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Review

Challenge of Water Sources in Urbanizing China: an Analysis of Agricultural Water Footprint

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Abstract

It is widely recognized that China is facing the dual challenge of food scarcity and water shortage. A large amount of water is to be demanded for the country's huge population and rapid economic growth. The agricultural water footprint (AWF) proposes a new approach to indicate the interaction between food consumption and water utilization. This paper aims to quantify a long-time series of China's AWF, map its variation trend, and assess its potential influence. The findings show that the total agricultural water footprint (TAWF) has increased from 7,593 km^3 in 1990 to 10,929 km^3 in 2011 due to increases in population and in *per capita* agricultural water footprint (CAWF). Over the past few years, China has also held an increasing external AWF volume, which climbed up to nearly 10% of the TAWF respectively in 2009, 2010, and 2011. The animal WF proportion of a single urban resident was much higher than that of a rural one because of their different consumption patterns, but neither of their proportions varied significantly over the same period of time. China's CAWF increased over time and held a multi-year average value of 741 m^3·cap^{-1}·y^{-1}. The results suggest that CAWF stayed linear positively related to the urban population proportion (UPP) during the study period and that urbanization proves to be the dominant driving force to the water requirement for food consumption augmentation. Considering the irresistible economic growth and urbanization, China should take active measures to cope with troubles potentially brought by the increase in AWF and water dependency degree (WDD). Suggestions with regard to how to guarantee China's food and water resource security are raised in this paper.

Keywords: agricultural water footprint, temporal variability, virtual water, urbanization, water security, China

Introduction

With the world's largest population, China has become the world's biggest food consumer: it feeds 20% of the world's population, with an average annual consumption of nearly 500 M ton of grain and a mass of other products. Of the total (blue) water use nationwide, agricultural water use accounts for nearly 70%, making agriculture the largest water use sector in the country. Nevertheless, China's *per capita* (blue) water resources are merely 2,100 m^2, a quarter of the world's average level, making it one of the 13 most water-poor countries [1]. At the same time, uneven temporal and spatial distribution of water resources dries the vast areas north of the Yangtze River into a severe water shortage. The volume of (blue) water resources is less than 500 m^3·cap^{-1}·y^{-1} in North China Plain [2], one of China's major grain producing areas. In addition, China has experienced fast economic growth with an annual GDP growth rate of

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about 8% over the past two decades, the highest rate in recent world history [3]. Inter-sector competition over water resources intensifies as the society develops, worsening the water crisis even more. It is necessary to evaluate water demands for food consumption by inhabitants and its variation tendency so as to relieve the water crisis, ensure food security, and guarantee China's sustainable economic development.

With reference to the concept of ecological footprint and on the basis of the theory of virtual water [4], Hoekstra [5] introduced the concept of water footprint in 2002. Water footprint not only is an indicator of water use that reflects both water consumption and pollution, but can broaden water resources evaluation systems and provide water utilization information for decision-making [6]. It links the physical and virtual forms of water, broadens the denotation and connotation of the traditional water resources evaluation system, and faithfully reflects the demand and occupation of water resources in the respect of individual, business, process, product, or geographic area [6, 7]. The water footprint of a studied region is defined as the total freshwater needed for the production of goods and services consumed by inhabitants of the region [7]. The water footprint of consumers in a nation consists of two types: internal water footprint and external water footprint [7]. The internal water footprint is defined as the volume of domestic water resources used to produce goods or services consumed by the population, and the external water footprint as the volume of water resources used in other nations to produce goods or services consumed by the population of the nation in question [7, 8]. The concepts of internal and external water footprints carry great meaning for evaluating "regional water dependency," "water self-sufficiency," and "trade-related water savings" [7, 9, 10]. Most present studies have focused on quantifying the water footprint at the regional level or specific product consumption [11-15]. As a result, studies on China's water footprint have been carried out. Scholars, including Wang et al. [16], Ge et al. [17], Ma et al. [18], and Hoekstra and Chapagain [19], estimated the water footprint on a national scale. Most of their studies found that the *per capita* water footprint in China, its value ranging from 600 to 900 $m^3 \cdot cap^{-1} \cdot y^{-1}$, was lower than that in any developed country. By selecting the typical years of 1960 to 2003, Liu and Savenije [3] quantified how food consumption patterns have influenced water requirements in China and inferred that the effect of the food consumption patterns on China's water resources was substantial in the recent past and would be so in the near future.

On a smaller scale, Ma et al. [20] pointed out that northern and southern China had an equal share of total water footprint, up to 1304 billion m^3. However, south China imported from north China 52 billion m^3 of virtual water condensed in agricultural products, which does not make sense from a water resources point of view. Factors that could play a role in this paradox are the availability of suitable cropland, possibly labor availability, or national food security, and hence an integrated study would be required to give a more comprehensive assessment of the efficiency and sustainability of the South-North Water Transfer Projects. The water footprint in a vast number of provinces (including autonomous regions and municipalities) was assessed separately and the results show their values varied considerably among provinces [17, 21-24]. In general, *per capita* water footprint was greater in more developed cities and provinces in the southern and coastal regions of China, and smaller in less developed western provinces. Major grain-producing areas tend to consume a large sum of virtual water, while the municipalities and some other developed provinces hold a high proportion of external water footprint. Overall, the spatial scale has a tendency to narrow down progressively; some scholars set foot in water footprint assessing of a river basin [25, 26], city, and even the basic agricultural production unit that is an irrigation district [27]. As for the time span, almost all of the existing research pays close attention to the water footprint in a particular year or its average over a short period of time. Few of them, however, concern the analysis of long-time serial variation of regional water footprints, so how the social transformation (population growth, economic development, climate change, etc.) influences water footprint couldn't be reflected before.

This paper focuses on assessing the region-level water footprint for specific product consumption. Considering that agricultural production contributes 92% of a human's water footprint [28] and that almost 90% of an individual's water requirement goes to food production, this paper quantifies the water footprint of agricultural product consumption based on the established framework. A long-time serial (1990-2011) variation of agricultural water footprint (AWF) of China is analyzed in this study. Another attempt is that this paper calculates the AWF of urban and rural residents and assesses how their consumption patterns influence the AWF respectively. The interannual volume of net virtual water trade, external AWF, and water dependency are also calculated in the present study. Upon these bases, this paper aims to analyze the variation trend of China's AWF and its influencing factors, explore the potential impact of change in water requirements on food safety and food security of the country, and briefly discuss the water resources management strategy for the future.

Material and Methods

Calculating Methods of Agricultural Water Footprint (AWF)

The annual agricultural water footprint (AWF), or the water required for agricultural food of a region, refers to the sum of direct and indirect water quantity used to produce the agricultural goods consumed by the residents of the region in a particular year. For a specific year, the total agricultural water footprint (TAWF) of China can be estimated by:

$$TAWF = \sum\left[VWC_i \times \left(C_i^r \times P_r + C_i^u \times P_u\right)\right] \qquad (1)$$

...where *VWC* is the virtual water content of product consumed, in m^3/kg; *i* is the agricultural product item; C_i^r and

C_i^u the product *i per capita* consumed by rural and urban inhabitants respectively, in kg; and P_r and P_u population of rural and urban inhabitants. The C_i^r can be collect from statistical data of Chinese government but C_i^u cannot, so we calculate it using Eq. (2).

$$C_i^u = (O_i + I_i - E_i - C_i^r \times P_r) / P_u \qquad (2)$$

...where O_i, I_i, and E_i are output, import, and export of product *i*, respectively, in kg.

Per capita agricultural water footprint (CAWF) is the TAWF divided by the population:

$$CAWF = TAWF / P \qquad (3)$$

AWF can be estimated through all necessary materials about the consumption, import, and export of main agricultural products in China as available in statistical yearbooks, so this research estimates the AWF of rural and urban Chinese residents as well as the trade volume of virtual water over the past 22 years by using Eqs (1-3).

Virtual Water Content (VWC) of Main Agricultural Products

The virtual water content (VWC) of products, including blue and green water, can be defined as the volume of water used to produce a unit of product in the place where the product is actually produced, or alternatively as the volume of water that would have been required to produce the product in the place where the product is consumed [29]. Hoekstra and Chapagain [19] used the term "water footprint" as its first definition but it does not imply "virtual" water trade in the literal sense. Hence, the term VWC in this paper is equivalent to the latter meaning.

The VWC of a plant product is generally calculated by dividing ET (the sum of crop transpiration and soil evaporation, in $m^3 \cdot ha^{-1}$ or mm) of the crop growth period by crop yield (in $kg \cdot ha^{-1}$) [30]. The VWC of an animal product is generally calculated as the total volume of water that has been used to grow and process its feed, to provide its drinking water, to clean its housing, and the like [29]. Generally, animal products have higher VWC values compared to crop items. Beef, mutton, goat meat, eggs, fish, and seafood have VWC of 19.99, 18.01, 8.65, and 5.00 $m^3 \cdot kg^{-1}$ respectively. In contras, sugar and sweeteners and vegetables and fruits have VWC of about 0.15 and 0.50 $m^3 \cdot kg^{-1}$. The VWC values of grain crops (including cereals, tubers, and legumes) are between 0.86 and 2.65 $m^3 \cdot kg^{-1}$ in China. Table 1 shows the VWC values for the main agricultural product items in China. The agricultural products selected in this study are divided into two categories and 18 small classes, and they cover all of the major agricultural products consumed by Chinese residents. All these values are obtained from domestic literature except the VWC values of animal fats, fish, and seafood.

In China, the food self-sufficiency rate is about 95% and agricultural product consumption mainly originates from the domestic market. Due to the small share of food imports, the VWC values are determined on the basis of China's specific production conditions. On this point, the VWC of specific products can be referenced in Table 1, including a small amount of net import.

Table 1. Virtual water content for mostly consumed agricultural product items of China.

Agricultural Product Items		Product Name	Virtual Water Content ($m^3 \cdot kg^{-1}$)
Plant Products	Cereals	Rice	1.37
		Wheat	1.19
		Maize	0.86
	Coarse cereals	Millet and broomcorn	1.32
	Tubers	Potatoes and other starchy roots	1.29
	Legumes	Soybeans and other legumes	2.65
	Plant oil crops	Rape	2.06
	Vegetables and fruits	Vegetables	0.50
		Fruits	0.51
	Sugar and sweeteners	Sugarcane	0.15
		Sugar beet	0.14
Animal Products	Meats	Beef	19.99
		Mutton and goat meat	18.01
		Pork	3.70
		Poultry	3.50
	Animal fats	Animal fats	4.00
	Eggs	Eggs	8.65
	Milk	Milk	2.20
	Aquatic products	Fish and seafood	5.00

Consumption of Main Agricultural Products in China

The output volume of main agricultural products *per capita* consumption of major foods by rural households, trade volume of all kinds of agricultural products, and China's population and its composition (rural and urban populations) in 1990-2011 can be collected from the China Statistical Yearbook (1991-2012) and the 60 years of Agriculture Statistical Data of the People's Republic of China.

Results

Per capita Agricultural Water Footprint (CAWF) of China

Fig. 1 presents the interannual variability of CAWF from 1990 to 2011 in China. The national CAWF increased during the study period, displaying an upward trend of 7 $m^3 \cdot cap^{-1} \cdot y^{-1}$. The CAWF in the beginning was 664 $m^3 \cdot cap^{-1} \cdot y^{-1}$ and exceeded 800 $m^3 \cdot cap^{-1} \cdot y^{-1}$ in the most recent three years. Each Chinese consumed 813 m^3 of water by eating agricultural products in 2010, ranking the highest during the study period. The average value of 1990-2011 was 741 $m^3 \cdot cap^{-1} \cdot y^{-1}$, and held a volume of 699 $m^3 \cdot cap^{-1} \cdot y^{-1}$ in the 1990s and 782 $m^3 \cdot cap^{-1} \cdot y^{-1}$ in the first 11 years of the 21st century.

Due to the difference in eating habits, the CAWF of urban residents differed greatly from that of rural ones. Each urban resident had a CAWF of about 920 $m^3 \cdot cap^{-1} \cdot y^{-1}$ during 1990-2011, and a rural resident just 632 $m^3 \cdot cap^{-1} \cdot y^{-1}$ in contrast. The CAWFs of both urban and rural residents increased during the study period. Urban resident CAWF increased from 857 to 964 $m^3 \cdot cap^{-1} \cdot y^{-1}$ and rural resident CAWF rose from 595 to 651 $m^3 \cdot cap^{-1} \cdot y^{-1}$. CAWF of urban residents is much higher than that of rural residents.

Total Agricultural Water Footprint (TAWF) of China

TAWF is the product of CAWF and population. Fig. 2 and Table 2 display the TAWF of rural, urban, and the whole country as well as the internal and external (virtual water input) in the study period. Since the CAWF has grown in step with population, the TAWF of China has increased over time. TAWF in 1990 was about 759 $km^3 \cdot y^{-1}$, and with a growth rate of 15.8 $km^3 \cdot y^{-1}$ it reached 1,093 $km^3 \cdot y^{-1}$ in 2011.

From the perspective of its component, the share of the rural population in TAWF was relatively high (53.8%), while the share of TAWF urban population was relatively small (46.2%) during 1990-2011. The interannual variability characteristic of rural resident TAWF was opposite that of the urban as the former decreased and the latter increased over time. Rural resident TAWF was 501 $km^3 \cdot y^{-1}$, sharing a proportion of 65.9% of the whole country in 1990; however, the TAWF dropped to 427 $km^3 \cdot y^{-1}$ and to 39.1% in recent years. Urban resident TAWF was only 258 $km^3 \cdot y^{-1}$ and accounted for 34.1% of the whole country. The shift of predominance in TAWF volume from the rural to urban area can be attributed to farmers moving to towns and cities.

Based on all agricultural products, produced domestically or not, the AWF can be divided into internal agricultural water footprint (IAWF) and external agricultural water footprint (EAWF). China imported many products, such as wheat, rice, vegetable oil, and soybeans, and also exported meats, eggs, aquatic products, and vegetables in recent years. The volume of virtual water input was greater than that of its output in the years except 1994, 1998, and 1999.

Table 2. Internal, external agricultural water footprint and water dependency degree of China from 1990 to 2011.

Year	TAWF ($km^3 \cdot y^{-1}$)	IAWF ($km^3 \cdot y^{-1}$)	EAWF ($km^3 \cdot y^{-1}$)	Water dependency degree (WDD, %)
1990	759	754	5	0.71
1991	779	775	4	0.45
1992	783	779	4	0.55
1993	807	806	1	0.15
1994	831	831	—	—
1995	827	818	9	1.08
1996	861	846	15	1.68
1997	891	889	3	0.28
1998	910	910	—	—
1999	925	925	—	—
2000	942	924	18	1.91
2001	960	930	30	3.14
2002	969	945	24	2.49
2003	996	947	49	4.88
2004	1001	935	66	6.63
2005	1008	939	69	6.84
2006	1020	948	72	7.08
2007	1031	953	78	7.57
2008	1061	968	93	8.72
2009	1085	984	101	9.28
2010	1074	967	107	9.98
2011	1093	994	99	9.05

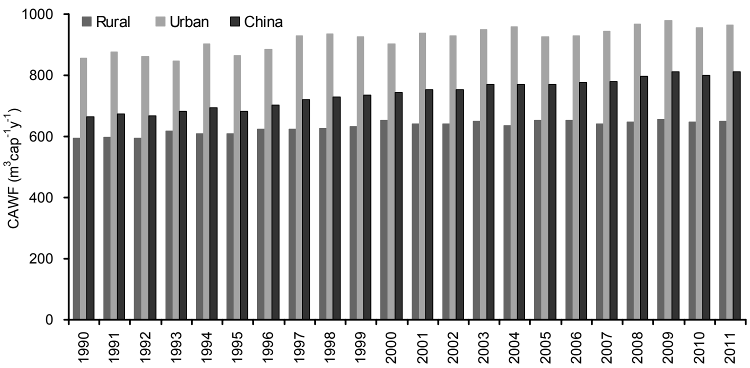

Fig. 1. The variation of CAWF of China over 1990-2011.

Therefore, China must rely on a part of net virtual import for its food consumption, and by reference to the concept of national water dependency [7]. The index water dependency degree (WDD, %) is defined in this chapter:

$$WWD = \frac{EAWF}{TAWF} \times 100\% \quad (4)$$

WDD indicates the degree of dependency of agricultural water resources, and a higher WWD implies a bigger hidden trouble due to the shortage of water resources.

It is demonstrated in Table 2 that China's self-sufficiency rate of AWF was very high before 2001. However, the situation changed substantially in subsequent decades. The EAWF was no more than 20 $km^3 \cdot y^{-1}$ and the WDD dropped below 2.00% from 1990 to 2000; however, both parameters have increased rapidly since 2001. The EAWF and WDD reached, respectively, up to around 100 km^3 and 10% in recent years. In a word, China needs to import massive virtual water in order to meet the food needs of its inhabitants.

AWF Component under the Change of Consumption Pattern

The composition of AWF can be observed from another perspective: the AWF consumed from animal and plant products. Since the value of virtual water content (VWC) of all products are time-invariant, the change of status of animal AWF and plant AWF could mirror the change of consumption patterns of Chinese inhabitants.

It is apparent in Fig. 3 that the proportion of animal AWF was a little less that of plant AWF on the whole, and the latter shared about 51% during the study period. The proportion of animal AWF in total agricultural water footprint (TAWF) as a whole was 43% in 1990. This figure rises above 50.0% in 2002 for the first time and peaks above 54% in 2011. China's diet structure encountered tremendous change over the past years and the animal AWF gradually dominated in AWF. This conclusion is consistent with the result by Liu and Savenije in 2008 [3].

In a detailed view, the variation of the proportion of AWF comes into view when every kind of animal product gets to be presented. The status at the start (1990) and end (2011) year of the study period are exemplified here. It is illustrated in Fig. 4 that the variation tendency of proportion in total AWF was not consistent among animal products. Proportions of meats, milks, and aquatic products increases by 6%, 3%, and 2% respectively over the past 22 years. The proportion of animal fats stabilized at 3%, and meanwhile that of eggs decreased by about 1 percentage point, although the *per capita* consumption of both kinds of products increased slightly from 1990 to 2011.

Viewed from a different angle, the proportion of animal water footprint differed greatly between rural and urban residents (Fig. 5). About 62 percent of the AWF came from animal product consumption in urban households, while

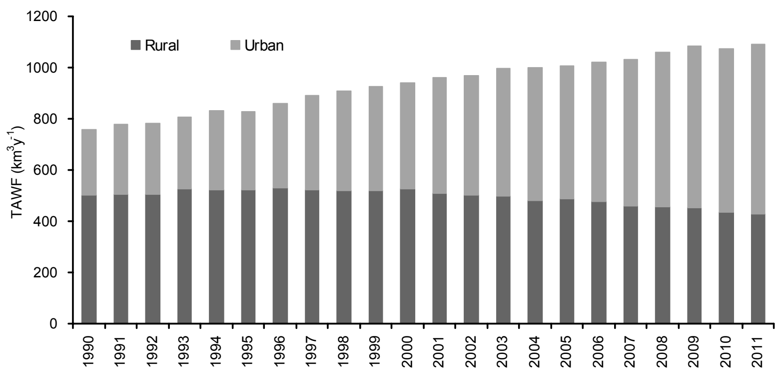

Fig. 2. Interannual variation of China's TAWF from 1990 to 2011.

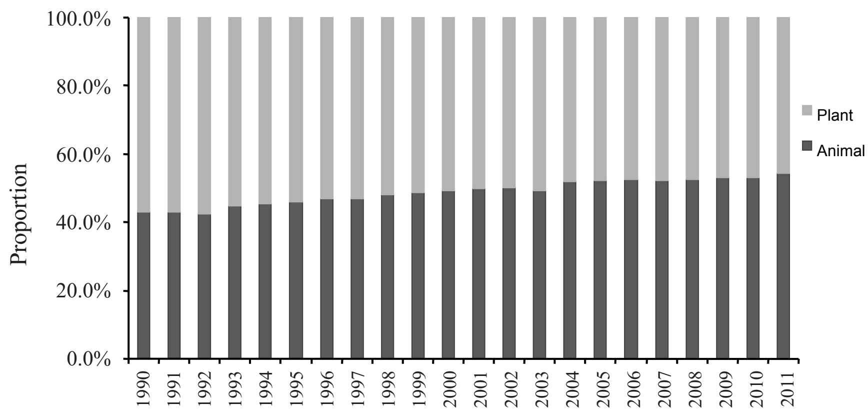

Fig. 3. Contribution of plant and animal product to Chinese AWF during 1990-2011.

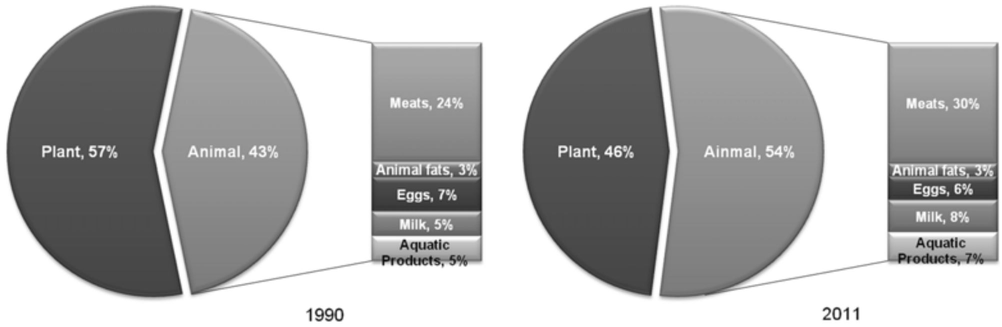

Fig. 4. Details of the composition of AWF in 1990 and 2011.

this figure was only about 38% in rural households. It is the decisive consumption pattern that makes Chinese urban residents demand more water for food than the rural ones.

The changing trends for rural and urban animal product proportions are the same. Both of them showed a slight increase from 1990 to 2003 and stayed steady after 2004. The proportions of animal water footprint in rural and urban households remained respectively at about 40% and 63% during 2004-11.

Analysis of AWF Variation

China's agricultural water footprint (AWF) is decided by the population size and the value of *per capita* agricultural water footprint (CAWF). The total population increased from 1.143 billion to 1.347 billion during 1990-2011, with a net increase of 204.02 million and an annual population inflation of nearly 10 million. China’s population growth was led by complex reasons, mainly social factors such as people's improved living standards, better health conditions, extended life expectancy, and dramatically dropped population mortality rates, etc. This chapter focuses on analyzing CAWF variation over a certain time span. The previous manifestations of related parameters including CAWF, animal water footprint proportion, and urban population proportion (UPP) are comparatively analyzed here, and some characteristic indexes are listed in Table 3. The average annual change rate (AACR) of index is calculated as follows:

$$AACR = \frac{1}{21} \times \sum_{i=1990}^{2010} \left[\frac{x_{i+1} - x_i}{x_i} \times 100\% \right] \quad (5)$$

...where x can represent the CAWF, animal water footprint proportion, or UPP.

Generally speaking, AACR of CAWF and animal water footprint proportion for the whole country are higher than those for rural and urban areas. The rural and urban CAWF increased at a rate of 0.44% and of 0.60% respectively, while the national CAWF rose by 1.00%. The same situation happened to the animal water footprint proportion as well. It rose by 1.13% annually nationwide, well above the rural (0.71%) and urban values (0.37%). The situation that average annual change rate of CAWF and animal water footprint proportion of both rural and urban residents stayed below the national value calls for further analysis. It is observed that the average annual change rate (AACR) of urban population proportion (UPP) reached up to 3.21%, significantly higher than any other index. In other words, the speed of rural populations turning into town populations is greater than that of the consumption structure change. So, urbanization may be closely associated with the growth of China's *per capita* agricultural water footprint. Fig. 6 shows the temporal relationship between UPP and CAWF. The coefficient of correlation is 0.9646, which presents that the CAWF was linear positively related to the UPP in the last 22 years. In a sense, it is urbanization that has brought out a more hungry need of water for food consumption in China.

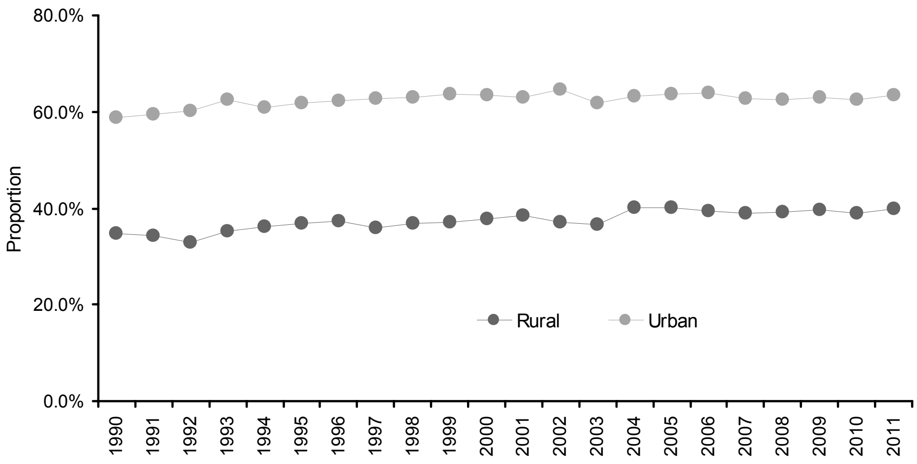

Fig. 5. Interannual variation of animal water footprint proportion of rural and urban residents.

Table 3. The characteristic parameters and average annual change rate (AACR) of CAWF, animal water footprint proportion, and urban population proportion (UPP) of China.

Index	CAWF ($m^3 \cdot cap^{-1} \cdot y^{-1}$)			Animal water footprint proportion (%)			Urban population proportion (%)
	Rural	Urban	China	Rural	Urban	China	
Minimum	595	848	664	33	59	43	26.4
Maximum	656	980	813	40	65	54	51.3
Average	632	920	741	39	62	49	37.4
Average annual change rate (AACR)	0.44%	0.60%	0.96%	0.71%	0.37%	1.13%	3.21%

Table 4. Comparison among main study result of capital water footprint of China.

Reference	Period/Year	Result ($m^3 \cdot cap^{-1} \cdot y^{-1}$)	This article ($m^3 \cdot cap^{-1} \cdot y^{-1}$)
[19]	1997-2001	700	736
[18]	1999	1049	735
[16]	2000	609	743
[34]	2002	381	754
[3]	2003	860	770
[17]	2007	684.11	781

Discussions

In Comparison with Other Studies

China has been a hot spot since the concept of the water footprint was put forward and related researches were conducted. As the previous water footprint calculation was always based on agricultural product consumption, the result in this paper and that in the past are comparable (Table 4). Scholars, namely Hoekstra and Chapagain [19], Ma et al. [18], Wang et al. [16], Liu and Savenije [3], and Ge et al. [17], calculated the water footprint with either the top-down or bottom-up methods. Thus their findings did not make much difference from the result in this article. We are aware of that the main reason why the water footprint values in aforementioned literatures are not in conformity with those in this paper is the difference in product VWC and product category. Specifically speaking, the average VWC of grain crops is 1.33 m^3/kg in this article, while it is 1.05 and 1.13 m^3/kg in studies conducted by Ge et al. [17] and Wang et al. [16], respectively. The VWC of plant products in the study conducted by Hoekstra and Chapagain [19] is similar to those in this paper, but this is not the case for animal products. The VWCs of beef, pork, goat (sheep), chicken, eggs, and milk are 12.56, 2.21, 3.99 (5.20), 3.65, 3.55, 1.00 m^3/kg, respectively. As studied by Hoekstra and Chapagain [19], all of them are much lower than those selected in our study. Therefore, although more product categories are involved in the literatures above, the calculation result of its water footprint is slightly smaller than that in our study.

Ma et al. [18] and Liu and Savenije [3] got the water footprints of China, respectively, at about 1049 and 860 $m^3 \cdot cap^{-1} \cdot y^{-1}$, both of which were greater than the CAWF of 735 and 770 $m^3 \cdot cap^{-1} \cdot y^{-1}$ in this study. An obvious difference between the former studies and ours is the distinctive source of blue water during the process of VWC calculation. Ma et al. [18] gained the volume of blue water from domestic water quantity statistics. In other words, the crop water use was estimated on a regional scale, meaning that not only the soil evaporation (E) and crop transpiration (T) in the field but also the depletion (such as the water flow into ground water and can't be reused during the period of crop growth and consumption on the regional scale (irrigation district or basin) were considered by Ma et al. [18]. China's irrigation water use coefficient is less than 0.55 [33] as we know, so the water footprint value obtained by Ma et al. [18] is much bigger than that in this work. We also find that all of the methods, objectives and results of Liu and Savenije [3] are very similar to our research; both of them aim to calculate the water demand for agricultural product consumption of China. The former literatures considered more products such as alcoholic beverages. Hence, we got the results of 860 and 770 $m^3 \cdot cap^{-1} \cdot y^{-1}$ that might result from the difference in the number of product categories we two parties have selected.

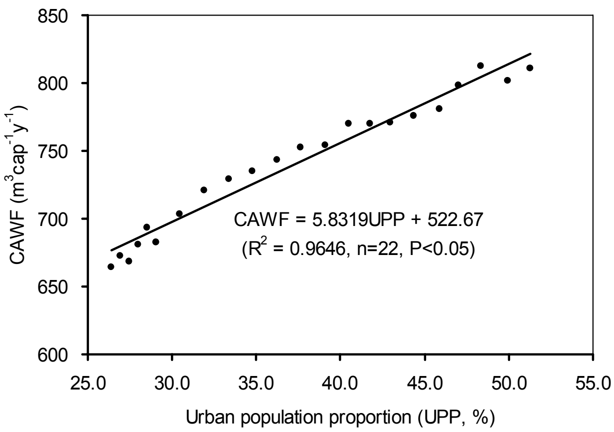

Fig. 6. Scatter graph between CAWF and urban population proportion (UPP).

As shown in Table 4, China's water footprint in 2002 reported by Zhao et al. [34] is 381 $m^3 \cdot cap^{-1} \cdot y^{-1}$, only about half of the CAWF of 754 $m^3 \cdot cap^{-1} \cdot y^{-1}$. Different from all the other literatures, the input-output framework was used in Zhao's research; more importantly, only the blue water footprint, instead of the green water footprint, was calculated. Studies show that green water contributes more than 50% of crop water consumption [35], so the gap between the two results is reasonable.

Future Status of AWF and How to Deal with It

It is a historical fact that China's *per capita* agricultural water footprint (CAWF) and the total agricultural water footprint (TAWF) increase over time, which is mainly caused by a large number of rural residents migrating to urban areas every year. Urbanization adheres to the demand of economic growth, and the Chinese government is helping boost the urbanization process at the moment. Urbanization is being accelerated and the urban population proportion (UPP) will reach 70% in the next 10 to 20 years [36].

China's agricultural water footprint (AWF) will keep on increasing with the urbanization process if no effective measures are taken. Water resources for food consumption demand amplification, indicating that water stress will intensify even further, and it may shake the water and food security of China. China should continue to carry out the current population policy so as to control population growth and manage the surge in demand of water. Family planning policy is a long-term, arduous and controversial task; we prefer to reduce the VWC of consumption goods, especially primary agricultural products. A minor defect in this paper is that it uses the same VWC values in every year and does not reflect any change over time.

In fact, the VWC of agricultural products, especially plant products, could be reduced by increasing yields, and improving crop varieties and irrigation technology, etc. The conclusion reported by Wu et al. [37] shows that, thanks to technology development, China's VWC of grain (grain production water footprint) was reduced from 3.38 m^3/kg in 1951-60 to 1.31 m^3/kg in 2001-10, a drop of 61.2%. Another study found out that the average water footprint (VWC) of integrated-crop production in Hetao irrigation district dropped by nearly 90 percent from 1960 (about 10 m^3/kg) to 2008 (about 1.2 m^3/kg), its main contributing factors including fertilizer consumption, utilization coefficient of irrigation water, pesticide consumption, wind speed, effective irrigation area, agricultural machinery power, and temperature [38]. China's VWC of crops in this study is about 1.33 m^3/kg (during 1996-2006), which is larger than any of those in western developed countries. For example, 0.79 m^3 water is consumed to produce 1 kg grain in the US and 0.63 m^3 water is consumed to produce 1 kg grain in the 15 EU countries [39]. This is because China's irrigation efficiency is very low and a mass of water resources is wasted, so there is great room for crop VWC to drop; furthermore, the decline in VWC of plant products could lead to a decrease in VWC of animal products. Reducing virtual water contents per unit grain is an important way to reduce the regional water footprint. Therefore, China should further strengthen its investment in agricultural technologies in the near future. By this means, the virtual water contents in crops are likely to fall. Then China's water footprint can be reduced and the sustainable use of water resources can materialize.

Potential Consequences of an Increasing Net Virtual Water Import

A situation that cannot be ignored is that China's net import of virtual water in food consumption is increasing year by year. The national grain self-sufficiency rate was more than 95%, while exterior water dependency degree (WDD, %) has risen to nearly 10% in the most recent three years. The surging increase of net virtual water trade import resulted from the adjustment of agricultural planting structure that changed the soybean trade volume. China continued exporting soybeans from 1990 to 1999, with a yearly volume of about 0.43 M ton, while the scenario has totally changed since 2000. China's soybean net import volume was in continuous rise during the previous decade, reaching 54.8 M ton and 52.6 M ton in 2010 and 2011, respectively; this means that 145 km^3 and 139 km^3 water resource flow into this country in the corresponding years throughout the soybean trade period. If the volume of soybean net import continues to increase, China's virtual water import and WDD of water resources will be further expanded. Tensions on water resources can be eased through 'virtual water' trades. Some scholars also have advised that China should lighten the water resource pressure through virtual water trade [3, 40]. However, an extensive quantity of increasing virtual water import is not a boon for China and the world. Issues such as having the largest population in the world, the largest volume of demand for food, and the most serious crisis in water resources (including water pollution) are facing China and may affect the world's food security: thus alleviating China's water scarcity is not only the "responsibility within the fence" [41].

Brown and Halweil [42] put forward the prediction that "China's water shortage could shake world food security" as early as 15 years ago. China's water resource issues also have attracted extensive worldwide attention and have been covered by major media outlets such as the *New York Times* and the *Economist* [41]. China's water shortage is of global concern as China and the rest of the world are increasingly connected, both economically and environmentally [43]. The water shortage could have a worldwide impact if China's ability to produce sufficient food to feed a large and growing population is restricted [44, 45]. Addressing the issue will benefit global sustainable development, especially since water scarcity is threatening China's economic development and its sustainability. In addition, other factors such as geopolitics, price-fixing, and transgenosis determine that China should not grow excessive agricultural products and rely on virtual water imports. Hence, China has to seek ways to solve its water problems from their own root causes, so as to increase the self-sufficiency degree of water footprint and reduce external dependence. China should take positive steps to protect arable land, increase crop yield, and develop water-saving agriculture to improve irrigation efficiency (E_i) and water productivity (WP), and optimize the planting structure so that the water and food security and the economic growth rate can be guaranteed by itself.

Conclusions

This paper calculates the agricultural water footprint of China during 1990-2011 using the bottom-up method. It then assesses the temporal variability of agricultural water footprint and composition, and explores the connection of water consumption with water and food security of the country. The following main conclusions can be drawn.

Both the CAWF and TAWF increased over time and their multi-year averages were 741 $m^3 \cdot cap^{-1} \cdot y^{-1}$ and 9,369 km^3, respectively, in the study period. There was a large gap between rural and urban residents' AWFs due to their differences in consumption patterns. China also held an increasing external AWF volume, making up nearly 10% of the total in the most recent years.

The increase in water demand for food consumption by years is determined by rises in CAWF and population size. The animal water footprint proportion of neither rural nor urban households changed significantly from 1990 to 2011. Urbanization is the dominant driving force of the CAWF growth as a result of urban residents holding a higher CAWF and animal water footprint proportion.

China is facing a "State of Flux" on food and water supplies. It needs to cut down the VWC of goods and raise the self-sufficiency degrees of agricultural products and water resource consumption. Measures such as controlling the quantity of population, developing water-saving agriculture, optimizing planting structure, improving crop yields, etc., can be taken.

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