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An Evaluation of China's Water Footprint

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Abstract The water footprint is an indicator of freshwater consumption that looks not only at direct water consumption of a consumer or producer, also at the indirect water consumption. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. Based on the concept and calculating method of water footprint, this paper estimates the water footprint of China in 2007. The result shows that the total water footprint of China is 856.34×10^9 m^3 and the per capita water footprint is 648.11 m^3/year. The spatial difference of per capita water footprint is obvious among all provinces of China. Generally, the more developed cities, the southern and coastal provinces have a higher per capita water footprint, lower water footprint intensity and higher efficiency of water consumption, while the North West China has lower water utilization efficiency. China is one of the thirteen water scarce countries in the world and spatial distribution of water resources is non-uniform. In addition to the virtual water trade, government should apply advanced technology and best available management practices, improve the efficiency of water use, reduce

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virtual water content per unit product, and continue nation-wide readjustment of industrial structure to guarantee an efficient use of limited water resources.

Keywords Water footprint · Virtual water · Spatial analysis · China

1 Introduction

Freshwater with acceptable quality and adequate quantity is not only a prerequisite for human societies, but also for natural ecosystems that perform functions essential for human and life on earth (Costanza and Daly 1992). In the wake of population growth and social development, the demand-supply imbalance of global water resources has been increasingly serious, and water shortage has become an important limiting factor for the sustainable development of many nations. The total water resources in China account for 6% of the world's total, ranking the fourth in the world. However, China's per-capita water resources ranks 121st in the world, only a quarter of the world's average level, making China one of the 13 water-poor countries (Xu and Long 2004). Development is a perpetual theme of human society, but water and water environment, which are the material basis for the realization of sustainable development, are facing serious challenges. Water shortage, water pollution and flood disasters have threatened and restricted the potential for the sustainable development of mankind. It is necessary to calculate the actual demands for water resources by human to keep water exploitation and use within sustainable range.

The water footprint concept was introduced in 2002 by Hoekstra, a Dutch researcher. It is used to describe the impact of human consumption on water resources systems (Hoekstra 2003). The idea derives from the theory of 'ecological footprint', which was introduced in 1992 by William Rees, a Canadian economist (Wackernagel and Rees 1996; Wackernagel et al. 1997). The two 'footprint' concepts are regarded as complementary indicators of natural capital use in relation to human consumption. None of the indicators can substitute the other one, simply because each one provides different information. The ecological footprint denotes the bio-productive area (hectares) needed to sustain a population, the water footprint represents the freshwater volume (cubic metre per year) required (Hoekstra 2009). The water footprint is an indicator of freshwater consumption that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business (Hoekstra et al. 2009). The sum of water for domestic, agricultural and industrial consumption has been used as a main representative indicator to evaluate water consumption of a nation or region, but this method has overlooked the use of soil water in agricultural production and the impact of cross-region virtual water trades. Water footprint has included blue water and green water, enriched the denotation and connotation of traditional evaluation system for water resources and connected real water with virtual water, so that the actual demands for and occupancies of water resources can be reflected. Water footprint has provided a new method to evaluate the quantitative relations between the type of household consumption and water use of a nation or region in the field of water resources. It also provides a useful decision basis for the scientific use of limited water resources and can help to realize the sustainable use of water. The idea and calculating method of water footprint is introduced in this article to calculate the footprint of each province in China in 2007. The present state of the occupancy of water resources in China is analyzed and the ways to reduce water footprint and the water stress are also discussed.

2 Materials and Methods

2.1 Data Sources and Processing

Our data sources include: (1) *China Monthly Data Book of Terrestrial Surface Climate*, *China Data Book of the Growth and Development of Crops and Soil Moisture of Croplands Calculated in Ten-Day Periods*(from China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn), meteorological data, crop cultivation dates and maturity records in 2007 from *Isogram Study of Main Crop Water Requirements in China* (CCWRICG 1993); (2) CROPWAT software for computing crop water requirements used by Food and Agriculture Organization of the United Nations; (3) The data provided by Chapagain and Hoekstra (2003a) about the quantity of virtual water in animal products in China; (4) Statistical yearbooks 2008 in 31 provinces, municipalities and autonomous regions of China; (5) *China Water Resources Bulletin 2007*; (6) *China Rural Statistical Yearbook 2008*.

2.2 Calculating Methods

The water footprint of a nation or region refers to the sum of direct and indirect water quantity used to produce the goods and services consumed by the residents of the nation or region. Usually, it can be calculated in two ways: top–down method and bottom–up method. And the bottom–up method depends on the quality of consumption data, while the top–down method relies on the quality of trade data. When the different databases are not consistent with one another, the results of both approaches will differ (Chapagain and Hoekstra 2004; Van Oel et al. 2009).

In an economic perspective, these two methods can be comprehended from two different angles, including production and consumption. The first method decomposes water footprint into internal water footprint and external water footprint from the angle of a water footprint producer, but detailed records of the inflow and outflow of products in a research area are needed. The second method multiplies the quantity of goods and services consumed by the residents of a nation by their respective volume of each goods' virtual water and then calculate the summations of these products. However, virtual water content in commodities may vary according to different regions and production conditions. All necessary materials about consumption are available in statistical yearbooks, but one drawback is that some data are incomplete.

Both methods have their distinguishing features. Top–down method is used in this paper and national water footprint is the summation of that in each province. However, statistical information on regional trade data between provinces is insufficient in China. This research estimates the trade volume of virtual water between regions from the perspective of production and consumption to solve the sufficiency. We assume that the produced goods would first support local consumption and trading can make up the insufficiency in supply, whereas all surplus commodities are assumed to be used in foreign trades, but in practice, surplus commodities are partially stored up and partially traded.

2.3 Main Calculation Contents

The concept of water footprint is put forward on the basis of virtual water research by Hoekstra. The calculations of both internal water footprint and external water footprint involve virtual water calculation. According to present researches, agriculture is the biggest consumer of water resources in the world. A large quantity of water resources are contained or reserved in various agricultural products. The virtual water content of an industrial product can be calculated in a similar way as for agricultural products. There are nearly no methods and detailed standardized national statistics related to the production and consumption of industrial products we can use (Hoekstra and Chapagain 2007). Meanwhile, the amount of virtual water in industrial products is often left out, since its calculation is over-complicated and the actual consumption of water is usually very small. Therefore, the volume of virtual water in agricultural products and animal products are the most important parts in its calculation, and they are key factors in measuring water footprint (Long et al. 2003).

2.3.1 The Calculation of Virtual Water in Crop Products

Two principal methods of calculating virtual water volume in agricultural products are: research on production tree for different products proposed by Chapagain and Hoekstra (2003b); and calculation based on distinguishing different types of products put forward by Zimmer and Renault (2003). The calculating methods of virtual water content in agricultural products varied with product classifications. Zimmer and Renault categorize agricultural products into 6 principal types, including primary products, processed products, transformed products, by-products, multiple products and products with low or no water consumption.

The calculation of virtual water content in primary products of grains is the core of virtual water calculation in agricultural products. The quantity of water needed for the growth of certain crop is needed to calculate virtual water content in agricultural products, and the calculation is based on accumulated evapotranspiration during the growth periods of crops (Crop Water Requirement, (CWR, m^3/ha)). Main factors influencing the volume of CWR are: precipitation, temperature, air pressure, sunlight hours, wind speed, crop type, soil conditions and cultivation time. Standard Penman–Monteith equation recommended by Food and Agriculture Organization of the United Nations (FAO) is commonly used to calculate evapotranspiration (Xu et al. 2003). This study includes 25 kinds of crops, classified into nine categories: grain crops, oil crops, sugar crops, fruit crops, bast fiber crops, cotton, vegetables, tobacco and tea (Table 1).

We used CROPWAT, an FAO software to calculate CWR in our research (Hong Kong, Macao and Taiwan are not included due to data limitations). Primary geographical units in China, including provinces, municipalities and autonomous regions are divided into 246 geographical units, and 246 corresponding meteorological stations are selected to provide respective meteorological information (Fig. 1).

Table 1 List of the calculated crops

Crop categories	Crops
Grain crops	Rice, wheat, maize, sorghum, millet, barley, soybean, potato
Oil crops	Groundnut, rapeseed, sunflower
Sugar crops	Sugar beet, sugar cane
Fruit crops	Apple, citrus, banana, grape
Bast fiber crops	Ramie, jute, kenaf
Cotton	Cotton
Vegetables	Cabbage, tomato
Tobacco	Tobacco
Tea	Tea

Meteorological data and cultivation and harvest dates of 2007 from the 246 stations are applied to CROPWAT software to calculate the CWR of all the main crops, which are multiplied by their respective cultivated area. The summation of these products is the total water consumption of crops in each province. Virtual water content per unit product, or virtual water content per unit weight, can be obtained by dividing total water consumption of crops by the total yield. The average virtual water content for each of the nine categories of agricultural products is calculated

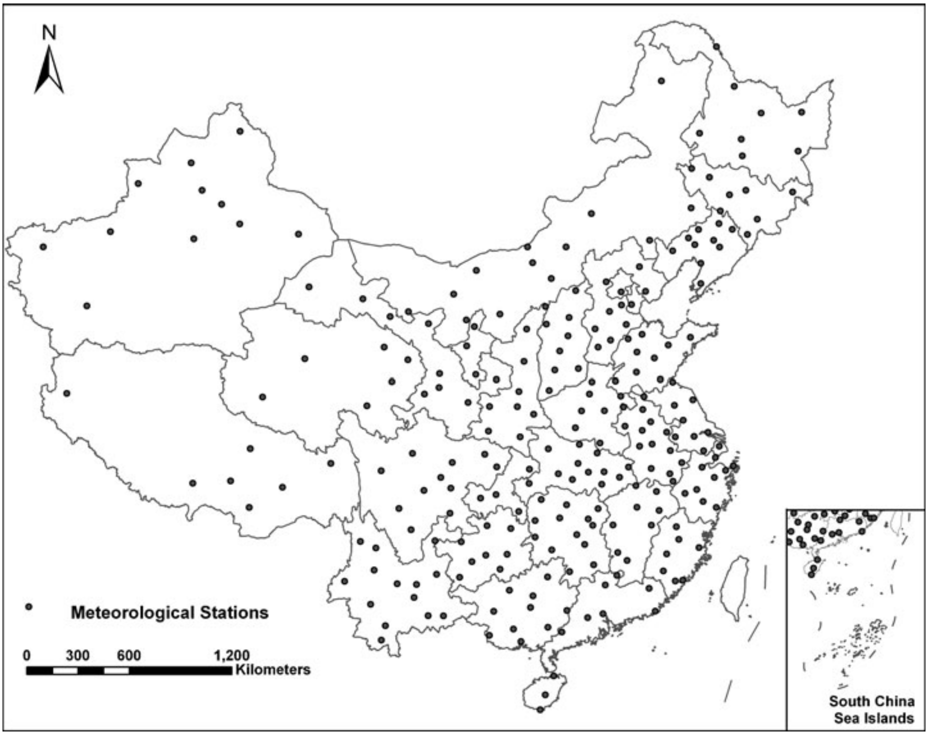

Fig. 1 A map of selected meteorological stations

based on a production-weighted average of the virtual water content of the various products per category.

2.3.2 The Calculation of Virtual Water in Animal Products

Virtual water content in animal products is the sum of water used for producing and processing fodder, drinking water for animals, water used for animal pen cleaning, and water used for butchering and processing. It is mainly decided by the breed of the animal, feeding system, fodder consumption and the climate condition in the breeding area. The calculation is a complicated process. The quantity of water resources consumed by live animals is first calculated and then allocated among different animal products. The estimate results about animal products in China provided by Chapagain and Hoekstra (2003a) are widely used in Chinese research (Wang et al. 2005a; Long et al. 2005; Ma et al. 2005, 2006).

3 Results

The estimated result of the water footprint in China in 2007 is shown in Table 2.

3.1 Virtual Water Content in Primary Grain Products of Each Province

Virtual water content per unit primary products of grains in China in 2007 is shown in Fig. 2: national virtual water content per unit grains is 1.05 m^3/kg, Inner Mongolia has the highest virtual water content at 1.47 m^3/kg, while Shandong has the lowest virtual water at 0.73 m^3/kg. Top ten provinces with highest virtual water content in crops are Inner Mongolia, Gansu, Ningxia, Hainan, Shanxi, Yunan, Heilongjiang, Guangxi, Shaanxi and Guizhou; while the ten provinces with lowest virtual water content in crops are Xinjiang, Qinghai, Jilin, Guangdong, Tibet, Hebei, Tianjin, Henan, Beijing and Shandong.

3.2 Water Footprint and its Indicator System in Each Province

China's total water footprint is 856.34×10^9 m^3 in 2007 and the calculations of water footprint in each province are demonstrated in Table 2, Figs. 3, 4 and 5. As it is shown in Figs. 3 and 4, water footprint in Guangdong is the highest (86.34×10^9 m^3), while that in Tibet is the lowest (1.97×10^9 m^3). From the perspective of compositional proportion of water footprint, external water footprint of Beijing is 7.04×10^9 m^3, which is 49.6% of its total water footprint, ranking the highest in the ratio of external water footprint to total water footprint among all provinces. The other regions with a large proportion of external water footprint are Guangdong (26.5%), Shanghai (25.8%), Jiangxi (23.9%) and Tianjin (20.2%). In contrast, provinces with the lowest proportions of external water footprint are Guangxi (2.57%), Shandong (2.32%), Hunan (2.26%), Guizhou (2.1%), Henan (1%) and Yunnan; especially in Yunnan, the proportion is zero.

The indicator system of water footprint in each province of China in 2007 is shown in Table 2 and Fig. 5. Provinces and more developed cities in northern China are short of water resources. Water shortage degrees in Tianjin, Beijing, Shanghai, Ningxia, Hebei, Shanxi, Shandong, Jiangsu, and Liaoning are all greater than 100%.

Table 2 The estimate result of the water footprint in China in 2007

Regions	Total water footprint (10^9 m^3)	Per capita water footprint (m^3/person·a)	Internal water footprint (10^9 m^3)	External water footprint (10^9 m^3)	Water shortage degree (%)	Rate of water self-sufficiency (%)	Water footprint intensity (m^3/10,000 RMB)
Beijing	14.18	868.43	7.15	7.04	595.9	50.4	157.5
Tianjin	8.52	763.93	6.80	1.72	753.8	79.8	169.7
Hebei	31.07	447.47	30.19	0.88	259.3	97.2	224.1
Shanxi	19.0	559.85	15.61	3.38	183.7	82.2	333.5
Inner Mongolia	14.94	621.14	14.30	0.64	50.5	95.8	248.2
Liaoning	26.63	619.68	23.58	3.06	101.8	88.5	241.7
Jilin	14.34	525.36	13.15	1.19	41.5	91.7	274.4
Heilongjiang	26.05	681.09	21.98	4.06	53.0	84.4	368.0
Shanghai	18.67	1004.63	14.59	4.08	541.0	78.2	155.5
Jiangsu	62.8	823.50	60.12	2.67	126.7	95.8	245.7
Zhejiang	32.27	637.70	30.08	2.19	36.2	93.2	173.1
Anhui	39.98	653.52	38.98	1.0	56.1	97.5	544.3
Fujian	25.69	717.27	23.86	1.83	23.9	92.9	280.4
Jiangxi	38.54	882.21	30.67	7.87	34.6	79.6	704.6
Shandong	51.98	554.88	50.77	1.20	134.3	97.7	200.8
Henan	38.79	414.40	38.40	0.39	83.4	99.0	257.6
Hubei	46.74	820.11	44.50	2.24	46.0	95.2	510.8
Hunan	42.05	661.67	41.10	0.95	29.5	97.7	459.8
Guangdong	86.34	913.77	63.45	22.89	54.6	73.5	281.5
Guangxi	32.97	691.55	32.13	0.85	23.8	97.4	560.2
Hainan	5.27	623.75	5.12	0.16	18.6	97.1	428.7
Chongqing	17.88	634.81	17.01	0.87	27.0	95.2	434.8
Sichuan	49.12	604.44	46.84	2.28	21.4	95.4	467.6
Guizhou	18.76	498.67	18.37	0.39	17.8	97.9	692.2
Yunnan	24.36	539.58	24.36	0.00	10.8	100.0	515.8
Tibet	1.97	694.19	1.87	0.11	0.5	94.6	576.0
Shaanxi	15.81	421.85	14.51	1.30	41.9	91.8	294.4
Gansu	15.27	583.50	14.84	0.43	66.8	97.2	565.7
Qinghai	3.44	623.33	3.04	0.40	5.2	88.4	452.2
Ningxia	3.72	609.52	3.54	0.18	357.5	95.2	445.7
Xinjiang	29.23	1395.08	28.50	0.73	33.8	97.5	836.4
China	856.34	648.11	–	–	–	–	312.9

As limited to data available, the calculation didn't include the districts of China: Hong Kong, Macao and Taiwan

The degrees in Tianjin, Beijing and Shanghai are as high as 753.8%, 595.9% and 541%. Water self-sufficiency rates of Beijing, Guangdong, Shanghai, Tianjin and Shanxi rank the lowest in China and the self-sufficiency degree in Beijing is only 50.4%. China's water footprint intensity is 312.9 m^3/10,000 RMB in 2007, and the spatial difference of water footprint intensity is obvious among all provinces of China. Water footprint intensity in Xinjiang is the highest (864 m^3/10,000 RMB), while that in Shanghai is the lowest (157 m^3/10,000 RMB). It can be concluded that the degrees of water shortage are low in most provinces, cities and regions of China, and their water self-sufficiency rates are mostly above 90%, which is a high level.

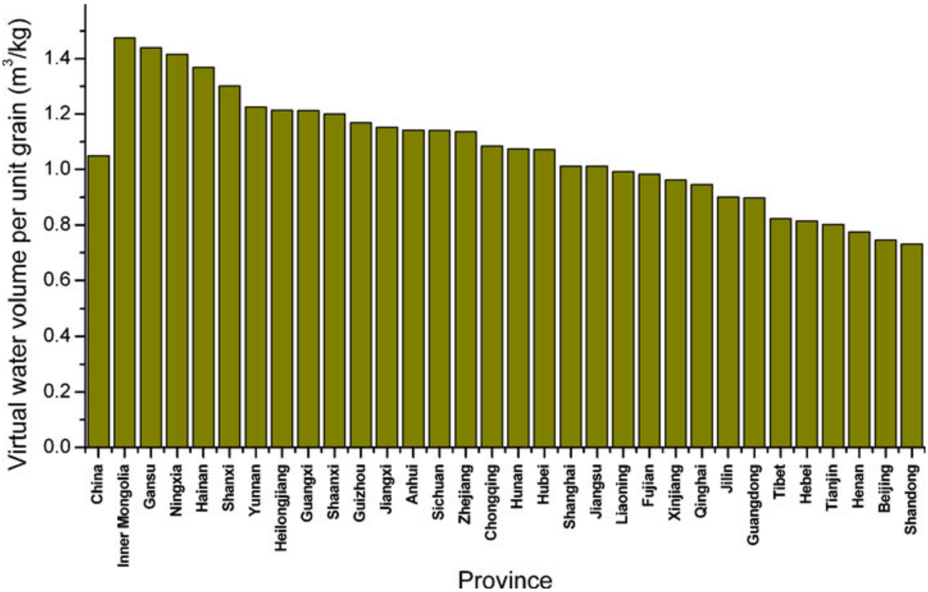

Fig. 2 Virtual water volume per unit grain of each province in China in 2007

The spatial difference of per capita water footprint is obvious among all provinces of China in 2007. It is illustrated in Fig. 6 that China's per capita water footprint is 648.11 m^3/year in 2007 and 14 provinces, including Xinjiang, Shanghai,

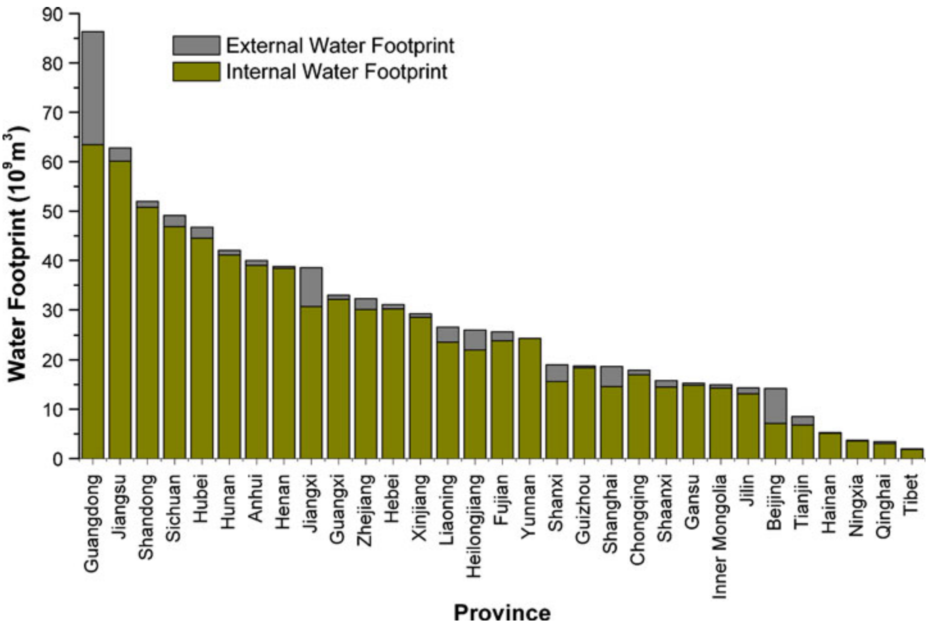

Fig. 3 Water footprint in each province of China in 2007

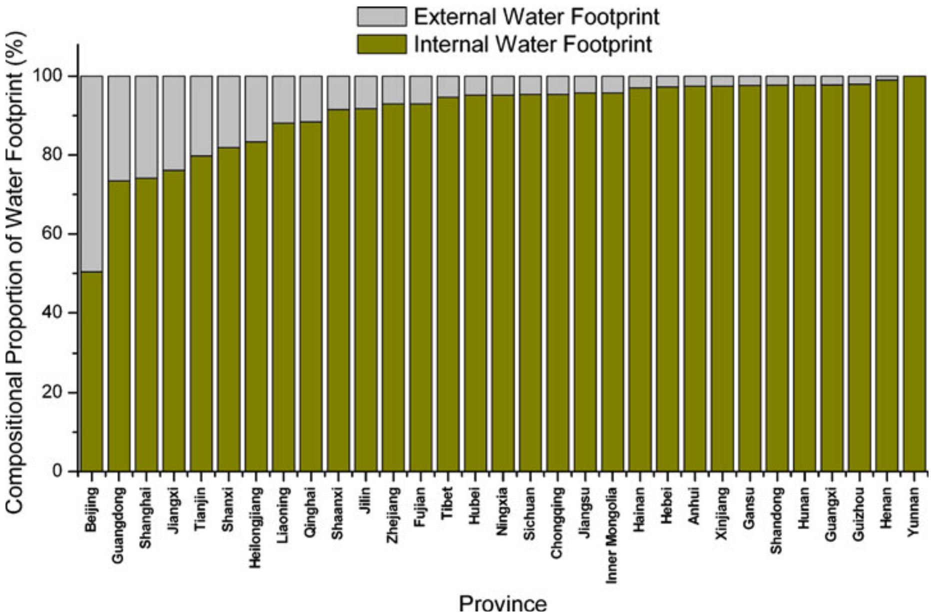

Fig. 4 Compositional proportion of water footprint in each province of China in 2007

Guangdong, Jiangxi, Beijing, Jiangsu, Hubei, Tianjin, Fujian, Tibet, Guangxi, Heilongjiang, Hunan and Anhui, overrun the national average level. Per capita water footprint in Xinjiang and Shanghai are 1,395.08 and 1,004.63 m^3/year, both being

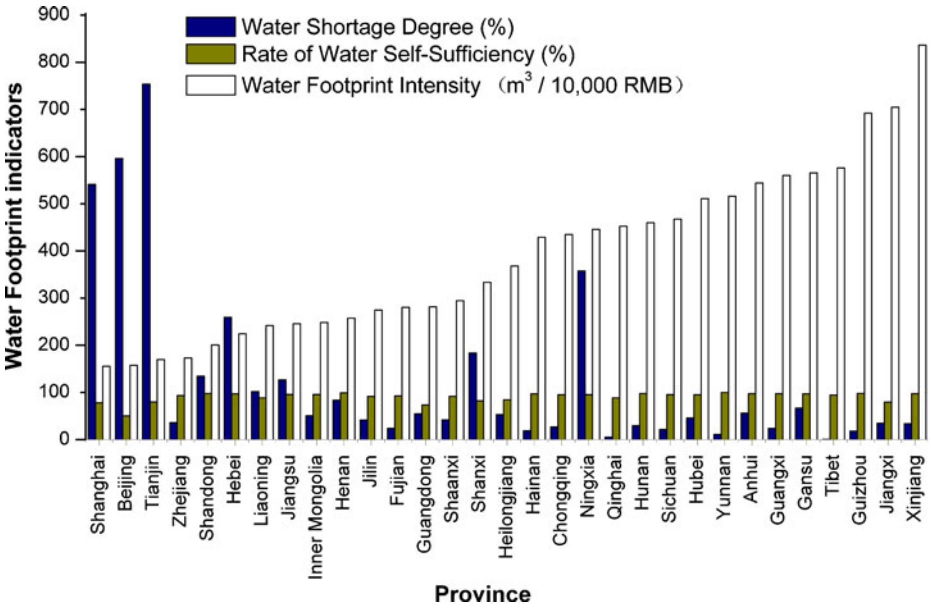

Fig. 5 Water footprint indicators of China's provinces in 2007

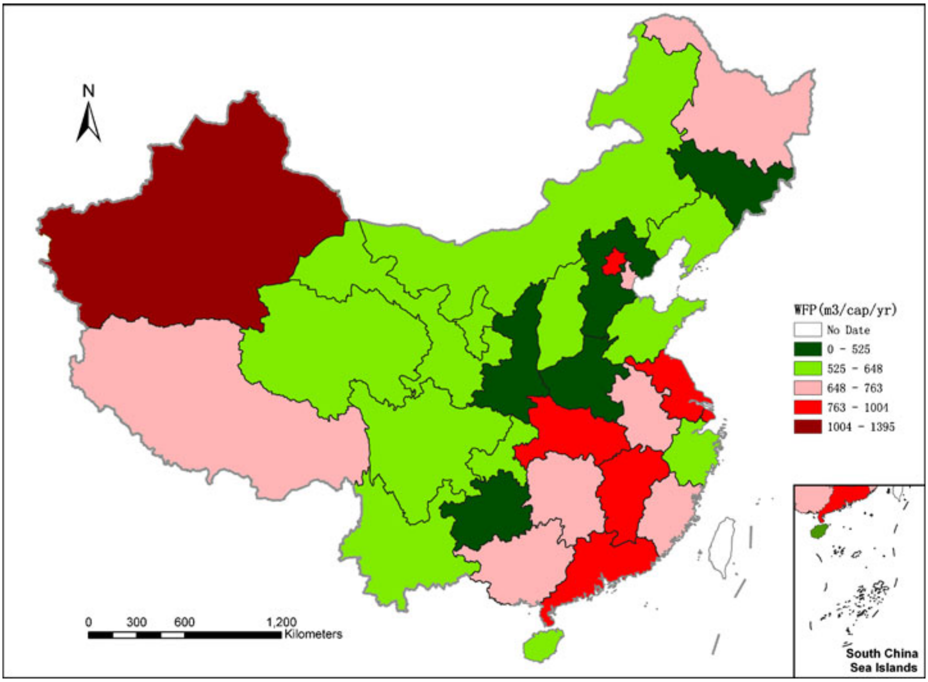

Fig. 6 Per capita water footprint of each province of China in 2007 (*green* means that the provinces' water footprint is equal to or smaller than the nations' average. Provinces with *red* have a water footprint beyond the nations' average)

more than 1,000 m^3/year. In contrast, per capita water footprint in Guizhou, Hebei, Shaanxi and Henan all stands below 500 m^3/year, and Henan has the lowest level of 414.4 m^3/year. Per capita water footprint consumption is generally higher than average in developed cities and provinces in the southern part and coastal regions of China.

4 Discussions

Water footprint measures the actual occupancies of water resources by human from the perspective of consumption. It connects water use with human consumption patterns, and it can be regarded as the best indicator for measuring the influences of human activities on water resource environmental, because the concept of water footprint has expanded water issues into socio-economic field (Xu et al. 2003; Cheng 2003). According to present researches, the main factors affecting the amount of water footprint are: (1) the volume of material consumption under the influence of economic incomes; (2) consumption patterns influenced by consumption habits, religious belief etc.; (3) production capacity of water and land resources influenced by climate, technology level and production practice (Cheng 2003).

4.1 The Relation between Virtual Water in Grains and Water Footprint

Water is normally needed in production and services and this kind of water resource used in the process of producing goods and services is called virtual water by Allan (1993, 1994). The theoretical bases for virtual water are resource flow theory, resource replacement theory and comparative advantage theory (Liu et al. 2006). Virtual water exists in various products in an 'invisible' form, so consuming products is essentially an indirect way of consuming water resources.

Since only a small volume of water in real form is directly used by human in their daily life (Gleick 2000; for example, a person usually needs 2~4 L of water resource per day to meet body requirement, but the volume of virtual water consumed to satisfy food consumption is 1000 times more), while consuming virtual water in products is the principal form of water consumption by human, virtual water consumption has become a major part of water footprint. At present, irrigated agriculture is responsible for about 70% of all freshwater abstractions by humans (Gleick 1993; Bruinsma 2003), while agriculture as a whole applies about 86% of the worldwide freshwater use (Hoekstra and Chapagain 2007). Agricultural products are necessities of life, and a large volume of water resources is actually contained and 'stored up' in various agricultural products, so they must be the main part of water consumption by human, and virtual water contents in the agricultural products of a region is bound to influence the volume of water footprint in that region. Reducing virtual water contents per unit grain is an important way to reduce regional water footprint; this is especially important for water-poor areas. Our calculation of the average volume of virtual water content in grains in China in 2007 is 1.05 m^3/kg, which is lower than the result (1.13 m^3/kg) by Wang et al. (2005b). However, China's water consumption in grain production is still larger than western developed countries. For example, 0.79 m^3 of water is consumed to produce 1 kg grain in the US and 0.63 m^3 of water is consumed to produce 1 kg grain in the 15 countries of the EU (De Fraiture et al. 2004). This mainly relates to water use efficiency, agricultural production technologies and management in China. Therefore, China should further strengthen its investment in agricultural technologies in the future, so that virtual water contents in crops may fall. Then China's water footprint can be reduced and the sustainable use of water resources can be realized.

Moreover, China is one of the 13 water-poor countries in the world and spatial distribution of water resources is non-uniform. It means that economizing on water is not enough and virtual water strategy should be adopted. Virtual water and virtual water strategy can be regarded as an effective tool of allocating water resources of the globe and between nations (regions) (Alaa 2010; Brown et al. 2009); they are also a new thinking and a new way to guarantee water resource security in China (Cheng 2003; Fang et al. 2010). We have found out that unreasonable use of water still exists in some places in China. For example, virtual water volume in grains is higher than average in some regions suffering an acute water shortage, including Gansu and Shaanxi (1.44, 1.20 m^3/kg). We should consider water use problems in China systematically in the future. We should think about cutting down the production of crops that consume large quantities of water to ease the stress on water resources and protect ecological environment in water-poor areas; while planting them in regions with rich water resources. Stress on water resources can be eased through 'virtual water' trades. We can also reduce China's water footprint by changing regional production structure to realize sustainable use of water resources in China on the basis of comparative advantage theory.

4.2 An Analysis on China's Water Footprint in 2007

China's water footprint is 856.34×10^9 m^3 in 2007; and per capita water footprint is 648.11 m^3/year, which is greater than the calculations of 601 m^3/year in 2000 provided by Wang et al. (2005b). The possible reasons for this are: (1) the years of calculations are different; (2) calculation methods are different. Wang adopts bottom–up method, while top–down method is used in this research. Wang's bottom–up method only considers domestic water and virtual water consumption of agricultural products, including grains, vegetables and meat, but virtual water volume consumed by industrial products is not taken into consideration, so the result is smaller than ours. According to the water footprint research results of International Institute for Hydraulic and Environmental Engineering in Netherlands, the annual per capita water footprint of the world is 1240 m^3/ year and per capita water footprint in the US, Canada, the UK, France, Germany, India, Japan, Russia and China are 2,480, 2,049, 1,245, 1,875, 1,545, 960, 1,153, 1,858, 702 m^3/year respectively (1997–2001) (Chapagain and Hoekstra 2004). And Ma et al. (2006) calculated the annual per capita water footprint of china in 1999 is 1,049 m^3/year. Compared with the Chinese part of the results, ours are still smaller. This might because of the different data sources and the way in which regional trade data between provinces are processed. Since trade data between provinces are not available due to the limitation of information, regional trade volume of virtual water is estimated from the perspective of production and consumption. This may lead to errors or even deficiencies in trade volume calculations of some commodities, such as the absence of the trade volume of industrial products, cotton, Chinese medicines and timber. China's water footprint is far below the world's average level. It is only half of the world's water footprint and even less than one third of that in the US. This phenomenon might relate to a country's level of economic development and eating habits. The living standards of Chinese residents are low and plant products, such as gains and vegetables, are mainly consumed. In contrast, living standards of western development countries are high; both water consumption volume and consumption proportion of animal products are much higher than that in China. Moreover, the volume of virtual water contents in animal products is higher than that in plant products, so per capita water footprint in China is lower than that in some developed countries.

4.3 An Analysis of Regional Differences in China's Water Footprint in 2007

According to the results, obvious spatial differences exist in water footprint composition, water footprint indicators and per capita water footprint among all provinces of China in 2007. From the perspective of proportions in water footprint composition, Beijing ranks the highest in the proportion of external water footprint among all provinces, being followed by Guangdong, Shanghai, Jiangxi and Tianjin; while Shandong, Hunan, Guangxi, Guizhou, Henan and Yunnan are provinces with the lowest proportions of external water footprint. Provinces and developed cities in northern China are short of water resources. The degrees in Tianjin, Beijing and Shanghai are as high as 753.8%, 595.9% and 541%. Water self-sufficiency rates of

Beijing, Guangdong, Shanghai and Tianjin rank the lowest in China and the self-sufficiency degree in Beijing is only 50.4%. Per capita water footprint in 14 provinces is above national average level. Per capita water footprint in Xinjiang and Shanghai are 1,395.08 and 1,004.63 m^3/year, both being more than 1,000 m^3/year. In contrast, per capita water footprint in Guizhou, Hebei, Shaanxi and Henan all stands below 500 m^3/year; and Henan has the lowest level of 414.4 m^3/year.

The China's water footprint intensity (312.9 m^3/10,000 RMB) in 2007 is very different from the reported previously (807 m^3/10,000 RMB, in 2000) by Long et al. (2006), likely due to nationwide readjustment of industrial set-up herein. But the result of water footprint intensity is consistently that spatial differences is obviously, and water footprint intensity is generally lower than average in developed cities and provinces in the southern part and coastal regions of China.

Per capita water footprint consumption, the proportion of external water footprint and water shortage degree are generally high in developed cities and provinces in the southern part and coastal regions of China, but their water self-sufficiency rate is low. Combine the research previously (Gao et al. 2008), we think the major reasons for differences between provinces are: (1) Spatial distribution of water resources is non-uniform in China. In general, the volume decreases from costal regions in the southeast to inner areas in the northwest. North China is poor in water resources, while South China is comparatively rich in water resources. (2) Virtual water volume in agricultural products is different in different provinces. Different locations of agricultural production, manner of production, climatic conditions may result in the differences in virtual water volume per unit agricultural product, which may then influence the quantity of water footprint. (3) Consumption structures of each province or region are different. Living standard, ethnic composition and living habits vary among different provinces or regions, but normally virtual water consumption is high where more meat is consumed. Therefore, diet structure can greatly influence the volume of water footprint. (4) The level of urbanization can cause differences in industrial structures and degrees of social aggregation, which become a reason for the differences in per capita footprint between provinces and regions. (5) The differences in per capita footprint between provinces and regions caused by the degrees of scientific technology.

China has a vast territory, and its spatial distribution of water resources is uneven. China is a multi-nationality country with various levels of urbanization, so regional differences in water footprint must be taken into consideration in the study on China's water footprint. Only in this way can we solve China's water problems in a systematic way.

5 Conclusion and Prospect

In this paper, the meteorological data of the year 2007 is from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), while the previous study about China adopted the data from FAO CLIMAT database, it can not accurately reflect the climate situation of the study year since the data is outdated. Since lack of statistical data about China's provinces and provincial trade information, this research estimates the trade volume of virtual water between regions from the perspective of production and consumption to solve the sufficiency problem. Our calculations and analyses show that China's per capita water footprint is 648.11 m^3/year in 2007. Per capita water footprint is generally higher than national average in more developed cities and provinces in the southern and coastal regions of China. We should apply advanced technology and best available management practices, improve the efficiency of water use, reduce virtual water content per unit product, and continue nation-wide readjustment of industrial structure to guarantee a fast and stable economic growth. Furthermore, a balanced and reasonable distribution of water resources should be achieved through virtual water trades, so that efficient use of limited water resources can be realized.

Water footprint can reflect the actual demands and occupancies of water resources of an individual, a region or a nation. Evaluating water footprint can reflect the water stress human placed on aqua system. It also provides a useful decision basis for the scientific use of limited water resources. However, present research has proved that the study on water footprint needs improving in certain areas: the calculations of virtual water contents in crops, animal products and industrial products need further improvement; the concept of water footprint mainly represents the quantity of water resources, while water quality management is still inadequate. Most of the water footprint of China is also concentrated in certain regions, certain year and without tracking long-term time dynamics of the system. The overall systematic research on China's water footprint has significant importance. It should get more attention in future research.

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References

Alaa E-S (2010) Virtual water trade as a solution for water scarcity in Egypt. Water Resour Manage 24:2437–2448

Allan JA (1993) Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. In: Priorities for water resources allocation and management. ODA, London, pp 13–26

Allan JA (1994) Overall perspectives on countries and regions. In: Rogers P, Lydon P (eds) Water in the Arab World: perspectives and prognoses. Harvard University Press, Cambridge, pp 65–100

Brown S, Schreier H, Lavkulich LM (2009) Incorporating virtual water into water management: A British Columbia example. Water Resour Manage 23:2681–2696

Bruinsma J (ed) (2003) World agriculture: towards 2015/2030: An FAO perspective. Earthscan, London

Chapagain AK, Hoekstra AY (2003a) Virtual water flows between nations in relation to trade in livestock and livestock products. Value of Water Research Report Series No. 13, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report13.pdf

Chapagain AK, Hoekstra AY (2003b) Virtual water trade: a quantification of virtual water flows between nations in relation to international trade of livestock and livestock products. Value of Water Research Report Series No.12, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report12.pdf

Chapagain AK, Hoekstra AY (2004) Water footprints of nations. Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report16.pdf

Cheng GD (2003) Virtual water-A strategic instrument to achieve water security. Journal of Chinese Academy of Sciences 4:260–265

China Major Crop Water Requirement Isograms Collaborative Group (CCWRICG) (1993) The major crop water requirement isograms' research in China. China Agricultural Science and Technology Press, Beijing

Costanza R, Daly HE (1992) Natural capital and sustainable development. Conserv Biol 6:37–46
De Fraiture C, Cai X, Amarasinghe U, Rosegrant M, Molden D (2004) Does international cereal trade save water? The impact of virtual water trade on global water use. Comprehensive Assessment Research Report 4. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. http://www.iwmi.cgiar.org/assessment/FILES/pdf/publications/ResearchReports/CARR4.pdf
Fang SF, Pei H, Liu ZH, Beven K, Wei ZC (2010) Water resources assessment and regional virtual water potential in the Turpan Basin, China. Water Resour Manage 24:3321–3332
Gao MX, Ren ZY, Guo B, Li XY (2008) Analysis on regional differences of water footprint in China in 2000 based on GIS. Agricultural Research in the Arid Areas 26(1):131–136
Gleick PH (ed) (1993) Water in crisis: A guide to the world's fresh water resources. Oxford University Press, Oxford
Gleick PH (2000) The world's water 2000–2001. Island Press, Washington, DC
Hoekstra AY (2003) Virtual water trade: proceedings of the international expert meeting on virtual water trade. Value of Water Research Report Series No.12, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report12.pdf
Hoekstra AY (2009) Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. Ecol Econ 68(7):1963–1974
Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2009) Water footprint manual: state of the art 2009. Water Footprint Network, Enschede
Hoekstra AY, Chapagain AK (2007) Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour Manage 21(1):35–48
Liu BQ, Feng ZM, Yao ZJ (2006) Theory, method and progress on virtual water research. Resour Sci 28(1):120–127
Long AH, Xu ZM, Wang XH, Shang HY (2006) Impacts of population, affluence and technology on water footprint in China. Acta Ecologica Sinica 26(10):3358–3365
Long AH, Xu ZM, Zhang ZQ (2003) Water footprint of four provinces of North-west China in 2000. J Glaciol Geocryol 25(6):692–700
Long AH, Xu ZM, Zhang ZQ, Su ZY (2005) Primary estimation of water footprint of Gansu Province in 2000. Resour Sci 27(3):123–129
Ma J, Wang DX, Lai HL, Wang Y (2005) Water footprint-an application in water resources research. Resour Sci 27(5):96–100
Ma J, Hoekstra AY, Wang H, Chapagain AK, Wang DX (2006) Virtual versus real water transfers within China. Philos Trans R Soc B 361:835–842
Van Oel PR, Mekonnen MM, Hoekstra AY (2009) The external water footprint of the Netherlands: geographically-explicit quantification and impact assessment. Ecol Econ 69(1):82–92
Wackernagel M, Onisto L, Linares AC, Falfan ISL, Garcia JM, Guerrero IS, Guerrero MGS (1997) Ecological footprints of nations: how much nature do they use? How much nature do they have? Centre for Sustainability Studies, Universidad Anahuac de Xalapa, Mexico
Wackernagel M, Rees W (1996) Our ecological footprint: reducing human impact on the Earth. New Society Publishers, Gabriola Island
Wang XH, Xu ZM, Li YH (2005a) A rough estimate of water footprint of Gansu Province in 2003. J Nat Resour 20(6):909–915
Wang XH, Xu ZM, Long AH (2005b) Estimation of water footprint of China in 2000. J Glaciol Geocryol 27(5):774–780
Xu ZM, Long AH (2004) The primary study on assessing social water scarcity in China. Acta Geogr Sin 59(6):982–988
Xu ZM, Long AH, Zhang ZQ (2003) Virtual water consumption calculation and analysis of Gansu Province in 2000. Acta Geogr Sin 58(6):861–869
Zimmer D, Renault D (2003) Virtual water in food production and global trade: review of methodological issues and preliminary results. Value of Water Research Report Series No 12, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report12.pdf