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Discussions

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) is serious lack of fresh water resources, while crop production consumed about 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 because it is a typical region of groundwater overdraft in the NCP. In this study, water footprint (WF) was being used which was consisted of green, blue and grey components. The results showed: (1) the WF of the main crops production was about 51.0 km^3 in 2012 and winter wheat, vegetables and summer maize were in the top three leading among the main crops in the HSP, while the water footprint intensity (WFI) of cotton was the largest and vegetables were the smallest; (2) winter wheat and vegetables consumed the main groundwater and their blue water footprint (WFblue) accounted for 66.0% of the total WFblue in the HSP; (3) the crop structure scenarios analysis indicated that, with about 20% of arable land cultivating winter wheat-summer maize in rotation, 40% spring maize, 10% vegetables and 10% fruiters can promote the sustainable utilization of groundwater resources, at the same time can ensure sufficient supply of food, vegetables and fruits in the HSP.

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

analysis

1 Introduction

With the excessive consumption of water by people, freshwater scarcity has becoming a threat to human society (Dong et al., 2013). In the world, the largest freshwater consumer is agriculture, which consumed more than 70% of world's freshwater (UNEP, 2007; Lucrezia et al., 2014). To ensure the increasing food demand, global water consumption have almost doubled during the past 40 years (Gleick, 2003), and water resources have been heavily exploited for worldwide agriculture (Konar et al., 2011). In future, water use for food production will continue to meet the population growth and changes in dietary preferences (Rosegrant and Ringler, 2000). This will consume more water resources. China is a freshwater poor country with about 2100 m^3/y water resources per capita, accounting for only 28% of the world's per capita share. The spatial mismatch between water and arable land strengthened China's water challenge. There is about 70% arable land in the north of the Yangze River with only about 17% water resources of the national total in China. Currently, as a water shortage area north of the Yangze River, the NCP is facing the acutest water scarcity issue, accounting for only 1.3% of China's total available water with 225 m^3/y per capita (White et al., 2015).

As s metric to assess water use of the production system, the water footprint (WF) concept has been proposed (Heokstra, 2003), which included direct and indirect water use of a consumer or producer (Hoekstra et al., 2009). In recent years, many researchers 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 it can be focused local crop products. For a certain crop, the blue WF (WFblue) refers to the volume of irrigation water consumption, the green WF (WFgreen) is consistent with effective rainfall for plants, and the grey WF (WFgrey) represents the volume of water required to dilute pollutants to agreed maximum acceptable levels (Hoekstra and Chapagain, 2007). For the water consumption of each crop is different, the WF of different crops differ 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 green WF and 46% of grey WF respectively, vegetables account for 45% of blue WF, and wheat accounts for 26% of the total WF. Wang et al. (2015) found winter wheat conserved about 1.9×10^{9} m^{3} yr^{-1} of WFblue during 1998-2011 in the Hebei Plain.

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

The main aims of this study were: (1) to quantify the WF of main crops production in the HSP in 2012; (2) to discuss the reasonable crop structure based on WF analysis for different crop structure scenarios. Through this study, we propose a most suitable crop planting structure for this region, and give support to 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 about 62,000 km^{2}, are located in southern Beijing and Tianjin (Fig. 1). The climate in this region is temperate continental monsoon with a mean annual precipitation of 550 mm and a mean annual temperature of 11.5ºC. Precipitation has a non-uniform distribution throughout the year, and about 80% of the total precipitation occurs from July through September. In the HSP, most arable lands are irrigated by groundwater except for the eastern part where the saline shallow groundwater restrains the irrigation. The main crops in the plain are wheat, maize, cotton, peanut, the main vegetable species are Chinese cabbage, celery, cauliflower, onion, bean, rape, leek, coriander, fennel, and the main fruits are apple, pear, jujube and grape.

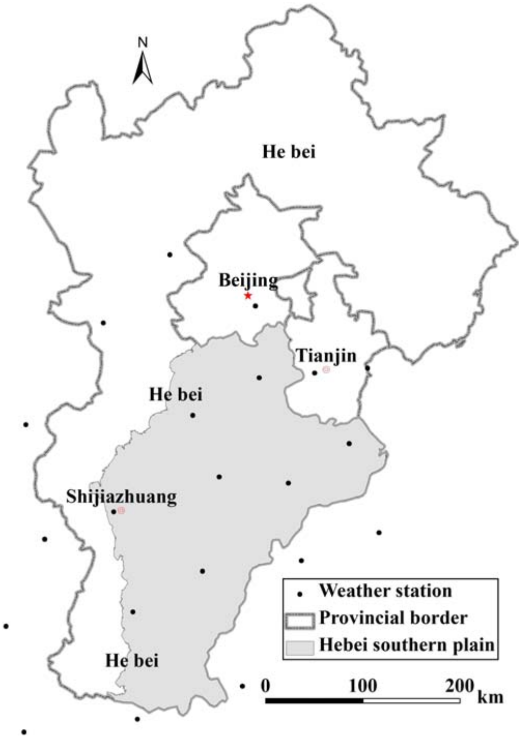

Fig. 1 Location of the Hebei southern plain

2.2 Data collection

The meteorological data for 25 weather stations (Fig. 1) around the HSP, including daily maximum temperature, minimum temperature, average temperature, wind speed, relative humidity, precipitation, sunshine duration, vapor pressure, atmospheric pressure were obtained from the China Meteorological Data Sharing Service System (China Meteorological Administration, 2012).

The statistics data for the plain in 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. Land-use map in

2012 (Fig. 2) of the plain were drawn based on the spot satellite images and the topographic map (1:10000). The main land-use types include cropland, construction land, forestland, waters, orchard, wetland, grassland and shrub land (Table. 1).

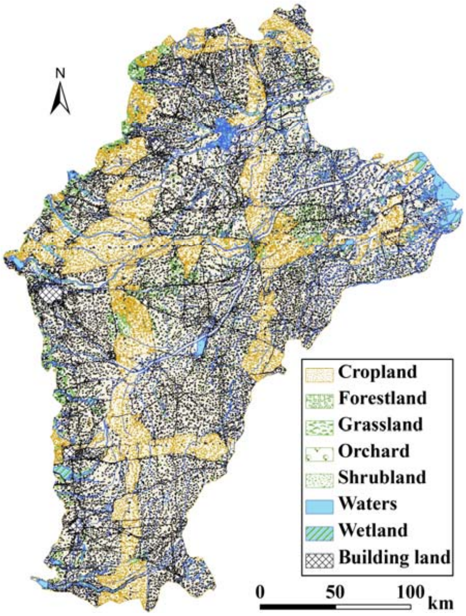

Fig. 2 Land-use map of the Hebei southern plain

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

2.3 Crop structure scenarios setting

The baseline for the crop structure (2012) in the HSP, consisted of 42.44% winter wheat-summer maize rotation, 11.50% spring maize, 18.65% vegetables, 5.75% fruiters, 12.35% cotton, 5.51% peanut, 0.66% rice, and 3.15% of others (side crops i.e. millet, sorghum, sweet potato and others). Eight different crop structure planning scenarios were formulated according to the main crops of the baseline with the cotton, peanut and side crops cultivating area unchanged (Table 2). These scenarios involved reducing winter wheat-summer maize and rice cultivating area to 40% and 0 separately, 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%, vegetables and fruiters to 10% (scenario 6); reducing winter wheat-summer maize to 20% and increasing spring maize to 28.99%, vegetables to 20% and fruiters to 10% (scenario 7); reducing winter wheat-summer maize to 20% and increasing spring maize to 28.99%, vegetables to 10% and fruiters to 20% (scenario 8) .

Table 2 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 crop production is the sum of the green, blue and grey components (Chapagain et al., 2006). The WF of 7 main kinds of crops planted in the HSP is calculated separately:

$$WF = \sum_{a=1}^{n} WF_a \tag{1}$$

$$WF = WF_{blue} + WF_{green} + WF_{grey} \tag{2}$$

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

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

$$WFI_a = WF_a / Y_a \tag{3}$$

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

Green water footprint was represented by crop evaporation or effective rainfall:

$$WF_{blue} = 10 \times ET_{blue} \times A \tag{4}$$

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

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

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

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

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

where P is the precipitation (mm).

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

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

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

where K_c is crop coefficient; 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 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.

For lacking of accessed data, the grey WF of crops only assimilate nitrogen contamination without considering the effect of pesticide and other fertilizer, which was calculated as the following equation (Hoekstra et al., 2009):

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

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 lack of accessed data, we ignored pesticide and other fertilizer here.

3 Results

3.1 WF and WFI of crop production

In 2012, the total WF of crops production in the HSP was about 51.0 km^3, of which 27.6% was WFgreen (14.1 km^3), 48.4% was WFblue (24.7 km^3) and 24.0% was WFgrey (12.2 km^3), respectively (Table 3). We found large difference of the WF, WFgreen, WFblue and WFgrey within the main crops: among these crops (wheat, maize, cotton, peanut, rice, vegetables, fruiters), winter wheat, vegetables and summer maize were three leading crops, taking 28.8% (14.7 km^3), 23.8% (13.1 km^3) and 19.3% (10.6 km^3) of the total WF, respectively; the WF of spring maize, cotton, peanut, rice, fruiters and others was 3.0 km^3 (5.4%), 4.0 km^3 (7.2%), 1.6 km^3 (2.9%),0.3 km^3 (0.6%),2.7 km^3 (4.9%) and 1.0 km^3 (1.8%), respectively. The WFgreen of these crops was 2.0 km^3 (accounted for 14.2% of the total WFgreen), 4.4 km^3 (31.5%), 1.4 km^3 (10.0%),1.7 km^3 (12.0%),0.7 km^3 (4.9%), 0.1 km^3 (0.7%), 3.0 km^3 (21.0%), 0.6 km^3 (4.9%), 0.2 km^3 (1.4%), respectively, in which vegetables was the largest, then was summer maize. The WFblue of these crops was 7.8 km^3 (accounted for 31.8% of the total WFblue), 3.3 km^3 (13.4%), 0.9 km^3 (5.4%),1.6 km^3 (7.2%),0.7 km^3 (2.9%), 0.2 km^3 (0.6%), 8.5 km^3 (23.8%), 1.1 km^3 (4.9%), 0.6 km^3 (1.8%), respectively, in which vegetables was the largest, then was winter wheat. The WFgrey of these crops was 4.8 km^3 (accounted for 39.4% of the total WFgrey), 2.9 km^3 (23.7%), 0.7 km^3 (5.4%), 0.7 km^3 (5.7%), 0.3

km^3 (2.9%), 0.1 km^3 (0.5%), 1.7 km^3 (13.9%), 1.0 km^3 (8.0%), 0.2 km^3 (1.5%), respectively, in which winter wheat was the largest, then was summer maize.

The situation of WFI was totally different from WF (Table 3). Among these crops, the WFI of cotton was the largest and vegetables were the smallest, and the former was about eight times as much as that of the latter; the WFI of winter wheat was basically equal to which of peanut.

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

Crop types	WFgreen	WFblue	WFgrey	WF	WFI
Winter wheat	2.0	7.8	4.8	14.7	1086.9
Summer maize	4.4	3.3	2.9	10.6	736.0
Spring maize	1.4	0.9	0.7	3.0	709.1
Cotton	1.7	1.6	0.7	4.0	1573.3
Peanut	0.7	0.7	0.3	1.6	1082.8
Rice	0.1	0.2	0.1	0.3	913.9
Vegetables	3.0	8.5	1.7	13.1	207.7
Fruiters	0.6	1.1	1.0	2.7	257.5
Others	0.2	0.6	0.2	1.0	1147.0
Total	14.1	24.7	12.2	51.0	

3.2 Scenario analysis of WF for different crop structure

Results from the seven scenarios (Table 4) illustrated that: (1) the WF (including 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 8 was essentially equal, and which of scenario 7 was slightly larger than them and scenario 6 was slightly larger than scenario 4; (3) the WF (including WFgreen, WFblue and WFgrey) was getting smaller and smaller from scenario 1 to scenario 5 with the planting area of winter wheat and summer maize rotation decreased to zero and spring maize increased to 53.94%. (4) the WFgreen of all the scenarios was nearly equal, and the value was approximately 12 km^3.

Table 4 WF (km^3) of different crop structure scenarios in the Hebei southern plain

Crop structure	WFgreen	WFblue	WFgrey	WF
Baseline	14.1	24.7	12.2	51.0
Scenario 1	12.7	24.2	11.9	48.7
Scenario 2	12.4	22.2	10.6	45.3
Scenario 3	12.1	20.4	9.4	41.9
Scenario 4	11.8	18.5	8.1	38.5
Scenario 5	11.5	16.7	6.9	35.1
Scenario 6	12.4	17.7	9.6	39.6
Scenario7	12.1	20.1	10.3	42.6
Scenario8	12.2	18.8	10.7	41.7

4 Discussions

4.1 Crop water consumption

In the HSP, the agricultural water consumption mainly came from irrigation (Yuan and Shen, 2013), and this study also proved this point. According to the above analysis, the water consumption of the crops (except maize, cotton and peanut) mainly came from irrigation, and their WFblue accounted for about 50% of the WF (Table 3). Although irrigation can directly increase yield of the crops, it also usually increased the crop WF (da Silva et al., 2013). In water shortage area, improving water use efficiency to reduce groundwater exploitation is imperative, and deficit irrigation was widely used to save groundwater resource in the NCP (Ma et al., 2013), which took better account of crop yield and water consumption.

The WFblue of vegetables was the largest in these crops, and then was winter wheat, which indicated vegetables and winter wheat consumed a large amount of groundwater. The WFgreen of maize was more than its WFblue, and the WFgreen of cotton and peanut was approximately equal to their WFblue, because the rapid growth stage of these four crops was from June to August, this period was basically synchronized with rainy season (July to September) in this region, and the precipitation can basically meet the needs of crop growth in this period. So in arid and semi arid area, cultivating rain fed crops is an effective approach to save groundwater. While for wheat, rice, vegetables, fruiters and others, the WFblue was significantly more than their WFgreen. The main reason was the precipitation can not meet the needs of these crops, and the water consumption of these crops mainly came from irrigation.

4.2 WF responses to crop structure

Crop structure affects the water consumption directly. From the above analysis, with the decrease of winter wheat-summer maize rotation planting area and the increase of spring maize (scenario 1 to scenario 5), the WF (including WFgreen, WFblue and WFgrey) decreased (Table 4), specifically, when the area of winter wheat-summer maize decreased 10% and spring maize increased 10%, the average WF, WFgreen, WFblue and WFgrey decreased 7.9%, 2.5%, 8.9% and 12.7%, respectively.

However, people consumed flour as the major staple food in the HSP and wheat is a ration crop here, we should plant a certain area of winter wheat to guarantee the food self-sufficiency in this region in spite of it consumed a lot of water resources. In per unit area, the water consumption of vegetable was much more than other crops (scenario 6 to scenario 7) in spite of its WFI was low-level, but the HSP should protect the basic supply of vegetables and fruits for Beijing, Tianjin and Hebei province, planting a certain area of vegetables and fruiters is necessary.

Crop structure changing directly affects irrigation water consumption (or WFblue) and indirectly affects the emissions of environmental pollutants which were closely linked with WFgrey. In the study area, crop water consumption mainly came from groundwater irrigation, it is an urgency to find out a reasonable crop structure by considering the sustainable use of groundwater and local people's daily life. According to the above scenario analysis, we found the crop structure of scenario 6 was reasonable. Because this structure can guarantee the regional self-sufficient of food, vegetables, fruits, cotton, peanut etc. at the same time 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 been called "the spring corn planting belt phenomenon" (Feng et al., 2007; Huang et al., 2012; Wang et al.,2014). Undoubtedly, this phenomenon can help to the restoration of groundwater resources in this region.

4.3 The main shortcomings of this study

Firstly, the estimation of WF (including WFgreen, WFblue and WFgrey) was affected by crop distribution for the underlying surface conditions, climatic conditions and irrigation conditions have spatial difference, but the crop distribution of the baseline mainly came from land-use map and statistical data and the crop structure scenarios did not take into account the crop distribution, this study only considered the crop planting area and ignored its distribution. Secondly, the scenarios setting had a certain randomness without considering planting area changes of cotton, peanut and others (Table 2), in fact, due to the difficulty of cotton management (e.g. it needs artificial picking) without high price, its growing area was likely shrinking and its distribution was changing. Thirdly, due to the development of urbanization in this region, the area of arable land has been shrinking, at the same time, some arable land was abandoned because many young people went to work in cities in many rural communities, but our scenario analysis did not take into account these phenomenons for lacking the corresponding data. Fourthly, 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 temperature 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 and temperature increases in the future, these climatic developments will affect the WF for crop production certainly and these questions are worth in-depth analyzing, which can provide valuable information for water resource management.

5 Conclusions

Adjusting crop farming structure was an important means to protect groundwater resources in the HSP. This study evaluated the reasonable farming structure by scenario analysis of the main crops WF in this plain and suggested that: with about 20% of arable land cultivating winter wheat-summer maize in rotation, 40% cultivating spring maize, 10% cultivating vegetables, 10% cultivating fruiters, without rice and other crops unchanging (i.e. scenario 6) were available to promote the sustainable development of agriculture in this region, which not only can protect the groundwater resources, but also can ensure the local supply of food, vegetables and fruits.

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