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Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China

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Abstract. Increasing water scarcity places considerable importance on the quantification of water footprint (WF) at different levels. Despite progress made previously, there are still very few WF studies focusing on specific river basins, especially for those in arid and semi-arid regions. The aim of this study is to quantify WF within the Heihe River Basin (HRB), a basin located in the arid and semi-arid northwest of China. The findings show that the WF was 1768 million $m^3\ yr^{-1}$ in the HRB over 2004–2006. Agricultural production was the largest water consumer, accounting for 96 % of the WF (92 % for crop production and 4 % for livestock production). The remaining 4 % was for the industrial and domestic sectors. The "blue" (surface- and groundwater) component of WF was 811 million $m^3\ yr^{-1}$. This indicates a blue water proportion of 46 %, which is much higher than the world average and China's average, which is mainly due to the aridness of the HRB and a high dependence on irrigation for crop production. However, even in such a river basin, blue WF was still smaller than "green" (soil water) WF, indicating the importance of green water. We find that blue WF exceeded blue water availability during eight months per year and also on an annual basis. This indicates that WF of human activities was achieved at a cost of violating environmental flows of natural freshwater ecosystems, and such a WF pattern is not sustainable. Considering the large WF of crop production, optimizing the crop planting pattern is often a key to achieving more sustainable water use in arid and semi-arid regions.

1 Introduction

As one of the most essential natural resources, water is greatly threatened by human activities (Oki and Kanae, 2006; Postel et al., 1996; Vörösmarty et al., 2000, 2010). There are still more than 800 million people lacking a safe supply of freshwater (Ban Ki-moon, 2012) and 2 billion people lacking basic water sanitation (Falconer et al., 2012). Water scarcity has been increasing in more and more countries all over the world (Yang et al., 2003). Especially in arid and semi-arid regions, nearly all river basins have serious water problems, such as rivers drying up, pollution or groundwater table decline (José et al., 2010; Vörösmarty et al., 2010). It is necessary to find new approaches and tools for integrated water resources management (Adeel, 2004) to help maintain a balance between human resource use and ecosystem protection (Dudgeon et al., 2006; Vörösmarty et al., 2010). New paradigms and approaches, e.g. water footprint (WF) and green and blue water, have been emerging in scientific communities to promote efficient, equitable and sustainable water uses, and these paradigms are believed to break new ground for water resources planning and management (Falkenmark, 2003; Falkenmark and Rockström, 2006; Hoekstra and Chapagain, 2007; Liu and Savenije, 2008).

WF is an indicator of water use introduced by Hoekstra (2003). It shows water consumption by source and polluted volumes by type of pollution. WF assessment is an analytical tool that can describe the relationship between

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human activities and water scarcity, and offer an innovative approach to integrated water resources management (Hoekstra et al., 2011). Earlier WF studies generally focused on five levels: process, product, sector, administrative unit, and global. At the process level, Chapagain et al. (2006) calculated the WF of cotton production for different processes. At the product level, Mekonnen and Hoekstra (2011) estimated the green, blue and grey WF of 126 crops all over the world for the period 1996–2005 with a high spatial resolution. The WF of pasta and pizza (Aldaya and Hoekstra, 2010) and coffee and tea (Chapagain and Hoekstra, 2007) have also been analyzed. At the sector level, Aldaya et al. (2010) calculated the WF of domestic, industrial and agricultural sectors in Spain and found that the inefficient allocation of water resources and mismanagement in the agricultural sector lead to water scarcity in Spain. At the national level, the WF of China (Liu and Savenije, 2008; Ma et al., 2006), India (Kampman et al., 2008), Indonesia (Bulsink et al., 2010), Netherlands (Van Oel et al., 2009), UK (Chapagain and Orr, 2008) and France (Ercin et al., 2012) have been assessed. At the global level, WF of goods and services consumed by humans have been quantified by Hoekstra and Chapagain (2007) and Hoekstra and Mekonnen (2012).

Although the body of literature on WF has been increasing fast, there are still very few studies focusing on specific river basins (UNEP, 2011), especially for those located in arid and semi-arid regions. Assessing WF at a river basin level is an important step to understand how human activities influence natural water cycles, and it is a basis for integrated water resources management and sustainable water uses. WF assessment studies at river basin level are rare in the literature largely due to the lack of statistical data at the river basin level. Among the very few studies, input-output models have been tested to estimate WF at the river basin level, such as for the Haihe River Basin (Zhao et al., 2010) and for the Yellow River Basin (Feng et al., 2012). It is still necessary to test whether a bottom-up approach (Hoekstra et al., 2011) promoted by the Water Footprint Network can be successfully used for WF assessments for specific river basins, particularly for those in arid and semi-arid regions.

Our study aims to (1) assess WF at a river basin level with a bottom-up approach; and (2) assess sustainability of WF on a monthly time step. We chose the Heihe River Basin (HRB) in inland northwest of China as a case area, and conducted a WF assessment by considering the agricultural (i.e. crop production and livestock production), industrial and domestic sectors. We assess the annual green and blue WF and compare the blue WF (WF_{blue}) with blue water availability (WA_{blue}) at a monthly level to pinpoint the most serious water scarce months. Located in northwest China, the Heihe River originates in the Qilian Mountains in Qinghai Province, flows through several counties in Gansu Province and Inner Mongolia, and terminates in oases in Mongolia (Fig. 1). The precipitation ranges from 480 mm in the upstream part of the basin to even less than 20 mm downstream. The extensive use of water in the upper and middle parts of the basin has led to a decrease in water resources downstream, causing salinization and desertification (Cheng, 2002; Feng et al., 2002; Chen et al., 2005). Previous research often pays attention to irrigation in this river basin (Chen et al., 2005; Zhao et al., 2005; Ji et al., 2006; Wang Y. et al., 2010), but a comprehensive WF assessment considering multiple sectors and multiple types of water (e.g. green and blue water) has never been done before. Such an assessment is a key to better understanding the entire picture of water consumption at the river basin level, and identifying ways to improve water management.

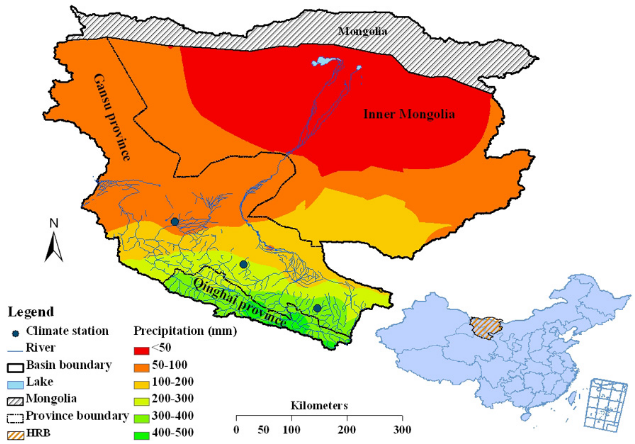

Fig. 1. Location of the Heihe River Basin (HRB) in China.

2 Method

2.1 Scope of WF accounting

In order to assess WF within the HRB, we need to know the WF of crop production (WF_c), WF of livestock production (WF_l), WF of the industrial sector (WF_i), and WF of the domestic sector (WF_d). There are two types of resources: blue water (surface water and groundwater), and green water (soil water) (Liu and Savenije, 2008). Both the blue and green components of WF are assessed. The blue and green WF (WF_{blue} and WF_{green}) accounting and sustainability assessment are mainly based on the standard methods proposed in the Water Footprint Assessment Manual (Hoekstra et al., 2011). Because of the lack of data on pollutant discharges in the HRB, we do not include the volume of water that is used to assimilate water pollution, or grey WF. In this article, we only estimate WF within China's territory due to the lack of data in Mongolia. In addition, the area of the HRB located in Mongolia is mainly desert, while crop and livestock production and other human activities are marginal. Neglecting this area will not lead to large errors for the WF of the entire river basin. We assess WF in the HRB over 2004–2006 and use the annual and monthly results for the presentation of results.

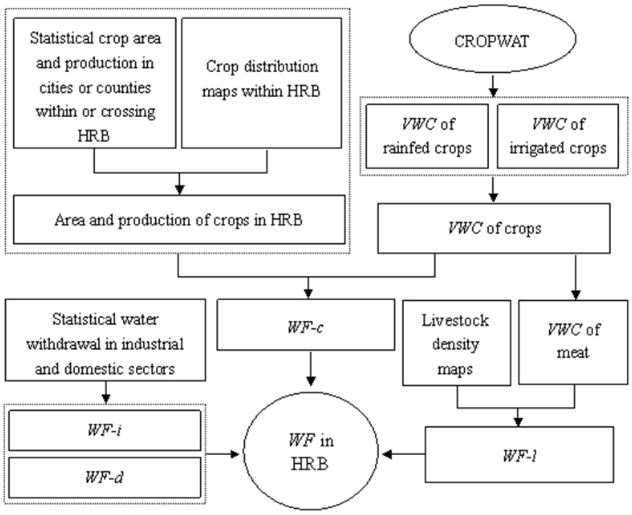

Fig. 2. The steps to calculate water footprint (WF) in the HRB.

Table 1. Annual harvested area and crop production within the HRB (2004–2006).

Crop Type	Representative Crop	Harvested Area	Production
		thou-(sand ha)	thou-(sand ton)
Wheat	Wheat	53	322
Maize	Maize	30	239
Other cereals	Barley	50	352
Soybean	Soybean	3	21
Starchy roots	Potato	11	87
Oil crops	Rapeseed	18	47
Sugar crops	Sugar beet	8	190
Cotton	Cotton	21	46
Apple	Apple	5	27
Other fruits	Pear	45	229
Vegetables	Tomato	27	740
Other crops	All above crops	†	366

† no data.

2.2 Crop production and livestock production in the HRB

Since many data are not available at a river basin level, we combine statistical data for administrative boundaries (e.g. a county or a city) with spatially explicit datasets to obtain the information at the river basin level. The steps to calculate the WF within the HRB are depicted in Fig. 2.

There are 15 Chinese cities or counties within or across the HRB. The statistics provide accurate information of harvested area and production of crops in these cities or counties during 2004–2006, but statistical information at river basin is not available. For these administrative regions, we need to calculate how much area is located within the HRB. With the 5 arc-minute crop distribution maps from the MIRCA2000 database from the University of Frankfurt (Portmann et al., 2010), we can calculate the shares of crop area (both rainfed and irrigated) of one specific crop in one city or county within and outside the HRB. Combining these shares with statistical harvested area of a city or county, the crop area of all administrative regions within the HRB can be estimated. Hence, the area of each crop can be obtained at the river basin level. A similar approach is used to estimate crop production within the HRB. The results of harvested area and production are shown in Table 1.

A total of 12 types of crops or crop groups were selected. Each type has its own representative crop (Table 1). These include cereal crops (wheat, maize and other cereal crops), soybean, oil crops (rapeseed), sugar crops (sugar beet), cotton, fruits (apple and other fruits), vegetables (tomato) and other crops. According to our estimate, the first 11 types of crops account for 86 % of the total crop production, while the other crops account for 14 % within the HRB.

The livestock (meat) production is calculated by multiplying the number of an animal type by its average meat production of the animal types. Beef, sheep/goat, pork and poultry are four main animal categories in the HRB and we only consider these livestock in our calculation. The density of animals per animal category (number km^{-2}) is obtained from the Animal Production and Health division of FAO (2011). This dataset provides spatially explicit information on animal densities in 2005 with a spatial resolution of 3 arc-minutes. The total number of an animal in the HRB can be estimated by summing up the animal number of all grid cells within the basin.

2.3 WF of crop production (WF_c)

WF_c is calculated by multiplying virtual water content (VWC) of each crop with its production and then summing up all crops. VWC is defined as the amount of water (m^3) that is needed to produce a product per unit of crop (ton) during the crop growing period. The green and blue components of VWC are calculated as the ratio of effective rainfall (ER, $m^3\,ha^{-1}$) or irrigation (I, $m^3\,ha^{-1}$) to the crop yield (Y, tha^{-1}). The VWC of crops is the sum of green VWC (VWC_{green}) and blue VWC (VWC_{blue}).

$$VWC_{green} = \frac{ER}{Y} \tag{1}$$

$$VWC_{blue} = \frac{I}{Y} \tag{2}$$

$$VWC = VWC_{green} + VWC_{blue} \tag{3}$$

The CROPWAT model (FAO, 2010a; Allen et al., 1998) is used to estimate ER and I of crops. Both the rainfed and irrigated conditions are taken into account. “Irrigation schedule option” is used to calculate ER and I by simulating soil water balance with a daily time step (Hoekstra et al., 2011). We do not estimate the green and blue water incorporated into the crops because in general they account for very small (e.g. 0.1 % of the evaporated water, up to 1 % at most) (Hoekstra et al., 2011).

The CROPWAT model needs climate, crop and soil parameters to model evapotranspiration and crop irrigation requirements. Climate data include temperature, precipitation, humidity, sunshine, radiation and wind speed. The climate data are obtained from the New LocClim database (FAO, 2005), which provides monthly climate data on 30-yr average (1961–1990). We selected three climate stations located in the HRB (see Fig. 1).Crop parameters such as crop coefficients, rooting depths, lengths of each crop development stage, the planting and harvest dates are based on the studies by Allen et al. (1998) and Chapagain and Hoekstra (2004). Soil parameters include values of available soil water content, maximum infiltration rate, maximum rooting depth, and initial soil moisture depletion. Available soil water content for the HRB is retrieved from global maps from the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2010b). The maximum infiltration rate depends on the soil types, which are predominantly sandy and loamy in the HRB (Qi and Cai, 2007). Because no information was available for maximum rooting depth and initial soil moisture content at the start of the growing season, default values in CROPWAT were taken (FAO, 2010a).

2.4 WF of livestock production (WF_l)

WF_l is calculated by multiplying VWC of a type of livestock meat with its production and then summing up all types of livestock types. VWC of meat is defined as the amount of water (m^3) that is needed to produce per unit of meat (ton).

The VWC of meat is made up of three components: the water used to produce feed crops that the animals eat, and the drinking and processing water requirements of livestock (Mekonnen and Hoekstra, 2012). The feed of the livestock is composed of grass, rough forage and maize. In the HRB, maize needs both precipitation and irrigation, while the other crops mainly use precipitation (Zhang, 2003). The percentage of blue and green water in maize is estimated with the CROPWAT model. Drinking and processing water is dominantly "blue". We assume that feed crops are all produced within the HRB based on common practice in the HRB. The feed water requirement (FWR, $m^3 kg^{-1}$) for an animal can be calculated by multiplying feed conversion efficiency (FCE) for a specific crop (FCE_f, kg dry mass of feed kg^{-1} of output) by the VWC of the feed crops (VWC_f, $m^3\ kg^{-1}$):

$$\mathrm{FWR} = \sum_{f=1}^{N_f} \mathrm{FCE_f} \times \mathrm{VWC_f}. \qquad (4)$$

Together with the drinking water requirement (DWR, $m^3\ t^{-1}$) and processing water requirement (PWR, $m^3\ t^{-1}$), this leads to the VWC of animal meat (VWC, $m^3\ t^{-1}$):

$$\mathrm{VWC} = \mathrm{FWR} + \mathrm{DWR} + \mathrm{PWR}. \qquad (5)$$

Feed requirement of animals, FCE, DWR and tPWR are retrieved from Zhang (2003).

In order to calculate the monthly WF of livestock production, we assume DWR and PWR are equally distributed in each month throughout the year. The monthly FWR and its green/blue components are estimated based on monthly water requirements of crops, which are calculated by the CROPWAT model.

2.5 WF of industrial and domestic sectors (WF_i and WF_d)

The WF of industrial and domestic sectors is estimated by multiplying water withdrawal with a water consumption ratio (WCR) for each sector. According to the Ministry of Water Resources of China, the water withdrawal for domestic purposes was 44.2 million m^3 and 95.2 million m^3 for industry within the HRB (Chen et al., 2005). WCR is 36 % for industrial sector and 67 % for domestic sector in the HRB (GSMWR, 2006).

2.6 WF sustainability assessment

The WF sustainability is assessed by comparing WF_{blue} with blue water availability (WA_{blue}) at a river basin level. When WF_{blue} exceeds WA_{blue}, there is reason for sustainability concern (Hoekstra et al., 2012).

According to Hoekstra et al. (2011), WA_{blue} is estimated as below:

$$\mathrm{WA_{blue}} = \mathrm{BWR} - \mathrm{FR}, \qquad (6)$$

where BWR means the blue water resources under natural conditions without human intervention, or the natural runoff. It is equal to the total amount of surface and groundwater flows. EFR stands for environmental flow requirements.

The annual and monthly natural runoff in the HRB is obtained from Zang et al. (2012), who simulate surface and groundwater flows under the natural conditions with a Soil and Water Assessment Tool (SWAT) (Arnold et al., 1994). It is often assumed that EFR accounts for a certain share of the natural runoff. We use a share of 80 % as suggested by Hoekstra et al. (2011) and Hoekstra et al. (2012).

3 Results

3.1 VWC of crops

Among all crops studied, cotton has the largest VWC of 3384 $m^3\ t^{-1}$ (Fig. 3). Soybean also has high VWC of 2216 $m^3\ t^{-1}$. Cereal crops in general have VWC values ranging from 763 to 1045 $m^3\ t^{-1}$. The blue water proportion

Table 2. Virtual water content (VWC), water footprint (WF) and blue water proportion (BWP) of crop and livestock production within the HRB (2004–2006).

Crop Type	VWC	WF	BWP
	($m^3\,t^{-1}$)	(million $m^3\,yr^{-1}$)	
Wheat	826	266	64 %
Maize	763	182	62 %
Other cereals	1045	368	27 %
Soybean	2216	48	72 %
Starchy roots	110	10	45 %
Oil crops	466	22	0 %
Sugar crops	94	18	0 %
Cotton	3384	156	56 %
Apple	855	23	34 %
Other fruits	918	210	34 %
Vegetables	150	111	48 %
Other crops	614	225	45 %
Pork	3910	10.32	26 %
Beef	20360	7.62	3 %
Sheep/goat	14670	42.87	0.3 %
Poultry	4029	5.01	39 %

(BWP) is defined as the ratio of VWC_{blue} to VWC (Liu et al., 2009). Soybean has the highest BWP value of 70 %, followed by wheat and maize with BWP values between 62 % and 64 % (Table 2). Sugar crops and oil crops have the lowest BWP because these crops are mainly rainfed. BWP of a crop is influenced by two factors: the share of irrigated area, and the crop characteristics, which are keys for irrigation water requirement.

3.2 WF of crop production (WF_c)

The average annual WF_c was 1638 million $m^3\,yr^{-1}$ in the HRB during 2004–2006. About 45 % (742 million m^3) of WF_c was due to the use of blue water, while the remaining 55 % (896 million m^3) was from the use of green water (Fig. 4). Cereal crops accounted for almost half of the WF_c. In particular, wheat and maize combined accounted for 27 % of WF_c. Wheat and maize comprised a large share (30 %) of cropland area. Cereal crops accounted for about 51 % of blue WF_c and 49 % of green WF_c. In particular, wheat and maize comprised 38 % and 19 % of blue and green WF_c, respectively. Not only in the HRB, but also for the whole China, wheat and maize are the major grain crops and account for a larger share of consumptive water use in cropland (Liu et al., 2007; Yang, 1999).

3.3 VWC of animal products

Beef has the largest VWC of almost 20 000 $m^3\,t^{-1}$, followed by sheep and goat (Table 2). As expected, animal meats have much higher VWC than crops. The high VWC of meat is largely due to the large feed consumption that requires a high amount of water.

Compared to crops, meat has a relatively low BWP, which ranges from less than 1 % to 40 % (Table 2). All the four types of livestock have much higher VWC_{green} than VWC_{blue} compared to crops. Among the four types of meat, sheep/goat meats have the lowest BWP of 0.3 %. Sheep and goat are dominantly raised in pasture land and they eat grasses in rainfed grassland without much addition to feeds such as maize. In contrast, poultry has a relative high BWP of 40 %. Chicken are raised in farmers' backyards or in chicken factories, and they rely heavily on feed stuff. Hence, the BWP of chicken is significantly influenced by these feeds. The VWC of meats and its green and blue components are closely related to the type of feeds and animal management systems.

3.4 WF of livestock production (WF_l)

The average annual WF_l was 65.82 million $m^3\,yr^{-1}$ in the HRB during 2004–2006. About 92 % of WF_l (60.71 million m^3) was green and only 8 % (5.1 million m^3) was blue (Fig. 5). Sheep and goat accounted for over 70 % of green WF_l. This is due to the large amount of meat production of sheep and goat. When checking blue WF_l, pork and poultry combined accounted for about 92%, while sheep and goat only accounted for about 4 %. The low BWP of sheep and goat meats largely explains the low share of blue WF_l of sheep and goat.

3.5 WF in the HRB

The average annual WF was 1768 million $m^3\,yr^{-1}$ in the HRB during 2004–2006 (Fig. 6). Almost 92 % was from crop production. Livestock production accounted for 4 %. The annual WF of industrial and domestic sectors in the HRB was 34 million $m^3\,yr^{-1}$ and 30 million $m^3\,yr^{-1}$, respectively. WF_i and WF_d combined were equivalent to WF_l. Agricultural production (crop and livestock production) was the main human activity within the HRB, and it accounted for 96 % of WF in the HRB. For WF_c, cereal crops were the largest water user; while for WF_l, sheep and goat were the biggest water user.

In the HRB, 54 % (956 million $m^3\,yr^{-1}$) of WF was green, while 46 % (811 million $m^3\,yr^{-1}$) was blue (Fig. 7). About 94 % of WF_{green} within the HRB was related to crop production, while cereal crops contributed the largest share. WF_l only represented 6 % of WF_{green}. Among WF_{blue}, crop production accounted for 91 %, domestic and industrial sectors each contributed about 4 %, while livestock production only accounted for less than 1 %. Livestock production only accounted for a marginal share of WF_{blue} because livestock in the HRB is mainly raised in pasture under rainfed conditions. Crop production, especially cereal crop production, was the main green and blue water consumer within the HRB.

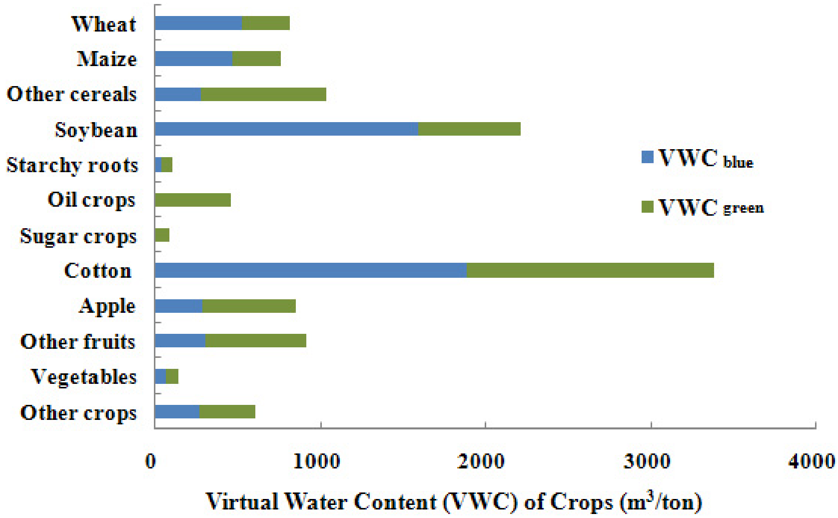

Fig. 3. Blue and green virtual water content (VWC) of crops within the HRB.

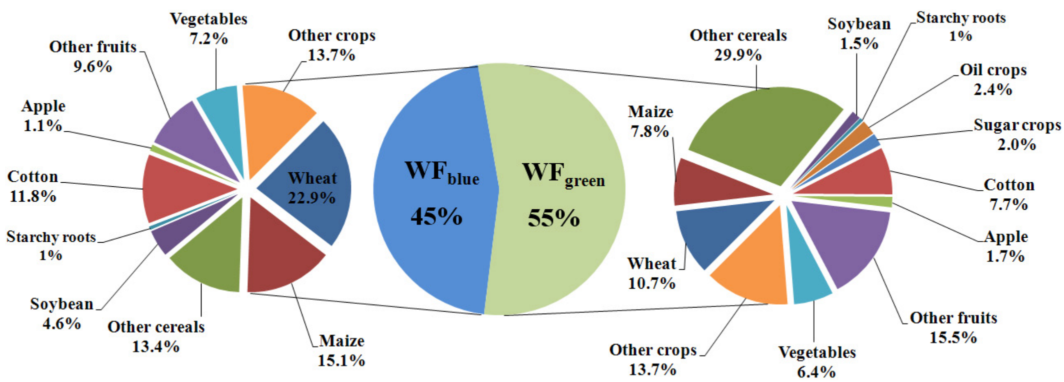

Fig. 4. Green and blue water footprint (WF_{green} and WF_{blue}) of crop production within the HRB over 2004–2006.

4 Discussion

4.1 Comparison with other studies

The per capita WF (green and blue) of the HRB is estimated to be 870 m^3 cap^{-1} yr^{-1}. According to Cai et al. (2012), in the Gansu province (the majority part of the HRB), the net virtual blue water export through food trade accounted for 10 % of the total natural runoff in the basin and 25 % of the total blue water use. From the water resources point of view, it is not a good solution to use precious water in arid and semi-arid regions to support a large amount of food trade. Crop pattern adjustment is a key to better water management.

For different crops, the VWC of crops estimated in this paper is slightly higher than China's average values from Liu et al. (2007). One exception is cotton, and its VWC value estimated here is about twice the national average value. The climatic condition is one important reason for the higher VWC values in the HRB. The HRB is located in arid and semi-arid regions with high potential evaporating capacity. We also find that the VWC values of livestock products in HRB are generally higher than those reported in Chapagain and Hoekstra (2004) and Liu and Savenije (2008). Especially for beef, its VWC value is 1.6 times the value calculated by Chapagain and Hoekstra (2004). The feed eaten by animals has higher VWC values in the HRB due to the dry climate conditions, leading to higher VWC of animal meats.

Zhang (2003) calculated VWC of crops and livestock in the city Zhangye located in the west of HRB. Except for starchy roots and oil crops, the VWC values of all other crops and livestock reported by Zhang (2003) are very close to our results. The VWC of starchy roots and oil crops calculated by Zhang (2003) is much larger than ours, mainly because rainfall in the Zhangye region is lower (157–103 mm yr^{-1}) than the HRB's average level. These two types of crops mostly depend on green water rather than blue water. Low precipitation leads to high VWC of these two crops in the Zhangye region.

In general, the BWP of crop production in the HRB is 45 %. It is much higher than the global average of 19 %

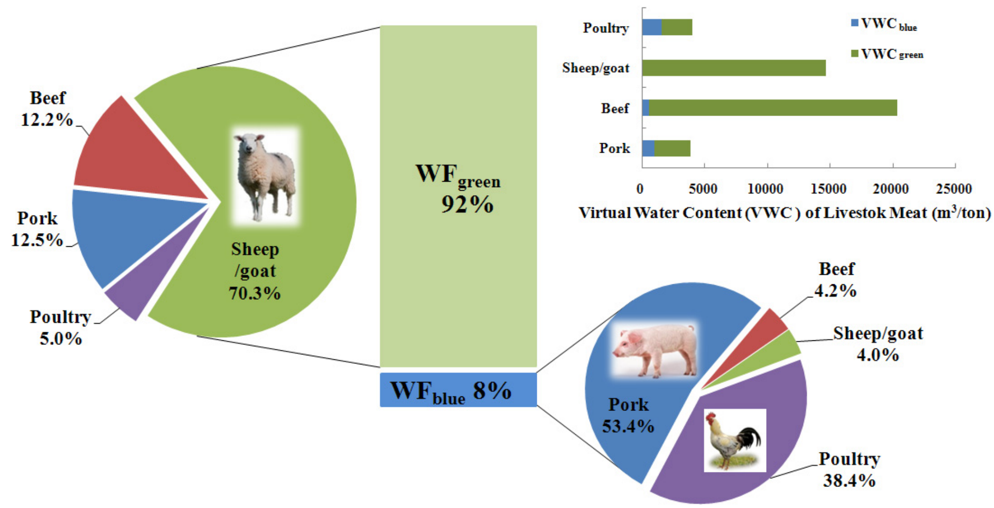

Fig. 5. Green and blue water footprint (WF_{green} and WF_{blue}) of livestock production within the HRB over 2004–2006.

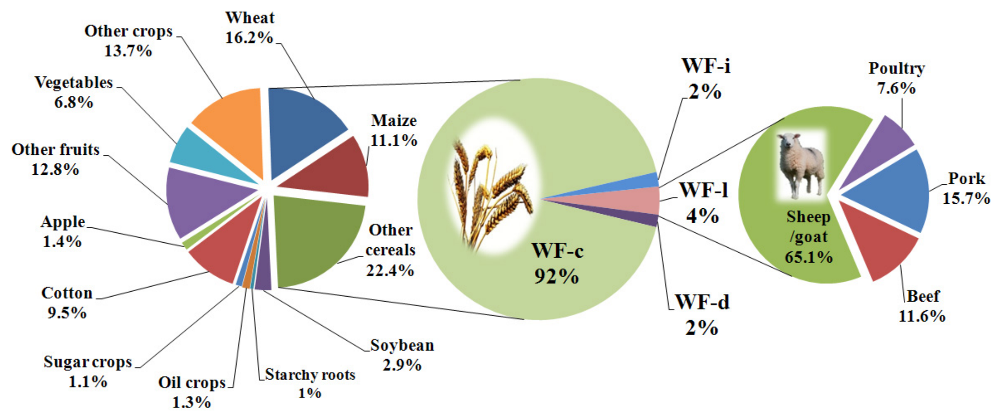

Fig. 6. Water footprint (WF) in the HRB over 2004–2006.

reported by Liu et al. (2009) and also higher than China's average of 32 % (Liu et al., 2007). The HRB is an inland river basin located in arid and semi-arid northwest China. Many types of crops largely rely on irrigation during their growth period. High temperature leads to high crop water requirements, while low precipitation leads to a high dependency on irrigation in the HRB. The BWP of livestock production estimated in this study is very close to that reported in Zhang (2003).

4.2 Sustainability analysis

In this study, we compare WF_{blue} with blue water availability (WA_{blue}) to indicate blue water scarcity (BWS) on both a yearly and monthly basis (Fig. 8). Natural runoff availability is high from April to September due to high precipitation in these months. WF_{blue} is also much higher from April to September than other months because crops mainly grow during these periods. The period from October to March is too cold for crops to grow. Additionally, these months have too little precipitation to support any rainfed crops.

Hoekstra et al. (2012) provide an approach to quantify BWS. At a river basin level, the BWS is defined as the ratio of the WF_{blue} to the WA_{blue} during a certain period. It is classified into four levels: low BWS (< 100 %), moderate BWS (100–150 %), significant BWS (150–200 %) and severe BWS (> 200 %). In the HRB, the annual WF_{blue} was 811 million $m^3\,yr^{-1}$ during 2004–2006, and it was greater than the WA_{blue} of 528 million $m^3\,yr^{-1}$. The average annual BWS value was 154 %; hence, according to the above definitions, significant BWS occurred on an annual basis in the HRB. WF_{blue} was 31 % of the total natural runoff; hence, runoff in the HRB was significantly modified by human activities. This indicates that water consumption for human activities has exceeded the sustainable level of water availability, and human WF was partly met at a cost of violating environment water flows.

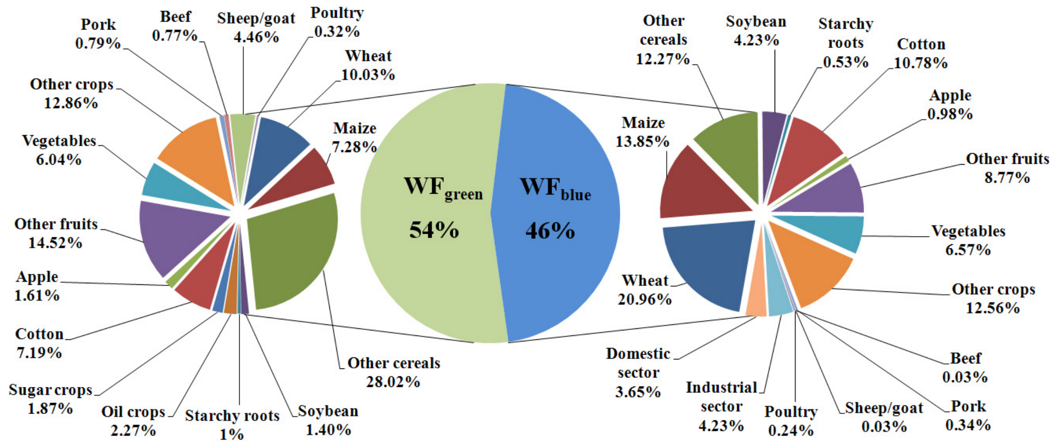

Fig. 7. Average annual green and blue water footprint (WF_{green} and WF_{blue}) within the HRB over 2004–2006.

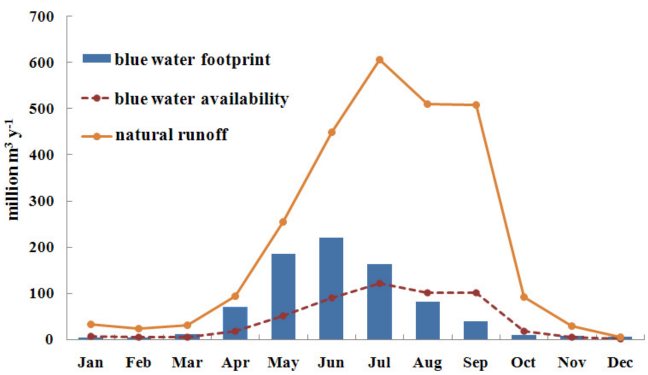

Fig. 8. Comparison between average monthly blue water footprint and blue water availability in the HRB over 2004–2006.

When comparing the monthly WF_{blue} with the monthly WA_{blue}, one can identify which months are confronted with what level of water scarcity. According to our estimate, WF_{blue} exceeded WA_{blue} in eight months of the year (Fig. 8). The HRB faced severe BWS in four months (April, May, June and December), significant BWS in two months (March and November), and moderate BWS in two months (February and July). Although high natural runoff availability occurred from April to July, WA_{blue} cannot meet human water demand, in particular for crop irrigation. From November to January, the HRB undergoes its dry season with a small amount of water available for the industrial and domestic sectors. It is clear that the environmental flow requirements are not met during two-thirds of the year. Natural runoff cannot meet human water demand and environmental flows at the same time. This leads to unsustainable water use, causing severe ecological degradation in the HRB, such as the river running dry and death of riparian vegetation (Kang et al., 2007).

4.3 WF and water withdrawal

Statistics on water use often report water withdrawal. However, we argue that WF is more suitable for measuring water consumption by human beings. A large part of water withdrawal will return to local water bodies and may be used again. For example, on a global scale, about 40 % of agricultural water withdrawals are not consumed, but go back to downstream water bodies as return flows (Perry, 2007; Shiklomanov, 2000). Hence, water withdrawal cannot completely demonstrate human appropriation of water resources. Moreover, WF can quantify how much and what type (blue or green) of water is consumed by human, while the traditional statistics on water withdrawal only account for blue water. Statistics on WF and its "color" components (green and blue) are suggested to be reported in statistics.

Taking the HRB as an example, according to our estimate, WF was 1768 million $m^3\,yr^{-1}$ in 2004–2006, among which 956 million $m^3\,yr^{-1}$ was green, and 811 million $m^3\,yr^{-1}$ was blue. At the river basin level, there is very little statistical information on water use, even for water withdrawal. The often used water withdrawal data of 2625 million $m^3\,yr^{-1}$ in many studies (Chen et al., 2005; Zhang, 2003) are for the year of 1999. Apparently, this number includes a large amount of return flow that could further be used within the HRB. The WF addresses consumptive water use and its green and blue components, and shows the "real" water consumption.

Including green water in water accounting is important. Traditional water resources assessment and management mainly pay attention to blue water. In the past decades, several studies conclude that green water management should be emphasized in addition to blue water (Savenije, 2000; Liu et al., 2009). Even in arid and semi-arid regions such as the HRB, WF_{green} is still higher than the WF_{blue}, as estimated in this article. Green water plays an important role in food production. Improving green water management and green water use efficiency is key to enhancing river basin water management and to guaranteeing food security. Unfortunately, this is still an area that needs to be significantly strengthened.

4.4 Shortcomings

There are several shortcomings in this study. First, there are no crop or livestock production data at the river basin level. We have to calculate them based on crop or livestock distribution maps with statistics for administrative units. Such calculations can lead to errors, but this method will remain necessary when statistical data are not available at the river basin level. Our study is the first attempt for the assessment of WF at the HRB, and it is very difficult to validate the results obtained from the models used, such as the VWC of crop from the CROPWAT model. More monitoring efforts can help such validation. Second, for the EFR value, we choose 80 % as a threshold based on Hoekstra et al. (2011, 2012). It is still questionable whether such a threshold can be used for river basins in arid and semi-arid regions such as the HRB. To address this issue, further efforts are still needed to study the environment flows that are required to sustain freshwater ecosystems and human livelihoods and wellbeing that depend on these ecosystems. One effective way is to set up a baseline of a "normal" water status, and evaluate the actual water requirements, especially from the local ecological systems. Third, it is very difficult to separate internal and external WF of HRB and separate productive WF (e.g. through transpiration) and non-productive WF (e.g. through evaporation). Internal and external WF have been calculated by Cai et al. (2012) for Gansu province, which covers 43 % of the HRB. The results show that the virtual water export of the agricultural products accounted for 10 % of the total water resource and 25 % of the total water use in the province (Cai et al., 2012). Hence, the amount of virtual water trade was quite large in such an arid region. We did not provide a comprehensive calculation of internal and external WF in this paper for the HRB because previous research on virtual water trade was based on input-output models, but our approach in this paper is based on the Water Footprint Network method. For the Water Footprint Network method, either the food trade data or the food consumption data should be used to estimate virtual water trade. Unfortunately, both the datasets have not yet collected successfully. As to productive/non-productive water uses, Wang and D'Odorico (2008) suggested that a focus should be on maximizing transpiration water loss and minimizing evaporation water loss. Technologies such as stable isotope analysis can be helpful to trace the water cycling processes and provide an approach for the partitioning of productive and non-productive WF(Wang L. et al., 2010, 2012).

There are also several factors that we did not take into account. First, grey WF is not included due to the lack of comprehensive data on pollutant discharge. Ignoring grey WF will result in a conservative estimate of WF. Second, we do not calculate WF for the HRB outside China's boundary. However, as we have mentioned, this will not lead to large errors due to the marginal human activities for the HRB in Mongolia. Third, our study did not include green water sustainability assessment. Green water plays a key role in crop and livestock production, and it is also very important to keep healthy natural ecosystems. Competition of green water between human activities and natural ecosystems will lead to different levels of green water scarcity. There are two reasons why we did not conduct a green water sustainability analysis: the lack of a standard method, and the lack of information on how much green water should be maintained for natural ecosystems. However, such analysis is an important topic and it should be further strengthened to gain in-depth insights into human's intervention to green water resources. Fourth, although we provide a first attempt to estimate WF for the entire the HRB, such an assessment does not take into account the spatial difference of WF within the river basin. Spatial heterogeneity of climate conditions and land use/cover are very sharp in the HRB with high precipitation and glaciers upstream and low precipitation and desert downstream. There is a need to compare WF with water availability at the sub-basin levels. This is out of the scope of this paper, but it is what will be further investigated in the next step. Fifth, we mainly use the results of VWC or natural runoff from the model simulations without tracing the hydrological processes or supply chain. How detailed the calculation of WF should be depends on the objective of the research. To study product WF, it is often necessary to trace the supply chain of the product, and add up all the water needed in each chain. However, WF assessments at a river basin level are often based on the product WF results without tracing and measuring the water cycling processes. Last but not least, there is also a need to further analyze the economic and social impacts (e.g. trade, income, employment, etc.) of WF to enable the WF to become a more comprehensive indicator for decision makers.

Overall, accurate assessments of WF still remain a challenging task due to the complex processes of water cycles and human activities, and the lack of many important input data at a river basin level. However, it is worth extra efforts to collect more detailed information to increase the accuracy of WF assessment at river basin scale.

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