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ARTICLE

Estimating water footprint of paddy rice in Korea

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Abstract The purpose of this article is to examine the issues of low grain self-sufficiency and the high portion of agricultural water use in South Korea, and to trace the water footprint (WF) of rice products. In this study, different types of water use were described as green, blue, and gray WFs and were analysed using suitable estimation methods to determine irrigation water requirements in South Korea. Virtual water (VW) import and export of rice product were calculated based on international trade statistics during 2004–2009, and the WF of the national consumption was estimated. The WF of rice was 844.5 m^3/ton, and green, blue, and gray water accounted for 294.5, 501.6, and 48.4 m^3/ton, respectively. The VW import and export were 404.17 and 2.03 Mm^3/year, respectively, against an import 199.5 times that of the export. Three countries (China, USA, and Thailand) accounted for over 95 % of the total VW imports of rice products into South Korea. The total WF was 5,712.08 Mm^3/year, thus the WF per capita for rice was estimated at 118.1 m^3/year. The internal WF of rice consumption was 5,308.05 Mm^3/year, and the external WF was 404.03 Mm^3/year. The WF of total agricultural water use should be analyzed for sustainable agricultural production and water management, and these results should be applied in establishing long-term policies for agricultural water resources.

Keywords Paddy rice · Virtual water · Water footprint · South Korea

Introduction

South Korea (hereinafter called Korea) is one of the largest agricultural product import countries. The average self-sufficiency ratio for grain was 28.5 % during 2004–2009, and those for wheat, maize, and soybean were only 0.3 %, 0.9 %, and 10.0 %, respectively. The self-sufficiency ratios for these crops are very low compared to those of rice and starchy roots crops, with rates of 95.6 and 98.0 %, respectively (Ministry for Food, Agriculture, Forestry and Fisheries 2011). Rice is one of the major crops feeding the world population and is the most important in South Asia and Africa (Chapagain and Hoekstra 2010). Large irrigation projects are often constructed to meet the water demands of rice production. As a result, rice production is one of the largest water consumers in the world. In Korea, agricultural water resources have been heavily developed starting in the early 1970s to achieve stable and sustainable rice production. Paddy rice water demand was 34.5 % (12.90 Gm^3/year) of the total fresh water resources (37.35 Gm^3/year) in 2011 by the Comprehensive Water Resources Plan (Water Vision 2020) report (Ministry of Construction and Transportation 2006). Most agricultural water use is concentrated on the production of rice.

Various studies have developed the water footprint (WF) concept, which is an empirical indicator of how much water is consumed and when and where over an entire country. The WF defines the total volume of direct

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and indirect water used to produce a good or service by a consumer or producer, measured at the point of production and based on the virtual water (VW) concept. WF is a multidimensional indicator including consumption volumes by source and polluted volumes by pollution type (Hoekstra et al. 2011). The WF has three components: the green WF is evapotranspiration (ET) of water supplied by rain; the blue WF is ET of irrigation water (IR) supplied from reservoirs, rivers, and groundwater; and the gray WF is the volume of water polluted in the production process (Hoekstra et al. 2011).

Manuals and methods to calculate WF have been developed (Hoekstra and Chapagain 2008; Hoekstra et al. 2009, 2011). It is possible to approach water issues by distinguishing between green, blue, and gray water. For formulating water policies aimed at reducing WF impact, it is useful to know which WF components are linked to various impacts. Many studies of green, blue, and gray WFs have been executed during the last 3 years. Aldaya et al. (2010) estimated the strategic importance of green water in relation to the international commodity trade. Besides having a lower opportunity cost, the use of green water for the production of crops has generally less-negative environmental externalities than the use of blue water. Mekonnen and Hoekstra (2010) estimated the green, blue, and gray WFs of wheat in a spatially explicit way, both from a production and consumption perspective. Chapagain and Hoekstra (2010) assessed the green, blue, and gray WFs of rice using growing condition data on the actual irrigation of major producers such as Japan and Korea. The national WF of rice production and consumption was estimated using international trade and domestic production data. In addition, there have been various WF studies relating to the international crop products trade at the global scale. Mekonnen and Hoekstra (2011b) quantified the green, blue, and gray WFs of global crop production in a spatially explicit way by taking a high-resolution approach, estimating the WF of 126 crops on a 5 by 5 arc minute grid for the period of 1996–2005. Mekonnen and Hoekstra (2011a) estimated and mapped the WFs of nations from both a production and a consumption perspective and estimated international VW flow (VWF) related to trade in agricultural products such as cereals, meats, and industrial products during the period of 1996–2005. In Korea, WF studies have focused on VW content (VWC) and the VWF of crop products. Yoo et al. (2009) estimated the VWC of 44 primary crops in Korea from 2003 to 2007. They showed that an average of 13.7 Gm^3/year of VW was used for the production of 44 primary crops. Of this total, 11.1 Gm^3/year VW was used for grain crops and 10.1 Gm^3/year (91 %) was dedicated to rice production. Yoo et al. (2012) analyzed the VWC and international VWF of major crop products. The amount of imported VW was 16,804 Mm^3/year, and the amount exported was 226 Mm^3/year and the net imported VW was 16,578 Mm^3/year. Korea imported 449.2 Mm^3/year of rice VW, and 199.0 Mm^3/year rice VW was imported from China and Thailand, accounting for 80.5 % of the total rice VW imports. Although various studies analyzing the VW and WF of rice have been carried out, few attempts have been made to estimate the green, blue, and gray water of rice applied to the rice cultivation method in Korea.

When considering the low food self-sufficiency and high portion of water use in agriculture, estimation of the WF of rice is required to analyze the national WF in Korea. Tracing the WF of rice products, including international trade, is very important to designing up a national water resources policy, because rice consumes a large portion of the water in Korea. All the components of a total WF need to be specified both geographically and temporally. The crop water requirement of agricultural products can vary with the growth and climate conditions in each country. There can be large differences in effective rainfall (EFR) and IR requirements of paddy rice depending on transplanting, flooding cultivation, ponding water depth (PD), and other factors. From the perspective of food security, as well as from the viewpoint of sustainable consumption, WF should be calculated using the farming methods of the crop production area.

The aim of this study is to estimate the green, blue, and gray WF of rice product using a method of estimation of IR requirement suggested by the design criteria of the agricultural water system in Korea and VWFs of rice products based on international trade statistics from KATI (Korea Agricultural Trade Information) during 2004–2009. Green and blue water are calculated using the water balance model in paddy field. Gray water is estimated by referencing the several studies for T-N (total nitrogen) and T-P (total phosphorus) runoff in paddy fields.

Methods and data

Water footprint of crop growth

The total WF of growing crops or trees (WF$_{\mathrm{proc}}$) is the sum of the green, blue, and gray components:

$$\mathrm{WF_{proc}} = \mathrm{WF_{proc,blue}} + \mathrm{WF_{proc,green}} + \mathrm{WF_{proc,gray}}\ (\mathrm{unit: volume/mass}). \tag{1}$$

The distinction between blue and green WFs is important because direct and indirect impacts (e.g., hydrologic, environmental, and social impacts) and the economic costs of irrigation water used for production differ from the impacts and costs of rainwater. The gray WF is defined as the volume of water required to dilute the pollutant loads based on standards of water quality (Hoekstra et al. 2011).

The calculation framework to quantify the WF of rice is based on Hoekstra and Chapagain (2008) and Hoekstra et al. (2009, 2011). In an earlier study, Chapagain and Hoekstra (2004) and Yoo et al. (2009) assumed a constant percolation loss of 300 mm in rice fields and added the VWC of rice. Both the VWC and the WF are indicators of the water volume required to produce one ton of crop; however, there are slight differences in the calculation of each of them. Gray water is contained in WF, but not contained within VWC. In addition, the VWC considers both ET and percolation without distinguishing between green and blue water. In case of WF, the percolation, transplanting water demand, and residual soil moisture are not included in the blue and green water estimations because they are regarded as stored in the soil or returned to the watershed. That is, the WF refers to a real loss, whereas percolation is not actually a loss in a watershed (Chapagain and Hoekstra 2010). The VWC and WF of the Korean paddy rice have been suggested in various studies. For VWC, Hoekstra and Hung (2002) determined the VWC to be 1,639 m^3/ton; Chapagain and Hoekstra (2004) to be 1,301 m^3/ton; and Yoo et al. (2009) to be 1,600.1 m^3/ton. Chapagain and Hoekstra (2010) determined the WF to be 828 m^3/ton (green 356 m^3/ton, blue 388 m^3/ton, and gray 84 m^3/ton).

Blue and green WFs of paddy rice

Blue and green WFs were calculated using the net IR requirement (NIWR) and the EFR calculation method, both of which are suggested design criteria in Korea (Yoo et al. 2008). The NIWR is defined as the depth of water required to meet the water loss through crop ET (ET_c) of disease-free crops growing in large fields and to achieve full production potential under a given growing environment. The NIWR for paddy rice was formulated as described by Eq. (2) using a water balance concept (Jensen et al. 1990),

$$\mathrm{NIWR} = \mathrm{ET_c} + \mathrm{DP} + \mathrm{LR} + \mathrm{MR} - \mathrm{EFR}, \tag{2}$$

where ET_c is the crop evapotranspiration (mm); DP is the deep percolation (mm); LR is the leaching requirement (mm); MR is the miscellaneous water requirements (mm) for germination, frost and wind erosion protection, blossom delay, and plant cooling (Jensen et al. 1990); and EFR is the effective rainfall (mm) as defined below.

In general, the LRs and MRs in ponding rice fields are negligible. Therefore, Eq. (3) is a simpler and more commonly used equation for computing the NIWR in a paddy field.

$$\mathrm{NIWR} = \mathrm{ET_c} + \mathrm{DP} - \mathrm{EFR}. \tag{3}$$

Paddy fields are kept saturated using transplanting water demand and maintained ponding water during the crop-growing period. The transplanting water demand was assumed to be 140 mm as suggested by Ministry of Agriculture and Forestry (1998) in Korea. As mentioned above, although blue and green water exclude DP and transplanting water demand, the consumptive use of water, including DP, is required to calculate the EFR. In this study, blue water is defined as the NIWR excluding DP, transplanting water demand and moisture residue in soil.

The estimation of consumptive use water is determined by the crop coefficient (K_c)–reference crop evapotranspiration (ET_o) procedure. The ET_o is computed for a hypothetical reference crop according to the FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998) and is then multiplied by an empirical K_c to produce an estimate of ET_c, as in Eq. (4),

$$\mathrm{ET_c} = K_c \times \mathrm{ET_o}. \tag{4}$$

Accordingly, the ET_o is calculated using the FAO Penman–Monteith equation. The K_cs used in this study were the ones suggested by Yoo et al. (2008). In this study, the transplanting and irrigation periods were defined as from May 21 to May 31 and from June 1 to September 10, respectively, in the central region and from June 1 to June 10 and from June 11 to September 20, respectively, in the southern region.

DP is primarily a function of soil texture. It varies from 2 mm/day (heavy clay) to 6 mm/day for sandy soil on average for the entire period of rice cultivation. In Korea, most paddy rice irrigation systems have been developed under soil conditions that are clay textured and have relatively low percolation rates (Jang et al. 2007). Previous studies have shown that about 4–6 mm/day of water percolates into paddy soils during irrigation seasons (Lee 1988). DP in paddy fields was assumed to be 4.0 mm/day for the entire period of rice cultivation except for land drying days, when the field is left to dry out for easy cultivation and harvesting.

The EFR is the amount of water available for crop growth from rainfall (RF) after surface runoff (SR) loss. The EFR during irrigation seasons depends on the RF amount, RF intensity, topography, soil infiltration rate, soil moisture, water management practices, and other factors. It is difficult to estimate EFR because of percolation rate changes with time and soil conditions and the spatial and temporal variability of rain (Malano et al. 2004). The EFR in paddy fields is calculated using a freeboard model (International Rice Research Institute 1977) to simulate the value of PD. The freeboard model is formulated as in Eq. (5):

$$\mathrm{PD}_t = \mathrm{PD}_{t-1} + \mathrm{IR}_t + \mathrm{RF}_t - \mathrm{ET}_{ct} - \mathrm{DP}_t - \mathrm{SR}_t, \tag{5}$$

where t is the time (day), PD is ponding water depth (mm), SR is surface runoff in the paddy field outlet (mm), IR is irrigated water (mm), and RF is rainfall (mm). RF below 5 mm/day is considered ineffective RF (Dastane 1978; Chung et al. 2007).

Therefore, EFR is expressed as in Eq. (6):

$$\begin{aligned} \mathrm{EFR}_t &= \mathrm{RF}_t && \text{for } \mathrm{SR}_t = 0, \\ \mathrm{EFR}_t &= \mathrm{RF}_t - \mathrm{SR}_t && \text{for } \mathrm{SR}_t > 0. \end{aligned} \tag{6}$$

Assumptions required for the freeboard model include a paddy field outlet height of 80 mm and that irrigation is supplied for controlled PD for each growth stage, as suggested by Yoo et al. (2008).

Gray WF

The gray component of the WF for growing a crop or tree ($\mathrm{WF}_{\mathrm{proc,gray}}$, m^3/ton) is calculated as the chemical application rate to the field per hectare (AR, kg/ha) times the leaching-runoff fraction (α) divided by the maximum acceptable concentration ($c_{\max}$, kg/m^3) minus the natural concentration of the pollutant considered (c_{nat}, kg/m^3) divided by the crop yield (Y, ton/ha) (Hoekstra 2011).

$$\mathrm{WF}_{\mathrm{proc,gray}} = \frac{(\alpha \times \mathrm{AR})/(c_{\max} - c_{\mathrm{nat}})}{Y}. \tag{7}$$

The volume of polluted water depends both on the pollutant load and the adopted permissible limit. Owing to data limitations, this study selected T-N and T-P as representative elements for estimation of the gray WF. To avoid double counting, the gray WF takes the maximum of any of these requirements for individual-pollutant categories. The gray WF is estimated by referencing several studies for T-N and T-P runoff in paddy fields in Korea. From the results of these studies, the T-N and T-P runoff averages during the growing season were 12.90 and 1.01 kg/ha, respectively. The results of the studies are as follows:

- T-N 12.40 kg/ha, T-P 2.17 kg/ha (Hong and Kwun 1989),
- T-N 12.10 kg/ha, T-P 0.42 kg/ha (Kim et al. 1999),
- T-N 16.00 kg/ha, T-P 0.27 kg/ha (Oh et al. 2002),
- T-N 11.27 kg/ha, T-P 0.98 kg/ha (Seo et al. 2002),
- T-N 12.73 kg/ha, T-P 1.21 kg/ha (Yoon et al. 2003),
- Average T-N 12.90 kg/ha, T-P 1.01 kg/ha.

The permissible limit of T-N and T-P of waste water bodies in Korea, as set by the Ministry of Environment, is 40 mg and 4 ppm, respectively. We used those values to estimate the volume of water necessary to dilute leached T-N and T-P to the permissible limit. Table 1 shows a comparison of the rice WF estimation methods of Chapagain and Hoekstra (2010) and this study.

WF of a product

The WF of a primary crop is used to determine that of a processed products based on product and value fractions (Chapagain and Hoekstra 2004; Hoekstra et al. 2009). The product fraction is defined as the weight of processed product obtained from a ton of root product. If more than two processed products are obtained from processing a root product, it is necessary to share the WF of the root product over its processed products based on product and value fractions. The value fraction of a processed product is the ratio between the market value of the processed product and the total market value of all the processed products obtained from the root product (Chapagain and Hoekstra 2010). Therefore, the WF of the processed product is expressed as Eq. (8):

$$\mathrm{WF}_{\mathrm{prod}}[p] = \left(\frac{\mathrm{WF}_{\mathrm{prod}}[i]}{f_{\mathrm{p}}[p, i]}\right) \times f_{\mathrm{v}}[p], \tag{8}$$

where $\mathrm{WF}_{\mathrm{prod}}$ is the water footprint of a product; f_{p} is product fraction; f_{v} is the value fraction; p is the processed product; and i is input product or root product.

VWFs by product trade

The VWF between two countries is the volume of water that is transferred in virtual form from one place to another through product trade. The VWFs between countries due to trade in rice products are calculated by multiplying a product trade (ton/year) by its WF (m^3/ton) in the exporting country (Hoekstra and Chapagain 2008). The VW export and import of a country are the VWs used to make exported and imported goods or services.

International VWFs can be calculated by multiplying the product trade flows by their associated WF (Hoekstra and Chapagain 2008):

$$\mathrm{VWF}[n_{\mathrm{e}}, n_{\mathrm{i}}, p] = T[n_{\mathrm{e}}, n_{\mathrm{i}}, p] \times \mathrm{WF}[n_{\mathrm{e}}, p], \tag{9}$$

where VWF denotes the virtual water flow (m^3/year) from the exporting country n_{e} to the importing country n_{i} as a result of trade in product p; T is the product trade (ton/year) from the exporting to the importing country; and WF is the water footprint (m^3/ton) of the product, defined as the volume of water used to produce the product in the exporting country. In this study, statistical data on international trade of rice products were taken from KATI during the period of 2004–2009. The WFs of rice products calculated by Chapagain and Hoekstra (2010) were used for the other countries.

WF of national consumption

The WF of national consumption can be classified into an internal and an external component. The internal WF is the domestic water used for producing goods and services consumed by the population in a country. The external WF is the volume of water required to produce goods and services imported from other counties and consumed in the country (Hoekstra et al. 2011). The VW export is exported

Table 1 Comparison of WF estimation method

Items	Chapagain and Hoekstra (2010)	This study
Meteorological station	3 Locations	69 Locations
Period	2000–2004	2004–2009
Cultivation type	Wetland system	Wetland system with optimal water ponding depth
Growing period (days)	120	120
Land drying period (days)	15	30
Crop water requirement	CROPWAT4	Daily water balance model
ET	FAO Penman–Monteith	FAO Penman–Monteith
EFR	USDA SCS method	Freeboard model
Percolation (mm/day)	2.5	4.0
Transplanting water (mm)	100	140
Time step (days)	5	1
Permissible limit of waste water	NO_3-N (10 mg/l)	T-N: 40 mg/l T-P: 4 mg/l
Pollutant load	5 % of the NO_3-N application rate	T-N: 12.90 kg/ha T-P: 1.01 kg/ha

and re-exported water of domestic or foreign origin. The VW import is water consumed through the external WF of the country and re-exported VW. The sum of the WF within a nation and the VW import is equal to the sum of the VW export and the WF of national consumption. The internal and external WFs are assessed following the scheme shown in Fig. 1. The internal WF of rice consumption consists of the domestic water resources consumed and polluted to produce rice. The external WF refers to the water used in the country through imported rice products (Chapagain and Hoekstra 2010).

Statistical and climate data collection

Statistics for rice production, harvested area, and yield

This study collected climate data from 68 meteorological stations and statistics including rice production, harvested area, and yield in each of the 16 regions to calculate the WF of paddy rice for the period from 2004 to 2009. Table 2 presents statistics on average from the period of 2004–2009. The total rice production, harvested area, and yield for the 6 years were 6,401,604 ton/year, 921,637 ha, and 6.95 ton/ha, respectively. Production and harvested area were relatively large in Jeonnam, and yield was relatively large in Chungnam.

International trade statistics of rice products

In this study, trade statistics of 23 rice products from 2004 to 2009 were collected from KATI. According to the KATI statistics, Korea imports 21 rice products and exports 20 rice products. Among those, the net imports and exports of seven products total more than 1,000 ton/year. Table 3 shows the average imports, exports, and net imports of the top seven imports from 2004 to 2009. Korea imported 259,311.8 ton/year and exported 1,278.0 ton/year of major rice products for a net import of 258,038.8 ton/year. Imports were about 203 times greater than exports. The top seven largest imports were "husked rice/brown rice" (210,677.8 ton/year); "total milled/white rice" (27,956.2 ton/year); "rice, broken" (1,342.7 ton/year); "bran oil" (5,686.9 ton/year); "rice in grain form, pre-cooked" (7,817.2 ton/year); "Bakers' wares n.e.s." (3,463.1 ton/year); and "cereal bran" (2,367.9 ton/year), all of these

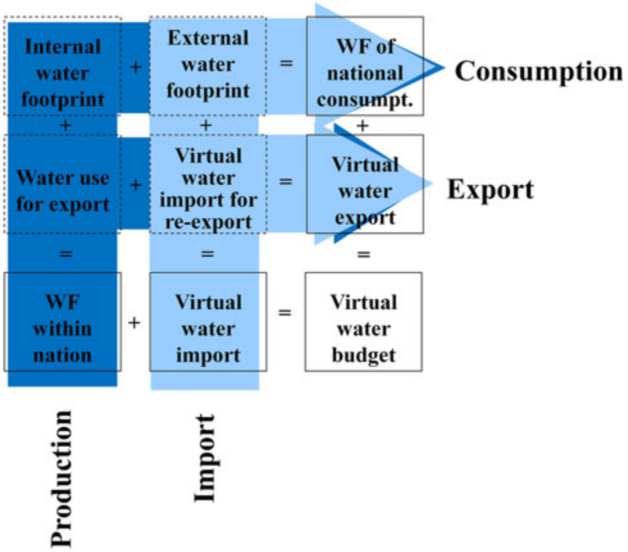

Fig. 1 Calculation scheme for assessing the WF of national consumption (Hoekstra et al. 2011)

Table 2 Average rice production, harvested area, and yield statistics for the period of 2004–2009

Regions	Production (ton/year)	Total share (%)	Harvested area (ha/year)	Yield (ton/ha)
Gangwon	270,296.5	4.2	42,232.5	6.40
Gyeonggi	674,276.0	10.5	103,777.5	6.50
Gyeongnam	598,626.5	9.4	91,375.8	6.65
Gyeongbuk	857,747.3	13.4	126,041.2	6.81
Jeonnam	1,220,550.5	19.1	194,792.7	6.27
Jeonbuk	1,006,569.3	15.7	142,745.8	7.05
Chungnam	1,173,069.5	18.3	164,089.7	7.15
Chungbuk	337,840.8	5.3	51,417.5	6.58
Others[a]	262,628.7	4.1	41,292.7	6.13
Total	6,401,602.2	100.0	957,765.4	–

[a] Seoul, six metropolitan cities, and Jeju

accounting for nearly 99.9 % of the total imports in rice products.

Results and discussion

WF of rice growth

The green and blue WFs were estimated using the NIWR and EFR results and the pollutant load runoff in paddy fields during 2004–2009. The calculated average water depth used in rice production in each of the rice producing regions is presented in Table 4, which shows the water percolated or remaining as residual soil moisture after crop harvest. The average green and blue water in ET and gray water (pollution) were 195.1, 332.4 and 32.3 mm/year, respectively. Percolation and residual soil moisture were 152.5 mm/year (green water) and 256.4 mm/year (blue water), respectively. The total water depth used in rice production was 968.7 mm. ET, pollution and percolation, and residual soil moisture accounted for 54.5 %, 3.3 %, and 42.2 % of the total water use, respectively. The total water depth can vary with growing period and climate conditions including ET and RF in each region. In Jeonnam, the ET_c is relatively high, and the EFR is the lowest, making its irrigation volume one of the highest.

Table 5 shows the WF and percolation per unit of paddy rice produced (m^3/ton) in Korea calculated, based on the share of regional production to total production. These figures are obtained by dividing the average depth of water used in rice production (mm/year) by the paddy yield per hectare (ton/ha). The WF refers to real loss to a watershed, while percolation is not actually a loss in a watershed. The average WF of rice production was 844.5 m^3/ton, and green, blue, and gray water uses accounted for 294.4, 501.6, and 48.4 m^3/ton, respectively. The green and blue water of percolation and residual soil moisture were computed to be 231.2 and 387.0 m^3/ton, respectively. The total WF for rice production (the total water used for rice production, m^3/year) was estimated using the rice WF and production by regions during 2004–2009 (Table 5). The total WF of rice production in Korea was 5,382 Mm^3/year. The top-three largest regions (Jeonnam, Chungnam, and Jeonbuk) accounted for 52.1 % of the total.

The WFs of rice in major countries have been reported by Chapagain and Hoekstra (2010) (Table 6). The rice WF of Korea was determined to be 829.4 m^3/ton in earlier study and was determined to be 844.5 m^3/ton in this study. The difference between these studies is small. The WF component ratios of blue, green, and grays WFs were reported to be 43.0 %, 46.9 %, and 10.1 %, respectively, in former studies, and the ratios found in this study were

Table 3 Average international trade of rice products during the period of 2004–2009 in Korea (KATI 2011)

Products (PC-TAS Code)	Import (ton/year)	Export (ton/year)	Net import (ton/year)	Major countries
Husked rice/brown rice (100620)	210,677.8	29.1	210,653.7	USA, China, Thailand, Australia
Total milled/white rice (100630)	27,956.2	251.9	27,704.3	USA, China, Thailand
Rice, broken (100640)	1,342.7	0.1	1,342.7	Thailand
Bran oil (15190)	5,686.9	17.4	5,669.5	Spain, Italy, China, Thailand, France
Rice in grain form, pre-cooked (190490)	7,817.2	456.3	7,360.9	China
Bakers' wares n.e.s. (190590)	3,463.1	341.9	3,121.2	Vietnam, China, Philippines
Cereal bran (230240)	2,367.9	181.4	2,186.5	China
Total	259,311.8	1,278.0	258,038.8	

Table 4 Average water depth used in rice production during the period of 2004–2009

Regions	ET (mm/year)		Pollution (mm/year)	Percolation and residual soil moisture (mm/year)		Total (mm/year)
	Green	Blue	Gray	Green	Blue	
Gangwon	204.3	297.9	32.3	172.0	249.5	981.5
Gyeonggi	231.5	303.5	32.3	178.5	232.2	1,003.3
Gyeongnam	180.5	344.0	32.3	141.2	267.7	991.1
Gyeongbuk	180.1	342.9	32.3	143.6	270.4	994.7
Jeonnam	176.4	355.0	32.3	134.6	266.4	990.0
Jeonbuk	191.5	329.0	32.3	148.9	254.8	981.9
Chungnam	208.9	317.3	32.3	167.4	251.1	1,002.4
Chungbuk	205.9	326.7	32.3	159.8	245.2	995.3
Others[a]	199.1	363.9	32.3	141.1	252.9	1,014.7
Average[b]	195.1	332.4	32.3	152.5	256.4	968.7

[a] Seoul, six metropolitan cities, and Jeju

[b] Average based on weighted production (ton/year)

34.9 %, 59.4 %, and 5.7 %, respectively. The difference between the ratios of the two studies has existed to some extent which seems to be caused by difference in EFR calculation among various component calculation methods. The rice WF (844.5 m^3/ton) of Korea was found to be 605.5 m^3/ton less than that of the world average (1,450 m^3/ton) and also to be smaller than those of major rice-producing countries, with the exception of Japan. The differences in WFs between countries are due to differences in crop yield, growing period, RF, ET, and fertilizer consumption. In Japan, where WF is the lowest, the average yield is relatively high and crop water requirements are very low. The green and gray water were relatively smaller in Korea than in other countries, and blue water was higher than in other countries, including Japan and China.

WF of rice products

Paddy rice is the primary form of rice which consists of the kernel (also called brown rice or husked rice) and the hull. Brown rice is processed to produce white rice (also called total milled) and part of rice bran and germ. White rice is further processed to produce broken rice and rice flour, rice bran and germ are processed to produce bran oil and cereal bran (Chapagain and Hoekstra 2010). To calculate the WF of rice products from paddy rice, a tree diagram of various products at various levels of production in terms of their product and value fractions is used. The WFs of these rice products are estimated based on the fractions. Table 7 shows the WF of rice products of Korea. The WFs of hull and brown rice which are primary-level products, were 218.4 and 1,001.0 m^3/ton, respectively. The WFs of white rice and bran, which are secondary-level products, were found to be 1,055.3 and 250.2 m^3/ton, respectively.

VWF of international trade of rice products

The average international VWFs were estimated using import and export data and the WFs of rice product during the period of 2004–2009 in Korea. Table 8 shows the results of VWFs through the crop products trade. The VW import was 404.17 Mm^3/year and export was

Table 5 WF and percolation per unit (m^3/ton) and total WF (m^3/year) of paddy rice produced during the period of 2004–2009

Regions	WF (m^3/ton)				Percolation and residual soil moisture (m^3/ton)			Total WF of rice production (Mm^3/year)
	Green	Blue	Gray	Total	Green	Blue	Total	
Gangwon	319.5	465.1	50.4	835.0	269.7	390.6	660.3	225.7 (4.2 %)
Gyeonggi	356.0	467.0	49.7	872.7	275.2	358.1	633.3	588.4 (10.9 %)
Gyeongnam	276.2	524.7	49.3	850.2	216.4	409.1	625.5	509.0 (9.5 %)
Gyeongbuk	264.9	503.9	47.5	816.3	211.5	397.9	609.4	700.2 (13.0 %)
Jeonnam	281.9	566.2	51.5	899.6	215.6	425.8	641.4	1,098.0 (20.4 %)
Jeonbuk	272.9	465.9	45.8	784.6	212.6	361.4	574.0	789.8 (14.7 %)
Chungnam	292.8	443.0	45.2	781.0	235.2	351.3	586.5	916.2 (17.0 %)
Chungbuk	314.0	495.9	49.1	859.0	244.5	373.3	617.8	290.2 (5.4 %)
Others[a]	332.9	621.6	54.3	1,008.8	234.3	427.3	661.6	264.9 (4.9 %)
Average[b]/total	294.5	501.6	48.4	844.5	231.2	387.0	618.2	5,382.3 (100 %)

[a] Seoul, six metropolitan cities, and Jeju

[b] Average based on weighted production (ton/year)

Table 6 Comparison of rice WF between major rice-producing countries

Countries	WF (m^3/ton) of paddy rice			
	Green	Blue	Gray	Total
Korea, Republic[a]	294.5	501.6	48.4	844.5
Korea, Republic[b]	356.3	388.6	84.5	829.4
Thailand[b]	942	559	116	1,617
Japan[b]	341	401	61	802
China[b]	367	487	117	971
USA[b]	227	835	101	1,163
Global average[b]	618	720	112	1,450

[a] This study

[b] Chapagain and Hoekstra (2010)

2.03 Mm^3/year, for a VW import 199.5 times that of export. The net import of blue water during the study period was 204.33 Mm^3/year and the net import of green water was 158.86 Mm^3/year. The net import of total VW, including the pollution component, was 402.14 Mm^3/year. The share of blue water to the total VW net import related to the international trade of rice products was 50.8 %, and that of green water was 39.5 %. The largest net import VW of a rice product was "husked rice/brown rice," with 298.31 Mm^3/year (37.8 % green water, 52.3 % blue water, 9.9 % gray water) for an import of 298.34 Mm^3/year and an export of 0.02 Mm^3/year.

The net import of total VW related to the international trade of rice according to the study of Yoo et al. (2012), in which the green and blue components were not separated, was 449.17 Mm^3/year based on the trade statistics of two rice products ("husked rice/brown rice" and "total milled/white rice") for the period of 2003–2007. This is comparable with the estimate found in this study, with the difference being 47 Mm^3/year. This is because earlier studies used VWC concepts that included percolation but not gray water.

Figure 2 depicts the four countries which are responsible for the largest net VW imports to Korea through the trade of rice products: China, USA, Thailand, and Spain. Korea imports 383.21 Mm^3/year of its VW from these four countries, with the largest portion of the VW, 169.42 Mm^3/year and accounting for 42.1 % of the total imported VW, coming from China. The next largest VW exporter to Korea is Thailand (105.75 Mm^3/year, 26.3 %), and the third is the USA (98.06 Mm^3/year, 25.6 %). These four countries account for 95.3 % of total VW import for rice products, demonstrating that Korea depends heavily on these four countries for rice products in terms of VW import.

Details of the net VW imports of brown rice are shown in Fig. 3. For brown rice, a total of 298.31 Mm^3/year of VW is imported, with more than 50 Mm^3/year of VW imported from each of three different countries. Korea imports 139 Mm^3/year (46.6 %) from China, which is the largest VW import of brown rice into Korea. The second largest VW exporter to Korea is the USA (27.9 %), followed by Thailand (24.6 %). These three countries account for 99.1 % of the VW of brown rice imported into Korea. The amounts of WF imported from these three countries in terms of green, blue, and gray water were 111.6 Mm^3/year (14.5 % USA, 47.2 % China, and 38.3 % Thailand), 154.8 Mm^3/year (38.6 % USA, 45.0 % China, and 16.4 % Thailand), and 29.3 Mm^3/year (24.7 % USA, 57.3 % China, and 18.0 % Thailand), respectively. The estimated green water ratio was relatively higher in Thailand, and the blue water ratio was relatively higher in the USA compared with other countries.

The total amount of exported VW from Korea to other countries was 2.03 Mm^3/year (35 % green water, 59 % blue water, and 6 % gray water) as shown in Table 8. Figure 4 shows the major VW export countries of rice product, which account for approximately 57.4 % of the total VW export. China, USA, and Australia import more than 0.2 Mm^3/year. USA is the largest VW exporter country, at 0.48 Mm^3/year and 23.7 % of the total. The VW export of rice products in Korea is very low compared to the VW import.

Table 7 The product fractions (f_p), value fractions (f_v), and WF of rice products in Korea

Product (PC-TAS Code)	Root product	f_p	f_v	WF of rice product (m^3/ton)
Rice, paddy (100610)	–	–	–	844.5
Hull	100610	0.20	0.052	218.4
Husked rice/brown rice (100620)	100610	0.80	0.948	1,001.0
Total milled/white rice (100630)	100620	0.93	0.980	1,055.3
Rice, broken (100640)	100630	0.95	1.000	1,110.8
Rice flour (110230)				
Rice bran, groat, and meal (110314)	100620	0.07	0.020	280.2
Bran oil (15190)	110314	0.18	0.954	1,484.4
Cereal bran (230240)	110314	0.82	0.046	15.8

Table 8 Average export, import, and net import VW of rice products during the period of 2004–2009 in Korea

Products (PC-TAS Code)	Components	Import (Mm^3/year)	Export (Mm^3/year)	Net import (Mm^3/year)
Husked rice/brown rice (100620)	Green	112.87	0.01	112.86
	Blue	155.98	0.01	155.96
	Gray	29.49	0.001	29.490
Total milled/white rice (100630)	Green	12.77	0.32	12.45
	Blue	21.99	0.54	21.46
	Gray	4.11	0.05	4.05
Rice, broken (100640)	Green	2.74	0.01	2.72
	Blue	1.70	0.02	1.67
	Gray	0.35	0.002	0.343
Bran oil (15190)	Green	28.35	0.20	28.14
	Blue	22.90	0.34	22.58
	Gray	4.47	0.03	4.43
Rice in grain form, pre-cooked (190490)	Green	0.32	0.03	0.29
	Blue	0.42	0.06	0.36
	Gray	0.10	0.01	0.09
Bakers' wares n.e.s. (190590)	Green	2.24	0.13	2.11
	Blue	2.14	0.22	1.91
	Gray	0.49	0.02	0.46
Cereal bran (230240)	Green	0.28	0.0008	0.28
	Blue	0.39	0.0014	0.39
	Gray	0.09	0.0001	0.09
Total	Green	159.57	0.71	158.86
	Blue	205.52	1.20	204.33
	Gray	39.08	0.12	38.96

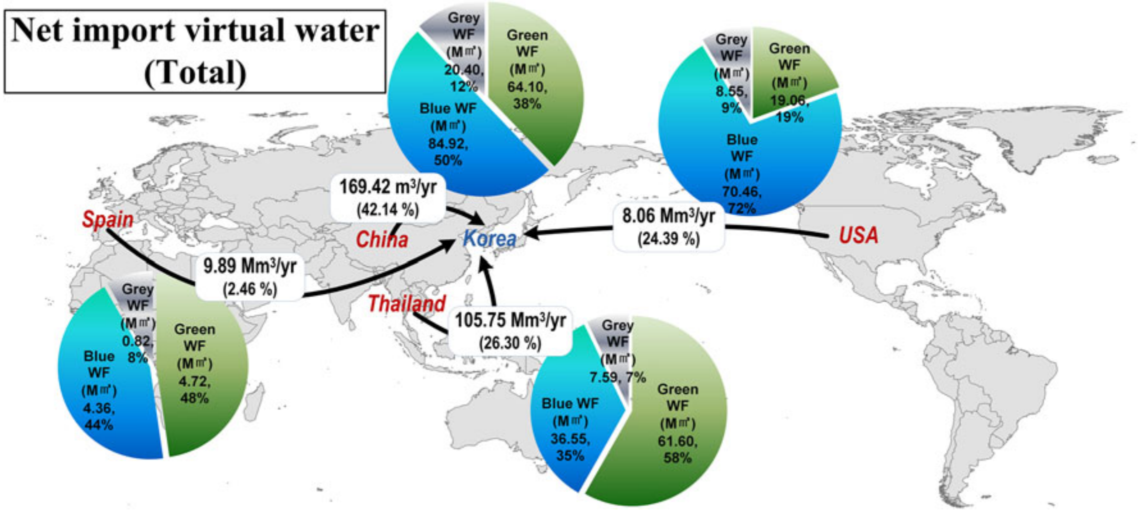

Fig. 2 The largest VW net imports of total rice products in Korea during 2004–2009

WF of rice consumption

Average rice production during the last 6 years in Korea was 6.40 Mton/year, and the corresponding water use for rice production was 5,382 Mm^3/year. The VW import through international trade was 404.17 Mm^3/year for rice products, whereas the VW export and support to North Korea was 98.24 Mm^3/year. The rice demand in Korea was a total of 4.83 Mton/year for white rice, with 80.4 % of this being consumed as staple food; 5.2 % as manufactured

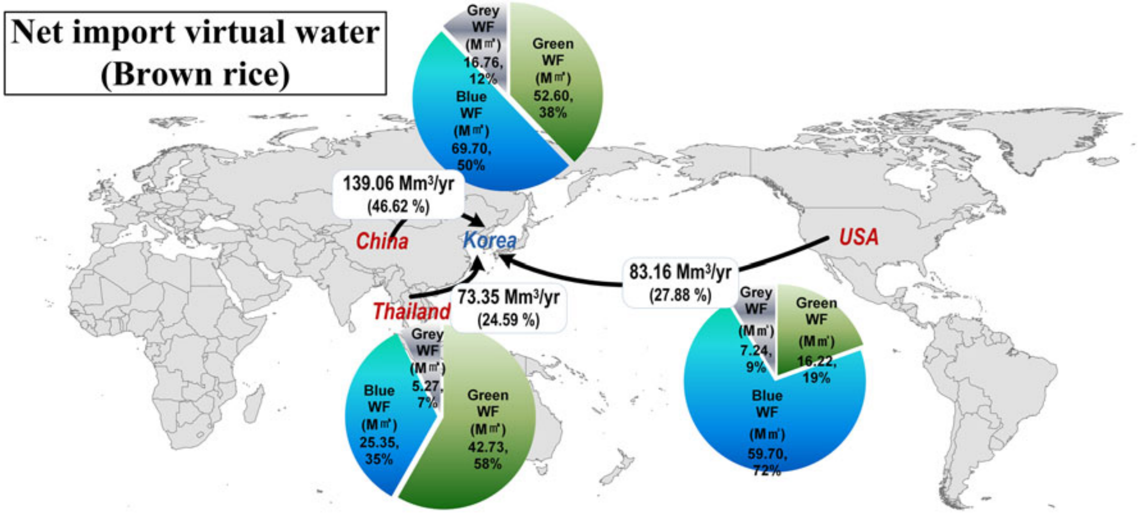

Fig. 3 The largest VW net imports of brown rice product in Korea during 2004–2009

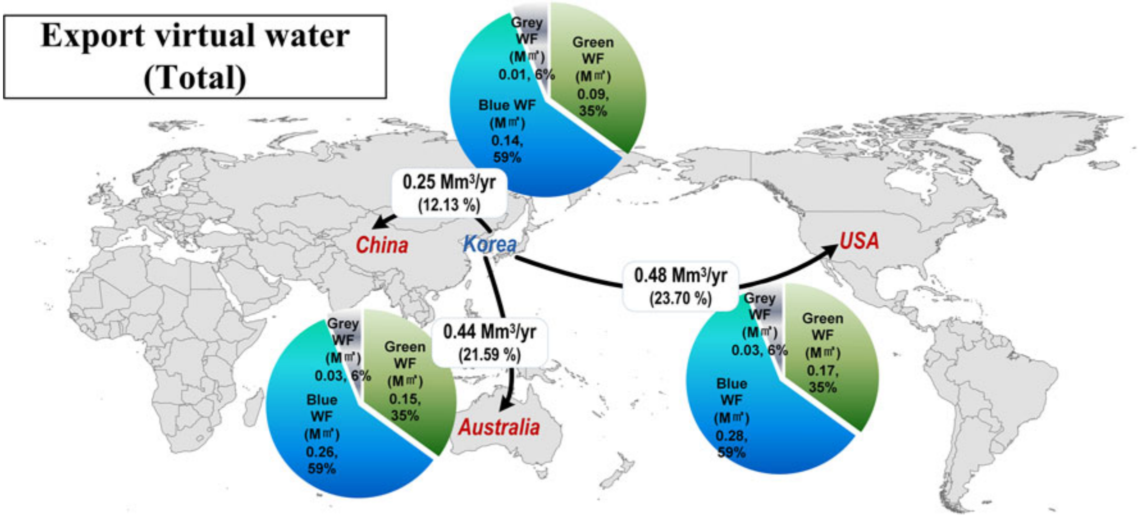

Fig. 4 The largest VW exports of total rice products in Korea during 2004–2009

foods such as crackers and cakes; 2.7 % as brewing; 0.9 % as seed; and 10.8 % as loss and other items. The WF of rice consumption in Korea based on the above rice usage is shown in Fig. 5. The internal WF was 5,308.05 Mm^3/year (92.9 % of the total WF), and the external WF was 404.03 Mm^3/year, and it was assumed that the internal WF value was 13.1 times the external WF. The total WF was 5,712.08 Mm^3/year, and thus the per capita WF of rice in Korea was estimated at 118.1 m^3/year (green 41.6 m^3/year, blue 69.4 m^3/year, and gray 7.1 m^3/year). The WF per capita reported by Chapagain and Hoekstra (2010) was 122 m^3/year. Though these total values are similar, the amounts of both green and gray water were smaller, and blue water was larger in this study. The largest ratio among the total WFs of rice consumption was that of staple food, at 4,594.4 Mm^3/year, or 95.1 m^3/year per capita WF.

Summary and conclusions

When considering the low grain self-sufficiency and the high portion of agricultural water use in Korea, including international trade in tracing, the WFs of rice products is important for designing the national water resources policies. From the perspective of food security, as well as from the viewpoint of sustainable consumption, WF should be calculated considering the farming methods of the crop production area. In this study, the green, blue, and gray

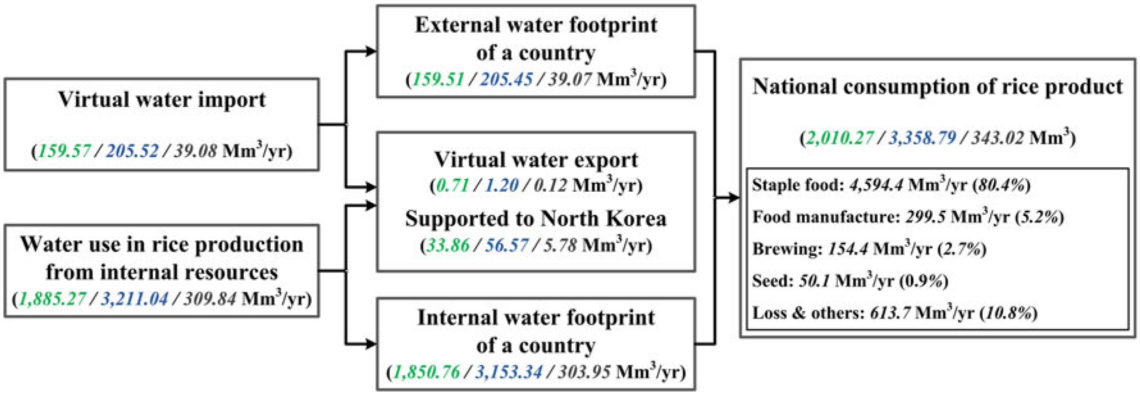

Fig. 5 WF of rice consumption in Korea during 2004–2009

WFs were estimated using paddy field water balance and freeboard model in Korea. VW amounts due to import and export of rice products were calculated based on international trade statistics from 2004 to 2009. The WF of the national consumption was also estimated.

The estimated WF of rice in Korea was 844.5 m^3/ton, and green, blue, and gray water accounted for 294.5, 501.6, and 48.4 m^3/ton, respectively. The total WF of rice in Korea was smaller than those of major rice producing countries, with the exception of Japan. International VWFs were estimated using import and export data and the WF of rice product in Korea. VW import was found to be 404.17 Mm^3/year and export was 2.03 Mm^3/year, for a VW import 199.6 times that of export. The net import of blue water during the study period was 204.33 Mm^3/year and the net imports of green and gray water were 158.86 and 404.14 Mm^3/year, respectively. China, USA, and Thailand accounted for over 95 % of the total VW imports of rice product into Korea, indicating a heavy dependence on import from these countries. The WF of rice consumption was estimated in Korea. The internal WF of rice consumption was 5,308.05 Mm^3/year (92.9 % of the total WF) and the external WF was 404.03 Mm^3/year. The internal WF value was 13.1 times the external WF. The total WF was 5,712.08 Mm^3/year, thus the WF per capita of rice in Korea was estimated to be 118.1 m^3/year (green 41.6 m^3/year, blue 69.4 m^3/year, and gray 7.1 m^3/year).

Although the area of rice cultivation is decreasing in Korea, the supply of rice has exceeded the demand. Reasons for this include that rice production per unit area has increased, rice consumption per capita has decreased because of the diversity of foods available, and the import of rice has increased because of the WTO, FTA, etc. Therefore, as part of the "Policy for Goal-establishing Food Self-sufficiency Rate in 2015 and 2020," the Korean government is planning to convert rice cultivation areas to other crops to raise the low self-sufficiency rate of other grains against rice in the long-term perspective. Stable crop production, appropriate agricultural water resources management, and supporting policies are essential to success in these agricultural policies. The results of this study are expected to be understood by the agricultural WF as well as by the total WF in Korea. Since the WF is composed of two factors, i.e., crop production and water resources, it can be utilized as a macroscopic indicator for the development of long-term agricultural water resources policies. The blue, green, and gray water calculations for paddy rice presented in this study are expected to provide basic data for the development of the technical and social aspects of agricultural water resources policies.

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