water

MDPI

Article

Assessing the Water Footprint of Wheat and Maize in Haihe River Basin, Northern China (1956–2015)

Yuping Han [1,2,3], Dongdong Jia [1,*], La Zhuo [4,5], Sabine Sauvage [6], José-Miguel Sánchez-Pérez [6], Huiping Huang [1] and Chunying Wang [1,2,3]

1 North China University of Water Resources and Electric Power, Zhengzhou 450046, China; han0118@163.com (Y.H.); 13526882916@163.com (H.H.); wangchunying1987@yahoo.com (C.W.)
2 Collaborative Innovation Center of Water Resources Efficient Utilization and Support Engineering, Zhengzhou 450046, China
3 Henan Key Laboratory of Water Environment Simulation and Treatment, Zhengzhou 450046, China
4 Institute of Soil and Water Conservation, Northwest A & F University, Yangling 712100, China; zhuola@nwafu.edu.cn
5 Institute of Soil and Water Conservation, CAS & MWR, Yangling 712100, China
6 EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France, Avenue de l'Agrobiopole, 31326 Castanet Tolosan CEDEX, France; sabine.sauvage@univ-tlse3.fr (S.S.), jose-miguel.sanchez-perez@univ-tlse3.fr (J.-M.S.-P.)
* Correspondence: dongdongjia06@163.com; Tel.: +86-185-0085-4530

Received: 17 May 2018; Accepted: 21 June 2018; Published: 29 June 2018

Abstract: Assessing the water footprint (WF) of crops is key to understanding the agricultural water consumption and improving water use efficiency. This study assessed the WF of wheat and maize in the Haihe River Basin (HRB) of Northern China over the period1956–2015, including rain-fed, sufficient, and insufficient irrigation conditions by different irrigation intensity to understand the agricultural water use status. The major findings are as follows: (1) The annual average total WF of wheat and maize production is 20.1 (52% green, 29% blue, and 19% grey) and 15.1 (73% green, 3% blue, and 24% grey) billion m^3 $year^{-1}$, respectively. The proportion of grey WF is much larger than the world average; (2) Wheat has larger unit WF (1580 m^3 t^{-1}) than maize (1275 m^3 t^{-1}). The unit WF of both wheat and maize shows exponentially decreasing trends, indicating that water use efficiency has been improved. The unit WF is heterogeneous in space, which is larger in Tianjin and Huanghua and smaller in the Southern HRB; (3) Rain-fed crops have the largest unit WF, followed by crops under insufficient and sufficient irrigation conditions for both wheat and maize. To improve the sustainability of water resources, the application of fertilizer must be reduced, and irrigation is an effective way to improve water use efficiency in water-abundant areas.

Keywords: water footprint; irrigation intensity; wheat; maize; Haihe River Basin

1. Introduction

Water scarcity has been a growing concern worldwide [1–3]. Agriculture consumes 70% of the global freshwater withdrawal [4]. With growing populations and expanding irrigated acreage, the water demand of agriculture continues to increase. Meanwhile, extensive application of fertilizer has caused severe, diffuse agricultural water pollution, which increases the competition for freshwater [5]. In some river basins, due to limited water supply facilities and high water prices, crops are irrigated with inadequate water supply under field conditions. A comprehensive and accurate assessment of the volume and structure of agricultural water consumption under those conditions is key to improving water use efficiency and effectively managing water resources.

The water resources can be divided into green and blue water resources during water resource planning and management [6,7]. The concept of the "water footprint (WF)" was introduced by Hoekstra [8] and it provides a tool to assist with water resource management and deals with water scarcity, such as changing consumption patterns or improving the water efficiency of production [9–12]. The WF of a product refers to the sum of the water volume consumed to produce the product [13]. The blue WF refers to the volume of surface and groundwater consumed (evaporated) as a result of the production of a good. The green water footprint refers to the rainwater consumed. For crops, this refers to the portion of rainfall that infiltrates the soil and is accessible by plants to generate vapor flow in support of biomass growth [9]. The grey WF of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards [13]. The WF of unit production, which is also recognized as the virtual water content [14,15] when assessing virtual water flows among regions, reflects the regional water productivity or water use efficiency.

Within the agricultural sector, WF has been intensively studied from global levels to regional levels. Mekonnen and Hoekstra [16,17] estimated the green, blue, and grey WF of global wheat and quantified the green, blue, and grey WF of global crop production for the period 1996–2005. Siebert and Döll [18] quantified the green and blue WF in global crop production, as well as potential production losses without irrigation. At the national level, Zhuo et al. [19,20] set up benchmark levels of consumptive WF of winter wheat and assessed the green and blue WF and virtual water trade in China under alternative future scenarios. Cao et al. [21] assessed the blue and green water utilization in wheat production of China. Zoumides et al. [22] employed a supply utilization approach along with two indicators, economic productivity of crop use and the blue water scarcity index, to assess the WF for the semi-arid island of Cyprus. Schyns and Hoekstra [23] demonstrated the added value of the detailed analysis of the human water footprint within Morocco and thoroughly assessed the virtual water flows. At the regional level, Bulsink et al. [24] analyzed the WF of an Indonesian province related to the consumption of crop products. Duan et al. [25] explored the spatial variations of the WF and their relationships with agricultural inputs in Northeast China. Gobin et al. [26] calibrated crop yield for a water balance model, "Aquacrop" at the field level and analyzed variability in the WF of arable crop production across European regions.

At the river basin level, Aldaya and Llamas [27] analyzed the WF and virtual water in the semiarid Guadiana Basin. Yin et al. [28] calculated the total WF and the net external WF of consumption in the Yellow River Basin of China. Zeng et al. [29] quantified the WF in the Heihe River Basin of China during 2004–2006. Zang et al. [30] reported on spatial and temporal patterns of both green and blue water flows, also in the Heihe River Basin. Zhuo et al. [31] estimated the inter- and intra-annual WF of crop production in the Yellow River Basin for the period 1961–2009. Assessing WF at the river basin level is an important step to understanding how human activities influence the water cycle and is a basis for integrated water resource management and sustainable water uses within the basin [29].

Prior studies analyzed or assessed the WF of crops by dividing them into pure rain-fed crops and irrigated crops with sufficient water. However, because of a lack of detailed long-term irrigation data, few studies assessed the WF with insufficient water supply restricted by water volume, water cost, and water supply facilities. Assessing the WF under those conditions can effectively improve our understanding regarding the agricultural water use status to improve agricultural water use efficiency. Additionally, few studies have investigated the spatial and temporal characteristics within the basin under the influence of many factors, such as climate, geography, soil property, and management practice (e.g., irrigation, fertilizer application). In order to effectively understand the agricultural water use status and reasonably allocate water resources within the basin, it is necessary to assess the spatial and temporal WF by dividing the basin into small regions according to administrative divisions which have their own record, climate, and geographical conditions. Among the above influences on spatial and temporal variations of the WF, irrigation is a key factor controlling the accuracy of WF assessment, especially in river basins facing water scarcity [22,23,32,33]. The irrigation quota is recommended by the local government to guide the farmers' irrigation practice. Furthermore, in the process, many factors such as climate, geography, soil property, and manner of irrigation are considered. It is close to the actual scene for irrigated crops [34]. Hence, the green, blue, and grey WF can be quantified with an irrigation quota to improve the accuracy of the WF assessment.

The Haihe River Basin (HRB), the political, economic, and cultural center of China, has 146 million inhabitants [35] and is also a main grain producing area, with more than 10% of the national production. However, it is a historical water scarcity basin. The amount of water resources is 305 m^3 per capita, which is approximately 1/7 of the Chinese average (2200 m^3) and also 1/27 of the world average [36–38]. Restricted by limited water resources, high water prices, water supply facilities, and different climate conditions, crops are irrigated with different intensity in different regions within the HRB. There are great differences in the WF accounting between insufficient irrigation conditions and traditional rain-fed and sufficient irrigation conditions. However, the WF assessment under these conditions and the subsequent spatiotemporal patterns are lacking for the HRB.

The specific objectives of this study are: (1) to take account of the WF of both wheat and maize within the HRB; (2) to analyze the temporal trends and spatial variations of the WF in the entire HRB during the period 1956–2015; and (3) to allocate the WF of wheat and maize based on administrative districts within the HRB.

2. Methods and Data

2.1. Study Area

The Haihe River Basin (HRB) is located between 112° E–120° E and 35° N–43° N, with a drainage area of 318,200 km^2 (Figure 1). It encompasses Beijing, Tianjin, and 23 other large and medium cities. The basin is in a continental monsoon climate zone with annual mean temperatures between −4.9 and 15 °C, and the annual precipitation ranges from 380 to 580 mm. The precipitation in the flood season (June–September) generally accounts for 70–85% of the annual precipitation. The observed average groundwater table of the entire HRB is 6–9 m and has a decreasing trend due to overexploitation [39,40]. The most widely distributed soils in HRB are cinnamon soil and fluvo-aquic soil, with two main soil textures, sandy clay loam and sandy loam, respectively [41]. Wheat and maize are widely planted in the basin. The planting areas of wheat and maize were 3.9 and 5.1 million hectares in 2015, accounting for 27% and 36%, respectively, of the total planting area [42]. The total production of wheat and maize were 24.7 and 28.1 million tons in 2015, accounting for 20% and 13% of the nation, respectively [42].

In this study, the HRB is divided into 11 regions to illustrate the spatial variations. It is firstly divided into six administrative regions, including Beijing, Tianjin, Hebei, Shandong, Shanxi, and Henan. Since the areas of Liaoning and Inner Mongolia within HRB are small, they are incorporated into Hebei and Shanxi according to climate and geographical conditions. Among them, Shanxi Province is further divided into two regions according to the different planting systems, climate, and geographical conditions, which are also the irrigation management divisions, as recommended by the government [43]. In the southern part of Shanxi, there is a traditional rotation of winter wheat and summer maize, while in the northern part the major crops are spring maize and no wheat planted. Hebei province is divided into five regions according to the different geographical conditions, which are also the irrigation management divisions, as recommended by the government [43]. In Zhangjiakou and Chengde of Hebei, the major planting crop (spring maize) is different from that of other regions (traditional rotation of winter wheat and summer maize). A corresponding weather station was selected in each region (Table 1); the locations of the stations are shown in Figure 1.

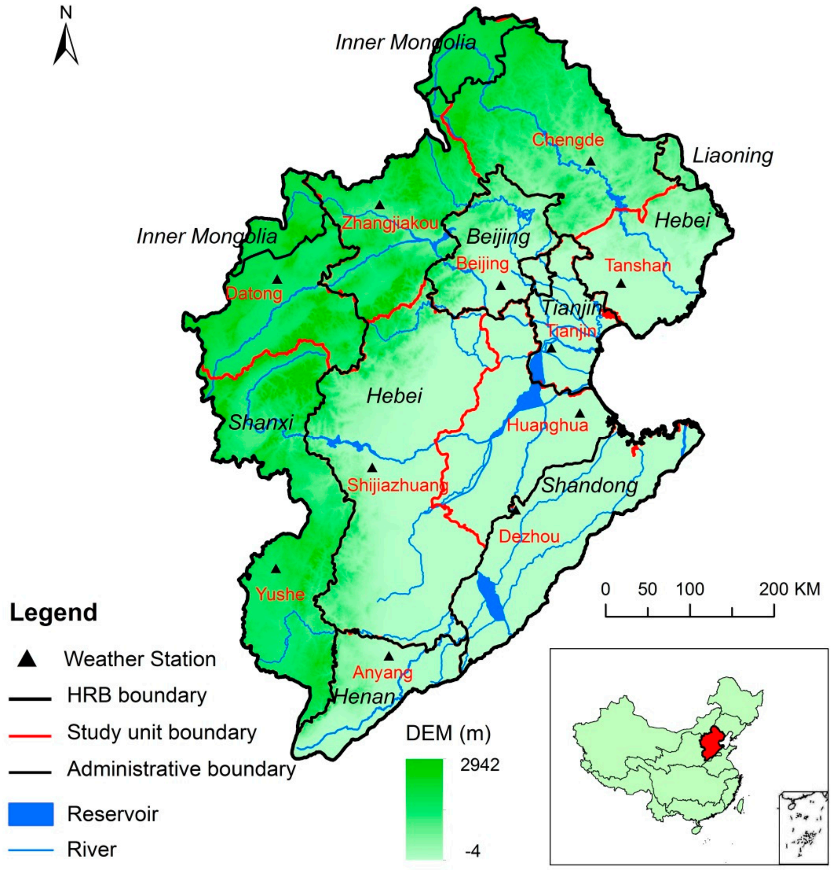

Figure 1. Locations of the study area and weather stations.

Table 1. Division of the study area and corresponding weather stations.

Code	Station	Area ($\times 10^3$ km^2)	Data Period	Weather Station Parameters			Geographical Characteristics
				Longitude (°C)	Latitude (°C)	Altitude (m)	
1	Beijing	16.4	1956–2015	116.47	39.80	31.3	Beijing municipality
2	Tianjin	11.5	1956–2015	117.07	39.08	2.5	Tianjin municipality
3	Shijiazhuang	60.7	1956–2015	114.42	38.03	81.0	Piedmont plain of Taihang
4	Tangshan	23.6	1957–2015	118.15	39.67	27.8	Hilly and plain area of Yanshan
5	Huanghua	28.0	1956–2015	117.35	38.37	6.6	Low plain of Heilonggang
6	Zhangjiakou	26.0	1956–2015	114.88	40.78	724.2	Northwestern Hebei mountains
7	Chengde	42.0	1956–2015	117.95	40.98	385.9	Mountainous area of Yanshan
8	Datong	27.3	1956–2015	113.33	40.10	1067.2	North of Shanxi
9	Yushe	38.0	1957–2015	112.98	37.07	1041.4	Middle part of Shanxi
10	Anyang	14.9	1956–2015	114.40	36.05	62.9	Plain area of northern Henan
11	Dezhou	29.8	1956–2013	116.32	37.43	21.2	North of Shandong

2.2. Methods

The green, blue, and grey WFs are quantified following the framework of Hoekstra et al. [44]. To distinguish the spatial discrepancy, the HRB is divided into 11 regions according to irrigation intensity, which refers to the irrigation quota recommended by the government of each province within the basin. In each region, a corresponding weather station was selected to represent the regional meteorological conditions.

In each region, the growing conditions of crops are divided into rain-fed and irrigated conditions. The proportion of irrigated crops is obtained by dividing the cultivated areas by irrigation areas in the statistical yearbook of each province or municipality.

For rain-fed crops, the blue WF is zero and the green WF is quantified by summing up the daily actual crop evapotranspiration (ET_{a}) without irrigation. For irrigated crops, the consumptive WF (green plus blue) is quantified by summing up daily actual crop evapotranspiration under different irrigation intensities. The green WF is assumed to be equal to the (ET_{a}) as calculated in the rain-fed scenario. The blue WF is equal to the consumptive WF minus the green WF.

To further analyze the structure of WF, the green water coefficient is defined as the ratio of green WF to the consumptive green and blue WF [45].

The grey WF is calculated by quantifying the volume of water needed to assimilate the nitrogen fertilizers that enter into the groundwater or surface water because nitrogen is the most used fertilizer in the HRB. The grey WF is calculated as:

$$WF_{grey} = \frac{\alpha \times \text{AR}}{(c_{max} - c_{nat})} \tag{1}$$

where WF_{grey} is the grey water (m^3); α is the leaching-runoff fraction (%), which is assumed to be 10%; AR is the concentration of pollutants per hectare (g ha^{-1}); c_{max} is the maximum allowable concentration of pollutants in water bodies (10 mg L^{-1}) [46]; and c_{nat} is the natural concentration of nitrogen in the receiving water body (mg L^{-1}), and is assumed to zero.

The unit WF refers to the WF for per ton of wheat or maize, which is obtained by dividing the total WF by production.

The actual crop evapotranspiration (ET_{a}), which depends on reference evapotranspiration, crop factor, and soil water availability [47], is calculated as:

$$ET_{\text{a}}[t] = K_s[t] \times K_c[t] \times ET_o[t] \tag{2}$$

where $K_s[t]$ is a dimensionless transpiration reduction factor dependent on available soil water with a value between zero and one; K_c is the crop coefficient, which varies in time as a function of the growth stage of crops, the length of the growing stage, and the crop coefficient of wheat and maize (Table 2); and ET_0 is the daily reference evapotranspiration (mm day^{-1}), which is calculated by the Penman–Monteith equation recommended by the Food and Agriculture Organization of the United Nations (FAO) [47].

The transpiration reduction factor, $K_s[t]$, is calculated based on a function of the maximum and actual available soil moisture in the root zone at daily time steps following Allen et al. [47]:

$$K_s[t] = \begin{cases} \frac{S[t]}{(1-p)S_{max}[t]} & S[t] < (1-p) \times S_{max}[t] \\ 1 & otherwise \end{cases} \tag{3}$$

where $S[t]$ is the actual available soil water in the root zone at time t (mm), which is simulated with a dynamic daily soil water balance method [16,19,48]. In this method, the irrigation quota is used as the irrigated water volume, which can be seen in Table 3. $S_{max}[t]$ is the maximum available soil water in the root zone (mm), and p is the fraction of S_{max} that a crop can extract from the root zone without suffering water stress. It is a function of crop type and potential crop evapotranspiration [47]:

$$p = p_{std} + 0.04(5 - ET_c) \quad (4)$$

where p_{std} is a crop-specific depletion fraction when the evapotranspiration is 5 mm day^{-1}, a value of 0.55 is used for both wheat and maize in this study [47].

Table 2. Crop characteristics for winter wheat and maize in the Haihe River Basin.

	Planting Date	Growing Period (d)	Relative Length of Crop Growing Stage (–)				Crop Coefficients (–)		
			L_ini	L_dev	L_mid	L_late	K_c_ini	K_c_mid	K_c_end
Wheat	1 October	253	0.40	0.30	0.20	0.10	0.55	1.15	0.4
Maize	11 June	112	0.20	0.27	0.33	0.2	0.3	1.2	0.4
Maize *	1 May	140	0.20	0.27	0.33	0.2	0.3	1.2	0.4

Notes: L_ini, L_dev, L_mid, and L_late refer to the length of crop growing stages for initial, crop development, mid-season, and late season, respectively, as a fraction of the whole growing period; K_c_ini, K_c_mid, and K_c_end refer to crop coefficients for initial period, mid-season, and at the end of the season, respectively; Maize * refers to spring maize planted in Zhangjiakou, Chengde, and Datong; data references from Allen et al. [47]; Chen et al. [49]; and Kang et al. [50].

Table 3. Irrigation intensity [43] of wheat and maize within the HRB.

Code	Station	Irrigation Intensity (mm year^{-1})		Code	Station	Irrigation Intensity (mm year^{-1})	
		Wheat	Maize			Wheat	Maize
1	Beijing	428	75	7	Chengde	-	135
2	Tianjin	300	120	8	Datong	-	150
3	Shijiazhuang	210	68	9	Yushe	250	165
4	Tangshan	240	68	10	Anyang	180	68
5	Huanghua	248	75	11	Dezhou	270	105
6	Zhangjiakou	–	135				

2.3. Data

The weather data are obtained from the China Meteorological Administration [51], including daily maximum and minimum air temperatures, wind speed at 2 m height, average relative humidity, and daily sunshine duration from 1955 to 2015. The provincial agricultural data, including actual yield, planting area, irrigation area, fertilizer, and production from 1956 to 2015 are available at the Department of Plantation Management of the China Agriculture Ministry [42]. The production, planting area, and yield data for cities are available from the statistical yearbooks for Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan from 1983 to 2015 [52]. The yield and production data are checked and revised. The default values of yield and production for cities are calculated by multiplying a regional affecting factor by the provincial data. The regional irrigation schedules are obtained from the norm of water intake for Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan [43].

3. Results

3.1. Total Water Footprint of Wheat and Maize in the HRB

The total WF of wheat and maize over the period 1956–2015 in the HRB was calculated, and the results are shown in Table 4. The total WF of wheat is 20.1 billion m^3 year^{-1} on average. The major portion of this water (52%) comes from green water, about 29% comes from blue water, and the remaining 19% is grey water. The total WF of maize is 15.1 billion m^3 year^{-1} on average. The major portion of this water (73%) comes from green water, about 3% comes from blue water, and the remaining 24% is grey water, on average. Per hectare of cultivated land, wheat (4900 m^3 ha^{-1}) requires more water (including grey water) than maize (4580 m^3 ha^{-1}) on average. In the last ten years, the average blue WF of wheat (6.3 Gm^3 $year^{-1}$) and maize (0.6 Gm^3 $year^{-1}$) accounts for 26% and 2%, respectively, of the total agricultural water withdrawal of the HRB (24.04 Gm^3 $year^{-1}$) [53].

Table 4. Total water footprint (WF) of wheat and maize in the HRB, 1956–2015.

Crops	Period	Planting Area * (10^6 ha $year^{-1}$)	Total WF * (Gm^3 $year^{-1}$)				GWC * (%)
			Green	Blue	Grey	Total	
Wheat	1956–1965	3.7 ± 0.2	9.9 ± 1.1	4.4 ± 0.7	0.1 ± 0.0	14.4 ± 0.9	69
	1966–1975	4.0 ± 0.2	9.9 ± 0.7	5.6 ± 0.4	0.9 ± 0.3	16.4 ± 1.1	64
	1976–1985	4.4 ± 0.2	11.1 ± 1.1	6.4 ± 0.4	3.1 ± 0.3	20.6 ± 1.2	63
	1986–1995	4.4 ± 0.1	11.6 ± 1.1	6.1 ± 0.6	5.2 ± 0.6	22.9 ± 0.7	65
	1996–2005	4.2 ± 0.3	10.8 ± 0.7	5.7 ± 0.7	7.0 ± 0.4	23.5 ±1.5	66
	2006-2015	4.0 ± 0.0	9.8 ± 0.6	6.3 ± 0.4	6.7 ± 0.2	22.8 ± 0.7	61
	Average	4.1	10.5	5.8	3.8	20.1	65
Maize	1956–1965	2.1 ± 0.2	7.2 ± 0.7	0.3 ± 0.2	0.1 ± 0.0	7.6 ± 0.7	96
	1966–1975	2.6 ± 0.1	8.9 ± 0.6	0.4 ± 0.2	0.6 ± 0.2	9.9 ± 0.7	96
	1976–1985	3.3 ± 0.1	10.9 ± 0.5	0.5 ± 0.2	2.3 ± 0.3	13.7 ± 0.7	96
	1986–1995	3.3 ± 0.1	10.8 ± 0.4	0.6 ± 0.3	3.9 ± 0.5	15.3 ± 0.8	95
	1996–2005	3.9 ± 0.1	12.5 ± 0.9	0.7 ± 0.4	6.5 ± 0.2	19.7 ± 0.9	95
	2006–2015	4.8 ± 0.1	15.9 ± 0.6	0.6 ± 0.3	8.0 ± 0.1	24.5 ± 0.6	96
	Average	3.3	11.0	0.5	3.6	15.1	

* Data are the mean ± SD for every decade. GWC refers to the green water coefficient.

To further analyze the structure of WF, the green water coefficient is defined as the ratio of green WF to the consumptive green and blue WF [45]. As shown in Table 4, the green water accounts for 65% and 96% of the consumptive WF for wheat and maize, respectively. For maize, 96% of the consumptive water comes from green water, because most parts of the HRB are planted with summer maize, which mainly grows in the flood season (June to September), with 70–85% of the annual rainfall. The green water coefficients estimated in this study are very close to the previous studies by Mekonnen and Hoekstra (2010) [16] and Liu et al. [45] (80% for all crops).

The total WF has different temporal variation trends for wheat and maize. For wheat, it increased (by 64%) from 1956 to 1997 and then decreased (by 3%) following the changing trends of planting areas. For maize, it continually increased (up to 144%) over the study period due to the continual increase of planting areas. For both wheat and maize, the grey water increased before 2001 due to the increased application of the nitrogen fertilizer. The growth rate of the nitrogen fertilizer application was faster than the growth rate of the production, which reversed after 2002.

3.2. Unit Water Footprint of Wheat and Maize in the HRB

The unit WF refers to WF per ton of crop production, which is the converse of the crop water productivity, and can reflect the water use efficiency of crops [45]. Lower unit WF implies higher water use efficiency. Wheat (1580 m^3 t^{-1}) has a larger unit WF than maize (1275 m^3 t^{-1}), on average. In 2006–2015, the unit WF for wheat and maize production was 1022 m^3 t^{-1} and 934 m^3 t^{-1}, respectively.

The unit WF for both wheat and maize have exponentially decreasing trends along with the increasing production, indicating that water use efficiency has improved (Figures 2 and 3). The yield increased significantly due to the agricultural technology development, such as the large application of fertilizer, and innovation in agriculture management practices, such as the household contract responsibility system in the 1980s across China, which raised farmer's enthusiasm and increased the yield.

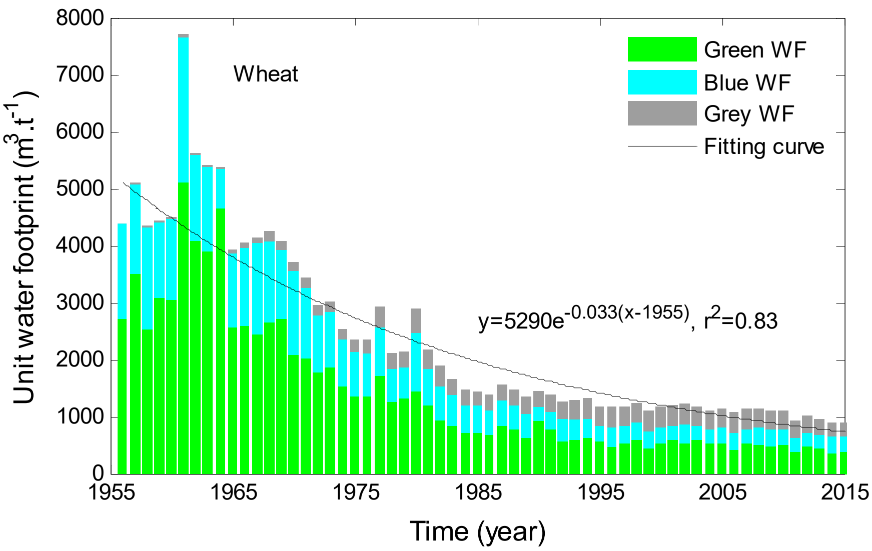

Figure 2. Unit WF and historical trend for wheat in the HRB over the period 1956–2015.

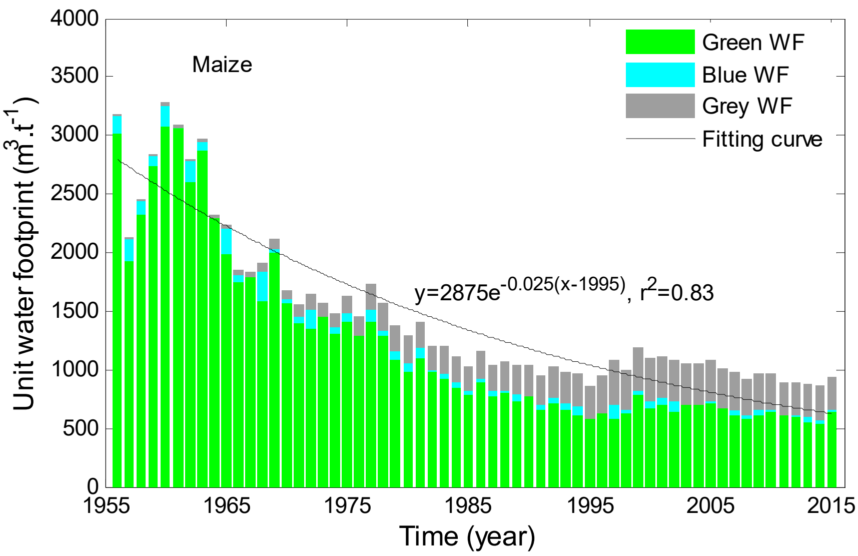

Figure 3. Unit WF and historical trend for maize in the HRB over the period 1956–2015.

The temporal variation trends of unit WF are fitted well by an exponential function with a non-linear least square method. It can be described as $y = 5290e^{-0.033(x-1955)}$ (R^2 = 0.83) (Figure 2) and $y = 2784e^{-0.026(x-1955)}$ (R^2 = 0.79) (Figure 3) for wheat and maize, respectively. The unit WF value was significantly high in 1961, with a value of 7533 m^3 t^{-1}, and that was because China experienced severe drought; at that time the production (1.6 million tons) was nearly half of the national average. In addition, in 1960 maize production decreased largely due to the severe drought, which resulted in a larger WF for maize (3254 m^3 t^{-1}).

The grey WF for unit wheat production increased significantly from 26 m^3 t^{-1} to 366 m^3 t^{-1} over the period 1956–2001 due to the increasing application of fertilizer (from 2 kg ha^{-1} to 170 kg ha^{-1}) and then decreased 30% (276 m^3 t^{-1}) in 2015, mainly because the yield increased while the fertilizer application did not change much. For maize, it increased from 17 m^3 t^{-1} to 384 m^3 t^{-1} from 1956 to 1997, and then decreased 25% (276 m^3 t^{-1}) in 2015. In 2006–2015, the grey WF was 302 m^3 t^{-1} and 304 m^3 t^{-1} for unit wheat and maize production, respectively. It was 45% and 48% larger, respectively, than the world average estimated by Mekonnen and Hoekstra [17] (207 m^3 t^{-1}). This indicates that agricultural water pollution is more severe than in other regions in the world, so the application of fertilizer should be reduced to assimilate the agricultural water pollution in the HRB.

The unit WF can be described and fitted well with a power function of crop yield (Figure 4). It is $y = 4045x^{-0.816}$ ($R^2 = 0.99$) and $y = 3384x^{-0.795}$ ($R^2 = 0.98$) for wheat and maize, respectively. A similar relationship was studied by Mekonnen and Hoekstra. [17], who argued that the trend between unit WF and the yield of cereals follows a logarithmic function. This indicated that the WF of crops is largely influenced by agricultural management rather than by climate conditions. Crop variety improvement, mechanization technologies, the rational combination of irrigation and fertilizer, and the change from family-oriented to farm management could increase the yields of wheat and maize. Further, improving crop production is an effective way to reduce the unit WF and improve water use efficiency. This can also be used to estimate the unit WF in the HRB when lacking information or to estimate the crop water use in the future.

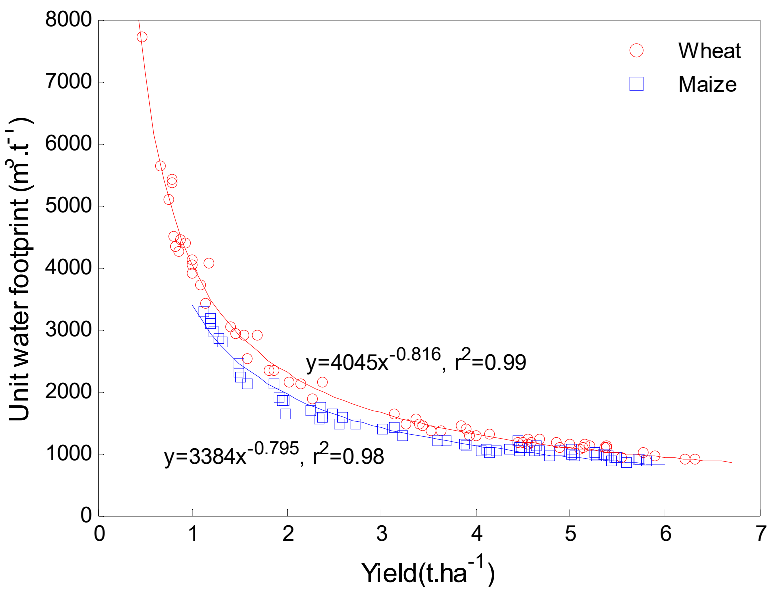

Figure 4. The relationship of unit WF and yield of wheat and maize in the HRB over the period 1956–2015.

3.3. Water Footprint Allocation among Administrative Units

Reasonable allocation of water resources within a river basin can reduce the competition for limited water resources among different regions and alleviate the intensified situation of water scarcity. The WF at the province (or municipality, which is the basic administrative district within the HRB) level was analyzed in the period of 2011–2015, and the results are shown in Table 5. Note that only the region located within the basin is calculated for each province or municipality.

The sum of the WF of wheat and maize is 47.39 billion m^3, which is much more than the water withdrawal of agriculture (24.76 Gm^3 $year^{-1}$). This is because the water withdrawal of agriculture excluded the green and grey water. The blue water of wheat and maize accounts for 28% of the total water withdrawal of agriculture. The total WF is 22.11 and 25.28 Gm^3 $year^{-1}$ for wheat and maize, respectively. The largest WF for wheat was found in Hebei Province, with a value of 13.12 Gm^3 $year^{-1}$ (43% green, 26% blue, and 31% grey), which accounts for 59% of the total WF of wheat in the basin. This is because Hebei has the largest arable land and crop area. The planting area of Hebei Province (2.4 Mha) occupies 60% of the HRB. The order for wheat WF is Hebei (59%) > Shandong (19%) > Henan (12%) > Shanxi (5%) > Tianjin (3%) > Beijing (2%) (Figure 5). For maize, the largest WF is also found in Hebei province, with a value of 15.93 Gm^3 $year^{-1}$ (65% green, 1% blue, and 34% grey), which accounts for 63% of the total WF of maize in the HRB. The order for maize WF is Hebei (63%) > Shandong

(13%) > Shanxi (10%) > Henan (6%) > Tianjin (5%) > Beijing (3%) (Figure 5), which is slightly different for Henan and Shanxi. The proportion of WF for maize in Henan (6%) is much smaller than that of wheat (12%) because, in Henan, wheat has a larger planting area (480 kha) than maize (290 kha) within the HRB. With wheat and maize WF combined together, Hebei province has the largest WF, which accounts for 61% of the total, followed by Shanxi (16%). Beijing and Tianjin account for 2% and 4% of the total WF, respectively.

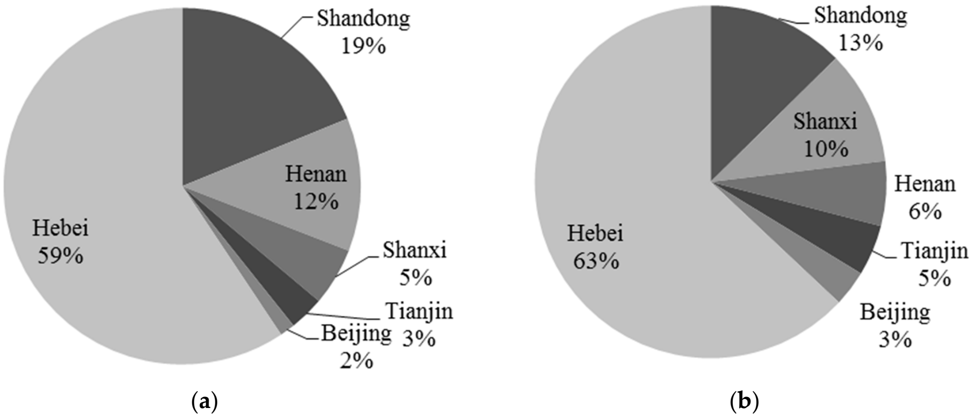

Figure 5. Allocation of WF between administrative districts within the HRB: (**a**) wheat; and (**b**) maize.

Table 5. WF for different administrative districts, 2011–2015.

Crops	Province	WF (Gm^3 $year^{-1}$)				Yield (t ha^{-1})	Unit WF (m^3 t^{-1})			
		Green	Blue	Grey	Total		Green	Blue	Grey	Total
Wheat	Beijing	0.07	0.14	0.09	0.30	5168	348	691	484	1523
	Tianjin	0.24	0.23	0.23	0.70	5211	458	440	442	1340
	Hebei	5.59	3.46	4.07	13.12	5807	408	252	298	958
	Shanxi	0.63	0.27	0.26	1.16	3866	627	268	256	1151
	Henan	1.12	0.73	0.82	2.67	6697	349	225	254	828
	Shandong	1.70	1.41	1.05	4.16	6630	347	289	215	851
	Total	9.35	6.24	6.52	22.11					
Maize	Beijing	0.41	0.01	0.41	0.83	6291	585	27	400	1012
	Tianjin	0.65	0.09	0.44	1.18	5213	652	89	440	1181
	Hebei	10.32	0.23	5.38	15.93	5341	620	13	323	956
	Shanxi	2.02	0.01	0.62	2.65	5685	561	4	173	738
	Henan	0.92	0.09	0.49	1.50	6088	526	50	279	854
	Shandong	2.18	0.13	0.88	3.19	7142	497	30	200	727
	Total	16.50	0.56	8.22	25.28					

The unit WF, which reflects the water use efficiency, was significantly different between different administrative districts in 2011–2015. The largest unit WF was found in Beijing and Tianjin for wheat and maize, respectively. The blue WF in Beijing (691 m^3 t^{-1}) was the largest for unit wheat production due to the large amount of irrigation (428 mm $year^{-1}$). Water-saving irrigation systems could be used to reduce the amount of irrigation water and improve the efficiency in the future.

3.4. Spatial Distribution of Unit Water Footprint

The unit WF of wheat and maize varies largely across regions, as shown in Figures 6 and 7. For unit wheat production, Tianjin has the largest WF on average (1956–2015). The second largest group is the region surrounding Tianjin, containing Beijing, Tangshan, and Huanghua. The remaining areas, containing Yushe, Shijiazhuang, Anyang, and Dezhou, have relatively smaller WF, because these areas are mainly grain-producing areas, especially Anyang and Dezhou, which have larger yields than the others due to efficient and centralized management.

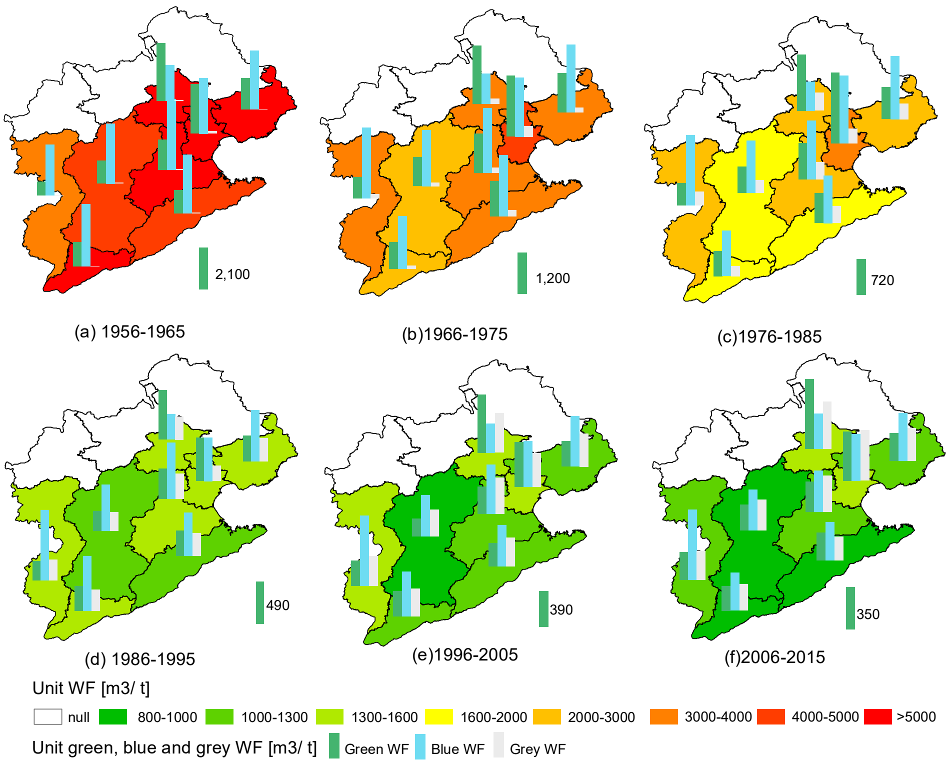

Figure 6. Unit WF of wheat in the HRB over 1956–2015 ($m^3\ t^{-1}$).

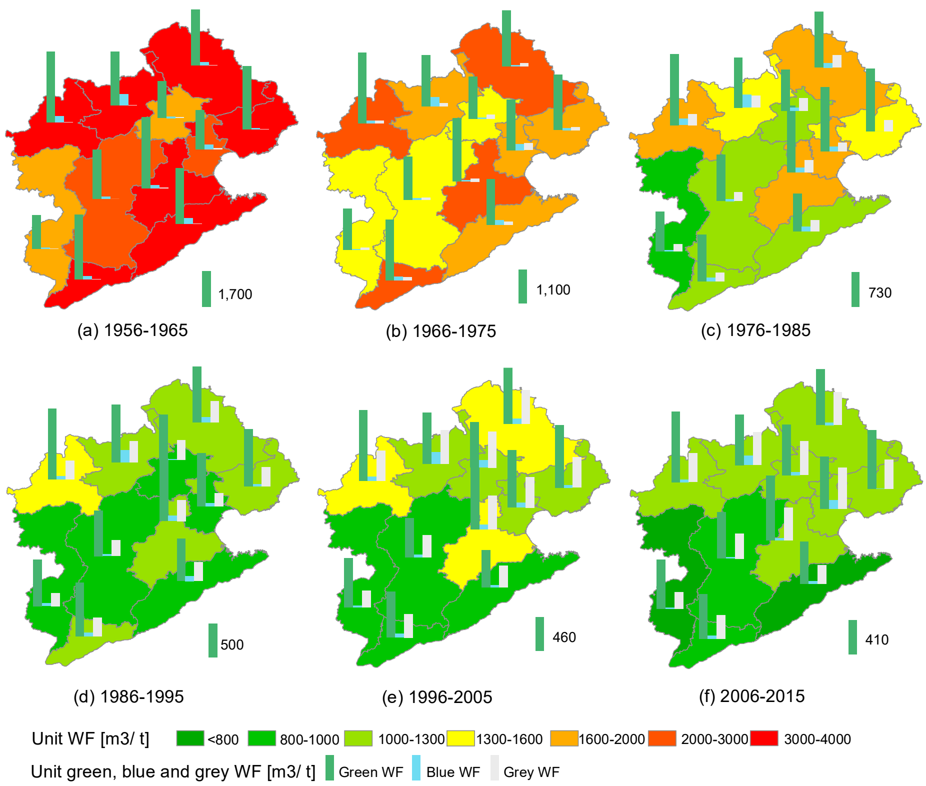

Figure 7. Unit WF of maize in the HRB over 1956–2015 ($m^3\ t^{-1}$).

The spatial distribution of unit WF for maize is different from wheat. First, the unit WF of spring maize planted in Northwestern HRB (Zhangjiakou, Chengde, and Datong) is larger than for summer maize in other regions. This is because the growing period of spring maize is longer than that of summer maize. In the summer maize-planted areas, Huanghua has the largest unit WF (1860 m^3 t^{-1}) on average. This is because the yield of maize in Huanghua is much smaller than in other regions. In contrast, relatively lower unit WF is found in the south of the HRB (e.g., Dezhou) because of the relatively higher yield.

The variation in space could be attributed to the different climate conditions, geography, soil properties, and management practices among these regions. Tianjin has the largest unit WF because of the lower yield and large application of fertilizer. Many factors might cause a lower crop yield, such as soil physiochemical properties and management practices. These factors should be further studied to improve crop productivity.

3.5. Water Footprint under Different Irrigation Conditions

Irrigation is a key factor affecting the accuracy of WF assessment. In this study, a comparison was made of the WF of wheat and maize under rain-fed and irrigated conditions with sufficient and insufficient water. The crops suffered water stress under conditions of rain-fed and insufficient irrigation, and the yields were simulated by a yield reduction fraction caused by the reduction of crop evapotranspiration proposed by Doorenbos and Kassam [54].

Maize production per hectare requires more water than wheat under all conditions. This is because maize has a much shorter growing period than wheat. The yield of wheat under sufficient water conditions is 93% larger than for rain-fed. This indicates that irrigation plays a vital role in the wheat growing period. For maize, the yield is relatively good even without irrigation, because it mainly grows in the rainy season and there is sufficient water during the crop-growing period.

For both wheat and maize, the unit WF under sufficient irrigation conditions was lower than rain-fed and crops under insufficient irrigation conditions (Table 6). This is because irrigation can significantly improve the crop yield, though more blue water is required. The result is close to other studies [17].

Table 6. Comparison of WF under different irrigation conditions, 2006–2015.

Crops	Irrigation Conditions	WF (m^3 ha^{-1})	Yield (t ha^{-1})	Unit WF (m^3 t^{-1})
Wheat	Rain-fed	4029	4.21	957
	Sufficient irrigation	7427	8.11	916
	Insufficient irrigation	6096	6.58	926
Maize	Rain-fed	4952	5.5	900
	Sufficient irrigation	5198	5.85	889
	Insufficient irrigation	5116	5.73	893

4. Discussion

4.1. Comparison of Unit Water Footprint with Other Studies

Results of unit WF in this study are compared to studies by Mekonnen and Hoekstra [17] during 1996–2005 and Cao et al. [21] in 2010 who estimated unit WF in each province of China, and their results were calculated in the HRB (Table 7). This can illustrate the discrepancies between large-scale datasets and what happens on a more local level [55].

Table 7. The comparison of unit WF with other studies in the HRB.

Study	Period	Crops	Unit WF in the HRB (m^3 t^{-1})			
			Green	Blue	Grey	Total
Mekonnen and Hoekstra [17]	1996–2005	Wheat	650	608	436	1694
This study			536	281	347	1164
Cao et al. [21]	2010	Wheat	597	329	-	926
This study			491	287	315	1093
Mekonnen and Hoekstra [17]	1996–2005	Maize	791	115	293	1199
This study			676	41	354	1071

For wheat, the unit WF in this study is 31% lower than that estimated by Mekonnen and Hoekstra [17] in 1996–2005 in the HRB. The green, blue, and grey WF in this study are 18%, 54%, and 20% lower than their estimates, respectively. That might be due to the different yield and irrigation areas. The yield estimated by Mekonnon and Hoekstra [17] was simulated by water stress proposed by Doorenbos and Kassam [54]. The maximum yield values were obtained by multiplying the corresponding national average yield values (4.0 t ha^{-1} in China in 1996–2005) by a factor of 1.2. The calculated yields were scaled to fit the national average FAO yield data [56] while, in this study, the yield of each province (4.8 t ha^{-1} in the HRB in 1996–2005) was obtained from the statistical data [42], which is 20% larger than the national average. The difference of yield might explain the discrepancy of green and grey WF, while the discrepancy of blue WF might be explained by different irrigation areas. Mekonnon and Hoekstra [17] used irrigation areas from the MICRA2000 grid database [57], which is larger than the irrigation areas from the statistical data [42] in this study.

To compare with Cao et al. [21], this study estimated the unit consumptive WF (green WF plus blue WF) for wheat in 2010, which was 778 m^3 t^{-1}, 16% lower than Cao et al. [21]. The green and blue WF are 18% and 13% lower than their estimates, respectively. In their study, the yield was obtained from the statistical yearbook of each province, which was the same as this study. The green WF being higher than this study could mainly be due to different calculation methods. Cao et al. [21] estimated green WF by effective precipitation on a 10-day time step, while in this study a daily water balance model was used, referring to Allan et al. [47]. The blue WF is higher than this study, because in their study it is the sum of the evaporated surface water from the water intake point to the field and the field evapotranspiration, while, in this study, only the field evapotranspiration is taken into account.

For maize, the unit WF in this study is 11% lower than the estimate by Mekonnen and Hoekstra [17] in 1996–2005 in the HRB. This can be explained by the discrepancy of green WF. Green WF takes a large proportion of evapotranspiration (the green water coefficient is 95% in this study) in the maize growing period. The green WF estimated by Mekonnen and Hoekstra [17] in the HRB was 15% larger than this study; this could mainly be due to the different growing period, since the yield estimated by Mekonnen and Hoekstra [17] is close to this study. The growing period estimated in this study (112 days) is based on the observed values provided by the China Meteorological Administration [51], and that estimated by Mekonnen and Hoekstra [17] was based on the FAO [56], which is at least 125 days for the growing period of maize. The longer growing period could result in higher evapotranspiration. The grey WF estimated by Mekonnen and Hoekstra [17] is lower than this study, which could be because that study assumed that crops receive the same amount of nitrogen fertilizer per hectare in all grid cells in a country, while in this study the application amount of nitrogen fertilizer of each province published by CAM [42] was used.

4.2. Management of Green and Blue Water

Green water accounts for a large proportion of consumptive WF, which is 65% and 96% for wheat and maize, respectively. This indicates that climate (precipitation) contributes more to WF than human activities (irrigation) in the HRB. Attention should be paid to the utilization of rain water in water-stressed arid and semi-arid environments in the future, which is an important way to alleviate the stress from water scarcity. For example, water ponds for rainwater harvesting and utilization could be built to promote rainwater utilization. Terraces could be built in mountainous areas of the Western HRB to improve rainwater use efficiency. Additionally, planting and harvesting dates should be carefully planned for utmost utilization of rainwater, though the precipitation is highly variable.

Blue water plays a vital role in the growing period of wheat and maize in the HRB [32,58]. Irrigation can improve crop production to feed more people, and could also improve water use efficiency (irrigated crops have smaller unit water footprint). Hence, we can build some water supply facilities in some water scarce regions for irrigation. Additionally, we can develop water-saving technologies, like drip irrigation, which can improve blue water use efficiency [59]. Considering that using blue water costs much more than using green water, especially in many water-scarce regions, we should comprehensively consider the degree of water shortage, water costs, economic levels, and the requirement of food in future agricultural water management.

4.3. Limitations in This Study

There were a number of limitations and uncertainties during the assessment of WF in this study. First, the limited data influences the accuracy of WF accounting and spatial distribution. In this study, only 11 weather stations were selected for WF assessment. Spatial and temporal climate variability could not be clearly shown over such large areas. The proportion of irrigated crops is assumed to be the same in each province (or municipality). The soil conditions are assumed to be uniform and the effect of terrain is not taken into account. Second, the same planting dates and length of growing period are assumed during the study period of 60 years. The temporal differences of planting dates and the length of growing period under climate variability were not taken into account, which could affect the crop WF calculation. Third, the irrigation data were chosen based on a series of norms of the water intake in each province. Though it is close to the real irrigation situation, there are still some discrepancies in different hydrological years. In addition, the crop parameters are assumed to be the same for both irrigated and rain-fed crops, following Mekonnen and Hoekstra [17]. However, in rain-fed crops, roots are deeper than those in irrigated crops, and that affects the soil water balance in the root zone. More accurate irrigation amounts and crop parameters for irrigated and rain-fed crops should be used in future studies to enhance the accuracy of agricultural WF assessment.

5. Summary and Conclusions

The spatial and temporal characteristics of WF of wheat and maize are analyzed in the period 1956–2015 in the HRB. The major portion of total WF comes from green water, especially for maize production, indicating that we should pay more attention to the management of rain water in the future. In all, 19% and 24% of total WF are required to eliminate agricultural water pollution for wheat and maize, respectively. Those are much higher percentages than the world average, indicating that fertilizer use efficiency should be improved in the future. The total WF of wheat and maize varied largely in 1956–2015, mainly following the changing planting areas.

Per ton of crop, wheat (1581 m^3 t^{-1}) required more water than maize (1275 m^3 t^{-1}). The unit WF of wheat and maize both have exponentially decreasing trends due to increasing production, indicating that water use efficiency has improved. However, increased production was mainly caused by increased fertilizer use, resulting in increased grey water.

Considering the total WF of crop production allocation based on administrative districts (only the area located in the HRB was considered), Hebei Province has the largest WF of both wheat and maize, which accounts for 61% of the total WF, followed by Shanxi (16%), and Beijing and Tianjin account for 2% and 4% of the total WF, respectively. The allocation of WF between administrative districts within the HRB provides an effective way to reduce the conflict among different regions over competition for limited water resources.

The WF varies largely in space. Spring maize has relatively larger unit WF than summer maize. Tianjin has the largest unit WF for wheat because of the poor yield and large application of fertilizer. Other factors might also cause poor crop yield, such as soil physicochemical properties and management practices. These factors should be further studied to improve water productivity. Spring maize has relatively larger unit WF than summer maize due to the longer growing period.

A comparison was made of the WF of wheat and maize under different irrigation conditions. Maize production per hectare requires more water than wheat for all conditions. For both wheat and maize, the unit WF under sufficient irrigation conditions is lower than rain-fed and crops under insufficient irrigation conditions, though much blue water is consumed.

Overall, this study assessed the WF of wheat and maize in HRB of Northern China over the period 1956–2015. The WF analysis for wheat and maize in the HRB shows very large spatial and temporal variations. Analyzing the spatial and temporal characteristics of WF is helpful for basin agencies to make proper water management decisions to improve agricultural water use efficiency and control diffuse agricultural water pollution.

In future studies, in order to improve the accuracy of WF assessment, high-resolution climate datasets and detailed soil datasets should be considered. Meanwhile, in order to obtain more accurate WF and calibrate and validate the model parameters, the soil water conditions and crop growing status in the HRB should be monitored by field experiments.

Author Contributions: Y.H. and D.J. conceived, designed, and drafted the manuscript; D.J. and H.H. planned and designed the methodology; L.Z., S.S., and J.-M.S.-P. revised the manuscript; Y.H. and C.W. guided and supervised the whole process; and all authors read and approved the final manuscript.

Funding: This research received no external funding.

Acknowledgments: This study was funded by the National Key Research and Development Program of China (2016YFC0401402), the National Natural Science Foundation of China (51279063; 51679089; 51609084; 51709107), and the Innovation Foundation of North China University of Water Resources and Electric Power for PhD Graduates. The authors also thank the editor and two anonymous reviewers for their insightful comments and constructive suggestions.

Conflicts of Interest: No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

References

1. Oki, T.; Kanae, S. Global hydrological cycles and world water resources. *Science* **2006**, *313*, 1068–1072. [CrossRef] [PubMed]
2. Vörösmarty, C.J.; Green, P.; Salisbury, J.; Lammers, R.B. Global water resources: Vulnerability from climate change and population growth. *Science* **2000**, *289*, 284–288. [CrossRef] [PubMed]
3. Vörösmarty, C.J.; McIntyre, P.; Gessner, M.O.; Dudgeon, D.; Pusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liermann, C.R. Global threats to human water security and river biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef] [PubMed]
4. FAO. *Coping with Water Scarcity: An Action Framework for Agriculture and Food Security*; Food and Agriculture Organization of United States (FAO): Rome, Italy, 2012.
5. Pimentel, D.; Berger, B.; Filiberto, D.; Newton, M.; Wolfe, B.; Karabinakis, E.; Clark, S.; Poon, E.; Abbett, E.; Nandagopal, S. Water resources: Agricultural and environmental issues. *BioScience* **2004**, *54*, 909–918. [CrossRef]
6. Falkenmark, M.; Rockström, M. *Balancing Water for Man and Nature: The New Approach to Ecohydrology*; Routledge: London, UK, 2004.
7. Falkenmark, M.; Rockström, J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *J. Water Resour. Plan. Manag.* **2006**, *132*, 129–132. [CrossRef]
8. Hoekstra, A.Y. Virtual Water Trade. In *Proceedings of the International Expert Meeting on Virtual Water Trade, Delft, The Netherlands, 12–13 December 2002*; Value of Water Research Report Series No. 12; UNESCO-IHE: Delft, The Netherlands, 2003.

9. Chenoweth, J.; Hadjikakou, M.; Zoumides, C. Review article: Quantifying the human impact on water resources: A critical review of the water footprint concept. *Hydrol. Earth Syst. Sci. Discuss.* **2013**, *10*, 9389–9433. [CrossRef]
10. Hoekstra, A.Y.; Mekonnen, M.M. The water footprint of humanity. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 3233–3237. [CrossRef] [PubMed]
11. Hoekstra, A.Y.; Chapagain, A.K. Water footprint of nations: Water use by people as a function of their consumption pattern. *Water Resour. Manag.* **2007**, *21*, 35–38. [CrossRef]
12. Hoekstra, A.Y. Water footprint assessment: Evolvement of a new research field. *Water Resour. Manag.* **2017**, *31*, 3061–3081. [CrossRef]
13. Hoekstra, A.Y. Human appropriation of natural capital: Comparing ecological footprint and water footprint analysis. *Ecol. Econ.* **2007**, *68*, 1963–1974. [CrossRef]
14. Allan, J.A. Overall perspectives on countries and regions. In *Water in the Arab World: Perspectives and Prognoses*; Rogers, P., Lydon, P., Eds.; Harvard University Press: Cambridge, MA, USA, 1994; pp. 65–100.
15. Allan, J.A. Virtual water: A strategic resources global solutions to regional deficits. *Ground Water* **1998**, *36*, 545–546. [CrossRef]
16. Mekonnen, M.M.; Hoekstra, A.Y. A global and high-resolution assessment of the green, blue and grey water footprint of wheat. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 1259–1276. [CrossRef]
17. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1600. [CrossRef]
18. Siebert, S.; Döll, P. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *J. Hydrol.* **2010**, *384*, 198–217. [CrossRef]
19. Zhuo, L.; Mekonnen, M.M.; Hoekstra, A.Y. Benchmark levels for the consumptive water footprint of crop production for different environmental conditions: A case study for winter wheat in China. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 4547–4559. [CrossRef]
20. Zhuo, L.; Mekonnen, M.M.; Hoekstra, A.Y. Consumptive water footprint and virtual water trade scenarios for China with a focus on crop production, consumption and trade. *Environ. Int.* **2016**, *94*, 211–223. [CrossRef] [PubMed]
21. Cao, C.X.; Wu, P.T.; Wang, Y.B.; Zhao, X.N. Assessing blue and green water utilization in wheat production of China from the perspectives of water footprint and total water use. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 3165–3178. [CrossRef]
22. Zoumides, C.; Bruggeman, A.; Hadjikakou, M.; Zachariadis, T. Policy-relevant indicators for semi-arid nations: The water footprint of crop production and supply utilization of Cyprus. *Ecol. Indic.* **2014**, *43*, 205–214. [CrossRef]
23. Schyns, J.F.; Hoekstra, A.Y. The added value of water footprint assessment for national water policy: A case study for Morocco. *PLoS ONE* **2014**, *9*, e99705. [CrossRef] [PubMed]
24. Bulsink, F.; Hoekstra, A.Y.; Booij, M.J. The water footprint of Indonesian provinces related to the consumption of crop products. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 119–128. [CrossRef]
25. Duan, P.; Qin, L.; Wang, Y.; He, H. Spatiotemporal correlations between water footprint and agricultural inputs: A case study of maize production in Northwest China. *Water* **2015**, *7*, 4026–4040. [CrossRef]
26. Gobin, A.; Kersebaum, K.C.; Eitzinger, J.; Trnka, M.; Hlavinka, P.; Takáč, J.; Kroes, J.; Ventrella, D.; Marta, A.D.; Deelstra, J.; et al. Variability in the water footprint of arable crop production across European regions. *Water* **2017**, *9*, 93. [CrossRef]
27. Aldaya, M.M.; Llamas, M.R. *Water Footprint Analysis for the Guadiana River Basin*; Research Report Series No. 35; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2008.
28. Yin, J.; Wang, H.; Cai, Y. Water footprint calculation on the basis of input-output analysis and a biproportional algorithm: A case study for the Yellow River basin, China. *Water* **2016**, *8*, 363. [CrossRef]
29. Zeng, Z.; Liu, J.; Koeneman, P.H.; Zarate, E.; Hoekstra, A.Y. Assessing water footprint at river basin level: A case study for the Heihe River Basin in northwest China. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 2771–2781. [CrossRef]
30. Zang, C.F.; Liu, J.; van der Velde, M.; Kraxner, F. Assessment of spatial and temporal patterns of green and blue water flows under natural conditions in inland river basins in Northwest China. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 2859–2870. [CrossRef]
31. Zhuo, L.; Mekonnen, M.M.; Hoekstra, A.Y.; Wada, Y. Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River Basin (1961–2009). *Adv. Water Resour.* **2016**, *87*, 29–41. [CrossRef]

32. Sun, S.K.; Wu, P.T.; Wang, Y.B.; Zhao, X.N.; Liu, J.; Zhang, X.H. The impacts of inter-annual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. *Sci. Total Environ.* **2013**, *444*, 498–507. [CrossRef] [PubMed]
33. Chukalla, A.D.; Krol, M.S.; Hoekstra, A.V. Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4877–4891. [CrossRef]
34. Shang, S.H.; Mao, X.M. Application of simulation based optimization model for winter wheat irrigation scheduling in North China. *Agric. Water Manag.* **2006**, *85*, 314–322. [CrossRef]
35. National Bureau of Statistics of the People's Republic of China. *Population Census of China in 2010*; National Bureau of Statistics of the People's Republic of China: Beijing, China, 2011.
36. Bao, Z.X.; Zhang, J.Y.; Wang, G.Q.; Fu, G.B.; He, R.M.; Yan, X.L.; Jin, J.L.; Liu, Y.L.; Zhang, A.J. Attribution for decreasing stream flow of the Haihe River Basin, northern China: Climate variability or human activities? *J. Hydrol.* **2012**, *460–461*, 117–129. [CrossRef]
37. Sun, S.K.; Wang, Y.B.; Wu, P.T.; Zhao, X.N. Spatial variability and attribution analysis of water footprint of wheat in China. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 142–148. (In Chinese)
38. CMWR (Ministry of Water Resources of China). *China Water Resources Bulletin 2011*; China Water and Power Press: Beijing, China, 2012.
39. Zou, J.; Xie, Z.H.; Zhan, C.S.; Qin, P.H.; Sun, Q.; Jia, B.H.; Xia, J. Effects of anthropogenic groundwater exploitation on land surface processes: A case study of the Haihe River Basin, northern China. *J. Hydrol.* **2015**, *524*, 625–641. [CrossRef]
40. Haihe River Water Conservancy Commission, Ministry of Water Resources. Groundwater Bulletin in Haihe River Basin. September 2013. Available online: http://www.hwcc.gov.cn/ (accessed on 15 March 2018).
41. FAO; IIASA; ISRIC; ISS-CAS; JRC. *Harmonized World Soil Database (Version 1.1)*; FAO: Rome, Italy; IIASA: Laxenburg, Austria, 2009.
42. CAM (China Agriculture Ministry). The Department of Plantation Management of China Agriculture Ministry. Available online: http://zzys.agri.gov.cn/nongqing.aspx (accessed on 23 October 2017).
43. Ministry of Water Resources of China; Department of Water Resources and Water Resources Management Center. *Norm of Water Intake for Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan of China (DB13/T 1161.1–2009; DB14/T 1049.1–2015; DB41/T 958–2014; and DB12/T 159.01–2003)*; Ministry of Water Resources of China: Beijing, China, 2013.
44. Hoekstra, A.Y.; Chapagain, A.K.; Aldaya, M.M.; Mekonne, M.M. *The Water Footprint Manual: Setting the Global Standard*; Earthscan: London, UK, 2011.
45. Liu, J.; Zehnder, A.J.B.; Yang, H. Global consumptive water use for crop production: The importance of green water and virtual water. *Water Resour. Res.* **2009**, *45*, W05428. [CrossRef]
46. Chapagain, A.K.; Hoekstra, A.Y.; Savenije, H.H.G.; Gautam, R. The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cottern producing countries. *Ecol. Econ.* **2006**, *60*, 186–203. [CrossRef]
47. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*; FAO Drainage and Irrigation Paper 56; Food and Agriculture Organization: Rome, Italy, 1998.
48. Zhuo, L.; Mekonnen, M.M.; Hoekstra, A.Y. Sensitivity and uncertainty in crop water footprint accounting: A case study for the Yellow River Basin. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2219–2234. [CrossRef]
49. Chen, Y.; Guo, G.; Wang, G.; Kang, S.; Luo, H.; Zhang, D. *Main Crop Water Requirement and Irrigation of China*; Hydraulic and Electric Press: Beijing, China, 1995.
50. Kang, S.Z.; Gu, B.J.; Du, T.S.; Zhang, J.H. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. *Agric. Water Manag.* **2003**, *59*, 239–254. [CrossRef]
51. CMA (China Meteorological Administration). China Meteorological Data Sharing Service System, Beijing, China. Available online: http://data.cma.cn/ (accessed on 29 November 2016).
52. NBSC (National Bureau of Statistics of China). *China Statistical Yearbook (1983–2015)*; China Statistical Press: Beijing, China, 1984–2016.
53. Zhou, X.; Pang, J.; Wu, Q.; Huang, H.; Cai, Y.; Chen, G. *China First Census for Water. Data Compilation of National Water Conservancy*; China Water and Power Press: Beijing, China, 2016.
54. Doorenbos, J.; Kassam, A.H. *Yield Response to Water*; Drainage and Irrigation Paper 33, FAO Irrigation and Drainage Paper N°33; FAO: Rome, Italy, 1979.

55. Zoumides, C.; Bruggeman, A.; Zachariadis, T. Global versus Local Crop Water Footprints: The Case of Cyprus. In *Solving the Water Crisis: Common Action toward a Sustainable Water Footprint*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2012; p. 7.
56. FAO. FAOSTAT On-Line Database, Food and Agriculture Organization of United States, Rome. 2008. Available online: http://faostat.fao.org (accessed on 10 October 2008).
57. Portmann, F.T.; Siebert, S.; Döll, P. MIRCA2000—Global Monthly Irrigated and Rainfed Crop Areas around the Year 2000: A New High-Resolution Data Set for Agricultural and Hydrological Modeling. *Global Biogeochem. Cycles* **2010**, *24*, GB1011. Available online: http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/data_download/index.html (accessed on 15 October 2009). [CrossRef]
58. Sun, S.K.; Wu, P.T.; Wang, Y.B.; Zhao, X.Y. Temporal Variability of water footprint for maize production: The case of Beijing from 1978 to 2008. *Water Resour. Manag.* **2013**, *27*, 2447–2463. [CrossRef]
59. Zwart, S.J.; Bastiaanssen, W.G.M. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manag.* **2004**, *69*, 115–133. [CrossRef]