Virtual Water, Green Water and Blue Water in China

Abstract

Virtual water has recently been considered as an effective strategy for efficient water resources management, especially for the countries where water is scarce. The research to combine the study of virtual water, green water and blue water is very important considering the important role of green water in the food production. This paper first introduces the concepts of virtual water, green water and blue water and their roles in water resources management and food production. It then explains the method used for the analysis of virtual green/blue water value and unit water value, after describing the country's water sector, food production and food trade in China. It finally examines the following contents in the context of China: 1) the virtual water value and unit water value for various crops; 2) virtual water value and its partitioning (green virtual water value and blue virtual water value) both for wheat and for maize and 3) the virtual water trade in the context of China.

It is concluded that nearly all the fruits and vegetables are fallen in the category of low water intensive crop based on the definition in this paper; most of the grains belong to the median water intensive crops, while many cash crops including cotton and tobacco are high water intensive crops. China policy should encourage the fruit and vegetable export, stable the grain export and promote the cash crop import taking China's comparative advantage into account. In terms of unit water value, which is defined as the value created by one unit quantity of water, it can be concluded that fruits and vegetables have a higher unit water value while the grains and most of the cash crops have a lower one. Farmers may change the crop pattern from low water value grain and part cash crops to higher water value fruits and vegetables to increase their annual incomes in the future.

Rice, wheat and maize are the three most important grains in China and deserve special research for the study of virtual water, green water and blue water. Wheat and maize are studied in this paper. Based on the annual yield and climatic data in 27 regions (22 provinces with 5 autonomous regions) of China in 1999, it is concluded that, averagely, the virtual water value is 1580 m^3/ton for wheat and 906 m^3/ton for maize in China in 1999. Green water accounts for 56.7% of the total wheat (main importing grain) production and 71.5 % of the total maize (main exporting grain) production in 1999.

During the period of 1992 to 2001, China has an annual virtual water import of 52 Gm^3/yr (57.7 % for green water and 42.3 % for blue water) and an annual virtual water export of 11 Gm^3/yr (63.6 % for green water and 36.4 % for blue water). There was a net annual virtual water import flow of 41 Gm^3/yr coming into China averagely. This accounts for 23.6 percent of the annual irrigation water demand in China given the water efficiency of 40 percent.

Keyword: Virtual Water, Green Water, Blue Water, Food Trade, China

1. Concept of Virtual Water, Green Water and Blue Water

The concept of "virtual water" was first defined as the volume of water needed to produce a commodity or service (Allan, 1997). For example, it takes approximately 1000-2000 m^3 of water to produce 1 ton of grain and 10,000 m^3 of water to produce 1 ton of meat. Therefore, the virtual water value, defined as the water volume to produce one unit quantity of commodity or service, is about 1000-2000 m^3 /ton for grain and about 10,000 m^3 /ton for meat. Virtual water has recently been considered as an effective strategy for efficient water resources management, especially for the countries where water is scarce. Professor Allan introduced the concept of virtual water to describe the fact that water scarce countries could mitigate water shortage problem by importing food from the other countries in the international food market, rather than producing the required food with their own scarce water resources. In the Middle East, the amount of water that enters the region as virtual water in the form of subsidized grain purchases is equivalent to the annual flow down the Nile (Allan, 1997).

Virtual water strategy not only benefits water shortage in the food imported countries, but also benefits the water use efficiency at the global scale. Food trade is virtually a kind of water reallocation. The virtual water value is quite different for different foods and may be quite different even for the same food in different production sites considering the various climate conditions. To produce 1 ton of maize takes about 900 m^3 of water in China. However, it takes only 400 m^3 in France (Renault, 2002). In another word, to transport 1 ton of maize makes 400 m^3 of virtual water in France becoming 900 m^3 of virtual water in China. To import 1 ton of maize from France to China, regionally, 900 m^3 of water is saved in China; globally, 500 m^3 of water is saved considering the different virtual water value in these two production sites. Food trade from the countries with low virtual water value to the countries with high virtual water value will lead to the higher water use efficiency at the global scale.

As the water embedded in a product, virtual water exists not only in the process of international food trade, but also in the process of daily food consumption. It is the passage from the production domain to the consumption domain which transforms real water into virtual water (Renault, 2002). The changing food preference may lead to the higher water uses for agriculture at least in the first quarter of 21st century. Meats normally have higher virtual water value than the grains. However, the higher income may lead to the higher water consumption in association with a larger portion of meat and other animal products in the diet. This can be explained from the income elasticity point of view in economics. Various foods have different income elasticity, which is defined as the ratio of percentage change in quantity to the percentage change in income. Meats normally have higher income elasticity of demand than grains have. It is estimated that the income elasticities of rice, wheat, beef, pork and other meats are -1.3664, -1.3333, 0.4549, 0.4427 and 0.0607 respectively at the retail level (Huang, 1985). This estimate shows that wheat and rice are inferior goods with income elasticities less than zero while beef pork and other meats are necessaries with income elasticities between zero and one. From the economic point of view, the increased incomes will lead to more consumption for the necessaries and less consumption for the inferior goods. The increase of income has been resulting in the larger consumption for meats and less consumption for grains. World Water Forum (2000) gives a conclusion that as incomes rise and urbanisation continues its rapid advance, preferences shift, first from maize and coarse grains to rice, and then from rice to wheat, accompanying shift in growth from cereals to meat and fish as well. Diet change will lead to the higher demand for the food production in turn since the virtual water value for meat is appropriately 10 times of that for grains.

"Green water" refers to the water in the unsaturated soil that is directly from the rainfall and used by the vegetation through the process of evapotranspiration. The concept of green water was first introduced by Falkenmark (1995) to distinguish it from the "Blue water", which is defined as the water in the lakes, rivers and aquifers. For the rain-fed agriculture, vegetation relies only on the green water in the process of evapotranspiration. While for irrigated agriculture, it relies both on green water and blue water (supplemental irrigation). Blue water occurs in two different forms: surface runoff (shallow blue water) in surface water bodies and the renewable groundwater runoff (deep blue water) in the aquifers. For the blue water, it seems reasonable to consider both the surface water and renewable ground water in the same colour since part of the river water is contributed by the ground water. A river will not dry out in a dry spell due to the base flow contribution. Engineers have already found it's not right to calculate the total water resources by simply adding the surface water with the groundwater due to the above transfer. Traditionally, the total water resources are equal to the sum of surface water and groundwater minus the double counting between these two resources.

Engineers prefer blue water partly because it can be easily captured, allocated, reallocated and measured compared with the so-called green water. The traditional water supply management focuses much on blue water to increase the supply through location, development and expansion of new water sources. However, green water is a very important resource for food production for by far it is responsible for about 60 % of the world staple food production (Savenije, 2002). Also it is responsible for most of the meat production in the grazing grassland. Green water, which is derived directly from the rainfall in the unsaturated soil, has more advantages than blue water considering the costly capital inputs (machinery, irrigation infrastructure, energy etc) and labour inputs used to divert blue water from the lakes, rivers or aquifers to the fields. Irrigated agriculture generally cannot compete with rain-fed agriculture in the international food market. The largest food exporting countries are normally those that have large rain-fed agriculture with vast plains where adequate and reliable rainfall is available, such as American, Canada and Northern and Central Europe. However, reasonable use of blue water will result in higher crop yield. The blue water normally has more water productivity than the green water has. Irrigated agriculture produces 40 percent of the crops on 20 percent of arable land globally and it is estimated that 70 percent of the gains in cereal production are expected to come from irrigated land over the next 30 years (FAO, 2003). Irrigated agriculture is by far the largest blue water consumer, which takes appropriately 69% of the total blue water globally, leaving some 21% for industrial use and 10% for domestic uses (FAO, 2002).

Water for food production comes from two sources: green water directly from the rainfall and blue water from supplemental irrigation. Consequently, virtual water comprises two parts: virtual green water and virtual blue water. For the research of virtual water, the green water and blue water should be studies simultaneously to get a deeper insight of water use. At the global scale, green water has a higher priority in the food production as discussed above. Reasonable choice of food production sites will lead to the higher water efficiency. Food trade, or virtual water trade, is likely an effective way to mitigate the water scarcity problem in the water short countries. At the regional scale, the water scarcity always means the competing use of blue water. For agriculture, blue water is advised to allocate to the crops with higher unit water value to improve the income of the local farmers.

2. Water Resources in China

2.1 Water Balance and Water Demand

In 1980s, the first water resource assessment was done by the Ministry of Water Resources based on the hydro-meteorological data from 1956 to 1979. Based on this assessment and combined with the concepts of green water and blue water, the water resources in China are presented in Table 1.

Water demand has traditionally shared by three major sectors: agriculture, industry and domestic. Agriculture is by far still the largest water consumer of water in China accounting for nearly 70% of the total water demand at present as shown in Fig 1. The total annual water demand was about 560 Gm^3/yr in 1999. Compared with the net potential renewable blue water available in Table 1, there is no water scarcity in China (at least in recent few years) if the county is considered as a whole.

Table 1. Water Resources Balance in China

Description	Yearly Average Flows (Gm^3)
Water Resources from Rainfall	
Precipitation=1+2+3-4	6200.00[a)]

1. Evapotranspiration (green water)	3472.00 [a)]
2. Surface runoff (shallow blue water)	2728.00 [a)]
3. Groundwater (deep blue water)	828.80 [a)]
4. Overlap between surface runoff and groundwater	727.90 [b)]
Total Blue Water Resources from Rainfall=2+3-4	2828.90 [a)]
Other Renewable Blue Water Resources	
5. Surface runoff entering the country	17.20 [a)]
6. Surface water from melt ice	56.00 [a)]
Total Other Renewable Blue Water Resources	73.20 [a)]
Total Renewable Blue Water Resources	2902.10 [a)]
Surface runoff leaving to neighboring countries	718.85 [b)]
Net potential renewable blue water available	**2183.25**

a) From Liu and Chen (2001).
b) From AQUASTAT (2003)

2.2 Water Problem in China

The above analysis disguises the large temporal and spatial variations in water resources distribution in China. Although China possesses the total water resources of 2800 Gm^3/yr, which is ranked sixth in the world after Brazil, the Russian Federation, Canada, the USA and Indonesia, due to the big population of nearly 1.3 billion, the annual renewable blue water resources per capita were only 2285 m^3/yr in 1998, which was only one quarter of the world average of 8345 m^3/yr (MWR, 1999; World Bank, 2000). Influenced by the monsoon climate, the water resources are distributed highly unevenly. Temporally, it is illustrated by the fact that about 70 percent of the precipitation occurs in the four months from June to September while over 80 percent of the stream flow occurs in these four months in northern China. This highly temporal distribution of water leads to the frequent seasonal water shortage for crops in agriculture. It is estimated that agriculture in China has an annual water deficiency of about 30 G m^3/yr, which may result in the food losses of 25 Million ton/yr (Liu and Chen, 2001). Spatially, in terms of annual precipitation, it can be concluded from Fig. 2 that the annual precipitation decreases gradually from the Southeast coastal areas (800 mm/yr or more) to the Northwest inland regions (200 mm/yr or less). In terms of annual runoff, there is an extreme regional imbalance between the distribution of annual runoff and distribution of cultivated land. The annual runoff is greatly unevenly distributed in the major river basins (shown in Fig. 3) in China. The Changjiang Basin with those river basins situated in the south of it yield a runoff accounting for more than 80 percent of the total national annual runoff, although the area of the cultivated land in these regions only account for 40 percent of the total cultivated land in China. The Huanghe Basin, Huaihe Basin, Haihe Basin basins and Northwest Interior Basins have a half of the national area, 45 percent of the total cultivated land and 36 percent of the total population, but only posses 12 percent of the total annual renewable water resources.

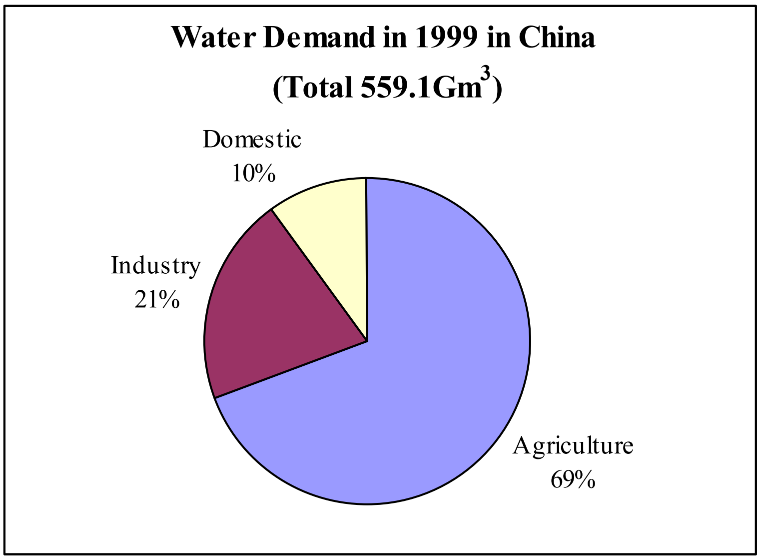

Figure 1. Water demand for agriculture, industry and domestic in China in 1999 (Liu and Chen, 2001)

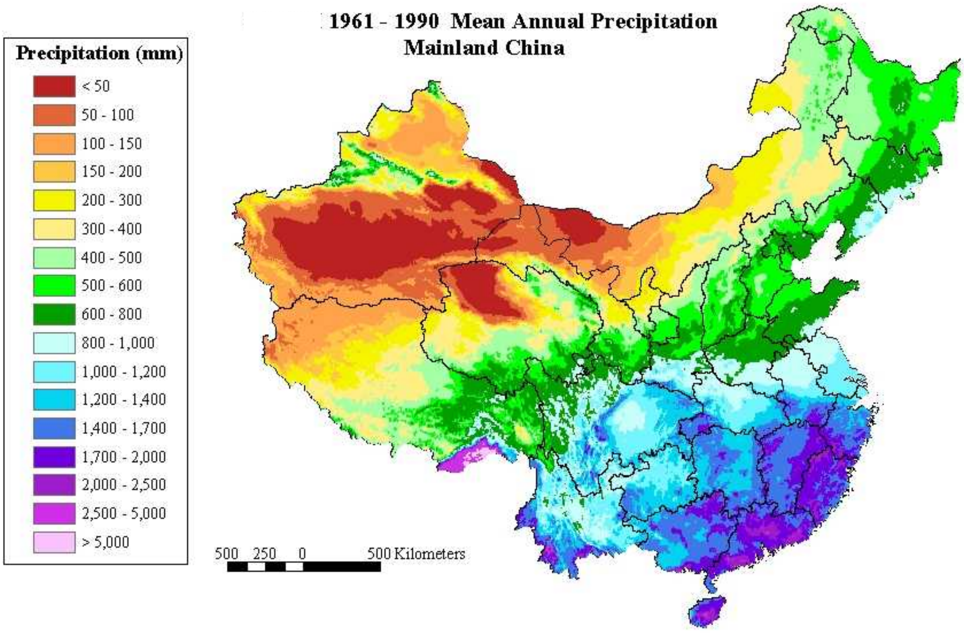

Figure 2. Mean Annual Precipitation in China.

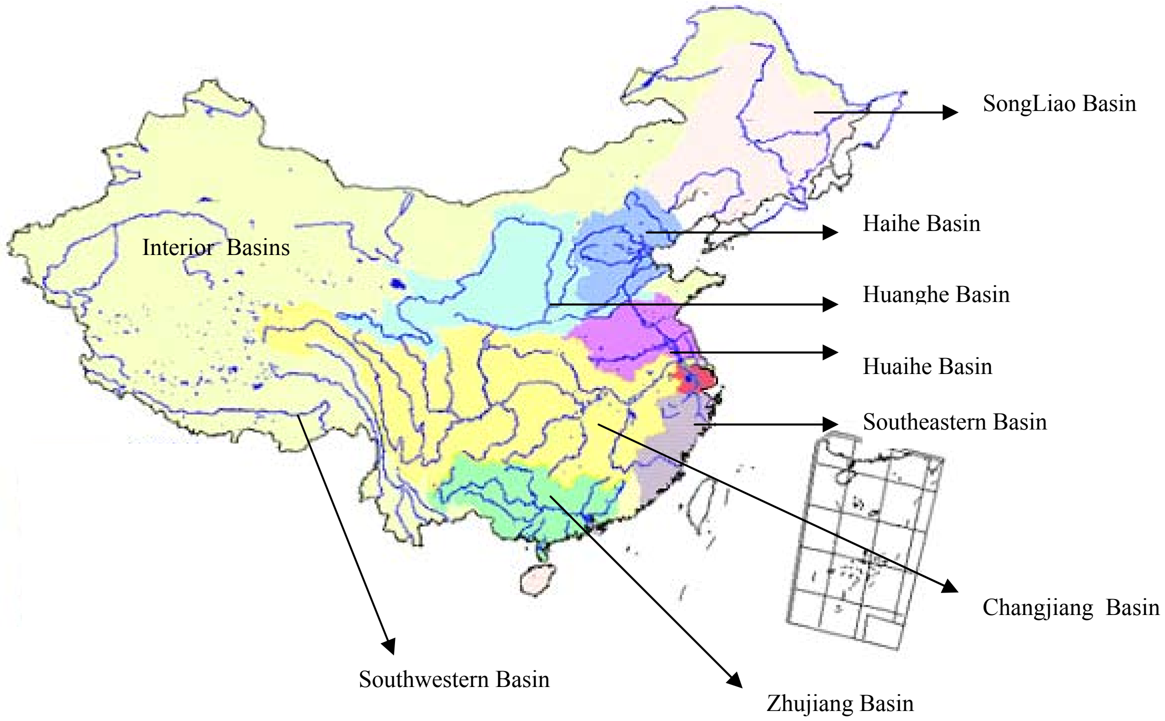

Figure 3. River Basins in China.

2.3. Irrigation in China

As mentioned above, the agricultural sector is by far the largest consumer of available blue water resources (certainly it is the only one sector who consumes green water resources) in China. The water scarcity problem is primarily a food problem in China although in some cities (especially the cities in Huang, Huai and Hai river basins) the water supply in domestic and industrial sectors is still a problem.

The territory of China can be divided into three irrigation zones (AQUASTAT, 2003). Perennial irrigation zone where the annual precipitation is less than 400 mm/yr covers mainly the northwest regions and part of the middle reaches of the Huanghe Basin; Necessary Irrigation zone where the annual precipitation ranges from 400 to 1000 mm/yr but it is highly uneven distributed due to the strong influence of the monsoon covers the HuangHuaiHai plain and northeast China; Supplementary irrigation zone where annual precipitation exceeds 1000 mm/yr covers the middle and lower reach of the Changjiang, Zhujiang and Minjiang Rivers and part of southwest China.

Irrigation (blue water) plays an important role for the food production in China. About three fourth of China's grain production comes from irrigated land, accounting for 40% of China's total arable land (Zhang, 1999). There has been a vigorous development in irrigation and drainage project since the founding of the People's Republic of China. It can be seen from Fig. 4 that the irrigated area has increased nearly half in 1978 compared to that in 1961. The grain yield of irrigated land is more than twice that of rain-fed agriculture in China (Jin and Young, 2001). Irrigation is extremely important to guarantee the food security both for China and for all over the world. Regionally, to support the annual population growth of 12 million over the first half of 21st century, China has to depend on the irrigation instead of the rain-fed agriculture considering the different yields. Globally, importing even a small share of China's grain consumption would place a claim on a large proportion of world grain exports (Jin and Young). The 20 million tons of grains imported in 1995 covered only 4% of China's grain consumption, but accounted for 10% of world grain exports (MOA, 1999). So, ample irrigation water supply (blue water supply) is quite important for China's food security and the world food security as well.

3. China Grain Production and Trade

3.1. Grain production in China (1961-1999)

Self-sufficiency for food has been a basic Chinese agricultural policy even since 1960s. Fig. 4 presents the total China grain production for the three major grains (rice, maize and wheat) and other grains including barley, millet, potatoes, sorghum and soybeans in association with China population and total irrigation area . The grain production and population data are obtained from FAOSTAT (2003). Based on this figure, the China grain production is analyzed as following:

1961-1978: During this period, the grain production rose steadily instead of significantly. Especially from 1966 to 1969, the increase of production was barely noticeable. In these years, all the economic activities were planned and directed by the China's government, including the provision of the necessary agricultural input and the distribution of the output. All the agriculture activities were carried out in the collectives farming system. The farmers had no possibility to choose the crop pattern and the agricultural inputs such as the seeds, fertilizer and tractors. They did not have enthusiasm for active and creative production. Although the improvement was small, the production still could keep pace with the population growth rate.

1978-1984: During this period, the annual grain production was increased by 5% on average, which was higher than the average annual population growth rate of 1.4 % in these 6 years. This improvement was mainly due to the implementation of the economic reforms initiated in 1978 in China. The economic reforms resulted in the shift from collective farming system to the household-based farming system. A basic agricultural policy, household responsibility system, has been carried out since early 1980s. This policy has motivated the farmers' productive enthusiasm greatly. It was the market, instead of the central government, that determined the agricultural input use and the production decision (Bach and Martin, 1997). The implementation of the above agricultural policy reform led to a dramatically rise in the total annual grain production in 1978, which was 11.2% higher than that in the previous year.

1985-1989: During this period, the annual grain production increased by 1.7%, while the population increased by 1.3 %. The annual grain production could only slightly keep up with the annual population growth. In this period, China was in the process of transition from a traditional planned system into a new market-oriented one. Due to the transition, new problems occurred including the fact that agriculture began to lose its comparative advantage to the industrial sector. The incentives for the farmers were lessened and much cultivated land was transformed into non-agricultural use. Grain production fell dramatically from 400 million ton/yr in 1986 to 373 million/yr in 1985. Except the bad weather, both the negative price signals to producers following a reform of the grain price system and a relaxation of the controls over input prices and input markets (Watson and Findlay, 1995) and the growth of the rural enterprises contributed to this production decline. Although the reform of the grain system slowed down in the following years (Bach and Martin, 1997), the increase in output was marginal. In 1988 and 1989, the annual grain production stayed at the same level as that in 1985.

1990-1998: During this period, the production of grains increased stably with an average rate of 2.2 % although there was a decline in 1994, which was partly due to the weather condition (FAO, 1995). The grain production increased much faster than the population growth (1 %) in the same period. The increase in the early 1990s was triggered both by the increased grain price in 1988 and 1989 while the increase in later years thanked greatly to the government's emphasis and effective measures. Two special conferences on agriculture were organized by the Central Committee of the Communist Party in China (CCCP) and the State Council in October 1993 and March 1994 in succession to address the issues of agriculture, rural areas and farmers. After that, a lot of effective measures were taken to promote agricultural development, including the so-called 'rice bag program' (provincial governor is responsible for the grain production), price ceilings for agricultural inputs, soaring price for agricultural products, procurement system reforms, grain anti-risk funds etc. All these effective measures encouraged the farmers' incentive greatly and thus promoted the stable food production.

1997-2001: During this period, the grain production experiences a dramatically decline although the population increased steadily. (reason)

From the above analysis, it can be seen that the grain production has been affected greatly by the agricultural policy. Reasonable agricultural policy, such as the price policy and the market system, will result in the higher grain production. From Fig. 4, it could also be concluded that the total production of these the three major grains (rice, wheat and maize) has occupies over 80 percent of the total grain production since 1961 and nearly 85% of the total since 1978. These three major grains are the most important grains in China and deserve detailed study for the food security research in China.

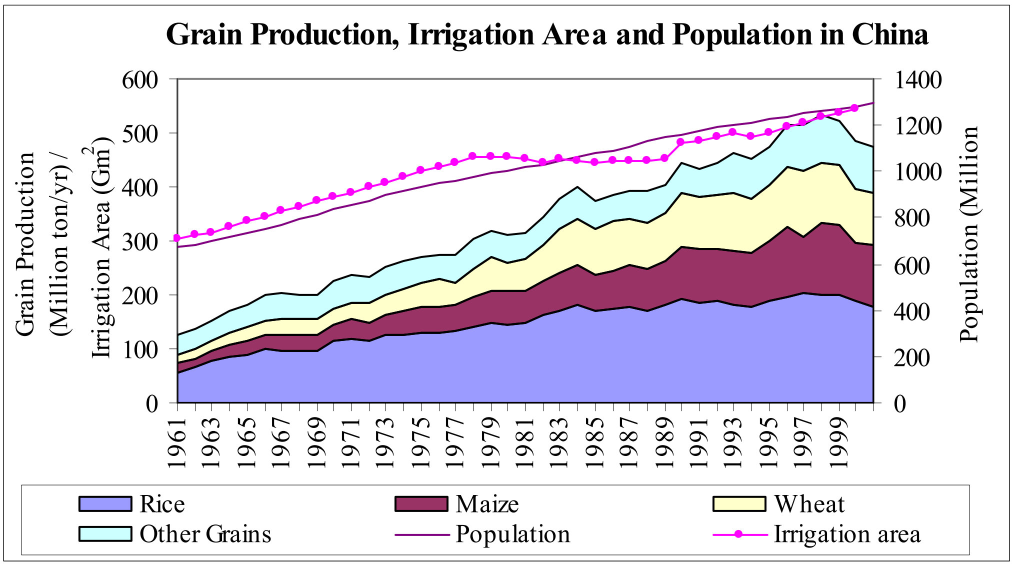

Figure. 4 Total Grain Production, irrigation area and population in China, 1991 through 1999

3.2. Grain Trade in China (1961-1999)

As a country with such a huge population and expending economy, China's food trade is absolutely important for the global food security. Although China's policy emphasis on grain self-sufficiency, China still imported as much as 17 percent of the World's traded wheat, 28 percent of its soybean oil, while exporting as much as 10 percent of the World's traded maize (Carter and Rozell, 2001).

The China's grain imports are influenced by the domestic wheat production shown in Fig. 5. The dip in China's grain imports in 1976, 1985, 1993 and 1997 coincides with a spike in domestic wheat production in the corresponding years, while the increased grain imports are normally consistent with the decreased wheat production. Wheat is the most important importer in China and wheat imports accounted for more than 60 percent of the total grain imports from 1961 to 1996. There have been three times of wheat import decline since 1961, first decline from 14.5 million ton/yr in 1982 to 6.1 million ton/yr in 1985 as domestic production increased due to the implementation of household responsibility system, second decline from 15.7 million ton/yr in 1989 to 7.3 million ton/yr in 1993 as the domestic production increased due to the increased grain price in 1988 and 1989. The book, *Who Will Feed China?,* written by Lester Brown (1995), which stated that China will absorbing most of the world's exportable grain and oilseed supplies, led to the third wheat imports decline. China's wheat imports dropped from 12.6 million ton/yr in 1995 to 1.7 million ton/yr in 2001. Another interesting phenomenon is that the China's soybean imports sharply climbed from 2.9 million ton/yr in 1995 to 16.4 million ton/yr in 2001 as shown in Fig. 4 because trade for soybeans has been more open and competitive for several years and restrictions against importing soybeans were almost completely removed during 2000 and 2001 (Carter and Rozell, 2001).

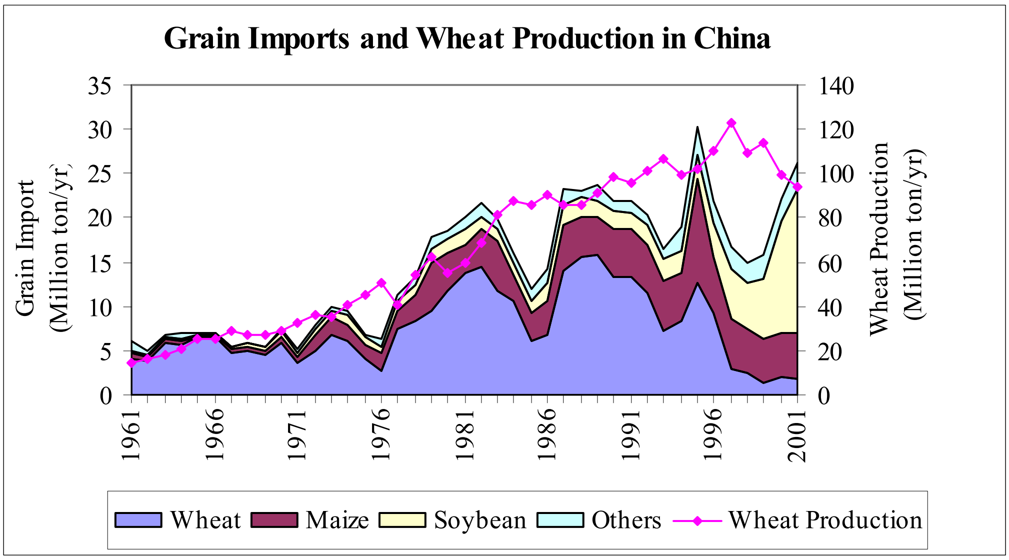

Figure 5. Grain imports and wheat production in China. 1961 through 2001

The total grain exports are greatly influenced by the maize exports for maize has been the largest exporting grain in China since middle 1980s. The maize exports have accounted for nearly 70 percent of the total grain exports since 1985 (Fig. 6). However, the fluctuation of the grain exports does not coincide with the domestic maize production so much as the total grain inports coincide with the domestic wheat production. There was a sharp decline in the maize exports from 8.74 million ton/yr in 1994 to 0.11 million ton/yr in 1995 mainly due to the drought in China's maize production sites, which led to a sudden drop in the total grain exports from 11.55 million ton/yr in 1994 to 0.87 million ton/yr in 1995 as shown. In 1996, the maize exports remained a low level such as 0.16 million ton/yr. After the drought and Brown's book , *Who Will Feed China?*, in 1995, many analysts said China would never again export maize. However, the maize exports climbed up dramatically to 6.62 million ton/yr in 1997 and reached an export peak of 10.5 million ton/yr in 2000.

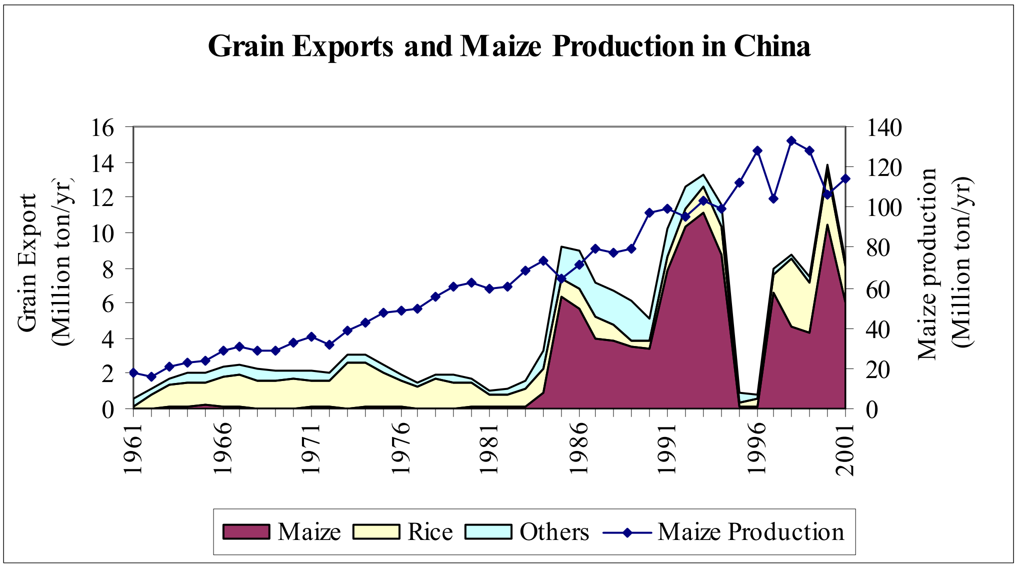

Figure 6. Grain exports and maize production in China. 1961 through 2001

4. Method in this paper

The method for the analysis of the virtual water, green water and blue water in the later parts are introduced, after defining some important concepts, in the follows.

Crop Water Requirement (CWR) refers to the accumulated crop evapotranspiration ET_c (in mm/day) over the complete growing period with a unit of mm.

Virtual Water Value (VWV) refers to the water volume to produce one unit quantity of commodity or service with a unit of m^3/ton;

Unit Water Value (UWV) refers to the value produced by one unit quantity of water with a unit of Y/m^3. (Y is the Chinese currency unit. The exchange rate in January 1995 was 1 US$ =8.465 Y).

The following formula is used to calculate the virtual water value of crop *c* in region *i* in year *j*:

$$VWV[i, j, c] = 10 * CWR[i, j, c] / CY[i, j, c] \qquad (1)$$

Here, CY [i, j, c] refers to yield of crop c in region i in year j with a unit of ton/ha.

The crop evapotranspiration ET_c is calculated by multiplying the reference crop evapotranspiration ET_0 with the crop coefficient K_c.

$$ET_c = K_c * ET_0 \qquad (2)$$

The reference crop evapotranspiration is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 12 cm, a fixed crop surface resistance of 70 s/m and an albedo of 0.23 This reference crop evapotranspiration closely resembles the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and with adequate water (Smith et al., 1992). Reference crop evapotranspiration is calculated on the basis of the FAO Penman-Monteith equation (Smith et al., 1992; Allen et al., 1994a, 1994b; Allen et al., 1998):

$$ET_0 = \frac{0.48\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3)$$

where:
ET_0 - reference evapotranspiration (mm day- I),
R_n -net radiation at the crop surface (MJ m^{-2} day^{-1})
G -soil heat flux density (MJ m^{-2} day^{-1}),
T -mean daily air temperature at 2 m height (°C),
u_2 -wind speed at 2 m height (m s^{-1}),
e_s -aturation vapour pressure (kPa),
e_a -actual vapour pressure (kPa),
es-ea -saturation vapour pressure deficit (kPa),
Δ-slope vapour pressure curve (kPa °C-1),
γ - psychometric constant (kPa °C-1).

The crop coefficient (K_c) depends upon the type of crop and the stage of growth. The length of crop development stages and the total growing period for various types of climates and locations is extensively given in FAO Irrigation and Drainage Papers 33 and 56. Typical values of K_c for the initial, middle and end stages also can refer to the above papers.

Crop water requirement breaks into two distinct parts: crop blue water requirement and crop green water requirement. The crop blue water requirement (CBWR) is the accumulated Net Irrigation Requirement (NIR, the amount of irrigation water to be supplied to the crop to satisfy its consumptive use in mm/day) over the complete growing period with a unit of mm. Net Irrigation Requirement is calculated with the following formula:

$$NIR = K_c * ET_0 - P_{eff} \qquad (4)$$

Here P_{eff} refers to the effective rainfall, for which two general formulas were proposed by FAO related to the average monthly rainfall P.

P_{eff} =0.8*P-25 for P> 75 mm/month (5)
P_{eff} =0.6*P-10 for P> 75 mm/month (6)

The crop green water requirement (CGWR) is equal to the crop water requirement minus the crop blue water requirement.

Based on the crop green water requirement and crop blue water requirement, the virtual green water value (VGWV) and virtual blue water value (VBWV) can be calculated with the similar formula to formula (1).

The following formula is used for the calculation of Unit Water Value:

$$UWV[i, j, c] = p[i, j, c]/VWV[i, j, c] \qquad (7)$$

Where p[i, j, c] refers to the price of crop c in region i in year j with a unit of Y/ton.

The average virtual (green/blue) water value in a region with N sub-regions is calculated with the following formulas:

$$\overline{VWV[j,c]} = \frac{\sum_{i=1}^{N}(P[i,j,c] \times VWV[i,j,c])}{\sum_{i=1}^{N} P[i,j,c]} \quad (8)$$

$$\overline{VGWV[j,c]} = \frac{\sum_{i=1}^{N}(P[i,j,c] \times VGWV[i,j,c])}{\sum_{i=1}^{N} P[i,j,c]} \quad (9)$$

$$\overline{VBWV[j,c]} = \frac{\sum_{i=1}^{N}(P[i,j,c] \times VBWV[i,j,c])}{\sum_{i=1}^{N} P[i,j,c]} \quad (10)$$

Where P[i, j, c] means the annual production of crop c in region i in year j with a unit of ton/yr.

The crop water requirement, crop blue water requirement and crop green water requirement are calculated with FAO's CropWat model for Window, which is available throught the web site of FAO (www.fao.org). The CropWat calculates the CWR, CGWR and CBWR with the method discussed above on the basis of the following assumptions (Hoekstra and Hung):
(1). Crops are planted under optimum soil water conditions. When the effective rainfall is not enough to satisfy the crop water requirement, the required water will be supplied by supplementary irrigation.
(2). Crop evapotranspiration under standard conditions (ET_c), this is the evapotranspiration from disease-free, well-fertilised crops, grown in large fields with 100 % coverage.
(3). Crop coefficients are selected depending on the single crop coefficient approach, that means single cropping pattern, not dual or triple cropping pattern.

5. Virtual Water, Virtual Green Water and Blue Water and Virtual Water Trade in China

5.1. Different Water Intensive Crops Based on Virtual Water Value

In this study, a commodity whose virtual water value exceeds about 2000 m^3/ton is considered as a high water intensive commodity for it requires huge volume of water to produce one unit of this commodity. For the countries with serious water scarcity, it is not recommended to produce or export the high water intensive commodity. Below this threshold but if the virtual water value is higher than 1000 m^3/ton, commodities are median water intensive. When the virtual water value falls below 1000 m^3/ton, commodities benefit from low water requirement and they are treated as low water intensive commodity.
Most of the meats are high water intensive and require huge water quantity to produce one ton of them. Oki et al. (2002) calculated that the virtual water value was 3900, 6100 and 24600 m^3/ton for chicken, pork and Japanese beef respectively.
Thirty four crops are chosen for the virtual water study in China, including 10 grains (maize, wheat, rice, potatoes, millet, barley, sorghum, soybean, groundnut and oats), 5 fruits (banana, grapes, water melon, mango and citrus), 11 vegetables (tomato, cabbages, carrots, cucumbers,

lettuce, onion green, onion dry, peas green, cauliflower, spinach and pepper) and 8 other cash crops except fruits and vegetables (cotton, tobacco, sunflower, safflower, artichokes, bean green, sugar beets and sugar cane). Beijing is chosen as the typical meteorological station. This study is based on the year of 1995 because the price data for all the studied crops are available in FAO website. The results are presented as below:
The above crops in China can be divided into three categories based on the virtual water value shown in Fig 7:

- Low Water Intensive Crops (with virtual water value less than 1000 m^3/ton): Nearly all the fruits and vegetables fall into this category except pepper which has a very high virtual water value (Citrus only has a fractionally higher virtual water value above 1000). Few grains, such as maize and potatoes, and some cash crops, such as bean green, sugar beets and sugar cane), are also low water intensive crops.
- Median Water Intensive Crops (with virtual water value between 1000 and 2000 m^3/ton): Most of the grains belong to this category except maize (low water intensive crop), oats (high water intensive crop) and soybean (high water intensive crop).
- High Water Intensive Crops (with virtual water value above 2000 m^3/ton): Many cash crops are in this category including cotton, tobacco, sunflower, artichokes and safflower. Oats, soybean and pepper are also high water intensive crops.

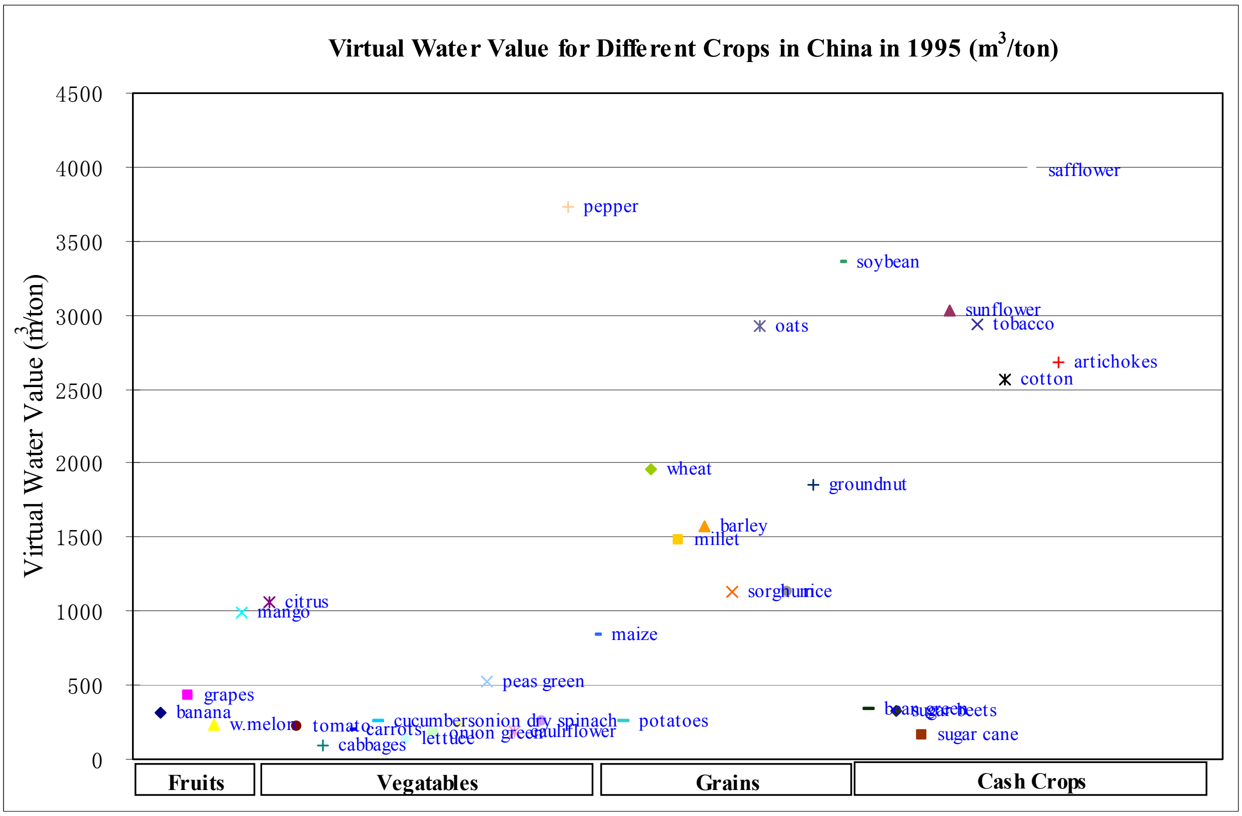

Figure 7. Virtual water value for different crops in China in 1995. Here cash crops refer to the crops except fruits and vegetables

Given the fact that China is one of the world's most water deficient countries with such a huge population of near 1.3 billion including 70 percent of rural population, China has a comparative advantage in labour intensive agricultural products instead of water intensive ones. China policy should encourage the fruit and vegetable export, stable the grain export and promote the cash crop import considering its comparative advantage.

China has already been moving towards a strategy consistent with its domestic comparative advantage. For grain export, China has a long-term low water intensive maize export, which accounts for nearly 70 percent of the total grain export since 1985 as stated above. For grain import, although wheat, a median water intensive crop, played the most important role traditionally, the wheat imports have dropped dramatically since 1995 with a sharp rise in high water intensive soybean imports.

5.2. Unit Water Value for Various Types of Crops

Given the big rural population, the farmers' welfare is one of the most important concerns in China. As China's economic is becoming more and more market-oriented, farmers have more opportunities to choose their crop patterns and agricultural inputs. This change may lead to more outputs of the higher water value production. Fig. 8 states the unit water value for different crops in China based on the virtual water value and water price in 1995. From this graph, it can be concluded that fruits and vegetables have a higher unit water value while the grains and most of the cash crops have a lower one except cotton, artichokes and bean green.

In China, a crop whose unit water value exceeds about 3 Y/ m^3, can be considered as a high water value crop. Below this threshold but if the unit water value is higher than 1 Y/ m^3, the crops are median water value crops. When the unit water value falls bellow 1 Y/ m^3, the crops experience low water value.

Farmers may change the crop pattern from low water value grain and part cash crops to higher water value fruits and vegetables to increase their annual incomes. For most of the high value crops (fruits and vegetables) fall in the category of low water intensive crops, this crop pattern change may result in the less agricultural water consumption, which will benefit the serious water shortage in China. However, this change also may lead to the less grain production, which may result in more food problems both for China although this consequence still needs to be seen. China decision makers should be very careful when making agricultural policies.

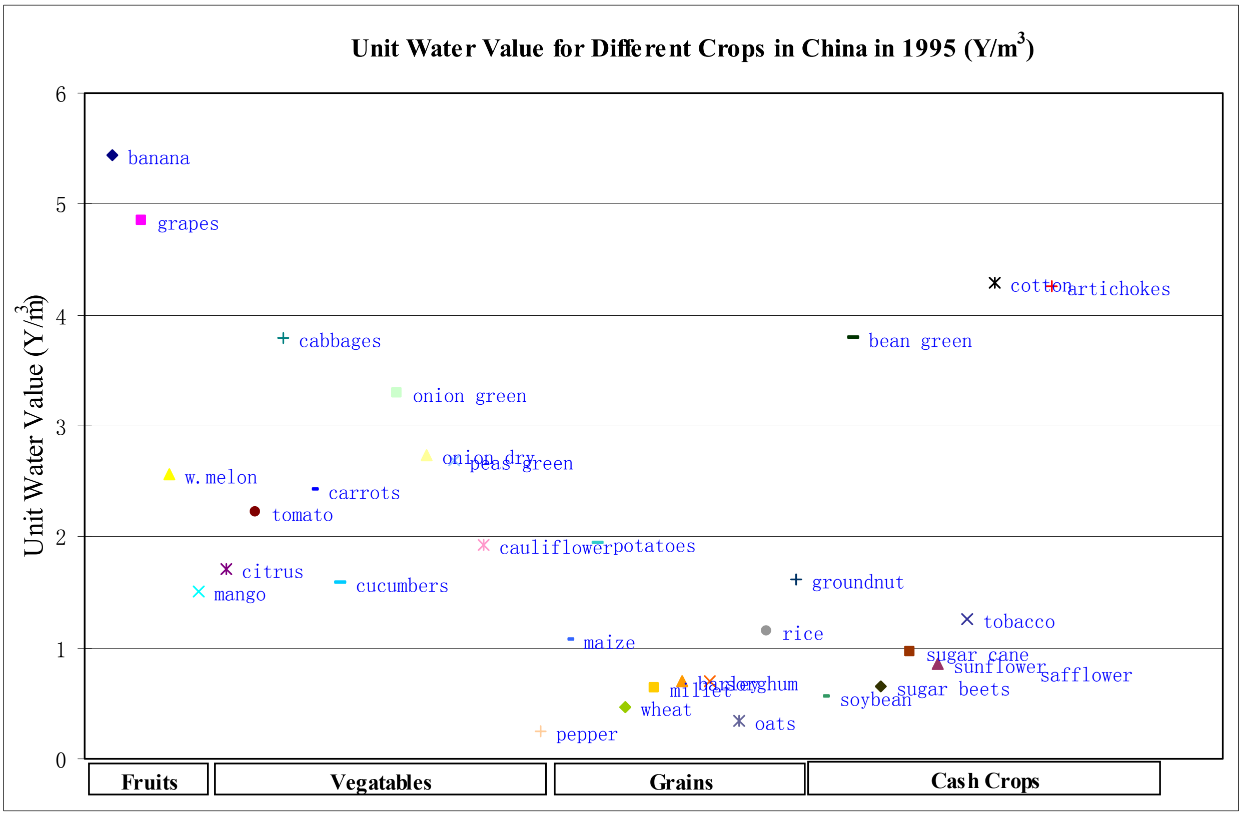

Figure 8. Unit water value for different crops in China in 1995. Here cash crops refer to the crops except fruits and vegetables

5.3. Virtual Water Value and its Partitioning for Wheat and Maize.

Rice, wheat and maize are the three most important grains in China both in terms of grain production and grain trade. Each of these three grains has accounted for more than 100 million tons (190 for rice, 110 for maize and 105 for wheat) of 480 million-ton annual grain production since 1990. The maize annual exports has accounted for 73 percent of the total annual exports since 1990 while the wheat imports accounted for more than 60 percent of the total annual imports from 1961 to 1996 although this percentage has fallen sharply due to the roaring soybean annual imports in recent years. It is necessary to have a detailed study for these three grains. Since CropWat cannot be used to calculate the crop water requirement for rice, the virtual water value for rice will not be studied in this paper.

In order to calculate the virtual water value and its partitioning for wheat and maize, twenty seven regions are studied including twenty one provinces and five autonomous regions from the mainland of China (Hainan province is included for maize but not included for wheat for there is no any wheat production in this province). The virtual water value in the other four municipalities of China, Beijing, Tianjin, Shanghai and Chongqing, is assumed to be equal to the virtual water value in Hebei, Hebei, Jiangsu and Sichuan Provinces respectively.

China is the largest wheat production country with an annual wheat production accounting for nearly 30 percent of the world total. There are two major types of wheat planted in China: winter wheat and spring wheat. Winter wheat is dominant and covers 84 percent of the total planting area in China, leaving another 16 percent for the spring wheat. Winter wheat is planted in autumn and harvested in the next summer. The growing period of wheat is quite different in various regions, varying from 120 days in the south parts to 270 days in the north parts of China. In some high altitude regions in the southwest of China, the growing period may be as long as 330 days. Spring wheat is planted in spring and harvested in summer or autumn in the same year. Spring wheat has a short growing period of 80-120 days.

China is the second largest maize production country whether in terms of planting area or annual production. Spring maize and summer maize are the two major types for maize in China although autumn and winter maize are also planted in some regions, especially in the south of China. Spring maize is planted in the last ten days of April or the first ten days in May and harvested in the middle ten days of September. Summer maize is planted in the middle ten days in June and harvested in the last ten days in September.

In this study, it is assumed that only one type of wheat is planted in one certain region, winter wheat or spring wheat. The same assumption is used for maize. Only one type of maize is planted in one certain region, whether spring maize or summer maize.

The typical meteorological stations for the different regions are listed in Table 2. In this table, the different wheat and maize types are also listed for different regions. The annual production and yield of maize and wheat in 1999 are referred to China Agriculture Statistic Yearbook (China Statistical Bureau, 2000). As to the input data to CropWat, the climatic data in the typical meteorological stations are taken from climate database, CLIMWAT, which is available through FAO's website; the crop parameters (crop coefficients in different crop development stages, the length of each crop in each development stage, the root depth etc) of winter/spring wheat and spring/summer maize are taken directly from the crop directory of the CropWat package, the planting dates are assumed as following: September 10 for winter wheat, April 10 for spring wheat, April 21 for spring maize and June 10 for summer maize.

Table 2. The Typical Meteorological Stations and Wheat, Maize Types Assumed in Studied Regions.

Regions	Typical Meteorological Stations	Wheat Types	Maize Types
Henan	Xinyang	Winter Wheat	Summer Maize
Shandong	Jinan	Winter Wheat	Summer Maize
Hebei	Shijiazhuang	Winter Wheat	Summer Maize
Jiangsu	Nanjing	Winter Wheat	Summer Maize
Sichuan	Chengdu	Winter Wheat	Summer Maize
Anhui	Hefei	Winter Wheat	Summer Maize
Shaanxi	Xi'an	Winter Wheat	Summer Maize
Hubei	Wuhan	Winter Wheat	Summer Maize
Shanxi	Taiyuan	Winter Wheat	Spring Maize
Liaoning	Shenyang	Winter Wheat	Spring Maize
Zhejiang	Hangzhou	Winter Wheat	Summer Maize
Fujian	Fuzhou	Winter Wheat	Summer Maize
Jiangxi	Nanchang	Winter Wheat	Summer Maize
Hunan	Changsha	Winter Wheat	Summer Maize
Guangdong	Guangzhou	Winter Wheat	Summer Maize
Guangxi	Nanning	Winter Wheat	Summer Maize
Guizhou	Guiyang	Winter Wheat	Summer Maize
Yunnan	Kunming	Winter Wheat	Summer Maize
Xizang	Lhasa	Winter Wheat	Summer Maize
Heilongjiang	Harbin	Spring Wheat	Spring Maize
Neimenggu	Huhehaote	Spring Wheat	Spring Maize
Jilin	Changchun	Spring Wheat	Spring Maize
Gansu	Lanzhou	Spring Wheat	Spring Maize
Xinjiang	Urumqi	Spring Wheat	Spring Maize
Ningxia	Yinchuan	Spring Wheat	Spring Maize
Qinghai	Xining	Spring Wheat	Summer Maize
Hainan	Haikou	-	Summer Maize

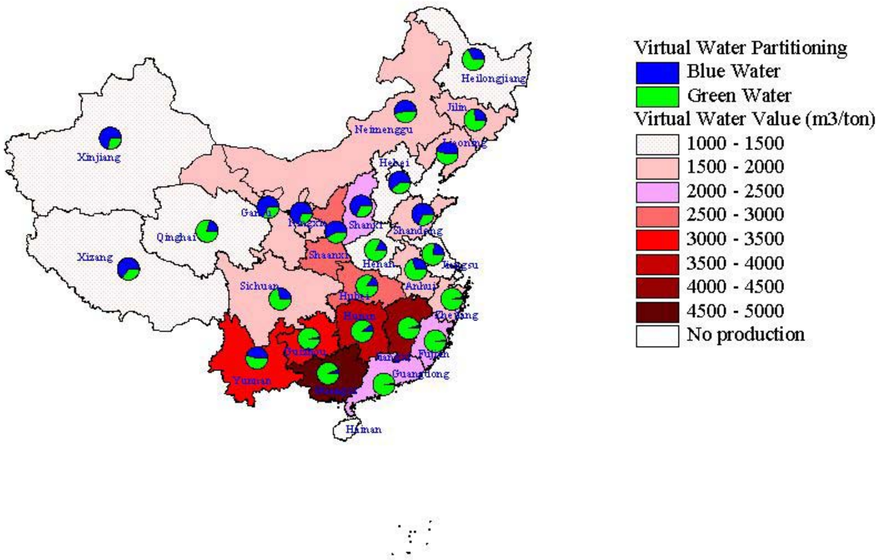

Figure 9. Virtual Water Value and its Partitioning for Wheat in the Mainland of China in 1999

Fig. 9 shows the virtual water value and its partitioning for wheat in different regions in China in 1999.Tthe virtual water value for wheat is concluded as following:

- Averagely, the virtual water value for wheat in China is 1580 m^3/ton in 1999. Based on the definition in this paper, wheat is a median water intensive crop in China
- Wheat is a median water intensive crop in 16 regions while it is a high water intensive crop in the other 10 regions. It belongs to median water intensive crop in all the top five maize production regions (Henan with an annual maize production of 23million ton/yr, Shandong with 21 million ton/yr, Hebei with 13 million ton/yr, Jiangsu with 11 million ton/yr and Anhui with 8.5 million ton/yr as shown in Fig.10). The low virtual water value in these regions are mainly due to the high yield (shown in Fig. 10) in the above top maize production regions, which are mainly located in Huaihe Basin and Haihe Basin.
- Virtual water value for wheat is higher in the south of China than that in the north. mainly due to the lower yield. The virtual water value is higher in Zhujiang Basin, Sountheastern Basin, part of Changjiang Basin and Huanghe Basin mainly due to the lower wheat yield in these regions and it is lower in Northeastern Basin and Interior Basins because of the higher yield.

As to the virtual water value partitioning for wheat, it is concluded as following:

- Averagely, green water accounts for 56.7 percent of the total wheat production in China in 1999.
- In the top five wheat production provinces, green water accounts for 83%, 32%, 38%, 78% and 76% in Henan, Shandong, Hebei, Jiangsu and Auhui provinces respectively
- Generally speaking, green water contributes more in the southern and northeastern parts of China and less in other regions. It accounts for more than 90 percent of the wheat production in Southeastern Basin, Changjiang Basin and Yhujiang Basin

because in these regions, the annual rainfall is averagely exceed over 1200 mm/yr. However, green water only contributes to less than 40 percent in most regions in Huanghe Basin.

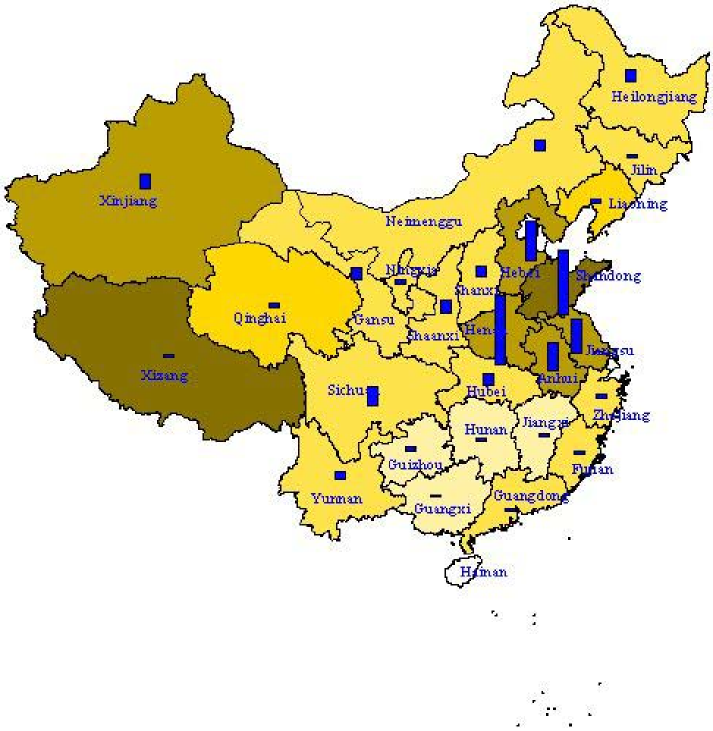

Figure 10. Wheat Annual Production and Yield in 1999

Fig.11 shows the virtual water value and its partitioning for maize in different regions in China in 1999. The virtual water value for maize is concluded as following:

- Averagely, the virtual water value for Maize in China is 906 m^3/ton in 1999. Based on the definition in this paper, maize is a low water intensive crop but its virtual water value is close to the threshold of median water intensive crops.
- Maize is a low water intensive crop in 13 provinces located in Huaihe Basin, Haihe Basin, Liaohe Basin, Southwestern Basin, western parts of Changjing Basin and Southern parts of Interior Basins while it is a median water intensive crop in the other 14 provinces.
- Maize is mainly a low water intensive crop in the top five maize production provinces (Jilin with an annual maize production of 16.92 million ton/yr, Shandong with 15.51 million ton/yr, Heilongjiang with 12.28 million ton/yr, Henan with 11.56 million ton/yr and Hebei with 10.88 million ton/yr as shown in Fig. 12).
- Virtual water value for maize does not coincide with the yield so much as that for wheat. High yield regions may have high water intensive maize, such as Xinjiang of Interior Basins, while low yield regions may have low water intensive maize, such as in Southwestern Basin and Xizang of Interior Basins

As to the virtual water value partitioning for maize, it is concluded as following:

- Averagely, green water accounts for 71.5 percent of the total maize production in China.

- Green water accounts for more than 90 percent of the maize production in Sichuan, Xinjiang, Yunnan, Hainan , Guizhou, Henan and Zhejiang. However, in the above provinces, only Henan is a major maize production site.
- Generally speaking, green water contributes greatly to the maize production in most regions of China except in some northern part of the Interior Basins, such as in Ningxia and Gansu Provinces, green water only accounts for less than 30 percent of the maize because of the low rainfall and high evaporation.

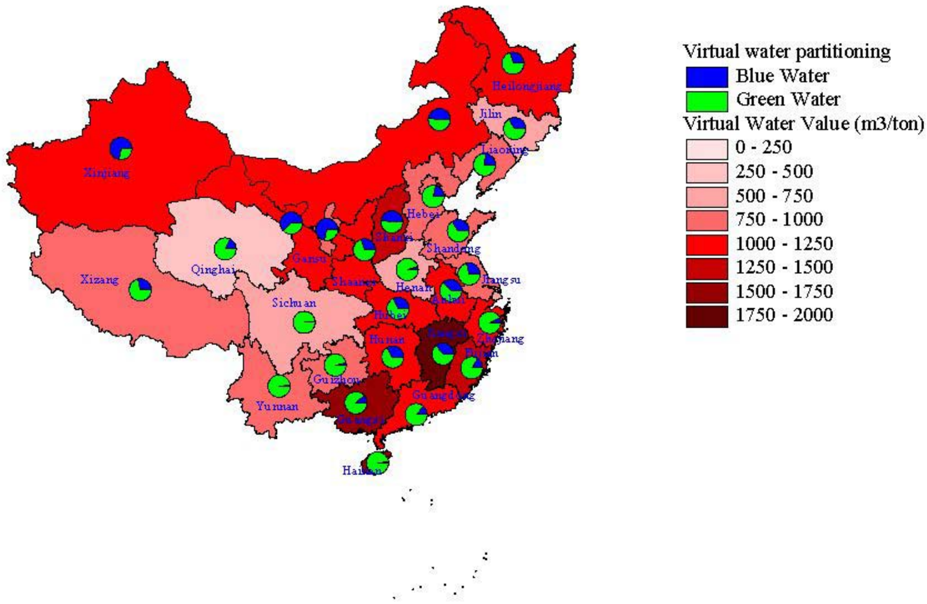

Figure 11. Virtual Water Value and its Partitioning for Maize in the Mainland of China in 1999

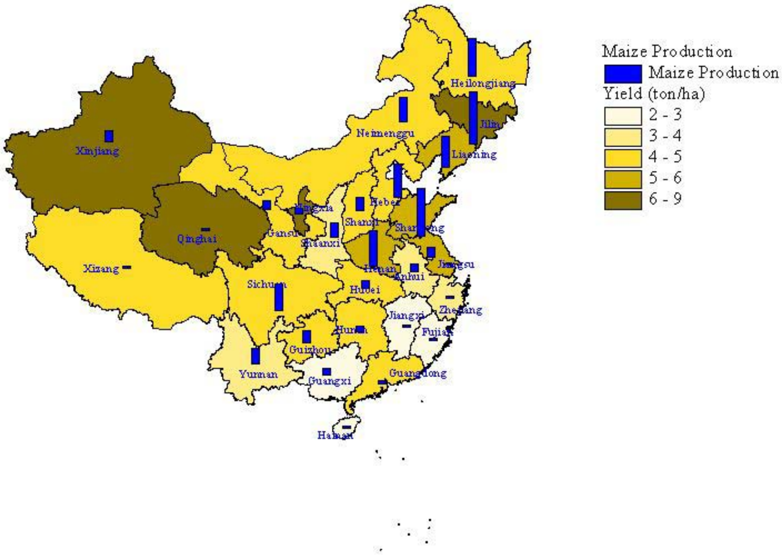

Figure 12. Maize Annual Production and Yield in 1999

5.4. Virtual Water Trade in China

The virtual water trade is calculated on the basis of the following assumption:
(1). crop water requirement for the same crop has the same value in different years;
(2). the virtual water partitioning for wheat and maize in any year is the same as that in 1999;
(3). the VWV for soybean is 3 times as high as that for wheat in the same year. The virtual water partitioning for soybean is the same as that for wheat.
(4). the VWV for rice is the same as that for wheat in the same year. The virtual water partitioning for rice is the same as that for wheat.
(5). the average VWV for other grains except wheat, maize, rice, soybean is 1.5 times as high as that for wheat in the same year. The virtual water partitioning for other grains is the same as that for wheat.

The grain-related virtual water trade in China is presented in Fig. 13 . The annual virtual water import was 52 Gm^3/yr (30 Gm^3/yr for green water and 22 Gm^3/yr for blue water) in average during the period of 1992 - 2001, while the annual virtual water export was 11 Gm^3/yr (7 Gm^3/yr for green water and 4 Gm^3/yr for blue water). So averagely, there was a net annual virtual water import flow of 41 Gm^3/yr (23 Gm^3/yr for green water and 18 Gm^3/yr for blue water) coming into China, which accounts for 1.9 percent of China's total net potential renewable blue water available shown in Table 1. For the net virtual blue water import (18 Gm^3/yr), taking the agriculture water efficiency of 45% in 1997 into account (Wang and Shen, 1997), the food trade saved 40 Gm^3 blue water annually, which accounted for more than 10 percent of the annual irrigation water demand. If the net virtual green water import is also taken into account, the food trade saved 91 Gm^3 of water annually, accounting for 23.6 percent of the annual irrigation water demand.

The annual virtual water import first dropped from 43 Gm^3/yr to 34 Gm^3/yr in 1993 and then climbed rapidly until it reached the peak of 55 Gm^3/yr in 1995. Afterward, the virtual water import decreased again to 40 Gm^3/yr in 1998. Then there was a dramatically increase and

reached a new peak 95 Gm^3/yr in 2001. The annual virtual water import increased by 27.5% from 1998 to 2001.
The virtual water export fluctuated quite often during the period of 1992-2001. In 1995 and 1996, there was barely any virtual water export due to the previous drought in the maize major production sites Afterward, the annual virtual water export began to increase and reached a peak 16.6 Gm^3/yr of in 2000. There was a decline again in 2000, with an annual virtual water export of 11.3 Gm^3/yr in this year.

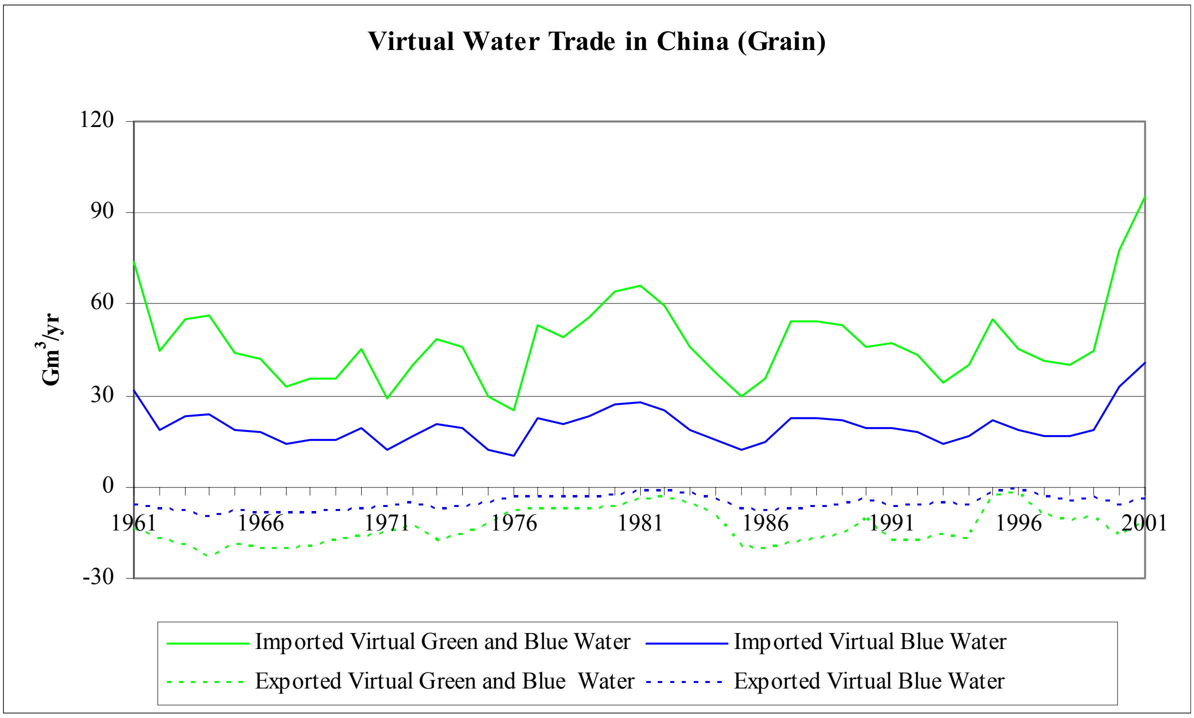

Figure 13. Virtual Water Trade in China. 1961 through 2001.

Conclusion

Virtual water has recently been considered as an effective strategy for efficient water resources management, especially for the countries where water is scarce. Virtual water strategy not only benefits water shortage in the food importing countries regionally, but also benefits the water use efficiency globally. The virtual water exists not only in the process of international food trade, but also in the process of daily food consumption. The changing food preference, therefore, may lead to the higher water uses for agriculture at least in the first quarter of 21st century.
Water for food production comes from two sources: green water directly from the rainfall and blue water from supplemental irrigation. There has been much research about the blue water uses both globally and regionally, however, the research about the green water is quite scarce although the green water by far contributes to about 60 % of the world staple food production. China has become a focal country in world food security due to the huge population, the limited resources and the expending economy. The grain production has been affected greatly by the agricultural policy in China. The sum of the production of rice maize and wheat has occupies 80 percent of the total grain production since 1961 and nearly 85 percent of the total since 1978. Although China's policy emphasis on grain self-efficiency, China still imported as much as 17 percent of the World's traded wheat, 28 percent of its soybean oil, while exporting as much as 10 percent of the World's traded maize. China's grain imports are influenced by the domestic wheat production while the total grain exports are greatly influenced by the maize exports.

It is concluded that nearly all the fruits and vegetables are fallen in the category of low water intensive crop as defined in this paper, while most of the grains belong to the median water intensive crops. Many cash crops including cotton and tobacco are high water intensive crops. Given the water scarcity and the huge population, especially the huge rural population into account, China has a comparative advantage in labour intensive agricultural products instead of water intensive ones. China policy should encourage the fruit and vegetable export, stable the grain export and promote the cash crop import. In terms of unit water value, it can be concluded that fruits and vegetables have a higher unit water value while the grains and most of the cash crops have a lower one except cotton and bean green. Farmers may change the crop pattern from low water value grains and part cash crops to higher water value fruits and vegetables to increase their annual incomes. This change may lead to the less grain production, which may result in more food problems both for China and for the whole world. China decision makers should be very careful when making agricultural policies.

Rice, wheat and maize are the three most important grains in China and deserve more detailed research. The following conclusions are drawn based on the annual yields and climatic data from 27 regions (22 provinces and 5 autonomous regions) in China: (1) For wheat, averagely, the virtual water value is 1580 m^3/ton in China in 1999 with higher value in the south and lower value in the north due to the different yield in various regions; averagely, green water accounts for 56.7 percent of the total wheat production. It contributes more in the southern and northeastern parts of China and less in other regions because of the uneven distribution of rainfall. (2) For the grain of maize, averagely, the virtual water value is 906 m^3/ton in 1999 in China. The virtual water value for maize does not coincide with the yield so much as for wheat. Averagely, green water accounts for 71.5 percent of the total maize production. It contributes greatly to the maize production in most regions of China except in some northern part of the Interior Basins.

During the period of 1992 to 2001, China has an annual virtual water import of 52 Gm^3/yr (30 Gm^3/yr for green water and 22 Gm^3/yr for blue water) and an annual virtual water export of 11 Gm^3/yr (7 Gm^3/yr for green water and 4 Gm^3/yr for blue water). There was a net annual virtual water import flow of 41 Gm^3/yr coming into China on average. Taking the water efficiency of 40 percent into account, this accounts for 23.6 percent of the annual irrigation water demand in China.

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