Water footprint of crop production for different crop structures in the Hebei southern plain, North China

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Abstract

The North China Plain (NCP) has serious shortage of fresh water resources, and crop production consumes approximately 75% of the region's water. To estimate water consumption of different crops and crop structures in the NCP, the Hebei southern plain (HSP) was selected as a study area, as it is a typical region of groundwater overdraft in the NCP. In this study, the water footprint (WF) of crop production, comprised of green, blue and grey water footprints, and its annual variation was analyzed. The results demonstrated the following: (1) the WF from the production of main crops was 41.8 km^3 in 2012. Winter wheat, summer maize and vegetables were the top water-consuming crops in the HSP. The water footprint intensity (WFI) of cotton was the largest, and for vegetables, it was the smallest; (2) The total WF, WFblue, WFgreen and WFgrey for 13 years (2000-2012) of crops production were 604.8 km^3, 288.5 km^3, 141.3 km^3 and 175.0 km^3, respectively, with an annual downtrend from 2000 to 2012; (3) Winter wheat, summer maize and vegetables consumed the most groundwater, and their blue water footprint (WFblue) accounted for 74.2% of the total WFblue in the HSP; (4) The crop structure scenarios analysis indicated that, with approximately 20% of arable land cultivated with winter wheat-summer maize in rotation, 38.99% spring maize, 10% vegetables and 10% fruiters, a sustainable utilization of groundwater resources can be promoted, and a sufficient supply of food, including vegetables and fruits, can be ensured in the

HSP.

Keywords: Hebei southern plain; water footprint; crop production; crop structure; scenario analysis

1 Introduction

Due to excessive water usage, freshwater scarcity has becoming a threat to human society (Dong et al., 2013). Worldwide, the largest freshwater consumer is agriculture, consuming more than 70% of the world's freshwater (UNEP, 2007; Lucrezia et al., 2014). Water resources have been heavily exploited by agriculture worldwide (Konar et al., 2011) and to ensure the increasing food demand, global water consumption has almost doubled during the past 40 years (Gleick, 2003), and future water use for food production will continue to be influenced by population growth and changes in dietary preferences (Rosegrant and Ringler, 2000), which will lead to the consumption of more water resources. China is a freshwater-poor country with approximately 2100 m^3/y of water resources per capita, accounting for only 28% of the world's per capita share. The spatial mismatch between water and arable land reinforces China's water challenge. About 70% arable land in the north of the Yangze River contains only approximately 17% of the national total water resources. Due to the current water shortage in the area north of the Yangze River, the NCP is facing its most severe water scarcity issue. The NCP presently contains only 1.3% of China's total available water with 225 m^3/y per capita (White et al., 2015).

As a method to assess the water use of production systems, the water footprint (WF) concept was proposed (Heokstra, 2003), which includes direct and indirect water usage of a consumer or producer (Hoekstra et al., 2009). In recent years, many researchers have used the WF to evaluate water use in agricultural production (Bocchiola et al., 2013; Chapagain and Hoekstra, 2011; Chapagain and Orr, 2009; Gheewala et al., 2014; Jefferies et al., 2012; Lamastra et al., 2014; Mekonnen and Hoekstra, 2010, Shrestha et al., 2013; Wang et al., 2014; Xu et al., 2014; Zang et al.,2014; Wang et al., 2015; Suttayakul et al., 2016). The WF of crops reflects the water consumption of different crops, and can focused on local crop products. For each crop, the blue WF (WFblue) refers to the volume of irrigation water consumed, the green WF (WFgreen) is consistent with the effective rainfall for plants, and the grey WF (WFgrey) represents the volume of water required to dilute pollutants to the agreed maximum acceptable levels (Hoekstra and Chapagain, 2007). Since the water consumption of each crop is different, the WF for different crops varies greatly. Xu et al. (2014) analyzed the WF of six kinds of crops in Beijing from 1978 to 2012, and found maize accounts for 57% of the green WF and 46% of the grey WF, vegetables account for 45% of the blue WF, and wheat accounts for 26% of the total WF. Wang et al. (2015) found that winter wheat conserved approximately 1.9×10^9 m^3 yr^{-1} of WFblue from 1998 to 2011 in the Hebei Plain.

The Hebei southern plain (HSP) was selected as the study area. It is located in the northwest of the NCP and has approximately 4.0×10^4 km^2 of arable land (accounting for approximately 13% of the NCP and 3% of China's total). In 2008, the HSP produced approximately 2.7×10^{10} kg of grain (accounting for approximately 5% of China's total) that had a water consumption approximately 3.0×10^{10} m^3 (Yuan and Shen, 2013). The over-exploitation of groundwater in this region has had devastating consequences: the groundwater table has decreased by more than 20 m within the past 30 years (Chen et al., 2003; Hu and Cheng, 2011). Because the WF of various crops is different and the crop structure of a region reflects the proportion of various crops growing within that region, the WF of the crop structure can illustrate the entire agricultural water consumption of that region. The study of the WF for crop structures can help promote the sustainable utilization of water resources for agriculture, and can be particularly valuable for areas facing water shortage.

The main aims of this study were: (1) to quantify the WF of production of main crops in the HSP from 2000 to 2012 and (2) to discuss a reasonable crop structure based on the WF analysis for different crop structure scenarios. In this study, we propose a suitable crop planting structure for this region, and support the development and implementation of policies on agricultural water management.

2 Materials and methods

2.1 Study area

The Hebei southern plain (114º20'E-119º25'E, 36º03'N-39º56'N), with an area of approximately 62,000 km^2, are located in southern Beijing and Tianjin (Fig. 1). The climate in this region is temperate monsoon with a mean annual precipitation of 550 mm and a mean annual temperature of 11.5 ºC. Precipitation has a non-uniform distribution throughout the year, and approximately 80% of the total precipitation occurs from July through September. In the HSP, most arable lands are irrigated by groundwater except in the eastern part where there is saline shallow groundwater. The primary crops in the plain are wheat, maize (including summer maize and spring maize), cotton, and peanut; the main vegetable crops are Chinese cabbage, celery, cauliflower, onion, bean, rape, leek, coriander, fennel, and the main fruits are apple, pear, jujube and grape.

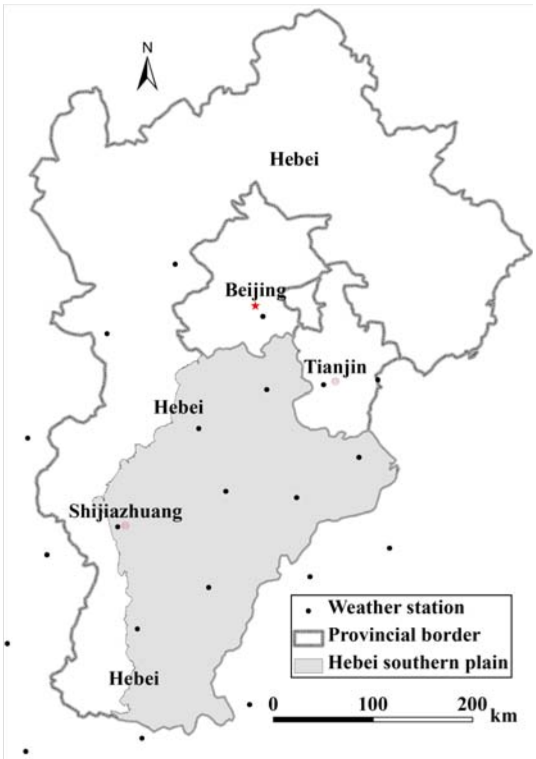

Fig. 1 Location of the Hebei southern plain

2.2 Data collection

The meteorological data from 21 weather stations (Fig. 1) around the HSP, including daily maximum temperature, minimum temperature, average temperature, wind speed, relative humidity, precipitation, sunshine duration, vapor pressure, and atmospheric pressure, were obtained from the China Meteorological Data Sharing Service System (China Meteorological Administration, 2000-2012).

The statistics data for the plain from 2000 to 2012, including crop yield, crop acreage and fertilization, were obtained from Hebei economic statistical yearbooks; and the data for water withdrawal were obtained from the water resources bulletins and relevant statistical yearbooks. The land-use map of the HSP for 2012 (Fig. 2) was drawn based off of spot satellite images and a topographic map (1:10000). The main land-use types include cropland, urban, forestland, water, orchard, wetland, grassland and shrub land (Table. 1).

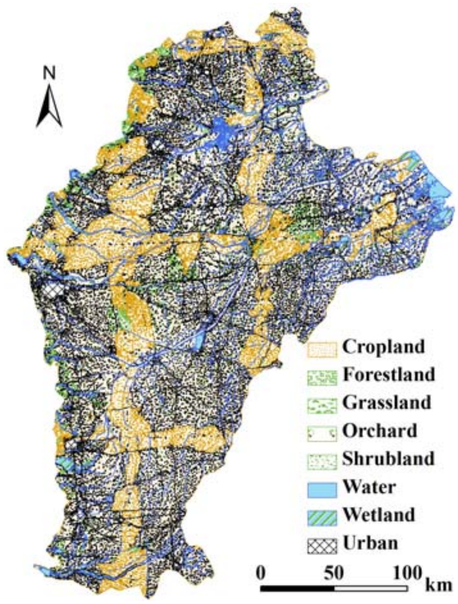

Fig. 2 Land-use map of the Hebei southern plain

Table 1 Area of each land-use type and their ratios (%)

Land-use	Forestland	Shrub land	Grassland	Cropland	Orchard	Building land	Waters	Wetland	Total
Area(10^5 hm^2)	3.66	0.31	0.72	42.80	2.61	7.02	2.91	1.83	61.85
%	5.91	0.49	1.17	69.20	4.21	11.35	4.70	2.95	100

The crop structure data were produced based on remote sensing data for this study area from 2000 to 2012 (Table. 2), which included MODIS NDVI (MOD13Q1), Terra/MODIS (MOD12Q1), and Landsat TM/ETM with spatial resolutions of 250 m, 1000 m and 30 m, respectively. Pan et al. (2015) and Wang et al. (2015) presented the details of this method. Compared with 2000, the crop planting area changed considerably; specifically, the planting area of winter maize-summer maize decreased by 34.76%, rice decreased by 31.61%, spring maize increased by 34.13%, vegetables increased by 26.05%, and fruiters increased by 33.04%, while cotton, peanut and others had a slight change, and the total cultivated area in HSP decreased by 12.58% in 2012 (Table. 2).

Table 2 Planting areas (10^5 hm^2) for the main crops and their percent change

Year	Winter wheat-summer maize	Spring maize	Vegetables	Fruiters	Cotton	Peanut	Rice	Others	Total
2000	29.54	3.89	6.72	1.96	5.59	2.42	0.44	1.38	51.94
2001	25.20	3.67	7.46	2.05	5.15	2.69	0.49	1.54	48.23
2002	22.79	3.91	6.85	2.26	7.27	2.47	0.45	1.41	47.41
2003	24.40	3.76	7.09	2.03	2.82	3.26	0.39	1.87	45.63
2004	24.11	4.89	7.27	1.86	3.45	2.86	0.34	1.64	46.42
2005	24.64	3.40	7.20	2.15	5.04	2.59	0.31	1.48	46.82
2006	24.69	4.41	6.96	1.76	4.24	2.51	0.30	1.43	46.31
2007	22.37	5.25	6.89	2.14	6.99	2.48	0.45	1.42	48.00
2008	24.31	4.18	7.43	2.36	4.62	2.68	0.32	1.53	47.43
2009	25.19	3.64	7.25	2.25	3.74	2.61	0.31	1.49	46.49
2010	23.24	4.85	7.20	2.12	3.99	2.59	0.31	1.48	45.79
2011	20.65	4.36	7.54	1.94	5.74	2.72	0.33	1.55	44.83
2012	19.27	5.22	8.47	2.61	5.61	2.50	0.30	1.43	45.41
Change (%)	-34.76	34.13	26.05	33.04	0.39	2.64	-31.61	3.27	-12.58

2.3 Crop structure scenarios setting

The baseline for the crop structure (2012) in the HSP, consisted of 42.44% of winter wheat-summer maize rotation, 11.50% of spring maize, 18.65% of vegetables, 5.75% of fruiters, 12.35% of cotton, 5.51% of peanut, 0.66% of rice, and 3.15% of others (side crops i.e., millet, sorghum, sweet potato and others). Taking into consideration the crop structure change from 2000 to 2012, the high ground-water usage for rice and winter wheat per unit and the local residents' pasta-based diet, eight different crop structure planning scenarios were formulated with the cotton, peanut and side-crops cultivating areas unchanged (Table 3). These scenarios involved reducing winter wheat-summer maize and rice cultivating area to 40% and 0% respectively; and increasing spring maize cultivating area to 13.94% (scenario 1); reducing winter wheat-summer maize to 30% and increasing spring maize to 23.94% (scenario 2); reducing winter wheat-summer maize to 20% and increasing spring maize to 33.94% (scenario 3); reducing winter wheat-summer maize to 10% and increasing spring maize to 43.94% (scenario 4); reducing winter wheat-summer maize to 0 and increasing spring maize to 53.94% (scenarios 5); reducing winter wheat-summer maize to 20% and increasing spring maize to 38.99%, and adjusting vegetables and fruiters to 10% (scenario 6); reducing winter wheat-summer maize to 20%, increasing spring maize to 28.99%, vegetables to 20% and fruiters to 10% (scenario 7); reducing winter wheat-summer maize to 20%, increasing spring maize to 28.99%, decreasing vegetables to 10% and increasing fruiters to 20% (scenario 8) .

Table 3 Crop structure planning scenarios for the Hebei southern plain

Crop structure		Winter wheat-summer maize	Spring maize	Vegetables	Fruiters	Cotton	peanut	Rice	Others	Total
Baseline	Area(10^5 hm^2)	19.27	5.22	8.47	2.61	5.61	2.50	0.30	1.43	45.41
	%	42.44	11.50	18.65	5.75	12.35	5.51	0.66	3.15	100
Scenario 1	Area(10^5 hm^2)	18.16	6.33	8.47	2.61	5.61	2.50	0	1.43	45.41
	%	40.00	13.94	18.65	5.75	12.35	5.51	0	3.15	100
Scenario 2	Area(10^5 hm^2)	13.62	10.87	8.47	2.61	5.61	2.50	0	1.43	45.41
	%	30.00	23.94	18.65	5.75	12.35	5.51	0	3.15	100
Scenario 3	Area(10^5 hm^2)	9.08	15.41	8.47	2.61	5.61	2.50	0	1.43	45.41
	%	20.00	33.94	18.65	5.75	12.35	5.51	0	3.15	100
Scenario 4	Area(10^5 hm^2)	4.54	19.95	8.47	2.61	5.61	2.50	0	1.43	45.41
	%	10.00	43.94	18.65	5.75	12.35	5.51	0	3.15	100
Scenario 5	Area(10^5 hm^2)	0	24.49	8.47	2.61	5.61	2.50	0	1.43	45.41
	%	0	53.94	18.65	5.75	12.35	5.51	0	3.15	100
Scenario 6	Area(10^5 hm^2)	9.08	17.71	4.54	4.54	5.61	2.50	0	1.43	45.41
	%	20.00	38.99	10.00	10.00	12.35	5.51	0	3.15	100
Scenario 7	Area(10^5 hm^2)	9.08	13.16	9.08	4.54	5.61	2.50	0	1.43	45.41
	%	20.00	28.99	20.00	10.00	12.35	5.51	0	3.15	100
Scenario 8	Area(10^5 hm^2)	9.08	13.16	4.54	9.08	5.61	2.50	0	1.43	45.41
	%	20.00	28.99	10.00	20.00	12.35	5.51	0	3.15	100

2.4 WF evaluation

The WF of a crop production is the sum of the green, blue and grey water footprints (Chapagain et al., 2006). The WF of seven primary type of crops planted in the HSP is calculated separately:

$$WF = \sum_{a=1}^{n} WF_a \qquad (1)$$

$$WF = WF_{blue} + WF_{green} + WF_{grey} \qquad (2)$$

where WF is the total water footprint (m^3 yr^{-1}); WF_a is the water footprint of each type of crop in the HSP; WF_{blue} is the blue water footprint (m^3 yr^{-1}); WF_{green} is the green water footprint (m^3 yr^{-1}), and WF_{grey} is the grey water footprint (m^3 yr^{-1}).

The WF intensity (*WFI*) of a crop production is evaluated by dividing *WF* with crop yield:

$$WFI_a = WF_a / Y_a \qquad (3)$$

where WFI_a is the WF intensity of a certain crop (m^3 ton^{-1}) and Y_a is the yield of that kind of crop (ton).

The green water footprint was represented by crop evaporation or effective rainfall:

$$WF_{blue} = 10 \times ET_{blue} \times A \qquad (4)$$

$$WF_{green} = 10 \times ET_{green} \times A \tag{5}$$

$$ET_{blue} = \max\{0, ET_c - P_e\} \tag{6}$$

$$ET_{green} = \min\{P_e, ET_c\} \tag{7}$$

where ET_{blue} is the blue water evapotranspiration during the growth period of crops (mm); ET_{green} is green water evapotranspiration (mm); A is the acreage of the calculated crop (hm^2) ; ET_c is the actual crop evapotranspiration (mm); P_e is the effective precipitation (mm), which can be calculated using the Soil Conservation Service Method developed by the U.S. Department of Agriculture (USDA).

$$P_e = \begin{cases} P \times (125 - 0.6P)/125 & P \le 250/3 \\ 125/3 + 0.1P & P > 250/3 \end{cases} \tag{8}$$

where P is the precipitation (mm).

ET_c can be calculated based on the reference evapotranspiration (ET_0) which is estimated according to the FAO56-PM model (Allen et al., 1998);

$$ET_c = K_c \times ET_0 \tag{9}$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{em} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{10}$$

where K_c is the crop coefficient, and the K_c of the crops was determined according to their growing stage (Duan, 2004); R_n is the net radiation at the vegetation surface (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}); T_{em} is the daily average temperature (ºC); u_2 is the wind speed at a 2 m height (m s^{-1}); e_s is the vapor pressure of the air at saturation (kPa); e_a is the actual vapor pressure (kPa); Δ is the slope of the vapor pressure curve (kPa $ºC^{-1}$); and γ is the psychrometric constant (kPa $ºC^{-1}$). A complete set of equations is proposed by Allen et al. (1998) to compute the variables in Eq. (10) according to available weather data and the time step computation, which constitute the FAO-PM method. G can be ignored for daily time step computations.

Due to a lack of accessible data, the grey WF of crops only assesses nitrogen contamination without considering the effect of pesticides and other fertilizers, and was calculated by the following equation (Hoekstra et al., 2009):

$$WF_{grey} = (\delta \times U_N \times 10^6) / \rho_0 \quad (11)$$

where U_N is the applied amount of N fertilizer (ton). δ represents the leaching rate to freshwater with values 5-15% (Zhang and Zhang, 1998) and we use ambient water quality standard for nitrogen (10 mg L^{-1}) as the permissible concentration (ρ_0). Due to a lack of accessible data, we ignored pesticides and other fertilizers.

3 Results

3.1 WF and WFI of crop production in 2012

The WF of crop production in 2012 was analyzed, and the results were taken as the baseline for the crop structure analysis. The total WF of the production of crops in the HSP was approximately 41.8 km^3, of which 24% was WFgreen (10.1 km^3), 47% was WFblue (19.7 km^3) and 29% was WFgrey (12.0 km^3) (Table 4). We found large differences among the WF, WFgreen, WFblue and WFgrey for the main crops: wheat, maize, cotton, peanut, rice, vegetables, fruiters. Winter wheat, summer maize and vegetables were the three leading crops in water consumption, taking 29% (12.0 km^3), 24% (10.1 km^3) and 18% (7.7 km^3) of the total WF, respectively. The WF of spring maize, cotton, peanut, rice, fruiters and others were 2.9 km^3 (7%), 3.8 km^3 (9%), 1.6 km^3 (4%), 0.3 km^3 (1%), 2.6 km^3 (6%) and 0.9 km^3 (2%), respectively. The WFgreen of these crops was 2.1 km^3 (accounting for 21% of the total WFgreen), 3.6 km^3 (35%), 0.9 km^3 (9%), 0.9 km^3 (9%), 0.5 km^3 (5%), 0.1 km^3 (1%), 1.3 km^3 (13%), 0.5 km^3 (5%), and 0.2 km^3 (2%), respectively, of which summer maize was the largest, followed by winter wheat. The WFblue of these crops was 5.1 km^3 (accounting for 26% of the total WFblue), 3.7 km^3 (19%), 1.3 km^3 (7%), 2.1 km^3 (11%), 0.8 km^3 (4%), 0.2 km^3 (1%), 4.9 km^3 (25%), 1.1 km^3 (6%), 0.5 km^3 (3%), respectively, of which winter wheat was the largest, followed by vegetables. The WFgrey of these crops was 4.8 km^3 (accounting for 40% of the total WFgrey), 2.9 km^3 (24%), 0.7 km^3 (5%), 0.7 km^3 (5%), 0.2 km^3 (2%), 0.1 km^3 (1%), 1.5 km^3 (13%), 1.0 km^3 (8%), 0.2 km^3 (2%), respectively, of which winter wheat was the largest, followed by summer maize. The situation of the WFI was totally different from the situation of the WF (Table 4). Among these crops, the WFI of cotton was the largest and for vegetables, it was the smallest, and the former was approximately six times greater than the latter; the WFI of summer maize was basically equal to that of spring maize.

Table 4 WF (km^3) and the WFI (m^3 ton^{-1}) of each crop

Crop types	WFgreen	WFblue	WFgrey	WF	WFI
Winter wheat	2.1	5.1	4.8	12.0	887.0
Summer maize	3.6	3.7	2.9	10.1	701.7
Spring maize	1.3	1.3	0.7	2.9	691.1
Cotton	0.9	2.1	0.7	3.8	1493.0
Peanut	0.5	0.8	0.2	1.6	1043.2
Rice	0.1	0.2	0.1	0.4	903.1
Vegetables	1.3	4.9	1.5	7.7	183.6
Fruiters	0.5	1.1	1.0	2.6	246.4
Others	0.2	0.5	0.2	0.9	1030.8
Total	10.1	19.7	12.0	41.8	

3.2 Annual WF of crop production

Over the past 13 years (2000-2012), the total WF of crop production in the HSP was 604.8 km^3, comprised of 288.5 km^3 WFblue, 141.3 km^3 WFgreen and 175.0 km^3 WFgrey, and decreased by 22% (from 53.7 km^3 to 41.8 km^3), 26% (from 26.5 km^3 to 19.7 km^3), 14% (from 11.7 km^3 to 10.1 km^3), and 23% (from 15.5 km^3 to 12.0 km^3), respectively, from 2000 to 2012 (Fig. 3). The main reasons for the downtrend of the WF was due to the urbanization of farmland and the decrease of the winter wheat planting area. In addition, the total WFblue of these crops was approximately twice the amount of the total WFgreen, and the total WFgrey was slightly more than the total WFgreen.

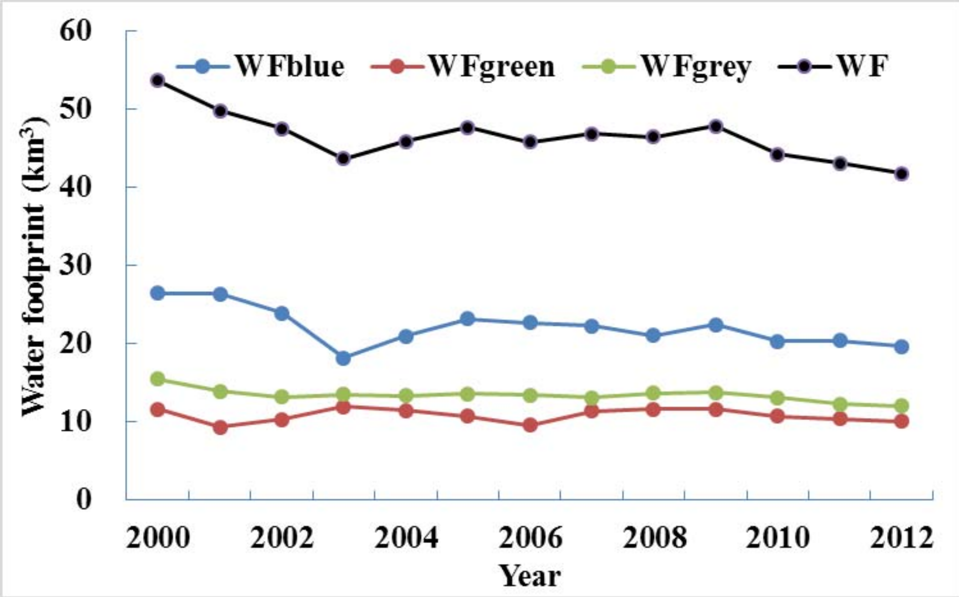

Fig. 3. WF of crop production in the HSP from 2000 to 2012

Table 5 shows the WF of each crop over 13 years. Winter wheat, summer maize and vegetables are the three leading crops for water usage, taking 33%, 28% and 16% of the total WF, respectively. Notably, summer maize accounted for 42% of WFgreen, 22% of WFblue and 27% of WFgrey; winter wheat accounted for 21% of WFgreen, 31% of WFblue and 44% of WFgrey; and vegetables accounted for 11% of WFgreen, 22% of WFblue and 11% of WFgrey (Table 5).

Table 5 WF (km^3) of each crop in the HSP from 2000 to 2012

Crop types	WFgreen	WFblue	WFgrey	WF
Winter wheat	30.0	89.1	77.6	196.7
Summer maize	58.8	62.6	46.6	168.0
Spring maize	10.5	13.8	6.9	31.2
Cotton	11.9	24.4	8.0	44.3
Peanut	6.2	12.8	3.4	22.4
Rice	0.8	3.5	0.9	5.2
Vegetables	15.4	62.3	18.7	96.4
Fruiters	4.8	12.5	10.3	27.7
Others	2.8	7.5	2.6	12.9
Total	141.4	288.5	175.1	604.8

3.3 Scenario analysis of WF for different crop structure

Results from the eight scenario (Table 6) illustrated that the following: (1) the WF (comprised of WFgreen, WFblue and WFgrey) of all the scenarios was smaller than the baseline, and those of scenario 5 were the smallest in the eight scenarios; (2) the WF of scenario 3 and scenario 6 were essentially equal, as were scenario 7 to scenario 8; (3) the WF reduced from scenario 1 to scenario 5 as the planting area of winter wheat and summer maize rotation decreased to zero and spring maize increased to 53.94%; (4) the WFgreen of the scenario 2,3,6,7 and scenario 8 were nearly equal, and the value was approximately 9 km^3.

Table 6 WF (km^3) of different crop structure scenarios in the Hebei southern plain

Crop structure	WFgreen	WFblue	WFgrey	WF
Baseline	10.1	19.7	12.0	41.8
Scenario 1	9.9	19.2	11.7	40.8
Scenario 2	9.4	18.3	10.4	38.1
Scenario 3	8.9	17.4	9.2	35.4
Scenario 4	8.4	16.4	7.9	32.7
Scenario 5	7.9	15.6	6.7	30.3
Scenario 6	9.1	16.8	9.6	35.5
Scenario7	9.1	18.6	9.9	37.6
Scenario8	9.2	17.6	10.7	37.5

4 Discussions

4.1 Crop water consumption

In the HSP, irrigation water has been the primary source of water for agricultural needs (Yuan and Shen, 2013), which was confirmed this study. According to the above analysis, water consumption of crops mainly came from irrigation, and their WFblue accounted for approximately 50% of the WF (Table 4 and Table 5). Although irrigation can directly increase crop yields, it also usually increases the crop WF (da Silva et al., 2013). In areas of water shortage, improving water use efficiency to reduce groundwater exploitation is imperative. Deficit irrigation has been widely used to save groundwater resources in the NCP (Ma et al., 2013) by taking better account of crop yield and water consumption.

During the 13 years, the WFblue of winter wheat was the largest of these crops, followed by summer maize, and then vegetables; which indicates that winter wheat, summer maize and vegetables consumed a large amount of groundwater. The WFblue of the crops, apart from summer maize and spring maize, was more than double their WFgreen; furthermore, the WFblue of rice and vegetables was more than quadruple their WFgreen.The WFgreen of both summer maize and spring maize were approximately equal to their WFblue. This was because the rapid growth stage of maize was basically synchronized with the rainy season (July to September) in this region, and the precipitation was able to meet the needs of crop growth in this period. Therefore, in arid and semi-arid areas, cultivating rain fed crops is an effective approach to save groundwater. While for other crops, the precipitation cannot meet their needs; therefore, water for these crops needs to come mainly from irrigation.

4.2 WF responses to crop structure

Crop structure affects the water consumption directly. The above analysis shows that, with the decrease of winter wheat-summer maize rotation planting area and the increase of spring maize (scenario 1 to scenario 5), the WF (comprised of WFgreen, WFblue and WFgrey) decreased (Table 6). Specifically, when the area of winter wheat-summer maize decreased 10% and spring maize increased 10% (relative to the total farmland area), the average WF, WFgreen, WFblue and WFgrey decreased 7.2%, 5.4%, 5.1% and 12.8%, respectively. However, since wheat is a staple food in the HSP and a ration crop, and this region needs to guarantee food self-sufficiency, areas should still be planted with winter wheat, despite its large consumption of water resources. Vegetables had a low-level WFI, however, the water consumption of vegetables per unit area, was much more than with other crops (scenario 6 to scenario 7). Despite this, the HSP should protect the basic supply of vegetables and fruits for Beijing, Tianjin and the Hebei province. Planting and keeping a certain areas with vegetables and fruiters is necessary.

Changes to crop structure directly affect irrigation consumption (or WFblue) and indirectly affect the emissions of environmental pollutants that can be measured by WFgrey. In the study area, water consumption for crops is primarily attributable to groundwater irrigation. It is imperative to identify a reasonable crop structure by considering the sustainable use of groundwater and the lifestyle of local people. According to the above scenario analysis, we found the crop structure of scenario 6 to be reasonable. Because this structure can guarantee regional self-sufficiency food, including vegetables, fruits, cotton, and peanuts, and the groundwater consumption of this structure was acceptable. In addition, policies on agricultural crop structure optimization should be encouraged, with the aim of relieving the pressure on groundwater for crop production and ensuring food security in this region. In recent years, winter wheat and summer maize were being replaced by spring crops in many places of the HSP, this was called "the spring corn planting belt phenomenon" (Feng et al., 2007; Huang et al., 2012; Wang et al., 2014). Clearly, this phenomenon can help in the restoration of groundwater resources in this region.

4.3 Main uncertainties of this study

First, the estimation of WF (comprised of WFgreen, WFblue and WFgrey) was affected by crop distribution, in regards to the spatial differences of underlying surface conditions, climatic conditions and irrigation conditions. The crop structure scenarios only considered the crop planting areas and did not take into account the crop distribution. In addition, the parameter of P_e can affect the WFgreen and WFblue values because it was calculated by an empirical formula, and the WFgrey only considered nitrogen contamination and ignored pesticides and other fertilizers, therefore, the calculated WFgrey, WFgreen, WFblue and WF had a certain deviation compared with the actual values. Second, the scenarios had a certain degree of randomness since there was no-consideration to changes in planting areas of cotton, peanut and others (Table 2). For example, with cotton lacking a high market value and having difficulties in its management (e.g., requiring artificial picking), its growing area was likely shrinking, and its distribution was changing. Third, due to the urbanization in this region, the area of arable land has been shrinking; likewise, some arable land was abandoned because many rural young people went to work in cities. Our scenario analysis, however, did not take into account these phenomena, as we lacked the corresponding data. Fourth, climatic variability has major effects on crop WF (Sun et al., 2010; Bocchiolaet al., 2013; Yang et al., 2013), and many researchers have found that this region has undergone an upward trend of temperatures and a declining trend of precipitation since the 1960s (Hu et al., 2002; Yuan et al., 2009; Sun et al., 2010). If precipitation continues to decline while temperature increase over time, these climatic developments will certainly affect the WF for crop production. These effects are worth an in-depth analysis, which could provide valuable information for water resource management.

5 Conclusions

This study analyzed the WF of crop production in the HSP and evaluated its temporal variation from 2000 to 2012. Over 13 years, the production of main crops consumed a total of approximately 604.8 km^3 of water, of which 288.5 km^3 of that was groundwater; additionally, the WF of the production of crops exhibited a downtrend yearly. Among the local main crops, winter wheat, summer maize and vegetables were the three leading crops in water consumption; their WF, WFblue, WFgreen and WFgrey accounted for 76.2%, 73.7%, 74.2% and 81.6% of the total, respectively.

In this region, adjusting crop farming structures has been an important means to protect groundwater resources; therefore, we evaluated reasonable farming structures by analyzing scenarios of the main crops' WF in this plain and suggest that: scenario 6 with approximately 20% of the arable land in cultivation of winter wheat-summer maize in rotation, 38.99% of spring maize, 10% of vegetables, 10% of fruiters, 0% of rice and no change to other crops, will promote the sustainable development of agriculture in this region. This scenario, not only can protect approximately 14.5% of groundwater resources (compared to the baseline), but can also ensure the local supply of wheat, vegetables, and fruits.

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