# Determination of virtual water content of rice and spatial characteristics analysis in China

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## Abstract

China is a water-stressed country, and agriculture consumes the bulk of its water resources. Assessing the virtual water content (VWC) of crops is one important way to develop efficient water management measures to alleviate water resources conflicts among different sectors. In this research, the VWC of rice, as a major crop in China, was taken as the research object. China is well-known for its massive land. The VWC of rice is largely different between regions. The VWC of rice of China should be assessed and the spatial characteristics should be also analyzed. The total VWC is the total volume of freshwater both consumed and affected by pollution during the crop production process including direct and indirect water use. Prior calculation frameworks of VWC of crops do not contain all contents of virtual water content of crops. In addition to the calculation of green, blue and grey water—the direct water in VWC—the indirect water use of rice was also calculated, using the Input-Output model. The percentages of direct green, blue, grey and indirect water in the total VWC of rice in China were 43.8%, 28.2%, 27.6%, and 0.4%. The total VWC of rice generally showed a roughly three-tiered distribution, and decreased from southeast to northwest. The higher values of direct green water of rice were mainly concentrated in Southeast and Southwest China, while these values were relatively low in Northwest

China and Inner Mongolia. The higher direct blue water values were mainly concentrated in the eastern and southern coastal regions and Northwest China, and low values were mainly concentrated in Southwest China. Grey water values were relatively high in Shanxi and Guangxi provinces and low in Northeast and Northwest China. The regions with high values for indirect water were randomly distributed but the regions with low values were mainly concentrated in Northwest and Southwest China. For the regions with relatively high total VWC the high values of blue water made the largest contribution, although for the country as a whole the direct green water is the most important contributor.

## 1. Introduction

The term *virtual water* was first proposed by Allan (1994) and defined as the water embodied in the traded products. Later the concept of virtual water was modified by Hoekstra and Chapagain (2007) to indicate the required water input to generate a product or service. The virtual water content of a product is the freshwater embodied in the product, not in the real sense, but in the virtual sense. It refers to the volume of the freshwater both consumed and affected by pollution for producing the product, measured over its full production chain (Hoekstra et al., 2011). In water-stressed regions, limited water resources should be used efficiently by not allocating the majority of resources to the production of water-intensive products, and should be made available for other economic purposes that can contribute more to the regional value-added by consuming less water (Allan, 2002; Chapagain and Hoekstra, 2008). Assessing the virtual water content (VWC) of products is the basis for developing such water resource management practices.

Hoekstra and Hung (2002) estimated the VWC of crops for many countries of the world. In their research, the crop VWC was determined through estimating the accumulated crop evapotranspiration over the growing period, and the VWC was not divided into subtypes. To better understand the VWC of crops, many scientists divide the VWC into subtypes and calculate them separately. The calculation of green (effective precipitation) and blue water (irrigation water withdrawn from ground or surface water) was first proposed in the studies of crop VWC. Research has been performed at global, national, provincial, and river basin scales. For example, Rost et al. (2008) made a global estimate of agricultural green and blue water consumption. Siebert and Döll (2010) computed the green and blue VWC of crops at a global scale, and found the global average VWC of cereal crops was 1109 $m^3$ $t^{-1}$ of green water and 291 $m^3$ $t^{-1}$ of blue water. Scientists have added the grey water to the VWC, defined as freshwater that is required to assimilate the pollutant load based on natural background concentrations and existing ambient water quality standards. Chapagain et al. (2006) first calculated the grey water in VWC of crops, finding that the global VWC of rice was an average of 1325 $m^3$ $t^{-1}$ and, further, that grey water occupied about 8% of the total VWC (Chapagain and Hoekstra, 2011). Mekonnen and Hoekstra (2011a) quantified grey VWC of global crop productions for the period 1996–2005, and found that green, blue, and grey water accounted for 78%, 12%, and 10% in the total VWC of crops.

China is one of the world's 13 most water-poor countries (Yu et al., 2006). In 2012, per capita use of water resources in China was only 2100 $m^3$, less than 30% of the world per capita consumption. Agriculture is the largest water user in China, accounting for nearly 70% of total water withdrawals (Ministry of Water Resources, 2012). Studies on the VWC of crops in China are relatively limited. Liu et al. (2007) through the perspective of crop water productivity estimated the virtual water use of winter wheat. Sun et al. (2013a) used the crop water requirement to calculate the China average VWC of wheat, maize and rice, and found the proportions of green and blue water are 50.98% and 49.02%, 76.27% and 23.73%, 61.90% and 38.10%, respectively. The VWC of rice was relatively low in the eastern part of Northeast China, Middle–Lower Reaches of the Yangtze River and the eastern part of Southwest China. In contrast, the high values of VWC for rice were located in the west of Inner Mongolia and south of Xinjiang Uygur Autonomous Region. Sun et al.

(2013b) estimated the VWC of crops as 3.91 $m^3$ $kg^{-1}$ in the Hetao irrigation district of China. The percentage of blue water was relatively high (90.91%), while the share of green water was small (9.09%). However, these studies all ignored the grey water.

Rice as a cereal grain is the most widely consumed staple food for a large part of the population, especially in Asia. According to data from FAOSTAT, rice is the gain with the second-highest worldwide production, after maize. China is the biggest rice-producing country in the world. In 2007, the planting area of rice is the second largest in China (about 29 million hectares) and makes up 34% of the total planting area of grain crops. Rice production is the largest grain production in China (around 186 million tons) and accounted for 41% of the total grain (Ministry of Agriculture of the People's Republic of China, 2008). There is not any research on the total VWC of rice and spatial distribution characteristics in China at provincial scale by the actual total water use. China is well-known for its massive land. The VWC of rice is largely different between regions. The VWC of rice of China should be assessed and the spatial characteristics should be also analyzed.

Prior research on crop VWC determination provides a good framework for this work. However, prior calculation frameworks of VWC of crops have some defects. Some use the water requirement of crops instead of the actual water use, and others ignore the freshwater affected by pollution during the crop production. Besides, in all calculation frameworks the indirect water use of crops was also ignored. On the basis of the previous frameworks, which mainly considered direct water use (blue, green, and grey water); we also considered indirect water (the sum of the virtual water of all products consumed in the process of rice planting). In this paper, we will calculate the total VWC of rice for 29 Chinese provinces, autonomous regions, and municipalities in 2007, including direct and indirect water use. Because of the lack of data, Tibet is not taken into account; and no rice is planted in Qinghai, so Qinghai is not taken into account, either. The spatial distribution characteristics of the VWC of rice also will be analyzed.

# 2. Methodology and data

## 2.1 Methodology

To reflect water consumption during crop production, direct and indirect water were taken into account. For the lack of data, we can’t divide the $\mathrm{VWC}_{\mathrm{indirect}}$ into $\mathrm{VWC}_{\mathrm{indirect,\ green}}$, $\mathrm{VWC}_{\mathrm{indirect,\ blue}}$ and $\mathrm{VWC}_{\mathrm{indirect,\ grey}}$.

$$\mathrm{VWC}_{\mathrm{total}}=\mathrm{VWC}_{\mathrm{indirect}}+\mathrm{VWC}_{\mathrm{direct}}=\mathrm{VWC}_{\mathrm{indirect}}+\mathrm{VWC}_{\mathrm{direct,\ green}}+\mathrm{VWC}_{\mathrm{direct,\ blue}}+\mathrm{VWC}_{\mathrm{direct,\ grey}} \quad (1)$$

where $\mathrm{VWC}_{\mathrm{total}}$ is the total volume of freshwater both consumed and affected by pollution during the crop production process ($m^3\ kg^{-1}$) ; $\mathrm{VWC}_{\mathrm{indirect}}$ is the freshwater both consumed and affected by pollution that can be associated with the production of the goods and services or the inputs used during the crop production process ($m^3\ kg^{-1}$); $\mathrm{VWC}_{\mathrm{direct}}$ is the freshwater both consumed and affected by pollution that is associated to the direct water use during the crop production process ($m^3\ kg^{-1}$); $\mathrm{VWC}_{\mathrm{direct,\ green}}$ is the precipitation consumed in crop production process ($m^3\ kg^{-1}$); $\mathrm{VWC}_{\mathrm{direct,\ blue}}$ is the surface water or groundwater consumed in crop production process ($m^3\ kg^{-1}$); and $\mathrm{VWC}_{\mathrm{direct,\ grey}}$ is the freshwater required to assimilate the load of pollutants during the crop production process($m^3\ kg^{-1}$).

### 2.1.1 Indirect water of crops

The Input-Output model represents the monetary trade of products and services among different sectors of an economic system (Leontief, 1941), and is adopted to calculate the indirect virtual water of crops supplied by each economic sector. The calculations are as follows (Chen, 2000; Kanada, 2001; Zhao et al., 2009; Zhang et al. 2011):

(1) Direct consumption coefficient matrix

The input-output table is used because it reflects the contact of the material and technical. This contact is reflected through the direct consumption coefficient.

$$\mathrm{A} = |a_{ij}| = |x_{ij}/x_i| \quad (2)$$

A is the direct consumption coefficient matrix (n×n dimensional matrix) in the IO table; $a_{ij}$ is the direct consumption coefficient, which means the monetary volume of products of sector $i$ directly consumed by sector $j$ when producing one unit product; $x_{ij}$ is the monetary volume of products from sector $j$ consumed by sector $i$ in its production process (RMB); and $x_i$ is the output of sector $i$ (RMB).

(2) Complete consumption coefficient matrix

Compared with the direct consumption coefficient, the complete consumption coefficient can more accurately measure the direct and indirect costs (the sum of the direct and indirect costs is completely consumed) of products or services from other sectors.

$$\mathrm{B} = \left|b_{ij}\right| = (\mathrm{I} - \mathrm{A})^{-1} - \mathrm{I} \tag{3}$$

B is the complete consumption coefficient matrix (n×n dimensional matrix) in the IO table; $b_{ij}$ is the complete consumption coefficient, which means the monetary volume of products of sector $i$ direct and indirect consumed by sector $j$ when producing one unit product; and I is a unit diagonal matrices.

(3) Water use coefficient

To account for indirect water, it is necessary to compute the water use coefficient of different sectors, which is the water needed to produce one monetary unit (RMB).

$$\mathrm{DWC}_i = w_i / x_i \tag{4}$$

where $\mathrm{DWC}_i$ is the direct water coefficient of sector $i$ ($\mathrm{m}^3\,\mathrm{RMB}^{-1}$) and $w_i$ is the direct water consumption of sector $i$ ($\mathrm{m}^3$). $\mathrm{DWC}_i$ is the amount of direct water intake to produce one monetary unit of production.

(4) Indirect water of agriculture

Indirect water consumption of agriculture is the amount of total water input from other sectors.

$$\mathrm{VW}^{\mathrm{a}}_{\mathrm{indirect}} = \sum_{i=1}^{n} (\mathrm{DWC}_i \times b_{i\mathrm{a}}) \times C_{\mathrm{a}} \tag{5}$$

where $\mathrm{VW}^{\mathrm{a}}_{\mathrm{indirect}}$ is the indirect water consumption of agriculture ($\mathrm{m}^3$); $b_{i\mathrm{a}}$ is the complete consumption coefficient of sector *i* for agriculture; and $C_{\mathrm{a}}$ is the total consumption of agriculture (RMB).

(5) Indirect water consumption of a crop

$\mathrm{VWC}^{\mathrm{i}}_{\mathrm{indirect}}$ ($\mathrm{m}^3\ \mathrm{kg}^{-1}$) is calculated according to the proportion of indirect water use of crop *i* in the total indirect water consumption of agriculture.

$$\mathrm{VWC}^{i}_{\mathrm{indirect}} = \frac{\mathrm{VW}^{\mathrm{a}}_{\mathrm{indirect}}\alpha_i}{\mathrm{SA}_i \times Y} \tag{6}$$

where $\mathrm{VWC}^{i}_{\mathrm{indirect}}$ is the indirect water consumption of crop *i* ($\mathrm{m}^3\ \mathrm{kg}^{-1}$); $\alpha_i$ is the proportion of indirect water use of crop *i* in the total indirect water consumption. Because of lack of data, we assume that the planting cost is proportional to the indirect water use. $\mathrm{SA}_i$ is the sown area of crop *i* (ha); and *Y* is the crop yield per unit area ($\mathrm{kg\ ha}^{-1}$). Thus $\alpha_i$ can be calculated as follows:

$$\alpha_i = \frac{\mathrm{PC}_i \times \mathrm{SA}_i}{\sum_{i=1}^{n}(\mathrm{PC}_i \times \mathrm{SA}_i)} \tag{7}$$

where $\mathrm{PC}_i$ is the planting cost of crop *I* per unit area ($\mathrm{RMB\ ha}^{-1}$).

### 2.1.2 Direct green water of crops

Direct green water use is the lesser of potential crop evapotranspiration and effective precipitation. Effective precipitation is defined as the amount of precipitation that enters the soil and will be available in the soil for crop growth (Sun et al., 2013b).

$$\mathrm{VWC}_{\mathrm{direct,\ green}} = \frac{10\min(\mathrm{ET_c}, P_{\mathrm{e}})}{Y} \tag{8}$$

where $\mathrm{ET_c}$ is the crop evapotranspiration during the growing period (mm)and $P_{\mathrm{e}}$ is the effective precipitation over the crop growing period (mm), calculated by the CROPWAT model using monthly climatic data (mm) (Clarke, 1998; FAO, 2003) .

Crop evaporation during the growing period is calculated as follows (Allen et al., 1998 ):

$$\mathrm{ET_c} = \mathrm{ET_o} \times k_{\mathrm{c}} \tag{9}$$

where $k_c$ is the crop coefficient, reflecting the differences in physical and physiological factors betweenthe actual and reference crops and $ET_o$ is the soil evaporation of the reference underlying surface (mm $d^{-1}$), calculated by the FAO Penman-Monteith formula (Allen et al., 1998),

### 2.1.3 Direct blue water of crops

The direct blue water of a crop is calculated using the irrigation water consumption, $I_c$. The irrigation water consumption is the net artificial application of water use by crops, which not includes the irrigation water losses during the transport process from the water sources to cropland and the return flows of irrigation water. The direct blue water is calculated according to the proportion of irrigation water consumption of crop $i$ in the total irrigation water consumption of the irrigation district (Sun, 2013b).

$$\mathrm{VWC}^{i}_{\mathrm{direct,\ blue}} = I^{i}_{\mathrm{c}}/Y = \frac{W_{\mathrm{A}}\beta_i}{\mathrm{SA}_i \times Y} \tag{10}$$

where $I^{i}_{\mathrm{c}}$ is the irrigation water consumption of crop $i$ per unit area ($\mathrm{m}^3\ \mathrm{ha}^{-1}$); $W_{\mathrm{A}}$ is the irrigation water consumption of the irrigation district ($\mathrm{m}^3$) and $\beta_i$ is the proportion of irrigation water use of crop $i$ in the total irrigation water consumption of the irrigation district. $\beta_i$ can be calculated as follows:

$$\beta_i = \frac{(\mathrm{ET}^{i}_{\mathrm{c}} - P^{i}_{\mathrm{e}}) \times \mathrm{SA}_i}{\sum_{i=1}^{n}[(\mathrm{ET}^{i}_{\mathrm{c}} - P^{i}_{\mathrm{e}}) \times \mathrm{SA}_i]} \tag{11}$$

where $\mathrm{ET}^{i}_{\mathrm{c}}$ is the crop evapotranspiration of crop $i$ during the growing period (mm); $P^{i}_{\mathrm{e}}$ is the effective precipitation over the crop $i$ growing period (mm); and $\mathrm{SA}_i$ is the sown area of crop $i$ (ha).

### 2.1.4 Direct grey water of crops

In this study we quantify direct grey water related to nitrogen use only. The direct grey water is calculated by multiplying the fraction of nitrogen that leaches or runs off by the nitrogen application rate and dividing this by the difference between the maximum acceptable concentrations of nitrogen and the natural concentration of nitrogen in the receiving water body and by the actual crop yield (Mekonnen and

Hoekstra, 2011a). Because of lack of data, the natural nitrogen concentrations were assumed to be 0. On average, 10% of the applied nitrogen fertilizer is lost through leaching (Chapagain et al., 2006). The maximum value of nitrate in surface and ground water recommended by the United States Environmental Protection Agency is 10 mg $L^{-1}$ (Chapagain et al., 2006).

$$\mathrm{VWC}_{\mathrm{direct,grey}} = \frac{N_{\mathrm{c}} \times 10\%}{10 - N_n} / Y \tag{12}$$

where $N_{\mathrm{c}}$ is the amount of nitrogen fertilizer consumption per hectare (g $ha^{-1}$) and $N_n$ is the natural concentration of nitrogen in the receiving water body (mg $L^{-1}$).

## 2.2 Data

The 2007 climate data for 29 regions, including monthly average maximum temperature, monthly average minimum temperature, relative humidity, wind speed, precipitation, and sunshine hours, are taken from the National Climatic Center (NCC) of the China Meteorological Administration (CMA). The agricultural data, including crop yield and sown area, are taken from the China Agricultural Yearbook (Ministry of Agriculture of the People's Republic of China, 2008). The average amount of nitrogen fertilizer of rice per unit area is taken from Li et al. (2010), Zhang et al. (2008) and Zhang et al. (2009). The irrigation water consumption for the 29 regions is taken from the Water Resources Bulletins (2007) of 29 regions. Water data for various sectors in the regions are from the Statistical Yearbooks (2008) of 29 regions. The IO data for the29 regions come from the official IO tables (2007) of 29 regions.

# 3. Results

## 3.1 Indirect water of rice

The $\mathrm{VWC}_{\mathrm{indirect}}$ of rice varied between 0.001 $m^3$ $kg^{-1}$ and 0.010 $m^3$ $kg^{-1}$. The average $\mathrm{VWC}_{\mathrm{indirect}}$ was 0.004 $m^3$ $kg^{-1}$. The regions with the same line had the same distribution characteristic of $\mathrm{VWC}_{\mathrm{indirect}}$ of rice in Fig. 1. The input to agriculture in relatively underdeveloped regions was relatively small; relatively developed regions invest more money in agriculture. Northwest and Southwest China are relatively underdeveloped with relatively low $VWC_{indirect}$ of rice. Beijing, Guangdong, and Shanghai are the three most developed regions and had the highest $VWC_{indirect}$ of rice in 2007 (Fig. 1). We found that $VWC_{indirect}$ of rice is directly related to the degree of regional economic development.

Of all sectors, the sector of forestry, animal husbandry, and fishery contributed the most $VWC_{indirect}$ of rice, accounting for 52.2%. The electricity and heat sector contributed 21.6% and the chemical industry sector contributed 9.6%. The rest of the sectors contributed less.

## 3.2 Direct green water of rice

The regional differences in $VWC_{direct, green}$ for rice were significant, owing to differences in climatic conditions and crop yields. The $VWC_{direct, green}$ of rice for 29 regions in 2007 ranged from 0.10 $m^3$ $kg^{-1}$ to 0.90 $m^3$ $kg^{-1}$. The average $VWC_{direct, green}$ of rice was 0.59 $m^3$ $kg^{-1}$. $VWC_{direct, green}$ of rice was increased gradually from northern to southern regions (Fig. 2). The regional variability of $VWC_{direct, green}$ of rice was in accordance with the distribution of precipitation in China. The regions with abundant precipitation usually have high $VWC_{direct, green}$ of rice. Precipitation in southern regions of China is far greater than that in northern regions of China. Consequently, the $VWC_{direct, green}$ of rice in southern regions would be higher than that in northern regions.

The regions with higher $VWC_{direct, green}$ values were concentrated in the Southeast China and Southwest China (Fig. 2). The high $VWC_{direct, green}$ in these regions is a result of high ratio between effective precipitation and rice yield. The regions in the Southeast China and Southwest China had relatively low rice yields, much lower than the national average, and relatively high effective precipitation, more than 400mm. For example, the $VWC_{direct, green}$ of rice was more than 0.80 $m^3$ $kg^{-1}$ in Hainan (Southeast China), Guangxi (Southwest China), and Yunnan (Southwest China). The

$VWC_{direct,\ green}$ of rice in Guizhou (Southwest China) was also relatively high, more than 0.80 $m^3$ $kg^{-1}$. This is mainly because the effective precipitation over the growing period of rice in this region was more than 590 mm, although rice yield in this region was higher than the national average.

The $VWC_{direct,\ green}$ of rice in Northwest China and Inner Mongolia were relatively low (Fig. 2). Because of high yields and low effective precipitation. Xinjiang (Northwest China) had the lowest $VWC_{direct,\ green}$ (0.10 $m^3$ $kg^{-1}$) because the rice yield in Xinjiang was 1.32 times higher than the national average and the effective precipitation over the growing period was small, less than 90 mm.

## 3.3 Direct blue water of rice

The differences in blue water requirements, actual irrigation water consumption, and rice yields resulted in significantly different $VWC_{direct,\ blue}$ values between regions. The $VWC_{direct,\ blue}$ values ranged from 0.07 $m^3$ $kg^{-1}$ to 1.65 $m^3$ $kg^{-1}$, and the average was 0.42 $m^3$ $kg^{-1}$. The regions with higher $VWC_{direct,\ blue}$ of rice were mainly concentrated in the eastern and southern coastal regions and in Northwest China (Fig. 3). The $VWC_{direct,\ blue}$ of rice was high in the municipalities of Beijing, Tianjin, and Shanghai; more than 0.83 $m^3$ $kg^{-1}$. These three municipalities have developed economies with relatively more developed agricultural irrigation system, so irrigation water consumption was relatively larger than that of other regions. Regions in Northwest China had higher $VWC_{direct,\ blue}$ values, perhaps because the effective precipitation in these regions was limited, making it necessary to increase the irrigation water supply for crops.

The $VWC_{direct,\ blue}$ values for rice in Southwest China were relatively low (Fig. 3). The $VWC_{direct,\ blue}$ values in Chongqing, Guizhou, Sichuan, and Yunnan were less than 0.16 $m^3$ $kg^{-1}$ because in these four regions the effective precipitation can almost meet the water requirements of rice, so the actual irrigation water consumption was limited. Jilin, Shandong and Henan were the other three regions with relatively low $VWC_{direct,\ blue}$ of rice. Limited irrigation water consumption in the three regions might only meet less than 25% of the irrigation requirement of rice. Therefore, the $VWC_{direct, blue}$ of rice in Jilin, Shandong and Henan was relatively low.

## 3.4 Direct grey water of rice

The $VWC_{direct, grey}$ values of rice ranged from 0.21 $m^3$ $kg^{-1}$ to 0.64 $m^3$ $kg^{-1}$ with an average 0.37 $m^3$ $kg^{-1}$. Regional differences in $VWC_{direct, grey}$ for rice were insignificant (Fig. 4). Because nitrogen use is similar between regions, $VWC_{direct, grey}$ mainly depends on rice yield. The rice yield of regions in Northeast China and Northwest China were relatively high, making the $VWC_{direct, grey}$ of rice in Northeast China and Northwest China relatively low. The rice yield of Shandong, Henan and Chongqing was much higher than the national average. That made the $VWC_{direct,grey}$ of rice in the three regions also relatively low. The highest $VWC_{direct, grey}$ values for rice were in Shanxi and Guangxi, because the rice yields of Shanxi and Guangxi in 2007 were the two lowest of all the regions studied.

## 3.5 Total VWC of rice

The $VWC_{total}$ values of rice for 29 regions are calculated and shown in Fig. 5. There were large differences in $VWC_{total}$ between regions, with values ranging from 0.80 $m^3$ $kg^{-1}$ to 2.59 $m^3$ $kg^{-1}$. The average $VWC_{total}$ of rice was 1.39 $m^3$ $kg^{-1}$. The $VWC_{total}$ values showed a roughly three-tiered distribution, gradually decreasing from southeast to northwest of China. The $VWC_{total}$ values in eastern coastal China, Southeast China, Beijing, and Tianjin were relatively high. The regions with lower $VWC_{total}$ values were mainly concentrated in the Northeast China and Norwest China.

Our result is large different to the result from Sun et al. (2013a). Follow their calculation the VWC of rice was relatively low in the eastern part of Northeast China, Middle–Lower Reaches of the Yangtze River and the eastern part of Southwest China. In contrast, the high values of VWC for rice were located in the west of Inner Mongolia and south of Xinjiang Uygur Autonomous Region. Their calculation framework only considered the crop water requirement. However, our calculation framework considers the effective precipitation and crop evapotranspiration, irrigation water consumption, freshwater that is required to assimilate the load of pollutants and the indirect water use. The difference of the $VWC_{direct, blue}$ and the added $VWC_{direct, grey}$ of rice caused the large difference of spatial distribution characteristic between actual $VWC_{total}$ of rice and the rice water requirement. Our result can be better to describe the spatial distribution characteristic of actual water use of rice in China.

# 4. Discussion

## 4.1 Comparison of calculations of total VWC of rice by different frameworks

Here, we compare four frameworks for total VWC determinations (Tab. 1). (1) In the crop water requirement (CWR) calculation framework, the total virtual water content of crops is divided into green and blue water. Green water use is the lesser of the potential crop evapotranspiration and the effective precipitation. Blue water use is the irrigation water requirement, which is the potential crop evapotranspiration minus green water use (Siebert and Döll, 2010; Sun et al., 2013a). (2) In the green, blue and grey water (GBG) calculation framework, the total virtual water content of crops is divided into green, blue, and grey water. The calculation methods for green and blue water are the same as in the CWR framework. Grey water is calculated by multiplying the fraction of nitrogen that leaches or runs off by the nitrogen application rate and dividing this by the difference between the maximum acceptable concentration of nitrogen and the natural concentration of nitrogen in the receiving water body (Chapagain et al., 2006; Bulsink, 2010; Mekonnen and Hoekstra 2011b). (3) In Sun's framework, the total virtual water content of crops is also divided into green and blue water. Blue water is calculated according to actual irrigation water consumption (Sun et al., 2013b). (4) In our framework, the total virtual water content of crops is divided into direct green, direct blue, direct grey and indirect water. The calculations for green and grey water are the same as in the GBG framework and the calculation method for blue water is the same as in Sun's framework. As described previously, we add indirect water to the total VWC of crops. However, in our calculation framework of VWC of crops, we made some assumptions and simplifications in the calculation of $VWC_{indirect}$, $VWC_{direct,\ blue}$ and $VWC_{direct,\ grey}$, which makes the uncertainty of the results. The uncertainty of the results cannot be completely eliminated. We could only make better assumptions and simplifications and use more accurate data to make our results more accurate.

The VWC of rice of Heilongjiang province in 2007 is used as an example to compare results among the four different frameworks. As shown in Tab.2, $VWC_{total}$ calculated by our framework is $0.97 m^3\ kg^{-1}$, which accounts for 66.9%, 57.7% and 133.8% of the $VWC_{total}$ of rice under the CWR framework, GBG framework, and Sun's framework, respectively. The $VWC_{total}$ calculated by our framework is lower than the $VWC_{total}$ calculated by CWR framework and GBG framework. Because the $VWC_{direct,\ blue}$ is calculated by the crop irrigation water requirement under CWR framework and GBG framework and calculated by the actual irrigation consumption under our framework. According to the calculation in our method, the actual irrigation consumption can't meet the irrigation water requirement of rice in Heilongjiang. The $VWC_{direct,\ blue}$ value calculated from the actual irrigation consumption under our framework is much lower than the $VWC_{direct,\ blue}$ values calculated under the CWR and GBG frameworks. Adding the $VWC_{direct,\ grey}$ value resulted in the $VWC_{total}$ calculated by our framework being larger than the $VWC_{total}$ calculated by Sun's framework. The contribution of $VWC_{direct,\ grey}$ is very important, accounting for 22.9% of the $VWC_{total}$ of rice under our framework, and cannot be ignored. The contribution of $VWC_{indirect}$ as calculated under our framework is limited and has little effect on the $VWC_{total}$ of rice in Heilongjiang.

## 4.2 Analysis of VWC structures of rice in China

Regional differences in $VWC_{total}$ values for rice were significant, as were regional differences inthe structure of the $VWC_{total}$ of rice. The average $VWC_{total}$ of rice in

China was 1.39 $m^3$ $kg^{-1}$. The percentages of $VWC_{direct, green}$, $VWC_{direct, blue}$, $VWC_{direct, grey}$, and $VWC_{indirect}$ in the $VWC_{total}$ for rice in China were 43.8%, 28.2%, 27.6%, and 0.4%, respectively.

Generally speaking, the regions in China mostly had the higher $VWC_{direct, green}$ of rice and the lower $VWC_{direct, blue}$ of rice. For example, in Chongqing the percentage of $VWC_{direct, green}$ was 67.6% and the percentage of $VWC_{direct, blue}$ was 6.6%; in Sichuan the percentage of $VWC_{direct, green}$ was 53.7% and the percentage of $VWC_{direct, blue}$ was 12.4 %. Six regions were the exceptions which had the lower $VWC_{direct, green}$ of rice and the higher $VWC_{direct, blue}$ of rice. In Beijing the percentage of $VWC_{direct, green}$ was 19.8% and the percentage of $VWC_{direct,blue}$ was 63.2%; in Tianjin the percentage of $VWC_{direct, green}$ was 14.7% and the percentage of $VWC_{direct, blue}$ was 69.1%; in Fujian the percentage of $VWC_{direct, green}$ was 29.9% and the percentage of $VWC_{direct, blue}$ was 49.7%; in Gansu the percentage of $VWC_{direct, green}$ was 33.5% and the percentage of $VWC_{direct, blue}$ was 37.9%; in Ningxia the percentage of $VWC_{direct, green}$ was 24.9% and the percentage of $VWC_{direct, blue}$ was 48.1%; and in Xinjiang the percentage of $VWC_{direct, green}$ was 12.1% and the percentage of $VWC_{direct, blue}$ was 61.6%. There were two reasons for the different situation of the six regions. Excessive consumption of irrigation water caused the lower percentage of $VWC_{direct, green}$ of rice and the higher percentage of $VWC_{direct, blue}$ of rice in Beijing, Tianjin and Fujian. Limited precipitation caused the lower percentage of $VWC_{direct, green}$ of rice and the higher percentage of $VWC_{direct, blue}$ of rice in Xinjiang, Ningxia and Gansu. For the country as a whole, the proportion of $VWC_{direct, green}$ of rice (43.8%) was larger than the $VWC_{direct, blue}$ of rice (28.2%). Rice growth mainly depend on the $VWC_{direct, green}$ in China.

Regional differences in $VWC_{direct, grey}$ values were insignificant. This shows that the grey water in all regions plays an important role in $VWC_{total}$. Agricultural pollution is an important issue in every region that cannot be ignored. Because the direct grey water estimated only considers chemical fertilizer pollution, and not the effect of pesticides and herbicides on water quality, the result of this estimation is a conservative estimate.

The values $VWC_{indirect}$ in the $VWC_{total}$ of rice for the 29 regions were comparatively less, ranging from 0.001 to 0.010m$^3$ kg$^{-1}$. The average $VWC_{indirect}$ of rice was 0.004 m$^3$ kg$^{-1}$. $VWC_{indirect}$ of rice is related to the degree of regional economic development. The region with the highest $VWC_{indirect}$ value was Beijing and the region with the lowest value was Ningxia. Because of the small contribution of $VWC_{indirect}$, $VWC_{indirect}$ may not be considered in future research on the VWC of rice. However the $VWC_{indirect}$ is expected to be higher in some agricultural products including potatoes, cotton and fruits. $VWC_{indirect}$ should be included in the $VWC_{total}$. For example, the proportion of $VWC_{indirect}$ in the $VWC_{total}$ of strawberry in 27 regions of China in 2007 ranged from 0.8% to 38.0%, with an average of 10.8%. The proportion of $VWC_{indirect}$ of strawberry is higher in the $VWC_{total}$. Therefore we cannot ignore the $VWC_{indirect}$ in the calculation of $VWC_{total}$ of some crops.

Assessing the VWC of crops is an important way to provide the basis for agricultural water resources management, and help to improve the efficiency of agricultural water use. Overall pressure on water resources might be relieved if we locate water-intensive production processes in regions where water is abundant and where it requires less VWC of product. China is well-known for its massive land. The VWC of rice is largely different between regions. The different rice planting structure between regions of China may cause a largely difference in agriculture water use. The VWC of rice in China should be assessed and the spatial characteristics should be also analyzed.

## 5. Conclusions

Faced with increasingly severe pressure on water resources, virtual water theory provides a feasible solution to improve global water use efficiency. Research on the VWC of crops can provide the basis for agricultural water resources management and help to improve the efficiency of agricultural water use. Rice is the most important food crop in China and also one of the largest water consumers, so it is important to study the total VWC of rice in China. Previous research constructed calculation frameworks using direct green water, direct blue water, and direct grey water of crops. Building onthat previous research, we also considered the indirect water of VWC. In this paper, we calculated the virtual water content of rice for 29 regions of China in 2007. The following conclusions were reached.

1. Analysis showed that the total VWC of rice in China decreased gradually from southeast to northwest.
2. The regions with high indirect water were randomly distributed. The indirect VWC of rice in Northwest China and Southwest China was relatively low.
3. The regions with higher direct green water were mainly concentrated in the Southeast China and Southwest China. The direct green water of rice for Northwest China and Inner Mongolia was relatively low. The regions with higher direct blue water of rice were mainly concentrated in the eastern and southern coastal regions of China and in Northwest China. The direct blue water of rice of Southwest China was relatively low. In the country as a whole, the percentage of direct green water of rice was far above that of direct blue water. Therefore, rice growth is mainly dependent on direct green water in China.
4. The direct grey water of rice in Northeast China and Northwest China was relatively low. But in all regions, grey water occupies a very important position in total VWC.

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Table 1. Comparison of VWC calculating frameworks

| VWC<br>Method | $VWC_{direct,\ green}$ | $VWC_{direct,\ blue}$ | $VWC_{direct,\ grey}$ | $VWC_{\ indirect}$ |
|---|---|---|---|---|
| Our method | $10min(ET_C, P_e)/Y$ | $VWC_{direct,blue} = I_c/Y = \frac{W_A \alpha_i}{A_i}/Y$ | $VWC_{direct,grey} = \frac{N_c \times 10\%}{10 - N_n}/Y$ | $VWC_{indirect} = \frac{VW^a_{blue,indirect} \beta_i}{A_i}/Y$ |
| Sun’s method | $10min(ET_C, P_e)/Y$ | $VWC_{direct,blue} = I_c/Y = \frac{W_A \alpha_i}{A_i}/Y$ | — | — |
| GBG method | $10min(ET_C, P_e)/Y$ | $10max(0, ET_c - P_e)/Y$ | $VWC_{direct,grey} = \frac{N_c \times 10\%}{10 - N_n}/Y$ | — |
| CWR method | $10min(ET_C, P_e)/Y$ | $10max(0, ET_c - P_e)/Y$ | — | — |

Table 2 The volume (m$^3$ kg$^{-1}$) and proportion (%) of VWC of rice in Heilongjiang Province by four different frameworks

| VWC<br>Method | $VWC_{direct,\ green}$ | $VWC_{direct,\ blue}$ | $VWC_{direct,\ grey}$ | $VWC_{indirect}$ | $VWC_{total}$ |
|---|---|---|---|---|---|
| Our method | 0.45 (46.0) | 0.29 (30.2) | 0.22 (22.9) | 0.01 (0.9) | 0.97 |
| Sun’s method | 0.45 (60.5) | 0.29 (39.5) | — | — | 0.74 |
| GBG method | 0.45 (26.6) | 1.01 (60.1) | 0.22 (13.3) | — | 1.68 |
| CWR method | 0.45 (30.7) | 1.01 (69.3) | — | — | 1.45 |

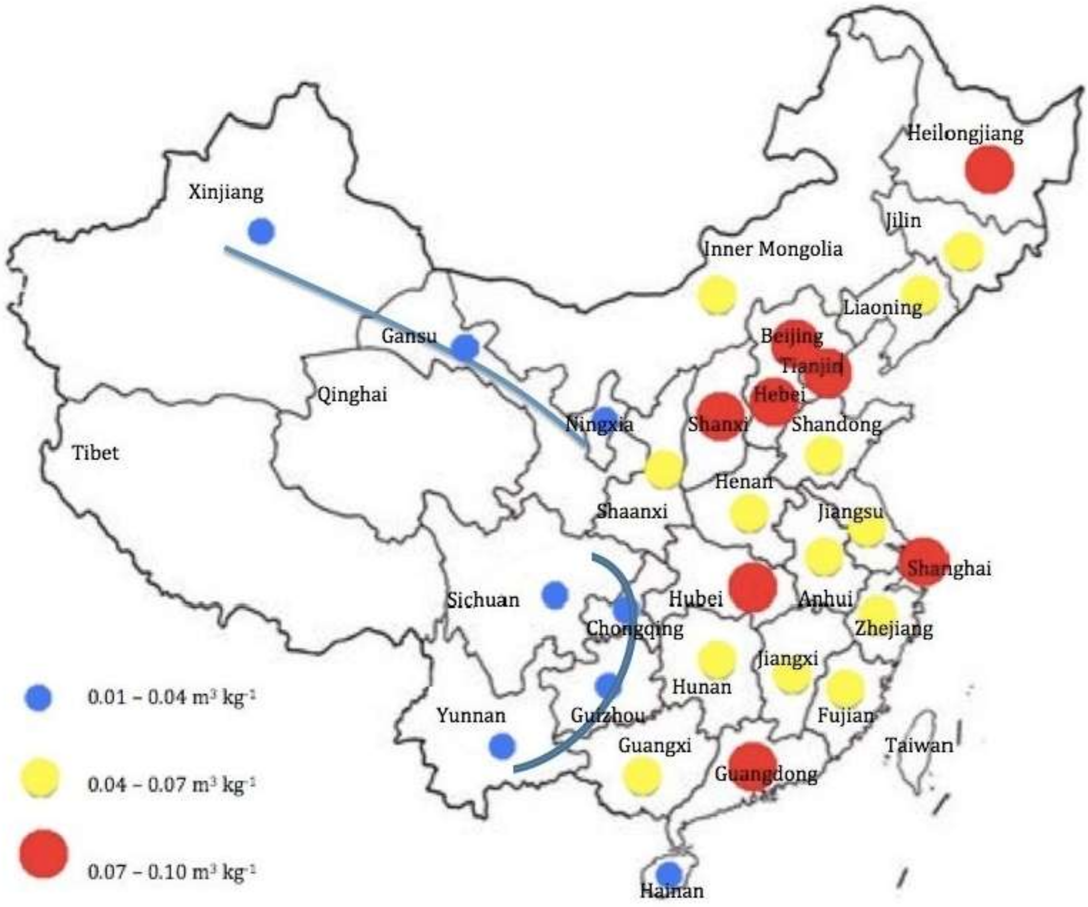

Figure 1. Indirect water of rice ($m^3$ $kg^{-1}$)

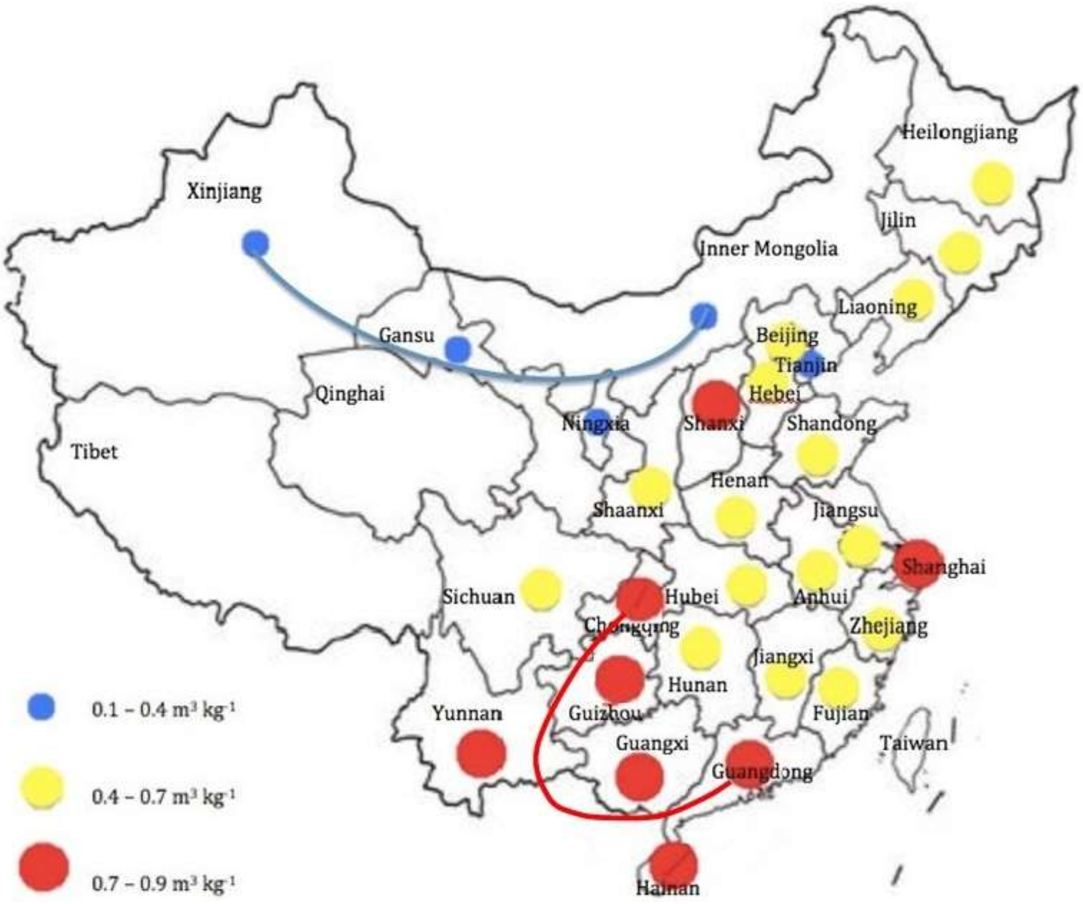

Figure 2. Direct green water of rice (m$^3$ kg$^{-1}$)

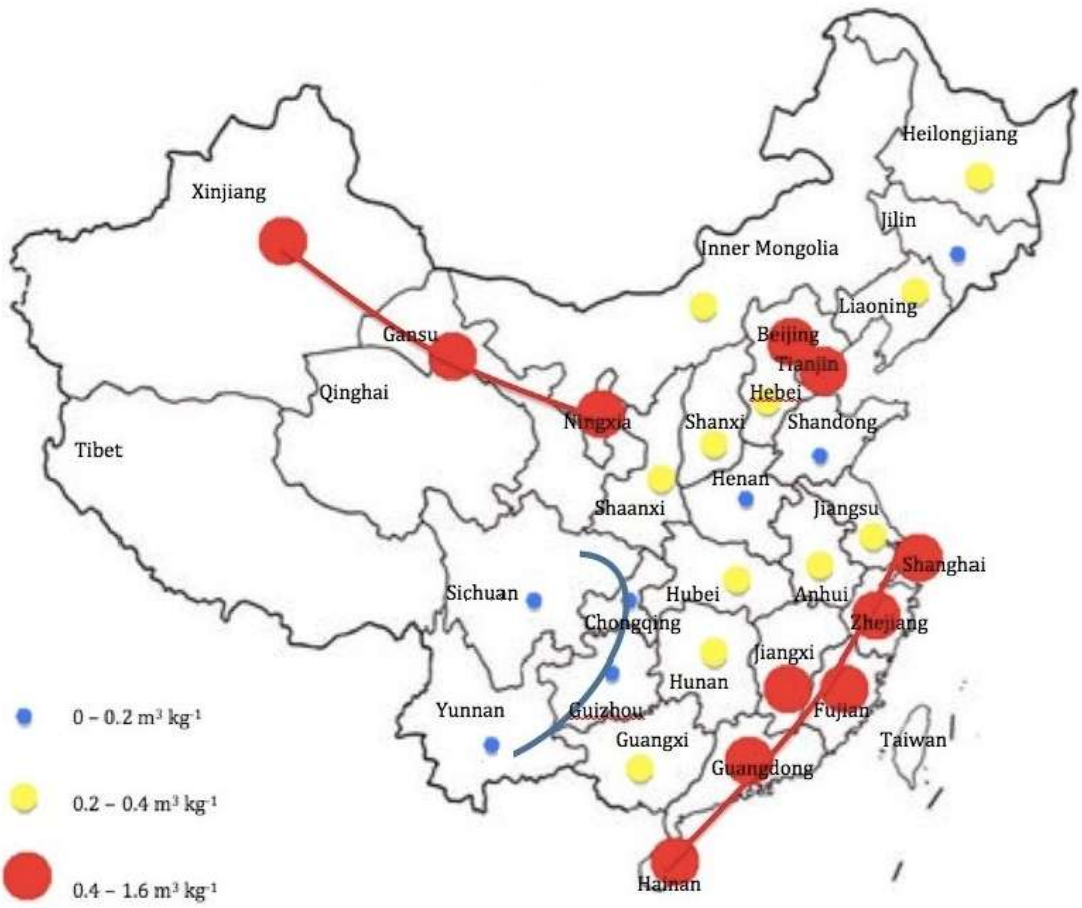

Figure 3. Direct blue water of rice (m$^3$ kg$^{-1}$)

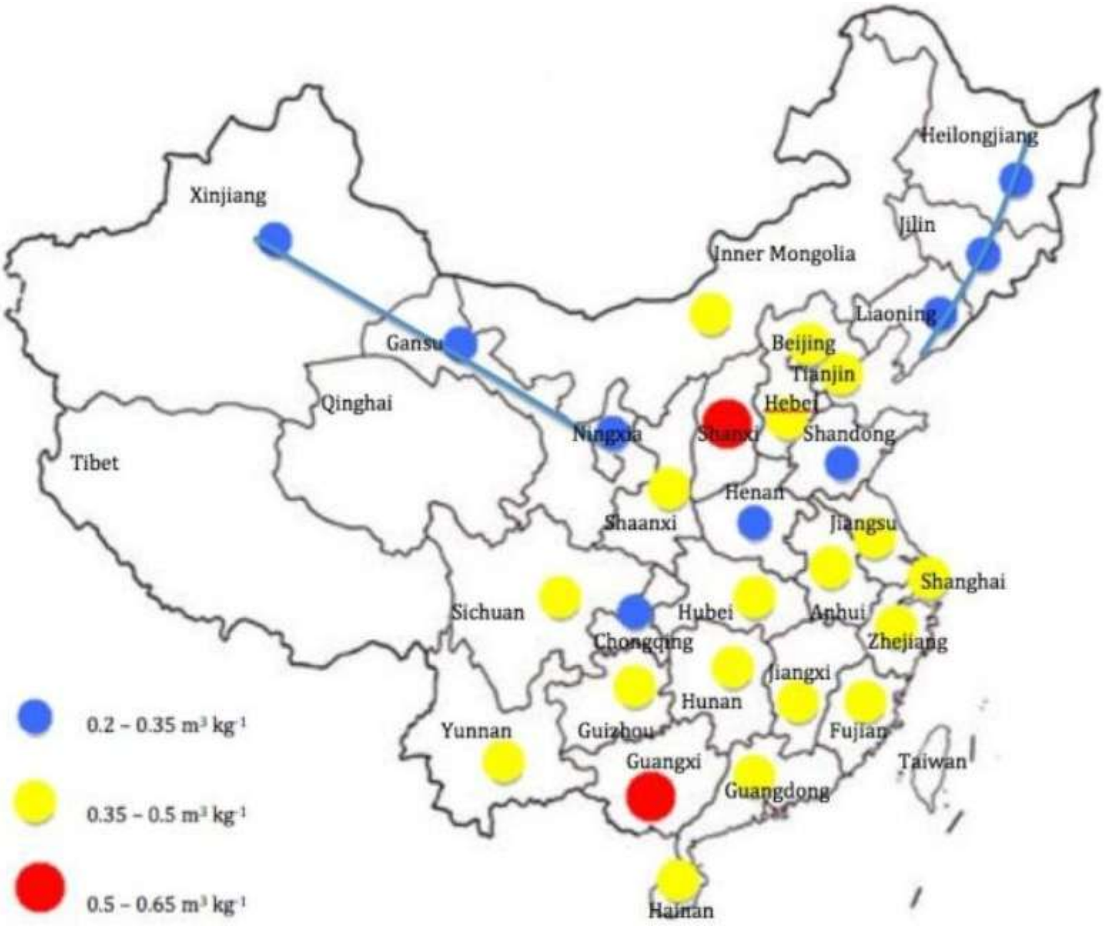

Figure 4. Direct grey water of rice ($m^3$ $kg^{-1}$)

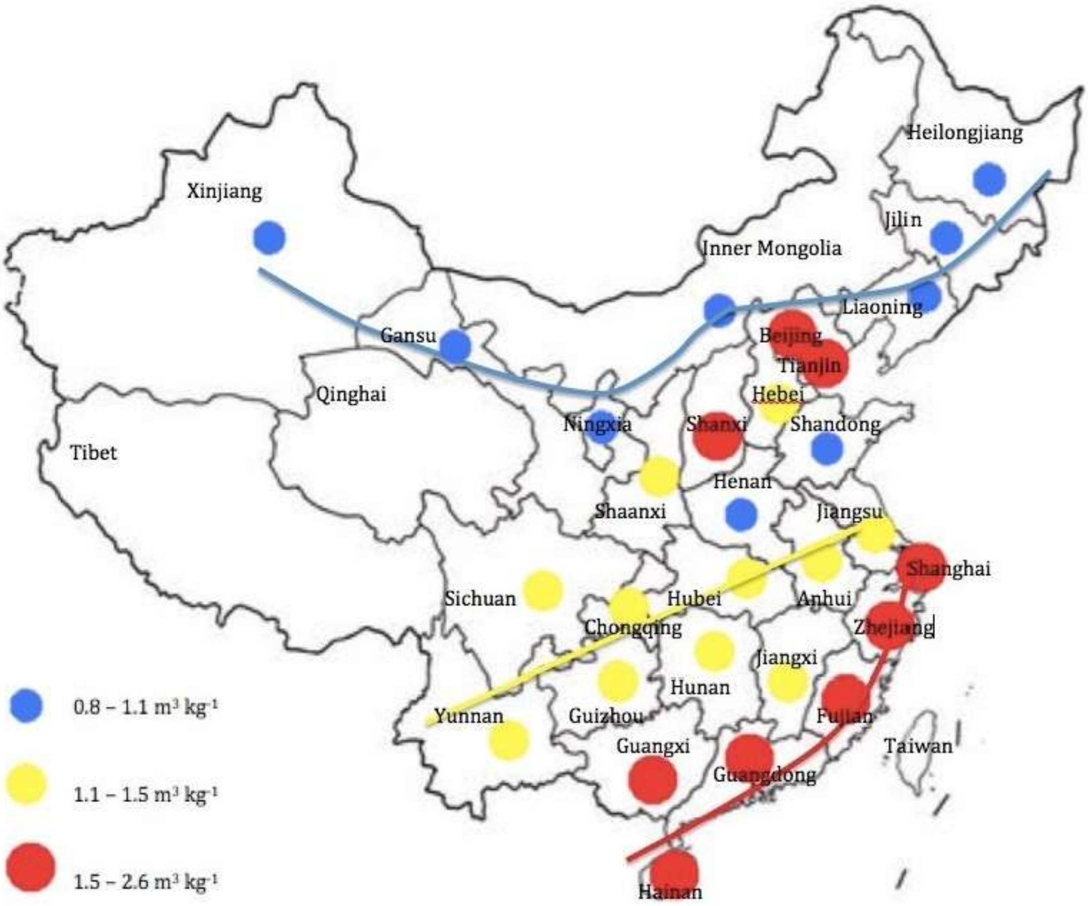

Figure 5. Total VWC of rice ($m^3$ $kg^{-1}$)