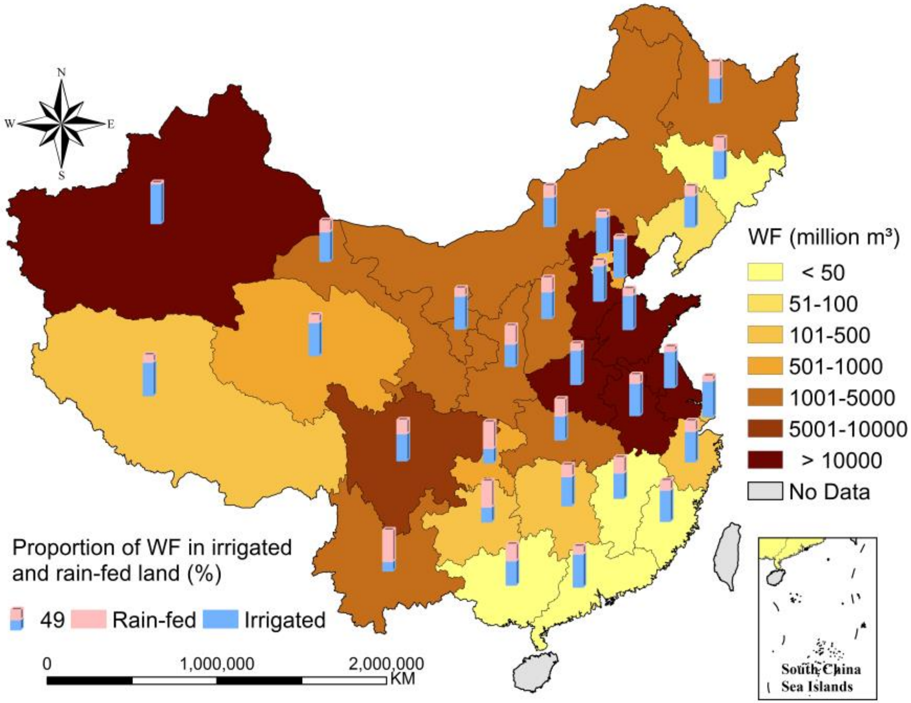

Fig. 2. Provincial water footprint of wheat production (WF) in 2010.

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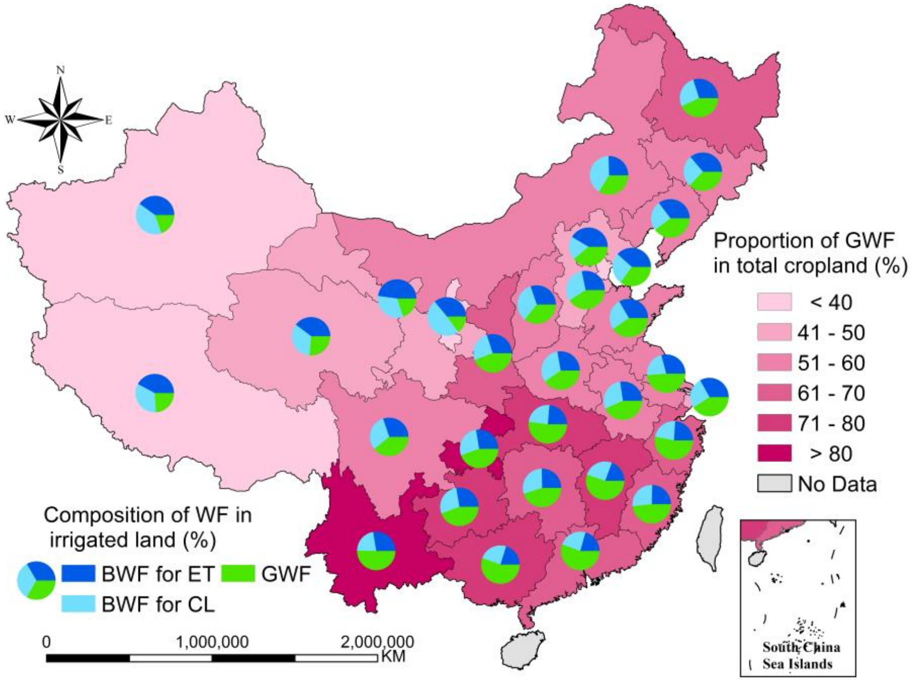

Fig. 3. Proportion of GWF in total crop land and composition of WF in irrigated land.

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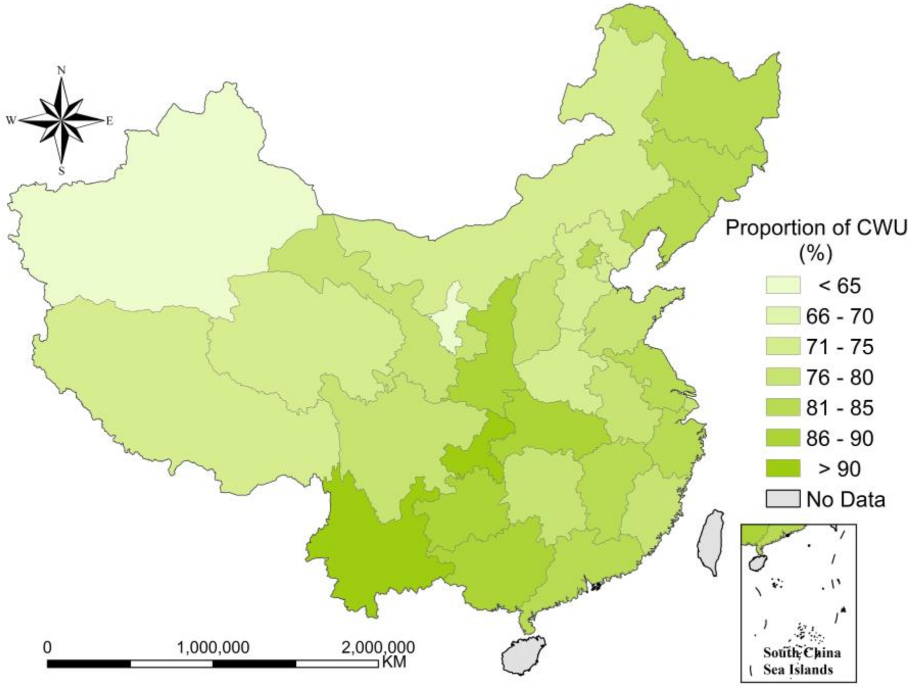

Fig. 4. Proportion of consumption water use (CWU) in WF in total cropland.

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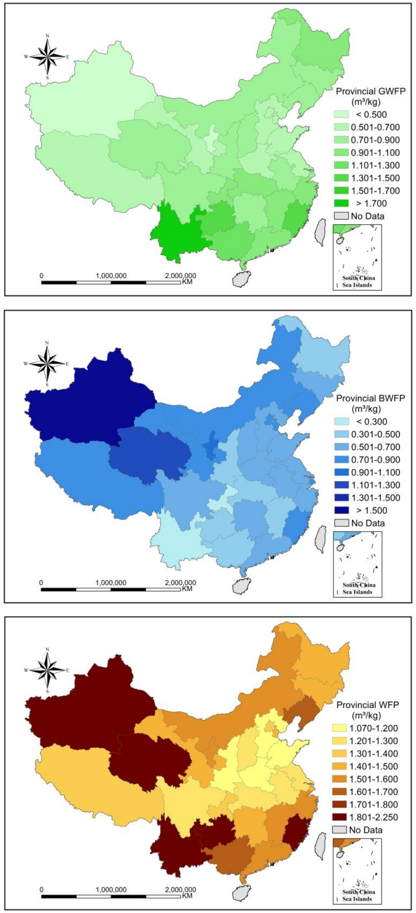

Fig. 5. The green, blue and total water footprint for per kg of wheat product.

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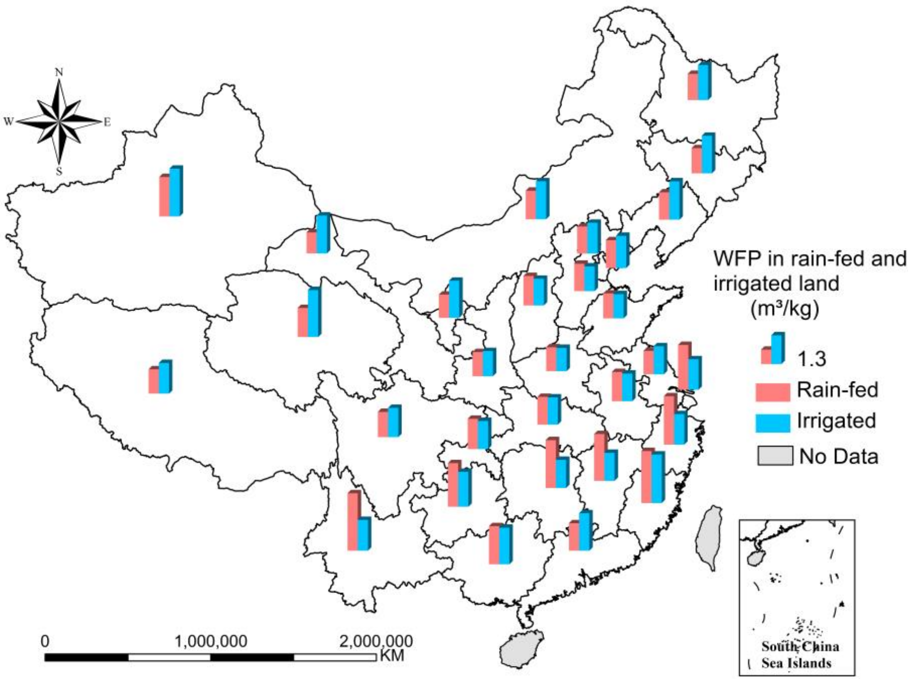

Fig. 6. Water footprint per kg of wheat product (WFP) in irrigated and rain-fed land.

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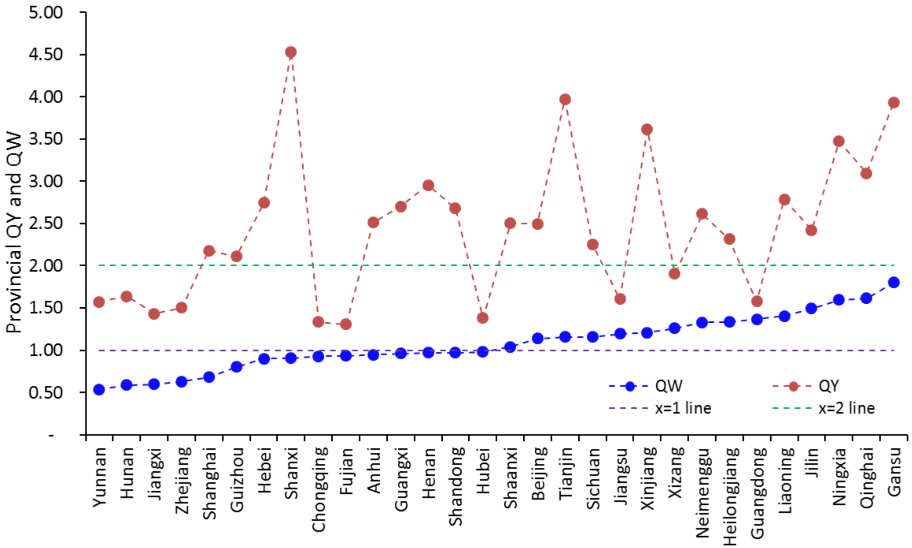

Fig. 7. Provincial value of QY and QW in 2010.

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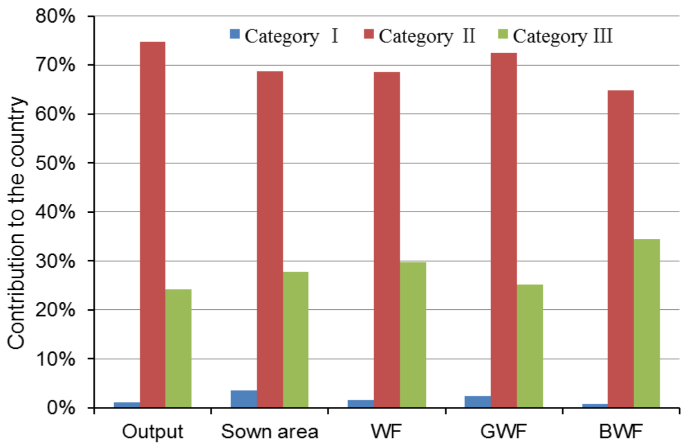

Fig. 8. Contributions of three categories to wheat production indicators.