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Analysis

The blue, green and grey water footprint of rice from production and consumption perspectives

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ABSTRACT

The paper makes a global assessment of the green, blue and grey water footprint of rice, using a higher spatial resolution and local data on actual irrigation. The national water footprint of rice production and consumption is estimated using international trade and domestic production data. The global water footprint of rice production is 784 km^3/year with an average of 1325 m^3/t which is 48% green, 44% blue, and 8% grey. There is also 1025 m^3/t of percolation in rice production. The ratio of green to blue water varies greatly over time and space. In India, Indonesia, Vietnam, Thailand, Myanmar and the Philippines, the green water fraction is substantially larger than the blue one, whereas in the USA and Pakistan the blue water footprint is 4 times more than the green component. The virtual water flows related to international rice trade was 31 km^3/year. The consumption of rice products in the EU27 is responsible for the annual evaporation of 2279 Mm^3 of water and polluted return flows of 178 Mm^3 around the globe, mainly in India, Thailand, the USA and Pakistan. The water footprint of rice consumption creates relatively low stress on the water resources in India compared to that in the USA and Pakistan.

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1. Introduction

Rice is one of the major crops feeding the world population and is most important ingredient in food composition in South Asia and Africa. Large irrigation projects are often constructed to meet the water demand in rice production. As a result, rice is one of the largest water consumers in the world. This paper quantifies how much fresh water is being used to produce rice globally, distinguishing between two different sources: irrigation water withdrawn from ground- or surface water (blue water) and rainwater (green water). It also quantifies the volume of polluted water related to the use of nitrogen fertilisers in rice production (grey water).

Rainwater and irrigation water are necessary for rice growth in two ways: to maintain soil moisture and – in wet irrigation – to maintain the standing layer of water over the paddy field. In the major rice-producing regions of the world, the crop is grown during the wet (monsoon) season, which reduces the irrigation demand by effectively using rainwater.

As much of the standing water in paddy fields percolates and recharges groundwater and surface water, there is a substantial contribution to the local blue water availability. Percolation can be seen as a loss to the paddy field, but for the catchment area it is not considered as a loss, because the water can be captured and reused downstream (Bouman et al., 2007b). In some irrigation systems in flood plains with impeded drainage or systems in low lying deltas a continuous percolation can even create shallow ground water tables closer to the surface (Belder et al., 2004). Although the paper focuses on the estimation of evapotranspiration from rice fields, it also estimates percolation flows, because evapotranspiration and percolation are both part of the soil water balance.

2. Method and Data

There are mainly two systems of rice production: wetland systems and upland systems. About 85% of the rice harvest area in the world is derived from wetland systems (Bouman et al., 2007b). About 75% of rice production is obtained from irrigated wetland rice (Bouman et al., 2007b). In Asia, rice fields are prepared by tillage followed by puddling. The soil layer is saturated and there is standing water during the entire growth period of the crop. In the USA, Australia, parts of Europe and some Asian countries, rice land is prepared dry and flooded later.

During the period of 2000–2004, the average annual global production of rice was 592 million metric tons with an average yield of 4.49 t per hectare. In the production database of the FAOSTAT data (2006), 115 countries are reported as rice producers. Table 5 presents the list of top 33 largest rice producers accounting for more than 98% of the global rice production. During the period 2000–2004, the global rice production came mainly from China (30.0%), India (21.4%), Indonesia (8.8%), Bangladesh (6.3%), Vietnam (5.7%), Thailand (4.5%), Myanmar (3.8%), Philippines (2.3%), Brazil (1.9%), Japan (1.9%), USA (1.6%), Pakistan (1.2%), and Korea R (1.2%). These

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13 countries together account for more than 90% of the global rice production. They account for more than 82% of the total export of rice-equivalent globally. About 6–7% of the world rice production is traded internationally.

The paper is based on data retrieved from variety of sources. It is inevitable that any errors in these sources can influence the result of this analysis. We have cross checked these data sources with other independent sources and found them to be consistent enough for this analysis.

2.1. Crop Water Use

The reference crop evapotranspiration (ET_o) and monthly average rainfall data for the concerned climate stations are taken from the CLIMWAT database (FAO, 1993) for all countries, but from FAOCLIM (FAO, 2001) for the USA. The ET_o data in these databases are derived using the Penman–Monteith equation as described (Allen et al., 1998). Using the CROPWAT model (FAO, 1992), the crop evapotranspiration (ET_c) and the available effective rainfall are calculated for the given set of data on ET_o, monthly rainfall, K_c and the crop calendar. Rice crop coefficients are taken from (Allen et al., 1998). Monthly data on rainfall and ET_o are distributed within the month to obtain data per 5 days. CropWat for Windows does this in two steps; first the rainfall from month to month is smoothed into a continuous curve. The default curve is a polynomial curve. In some cases when a smooth curve is difficult to fit then a linear interpolation between monthly values is made. Next, it is assumed that there are a given number of individual rainstorms in a month based on assumption that it is unlikely that the rain will fall at a continuous uniform intensity throughout each month (Clarke et al., 1998). We have selected the default value in CropWat model, which is one rainstorm in every 5 days period. As CROPWAT 4 (FAO, 1992) is not suitable to calculate the crop water requirement for rice (Clarke et al., 1998), we have used it only to get the values of ET_c and the available effective rainfall for a time step of 5 days. For each of the 13 countries, the crop evaporative demand (ET_c) is calculated for each season of rice production in all the regions. Data on the major crop season for each harvesting regions in each of these 13 countries, regional share of production (%) to the total national production and irrigation coverage per region, the crop planting date, crop length in days and relevant climate stations are taken from various sources (USDA, 1994; Directorate of Rice Development, 2001). We have used the USDA SCS (United States Department of Agriculture Soil Conservation Service) method to estimate the effective rainfall in CROPWAT model.

For rice cultivation in wetland systems, paddy fields are prepared and the soil is kept saturated. The common practice is to first prepare land by puddling. This is done by saturating the soil layer for 1 month prior to sowing. The volume of water (SAT) necessary for this stage is assumed to be 200 mm as suggested by Brouwer and Heibloem (1986). As lowland rice is grown in a standing layer of water, there is a constant percolation and seepage loss during this period. Percolation loss (PERC) is primarily a function of soil texture. It varies from 2 mm/day (heavy clay) to 6 mm/day for sandy soil. As rice is mostly grown in soil with more clayey texture, for the present study we have taken 2.5 mm/day as an average (Brouwer and Heibloem, 1986) for the entire period of rice cultivation except for the last 15 days when the field is left to dry out for easy harvesting. A water layer is established during transplanting or sowing and maintained throughout the growing season. Although the volume of water needed for maintaining the water layer (WL) is available for percolation losses and to meet the evaporative demand of the crop during the last phase of paddy growth, it is necessary to get this volume of water at the beginning of the crop period (Fig. 1). In this study, it is assumed that a water layer of 100 mm is established in the month of sowing. A time step of 5 days is chosen for the calculation. The total water demand (WD) is calculated by adding ET_c, WL, SAT and PERC for each time step.

For the last 15 days prior to the harvesting when the land is left to dry out, the volume of water required for evaporation is supplied by the effective rainfall in the period and any residual soil moisture maintained from the previous stages. Approximately 30 days before the land is left to dry out, the standing layer of water is slowly left to deplete without any augmenting water supply to maintain the water layer. This practice makes the best use of water supplied to maintain the WL in the previous stages. The method, thus, accounts the storage of water in time either as soil moisture or as water layer over the rice field.

Any residual soil moisture after the harvest is not included in the water footprint estimation. It is assumed that the initial soil moisture before the land preparation is negligible. It is also assumed that the contribution of capillary rise from the shallow ground water table in the rice fields is negligible. The net inflow and outflow of the overland runoff from the bunded rice fields are assumed to be zero as well. The schema to measure the depth of water available (WA) for use in different stages of crop development is presented in Fig. 2.

The water use in the rice fields is calculated for each 5-day cumulative period using the schema as presented in Fig. 3. If the total water demand WD is less than total water available WA, green water use is equal to the demand WD. In cases where the WD outstrips WA, the deficit is met by irrigation water supply. This deficit is called irrigation water demand. If a paddy field is 100% irrigated, it is assumed that the 'blue water' use in crop production is equal to the deficit. For areas equipped with partial irrigation coverage, the blue water use is estimated on a pro-rata basis.

In order to show the sort of detail we have applied, we give an example here for India. There are two major rice production seasons in India, known as Kharif (monsoon season) and Rabi (dry season). For the period of 2000–2004, the share of Kharif production to the gross national production is 86% and the remaining 14% is from Rabi. The data for harvested area, crop period, irrigated share, crop yield and total production are taken from the Directorate of Rice Development (2001). Crop water use depends on the crop calendar adopted and it is difficult to analyse multiple crop calendars that possibly exist in a region. The study assumes a single representative calendar is valid per region in India. The planting and harvesting time for the crop are assumed to be at the average of these dates gathered from various sources such as the Directorate of Rice Development (2001), IRRI (2006), and Maclean et al. (2002). The major Kharif rice-producing regions in India are Uttar Pradesh, West Bengal, Punjab, Bihar, Andhra Pradesh, Tamil Nadu, Madhya Pradesh, Orissa and Assam, producing 85% of the national Kharif rice production. The major Rabi rice-producing regions are Andhra Pradesh, West Bengal, Tamil Nadu, Karnataka and Orissa, producing 92% of the national Rabi rice production. The state-wise data for irrigated area are taken from the (Directorate of Rice Development, 2001). The rice production in Rabi is assumed to be fully irrigated and the remainder of the total irrigated area is attributed to the Kharif rice. The irrigation water requirement (m^3/ha) and the green water use (m^3/ha) are calculated per state for the major rice-producing regions. For the remaining regions, the average irrigation water requirement and green water use are calculated based on the data for the major regions. Blue water use is calculated by multiplying the irrigation requirement with the irrigated area in each season per state. The green water use in irrigated areas is calculated by multiplying the green water use (m^3/ha) by the total area in each season.

The example of India is followed for each of the other 12 countries. The planting and harvesting dates for all of the crop producing regions in these countries are chosen based on the major crop season in these regions (USDA, 1994; Directorate of Rice Development, 2001). For each production region, we have estimated the green water use, irrigation demand and blue water use based on whether it is a 'wetland system' or an 'upland system'. The national averages of green and blue water use are calculated based on the data per region and the share of production of each region to the total national production.

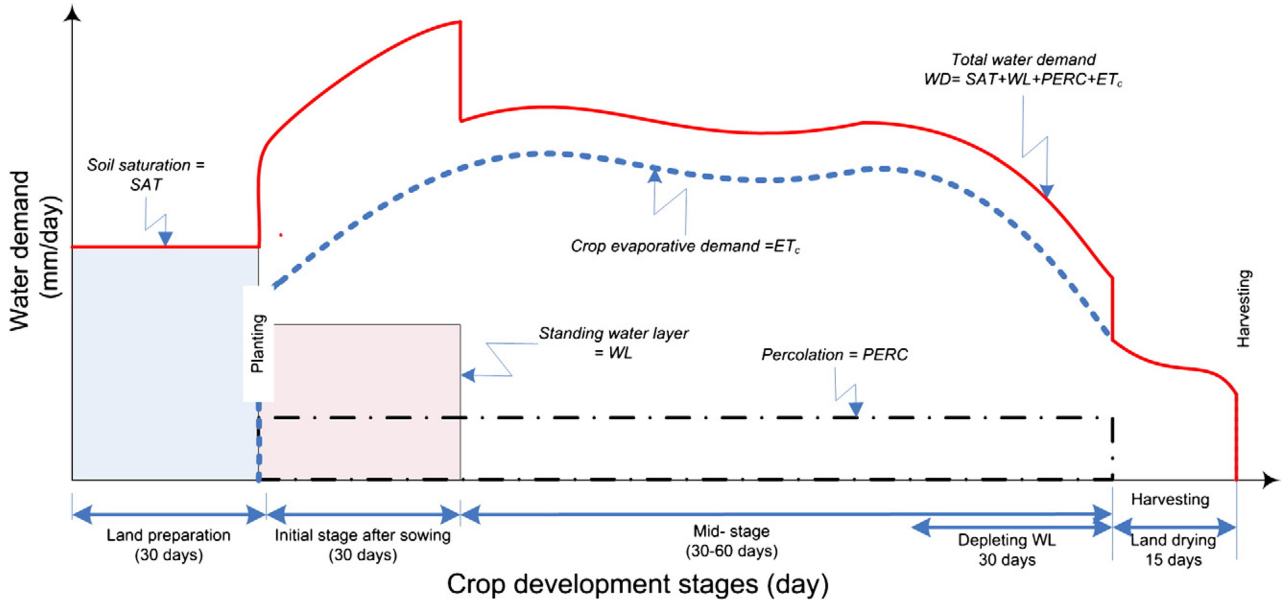

Fig. 1. The schema used to estimate the water demand at different stages of crop growth.

2.2. The Water Footprint of Paddy Rice

The water footprint is the volume of water used to produce a particular good, measured at the point of production. A number of studies have been conducted to quantify the water footprint of a large variety of different crop products (Chapagain and Hoekstra, 2003, 2004, 2007; Oki and Kanae, 2004; Hoekstra and Hung, 2005; Chapagain, 2006; Hoekstra and Chapagain, 2008). These studies provided a broad-brush to the global picture since the primary focus of these studies was to establish a first estimate of global virtual water flows and/or national water footprints. More detailed crop-specific studies have been produced for cotton (Chapagain et al., 2006), tea and coffee (Chapagain and Hoekstra, 2007), tomato (Chapagain and Orr, 2009) and sugar beet, sugar cane and maize (Gerbens-Leenes and Hoekstra, 2009). This is the first detailed global assessment of rice.

The calculation framework to quantify the water footprint of rice is based on Hoekstra and Chapagain (2008), Chapagain (2006), and Hoekstra et al. (2009). The water footprint of a product (m^3/unit) is calculated as the ratio of the total volume of water used (m^3/year) to the quantity of the production (ton/year). The water footprint has three components: the green water footprint (evaporation of water supplied from the rain in crop production), blue water footprint (evaporation of the irrigation water supplied from surface and renewable ground water sources) and the grey water footprint (volume of fresh water polluted in the production process). Most studies on the calculation of water footprints of products have taken the two evaporative components only (i.e., green and blue water footprint), excluding the grey water footprint. In an earlier study, Chapagain and Hoekstra (2004) have assumed a constant percolation loss of 300 mm of water per year from the rice field and added that to the total water footprint of rice. This is inconsistent, however, with the approach taken for other products in the same study. In the present study, a clear distinction between the evaporation and percolation is made. The percolation flow is not included in the water footprint.

The volume of polluted water has been estimated using nitrogen (N) as a representative element for estimations of the grey water

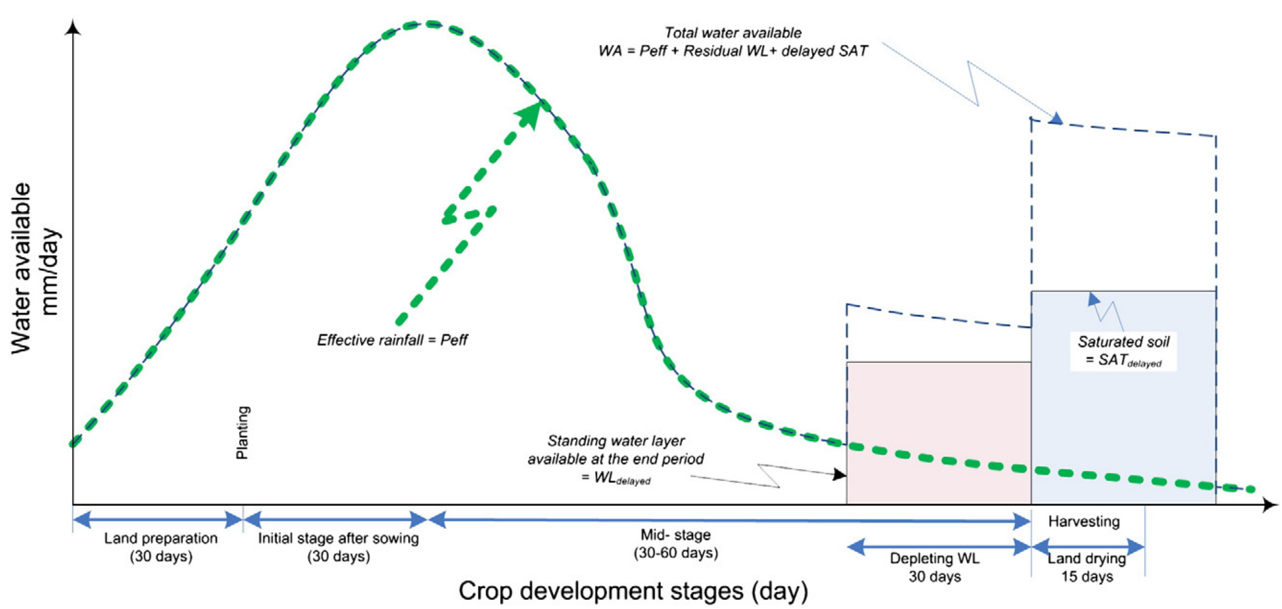

Fig. 2. The schema used to estimate the total water available at different stages of crop growth.

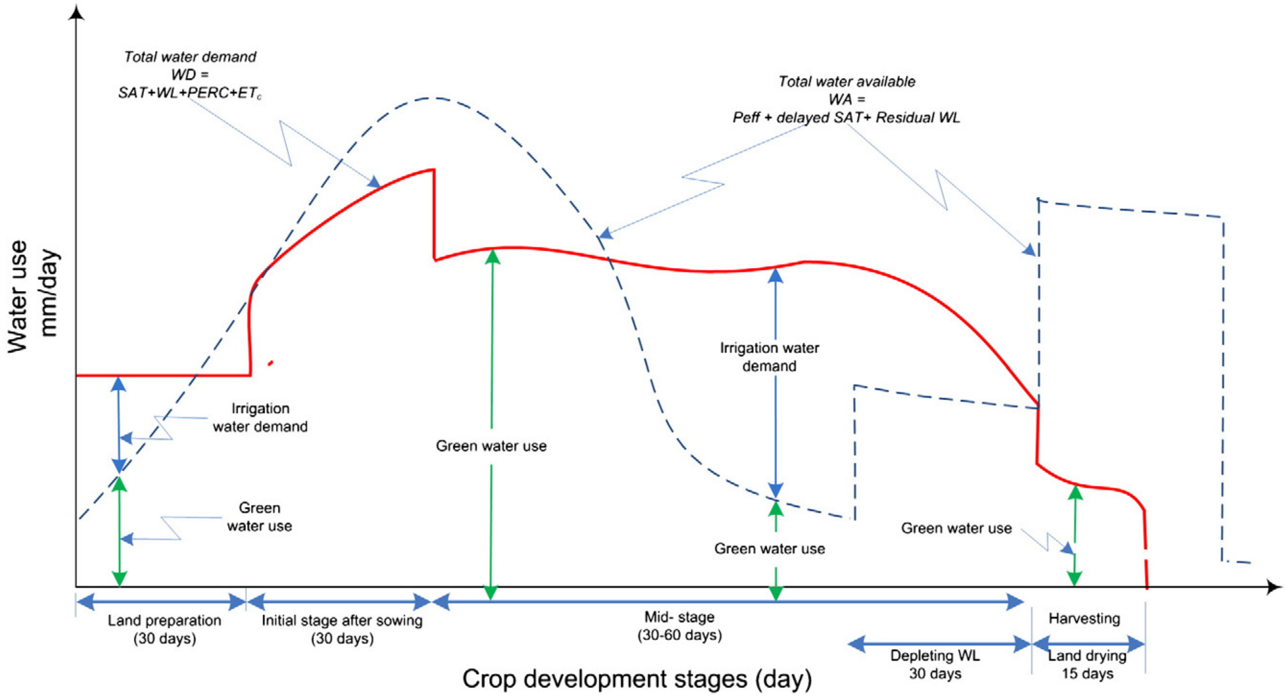

Fig. 3. Distinguishing the green water use and irrigation water demand.

footprint following Chapagain et al. (2006). Nitrogen recovery rarely exceeds 30–40% in wetland rice production systems (De Datta, 1995). In these systems, rice is primarily grown in clay soils, thus restricting the nitrogen loss by leaching. In general, irrigated systems have higher fertiliser application rates than rainfed systems. For example, in India during the period of 2003–2004, the fertiliser application in irrigated crop land amounted to 22% of the total national fertiliser application, whereas that for the rainfed crops was only 9.6%. In Indonesia 52% of the fertilisers used are applied to rice (FAO, 2005).

In wetland rice cultivation, the global NH_3 loss to the atmosphere is about 20% of the total N application, and 97% of this occurs in developing countries (FAO and IFA, 2001). For a continuous flooding rice system, the denitrification is never more than 10% where for an intermittent fallow system it is up to 40% (Fillery and Vlek, 1982). As reported by Xing and Zhu (2000), there is about 0–5% of leached nitrogen from upland rice fields, though this varies from 10 to 30% if the surface runoff is taken into account. Zhu et al. (2000) have suggested the leaching losses to be 2% of the application rate. The magnitude of nitrogen leaching depends on soil conditions (irrigation frequencies, rainfall pattern, soil texture, percolation rate, etc.) and methods of fertilization application (application rate, time, agronomical practices etc.). However, as the focus of this paper is rather global in nature, a first-order estimation of the volume of water polluted is made following the method presented by Chapagain et al. (2006). In this paper, we have taken a flat rate of nitrogen leaching equal to 5% of the nitrogen application rate and used the permissible limit of '50 mg nitrate-NO_3 per litre' as per the EU Nitrate Directives to estimate the volume of water necessary to dilute leached nitrogen to the permissible limit. The data on average fertiliser application rates for these countries is taken from IFA et al. (2002).

2.3. The Water Footprint of Processed Rice

The actual rice kernels are encased in an inedible and protective hull. Brown rice or husked rice has the outer hull removed, but still retains the bran layers that give it a characteristic tan color and nut-like flavor. Milled rice, also called white rice, is the product after milling which includes removing all or part of the bran and germ from the paddy.

On average, rice varieties are composed of roughly 20% rice hull, 11% bran, and 69% starchy endosperm. The endosperm is also known as the total milled rice which contains whole grains or head rice, and broken grains. Rice milling can be a one step, two steps or multi-step process. The maximum milling recovery (total milled rice obtained out of paddy, expressed as a weight percentage) is 69–70% depending on the rice variety. The global average of milling recovery is only 67%.

The water footprint of the primary rice crop is attributed to the processed products on the basis of so-called product fractions and value fractions (Chapagain and Hoekstra, 2004; Hoekstra et al., 2009). The product fraction is defined as the weight of a derived product obtained per ton of root product. The value fraction of a derived product is the ratio of the market value of the derived product to the aggregated market value of all the derived products obtained from the root product (Fig. 4).

2.4. International Virtual Water Flows

The virtual water flow between two nations is the volume of water that is being transferred in virtual form from one place to another as a result of product trade. The virtual water flows between nations related to trade in rice products have been calculated by multiplying commodity trade flows (ton/year) by their associated water footprint (m^3/t) in the exporting country (Chapagain and Hoekstra, 2008). Data on international trade of rice products are taken from PCTAS (ITC, 2006) for the period 2000–2004. The trade data on rice imports by Papua N. Guinea is erroneous in PCTAS and thus discarded in estimating the international virtual water flows with all of its trading partner countries.

2.5. Water Footprint of Rice Consumption in a Country

The water footprint of the consumption of rice in a nation can be divided into two parts, an internal and an external component. The internal water footprint of rice consumption refers to the consumption and pollution of national water resources for the part of rice

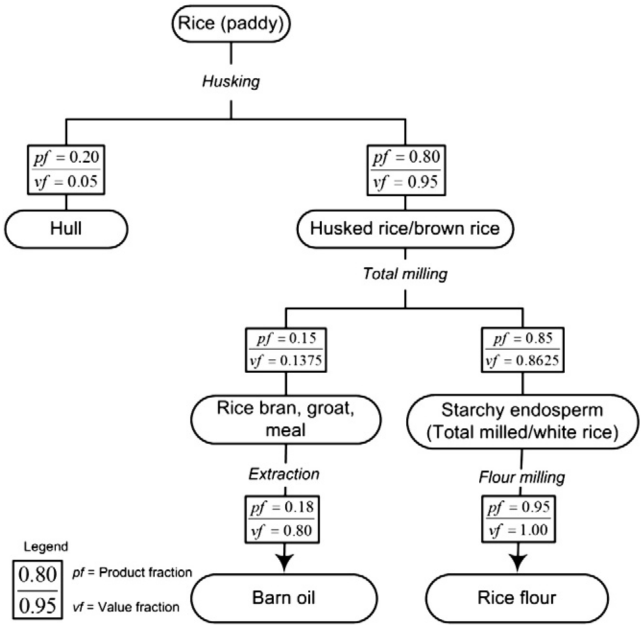

Fig. 4. Product tree of rice showing value fraction and product fraction per rice processing stage.

produced and consumed internally. Any consumption of the part of imported rice would create equivalent size of the external water footprint of the country in locations where the rice is imported from. The internal and external water footprints are assessed following the scheme shown in Fig. 5.

3. Water Footprint of Rice Production

The calculated average water depth used in rice production in each of the 13 major rice-producing countries is presented in Table 1. In the USA, the evaporation is relatively high, at the same time the effective rainfall is much lower, making the irrigation volume one of the highest. Rice fields in both the USA and Pakistan are 100% irrigated, making the blue water footprint high in these countries.

The total water use (m^3/year) for rice production in each country is calculated by multiplying the national harvested area of rice crops (ha/year) with the corresponding depth of water (mm/year) used in paddy fields. The water footprint of rice production is the sum of water evaporated from the rice fields and the volume of water polluted in the process (Table 2). It also presents the volume of water percolated or left over as residual soil moisture after the crop harvest in the fields. Total water use is the sum of the water footprint and percolation. The water footprint refers to a real loss to the catchment, while the percolation is actually not a loss to the catchment.

Table 1
Depth of water used in rice production (mm/year) for the 13 major rice-producing countries. Period 2000–2004.

	Evaporation (green)	Evaporation (blue)	Pollution (grey)	Percolation of rain water	Percolation of irrigation water
China	228	302	73	209	277
India	314	241	34	231	178
Indonesia	260	217	53	226	188
Bangladesh	192	202	36	192	202
Vietnam	139	92	58	190	125
Thailand	252	149	31	210	125
Myanmar	297	133	18	268	120
Japan	219	258	39	224	264
Philippines	277	139	26	254	127
Brazil	260	220	20	227	192
USA	168	618	75	104	383
Korea, Rep.	232	253	55	198	216
Pakistan	124	699	26	73	412

Table 3 shows the water footprint and percolation per unit of paddy rice produced (m^3/t). The figures follow from dividing total national water footprint and percolation related to rice production (m^3/year) by the gross national paddy production per year (ton/year). The volume of water evaporated per ton of rice is quite similar to the evaporation per ton of wheat, as also noted in Bouman and Tuong (2001). The higher evaporation rates per hectare as a result of the standing water layer in rice fields are apparently compensated by the relatively higher yields of rice (Bouman et al., 2007b).

Table 3 also shows the global average water footprint of rice, calculated based on the share of national production of the top 13 rice-producing countries to the total global production. Since the export share of these 13 countries to the total export volume during the period 2000–2004 differs widely, the global average water footprint of rice paddy is also calculated weighing the export share of these countries. As the top 13 largest rice-producing countries contribute 82% to the global share of rice export, the difference between these two averages is not

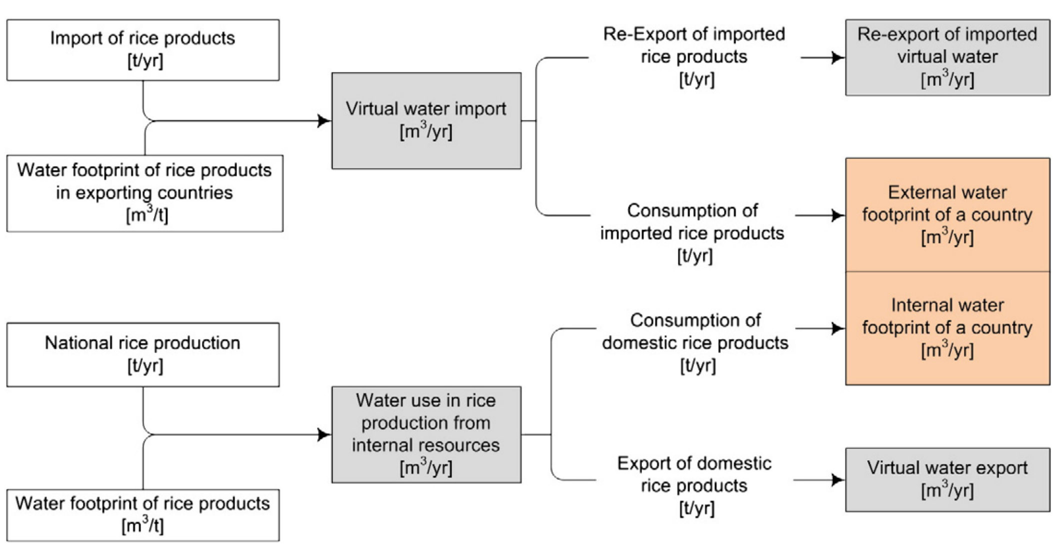

Fig. 5. The calculation scheme for assessing the water footprint of national consumption of rice products.

Table 2
Total national water footprint of rice production and percolation of water in the 13 major rice-producing countries (billion m3/year). Period 2000–2004.

	National water footprint of rice production (evaporation + pollution)				Percolation and residual soil moisture			Total water use (WF + percolation)
	Green	Blue	Grey	Total	Green	Blue	Total	
China	65.2	86.5	20.8	172.5	60.0	79.5	139.5	312.0
India	136.3	104.5	14.7	255.5	100.4	77.0	177.4	432.9
Indonesia	30.3	25.3	6.1	61.7	26.3	21.9	48.2	110.0
Bangladesh	20.4	21.5	3.8	45.7	20.5	21.5	42.0	87.7
Vietnam	10.5	6.9	4.3	21.7	14.3	9.4	23.7	45.3
Thailand	25.2	15.0	3.1	43.3	21.1	12.5	33.6	76.9
Myanmar	19.1	8.5	1.1	28.8	17.2	7.7	24.9	53.7
Japan	3.7	4.4	0.7	8.8	3.8	4.5	8.3	17.1
Philippines	11.2	5.6	1.0	17.9	10.3	5.2	15.5	33.4
Brazil	8.8	7.4	0.7	16.8	7.6	6.5	14.1	31.0
USA	2.2	8.0	1.0	11.1	1.3	4.9	6.3	17.3
Korea, R.	2.4	2.6	0.6	5.6	2.1	2.3	4.3	10.0
Pakistan	2.9	16.3	0.6	19.9	1.7	9.6	11.3	31.2

big. Global average results presented in the following sections are based on the global average water footprint based on production. Table 4 shows the global average water footprints of rice products.

Using the global average water footprint of paddy calculated and the production data for the rest of the countries, the global water footprint of rice production is estimated to be 784 billion m^3/year (48% green, 44% blue and 8% grey) (Fig. 6). The volume of water percolated in the rice fields plus any residual soil moisture left in the field after rice harvest is equal to 607 billion m^3/year, about half of which (52%) is sustained by rainfall in the rice field. Including percolation, the total blue water use in the rice field becomes 636 billion m^3/year, which is the number often quoted in the literature while referring to the total water used in rice production. If we add the total water footprint and the percolation water volume, it is equal to 1,391 billion m^3/year, which is nearly the same as the global water use in rice fields (1,359 billion m^3/year) as reported by Chapagain and Hoekstra (2004). Water footprints of rice production for all countries are presented in Table 5.

4. International Virtual Water Flows

International trade in rice during the period 2000–2004 resulted in a total international virtual water transfer of 31.1 billion m^3/year (45% green water, 47% blue water, 8% grey water). This means that international rice trade is linked to the evaporation of 28.7 billion m^3 of water per year with an additional 2.4 billion m^3 of fresh water being polluted each year in the exporting countries.

Table 4
The global average water footprint of rice products (m3/t). Period 2000–2004.

PCTAS code	Product description	Green	Blue	Grey
100610	Rice in the husk (paddy or rough)	632	584	109
100620	Rice, husked (brown)	750	693	130
110314	Rice groats and meal	688	636	119
100630	Rice, semi-milled, milled, whether or not polished or glazed	761	704	132
100640	Rice, broken	761	704	132
110230	Rice flour	801	741	139

The top 10 largest gross virtual water exporters are Thailand (9,627 Mm^3/year), India (5,185 Mm^3/year), USA (3,474 Mm^3/year), Pakistan (2,923 Mm^3/year), China (1,296 Mm^3/year), Vietnam (1,233 Mm^3/year), Italy (1,048 Mm^3/year), Uruguay (899 Mm^3/year), Egypt (644 Mm^3/year) and Australia (599 Mm^3/year) covering nearly 87% of the total virtual water export international trade in rice products globally. The largest gross importers are Nigeria (2,944 Mm^3/year), Indonesia (1,637 Mm^3/year), Iran (1,506 Mm^3/year), Saudi Arabia (1,429 Mm^3/year), South Africa (1,348 Mm^3/year), Senegal (1,346 Mm^3/year), Brazil (1,010 Mm^3/year), Japan (988 Mm^3/year) and Philippines (979 Mm^3/year) covering about 42% of the total import.

The average annual blue virtual water import during the study period was 14.6 billion m^3/year and the average green virtual water import was 14.1 billion m^3/year. The total average annual virtual water flows including the pollution component was 31.1 billion m^3/year. The share of green virtual water to the total global virtual water flows related to the international trade of rice products is 45%, and that of blue water is 47%.

5. Water Footprint of Rice Consumption

The largest consumer of rice in terms of water is India, followed by China, Indonesia, Bangladesh, Thailand, Myanmar, Vietnam, the Philippines and Brazil. The composition of the water footprint related to rice consumption for the set of countries responsible for more 98% of the global water footprint is presented in Table 6. The per-capita water footprint of rice consumption is quite high in Thailand (547 m^3/cap/year) compared to India (239 m^3/cap/year), Indonesia (299 m^3/cap/year), China (134 m^3/cap/year) and the USA (29 m^3/cap/year). This variation is also because the diet contains more rice in some countries compared to others.

From the perspective of food security as well as from the viewpoint of sustainable consumption it is interesting to know where water footprints related to national consumption actually 'land'. We give

Table 3
Water footprint and percolation per unit of paddy rice produced (m3/t) in the 13 major rice-producing countries. Period 2000–2004.

	Green water footprint	Blue water footprint	Grey water footprint	Total water footprint	Percolation of rain water	Percolation of irrigation water	Total percolation
China	367	487	117	971	338	448	785
India	1077	826	116	2020	794	609	1403
Indonesia	583	487	118	1187	505	422	927
Bangladesh	549	577	103	1228	550	578	1128
Vietnam	308	203	127	638	420	277	697
Thailand	942	559	116	1617	787	467	1253
Myanmar	846	378	50	1274	763	341	1103
Japan	341	401	61	802	348	409	757
Philippines	844	423	78	1345	775	388	1163
Brazil	791	670	61	1521	691	585	1276
USA	227	835	101	1163	141	517	658
Korea, R.	356	388	84	829	303	331	634
Pakistan	421	2364	88	2874	248	1394	1642
Average[1]	632	584	109	1325	535	490	1025
Average[2]	618	720	112	1450	522	538	1060

[1]Average based on weighted production data.
[2]Average based on weighted export data.

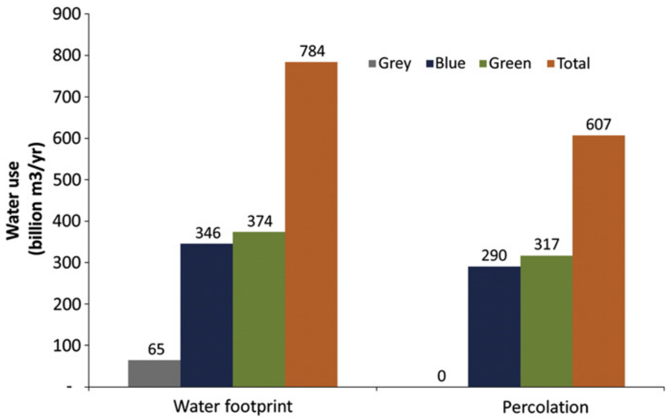

Fig. 6. The global water footprint of rice production and the total volume of water percolated in rice fields (billion m^3/year). Period 2000–2004.

here two examples, one for the USA and one for Europe. The total water footprint of the USA is 8422 Mm^3/year. The internal waterfootprint is relatively large (93% of the total water footprint) (Fig. 7). The external water footprint of the USA is 591 Mm^3/year and largely refers to water use in Thailand (70%), India (15%), Pakistan (5%), China (4%) and Australia (4%).

In contrast to the USA, the sizes of the rice consumption related internal and external water footprints of the EU27 are fairly comparable. Out of 5335 Mm^3/year, the internal component is 2877 Mm^3/year and the external one is 2457 Mm^3/year (Fig. 8). More than 70% of the total external water footprint of the EU27 rests on eight countries, namely India, Thailand, the USA, Pakistan, Egypt, Guyana, China and Vietnam. Fig. 9 shows the external water footprint of the EU27 in each of these countries, distinguishing between the green, blue and grey water footprint. The largest share of the blue water footprint is for rice imported from the USA and Pakistan. Although the total footprint on India is the largest, a large fraction of it is made up of green water. Though the total footprint on Egypt, Guyana and Vietnam is much lower than in Pakistan, the grey component on these countries is relatively higher than in Pakistan.

6. Discussion

Rice is a staple food for three billion people (Maclean et al., 2002), especially in Southeast Asia, the Middle East, Latin America, and the West Indies. In terms of human nutrition and caloric intake, it provides nearly one fifth of the direct human calorie intake worldwide, making it the most important food crop (Smith, 1998; Zeigler and Barclay, 2008). Rice consumption exceeds 100 kg per capita annually in many Asian countries (compare for example with the USA average of 10 kg) and is the principal food for most of the world's poorest people, particularly in Asia, which is home to 70% of those who earn less than $1 a day (Zeigler and Barclay, 2008). Rice production is deeply rooted in the socio-political culture in Asia which nearly produces nearly 90% of the global rice (Bouman et al., 2007a).

In probably a majority of cases, the green water footprint of rice production does not constitute significant negative environmental or economic impacts. Rainwater allocated for rice production generally has no opportunity cost, which means that alternative uses of the rain

Table 5
Water footprint of national rice production. Period 2000–2004.

	Area* ha	Yield* ton/ha	Production* ton/year	Water footprint of production (Mm^3/year)				Percolation (Mm^3/year)
				Green	Blue	Grey	Total	
China	28,670,030	6.2	177,657,605	65,241	86,460	20,786	172,486	139,518
India	43,057,460	2.9	126,503,280	136,258	104,544	14,683	255,486	177,427
Indonesia	11,642,899	4.5	52,014,913	30,309	25,323	6113	61,744	48,213
Bangladesh	10,641,271	3.5	37,217,379	20,415	21,463	3831	45,708	41,985
Vietnam	7,512,160	4.5	33,960,560	10,455	6888	4319	21,663	23,661
Thailand	10,038,180	2.7	26,800,046	25,247	14,980	3112	43,339	33,591
Myanmar	6,431,364	3.5	22,581,828	19,111	8538	1125	28,774	24,918
Philippines	4,056,577	3.3	13,322,327	11,246	5633	1034	17,914	15,491
Brazil	3,371,562	3.3	11,068,502	8753	7411	674	16,838	14,120
Japan	1,706,000	6.4	10,989,200	3744	4408	665	8818	8317
USA	1,285,671	7.4	9,520,015	2161	7951	964	11,076	6262
Pakistan	2,339,200	3.0	6,910,650	2909	16,340	611	19,859	11,345
Korea, R	1,045,173	6.5	6,808,450	2423	2644	575	5641	4320
Egypt	630,353	9.5	5,972,257	3774	3487	653	7913	6126
Nepal	1,545,156	2.7	4,220,395	2667	2464	461	5592	4329
Cambodia	2,045,837	2.0	4,165,772	2632	2432	455	5520	4273
Nigeria	2,211,800	1.4	3,085,600	1950	1802	337	4088	3165
Sri Lanka	809,552	3.5	2,822,732	1784	1648	308	3740	2896
Madagascar	1,219,074	2.2	2,715,380	1716	1585	297	3598	2785
Colombia	499,532	5.1	2,579,150	1630	1506	282	3417	2646
Iran	577,372	4.2	2,464,653	1557	1439	269	3266	2528
Laos	746,177	3.2	2,371,400	1498	1385	259	3142	2433
Malaysia	680,660	3.2	2,190,829	1384	1279	239	2903	2247
Korea, DPR	571,371	3.7	2,110,040	1333	1232	231	2796	2164
Peru	301,409	6.6	2,003,010	1266	1170	219	2654	2055
Ecuador	367,290	3.8	1,419,705	897	829	155	1881	1456
Italy	221,009	6.1	1,359,921	859	794	149	1802	1395
Guinea	649,437	1.7	1,123,543	710	656	123	1489	1153
Uruguay	168,635	6.3	1,069,425	676	624	117	1417	1097
Australia	113,307	8.7	985,385	623	575	108	1306	1011
Tanzania	498,186	1.7	861,572	544	503	94	1142	884
Argentina	153,400	5.6	852,764	539	498	93	1130	875
Spain	117,248	7.3	852,050	538	497	93	1129	874
Others	4,742,502		11,170,874	7055	6523	1222	14,804	11,461
Total	150,666,851	4.49**	591,751,209	373,907	345,512	64,655	784,073	607,019

*Source: FAOSTAT data (2006). The countries presented in the table are alone responsible for 98% of the global water footprint of rice production.
**Weighted average, calculated based on production per country.

Table 6
Water footprint of national rice consumption. Period 2000-04.

	Internal water footprint (Mm^3/year)				External water footprint (Mm^3/year)				Total water footprint (Mm^3/year)*			
	Green	Blue	Grey	Total	Green	Blue	Grey	Total	Green	Blue	Grey	Total
India	133,493	102,423	14,385	250,301	1	3	0	4	133,494	102,425	14,385	250,305
China	64,754	85,812	20,630	171,195	400	238	50	688	65,154	86,050	20,680	171,884
Indonesia	30,301	25,316	6111	61,727	797	689	151	1637	31,097	26,005	6262	63,364
Bangladesh	20,414	21,462	3831	45,707	146	112	16	273	20,560	21,574	3846	45,980
Thailand	19,639	11,653	2421	33,713	1	1	0	2	19,640	11,654	2421	33,714
Myanmar	18,989	8483	1118	28,591	–	–	–	–	18,989	8483	1118	28,591
Vietnam	9860	6496	4074	20,430	–	–	–	–	9860	6496	4074	20,430
Philippines	11,246	5633	1034	17,914	490	386	103	979	11,736	6020	1137	18,893
Brazil	8735	7396	673	16,804	451	474	84	1008	9186	7869	757	17,812
Pakistan	2480	13,935	521	16,936	–	–	–	–	2480	13,935	521	16,936
Japan	3724	4386	662	8772	360	537	86	983	4084	4923	748	9755
USA	1598	5554	679	7831	326	225	41	591	1924	5779	719	8422
Egypt	3467	3203	599	7269	–	–	–	–	3467	3203	599	7269
Nigeria	1949	1801	337	4088	1528	1204	211	2943	3478	3005	548	7031
Korea rep.	2409	2628	572	5609	82	103	21	205	2491	2732	592	5814
Nepal	2667	2464	461	5,592	15	14	2	31	2682	2478	463	5623
Cambodia	2628	2428	454	5511	46	31	6	83	2674	2459	461	5594
Iran	1552	1434	268	3254	676	726	98	1500	2227	2160	367	4754
Madagascar	1715	1585	297	3597	114	280	21	414	1829	1865	318	4012
Sri Lanka	1782	1647	308	3737	80	124	10	214	1862	1771	318	3951
Malaysia	1366	1262	236	2865	417	366	70	852	1783	1628	306	3717
Colombia	1629	1506	282	3417	73	65	12	150	1703	1570	294	3567
Laos	1498	1385	259	3142	–	–	–	–	1498	1385	259	3142
Peru	1266	1170	219	2654	38	42	7	87	1304	1212	226	2741
Ecuador	863	797	149	1809	1	1	0	3	864	798	149	1812
Guinea	710	656	123	1489	90	112	20	223	800	768	143	1711
Senegal	128	118	22	269	756	482	107	1344	884	600	129	1613
Saudi Arabia	–	–	–	–	650	694	82	1426	650	694	82	1426
Tanzania	541	500	94	1135	90	95	21	207	631	595	115	1341
South Africa	2	2	0	4	701	509	88	1298	703	511	89	1302
Mexico	171	158	30	359	160	579	70	809	331	737	100	1168
Russian fed	304	282	53	639	231	224	58	513	535	505	111	1152
Mali	511	472	88	1072	19	15	4	38	530	488	92	1110
Turkey	244	225	42	511	172	263	42	477	416	488	84	988
Venezuela	456	421	79	956	4	15	2	21	460	437	81	977
Cuba	385	356	67	808	72	71	26	169	457	428	92	977
Italy	403	380	69	853	39	44	6	89	442	424	75	941
Cote d'Ivoire	408	377	71	856	–	–	–	–	408	377	71	856
Australia	366	339	62	767	41	40	5	87	407	379	68	854
Dominican R	403	372	70	845	3	3	1	6	406	375	70	851
UK	–	–	–	–	331	423	55	808	331	423	55	808
Spain	321	301	56	678	52	57	9	118	373	358	65	796
France	57	53	10	120	306	302	49	658	364	356	59	778
Ghana	162	149	28	339	213	185	37	435	375	334	65	774
Argentina	358	331	62	750	8	7	1	16	365	338	63	766
Others	3290	3043	569	6902	3156	3972	547	7675	6446	7015	1116	14,577
Grand total	360,336	331,511	62,360	754,208	13,570	14,000	2295	29,865	373,907	345,512	64,655	784,073

*Note: It is the total water footprint of a nation related to rice consumption. It does not include water losses as a result of percolation and left over soil moisture in the rice fields. The countries presented in table are responsible for 98% of the total water footprint of rice consumption.

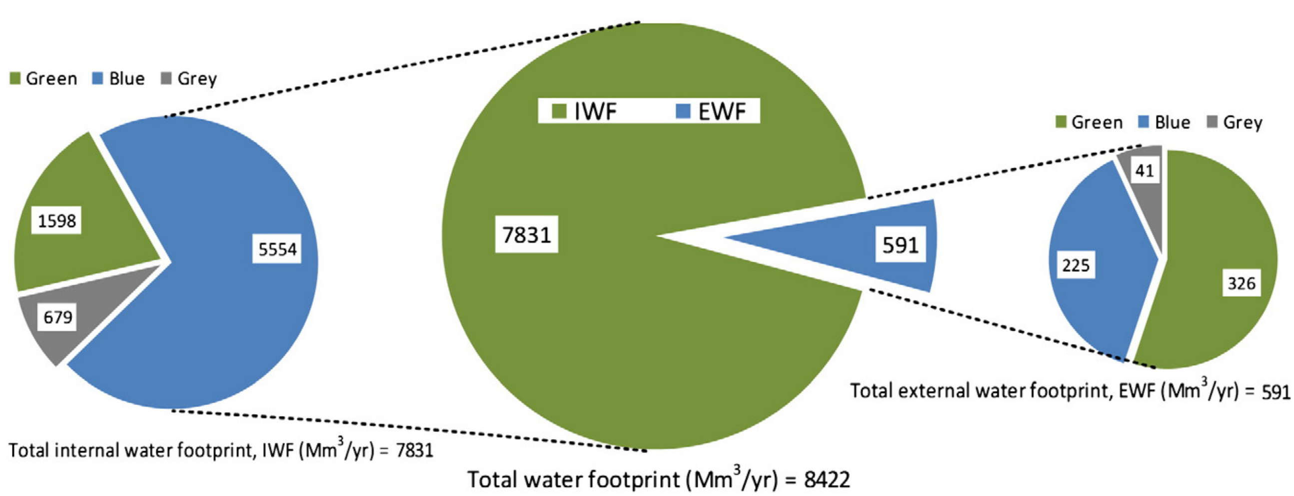

Fig. 7. Water footprint of rice consumption in the USA (million m^3/year). Period 2000–2004.

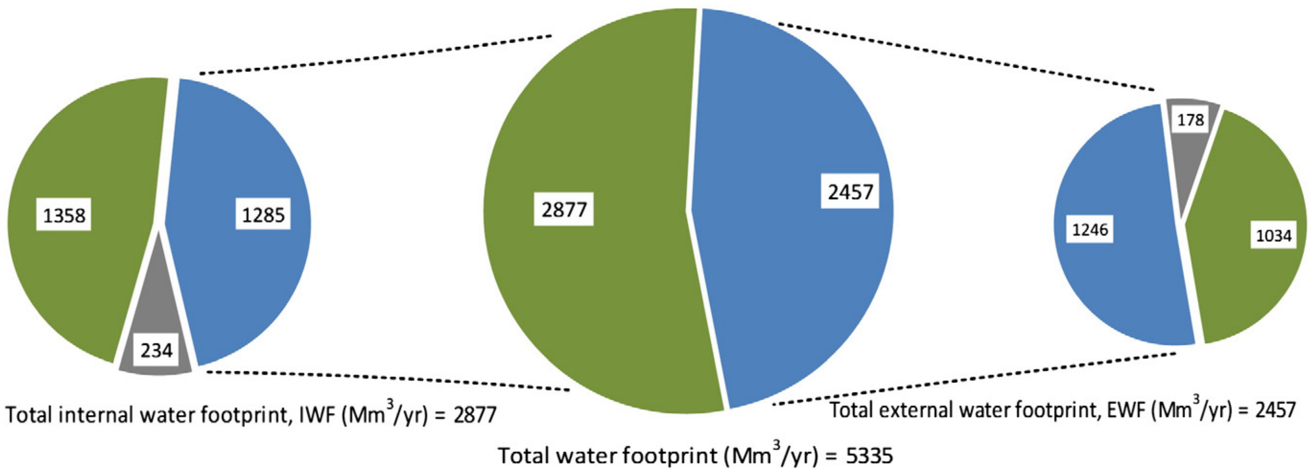

Fig. 8. Water footprint of rice consumption in EU27 countries (Mm^3/year). Period 2000–2004.

(natural vegetation, other crops) would not give higher benefits. Storing rainwater in the fields reduces or delays surface runoff and may thereby flatten peak flows in downstream rivers, which may be useful in the wet season during heavy rains. On the other hand, this mechanism may be absent or even reversed when rice fields are already full of water up to the point of overflow, in which case rain will become runoff very quickly. Although the green water footprint in rice production may not constitute significant environmental problems, reduction of the green water footprint at a global level is probably a key in reducing the blue water footprint in rice production. Better use of rain wherever possible, that means increasing yields per drop of rainwater, will reduce the demand for rice from areas where blue water is a necessary input.

From an economic point of view, reducing percolation of blue water in the rice fields is relevant, because it will reduce costs of water supply by reducing the absolute volume of water needed in the field. However, the environmental benefit may not be quite big as percolated blue water will remain within the same catchment as from where it was abstracted. As a lot of water is percolating in the first phase of the land preparation, a number of water saving technologies have been suggested (Bouman et al., 2007a), which are effectively used in the Philippines, India and China. The direct dry seeding method can increase the effective use of rainfall and reduce irrigation needs (Cabangon et al., 2002) in the phase of land preparation. Another way to reduce percolation from fields is to use System of Rice Intensification (SRI). SRI suggests ways to improve rice yields with less water, the main highlight being that it uses water just enough to keep the roots moist all the time without any standing water at any time. The argument behind SRI is that the main benefit of flooding the rice plant is to check the proliferation of weeds, thereby saving labour (Gujja et al., 2007), which can be a favourable option where the supply is limited or scarce.

Rice production is a so-called diffuse source of pollution and hence difficult to mitigate. The option to have optimal application of fertiliser so that the application exactly matches the plant uptake, as in the case of dry crops, is not suitable in rice production. There is inevitably percolation leaching a part of the fertiliser. The grey component of the water footprint can only be reduced with a reduction in the leaching of fertilisers and pesticides from the field, e.g., by increasing water use efficiency, using slow-release fertilisers and nitrification inhibitors, puddling the rice fields, planting catch and cover crops and using crop residues in situ (Choudhury and Kennedy, 2005). The loss of nitrogen may cause environmental and health problems. Although these problems cannot be alleviated completely, there are enough research findings that indicate that these problems can be minimized through a number of management practices (Choudhury and Kennedy, 2005). The fate of nitrogen in soil is mainly governed by different processes: plant uptake, ammonia volatilization, denitrification and losses to surface

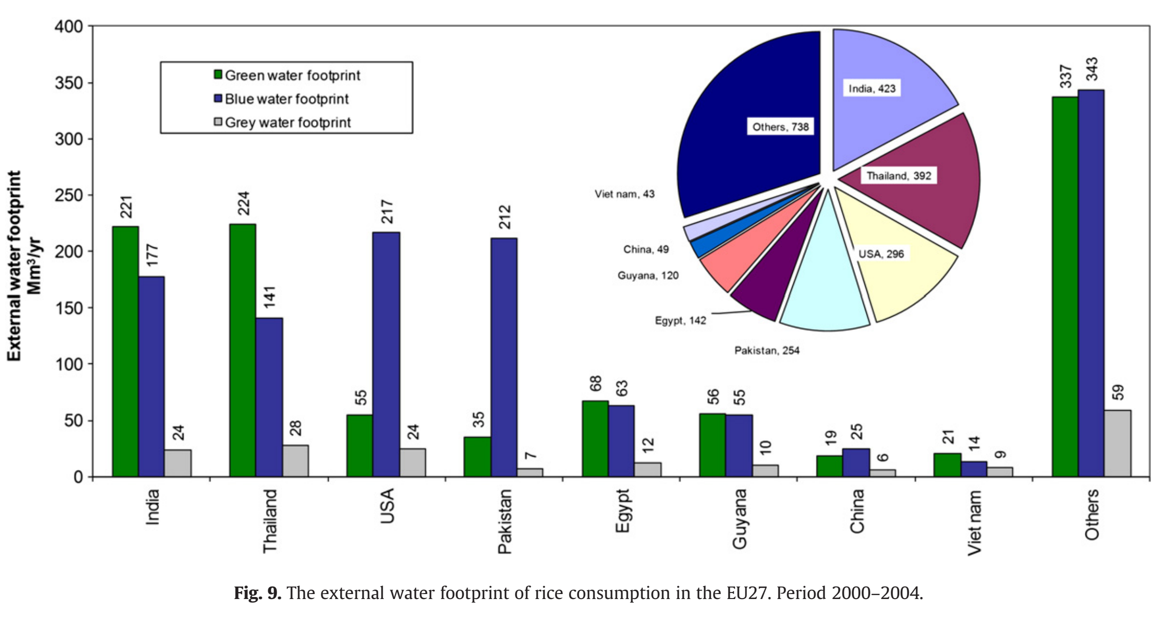

Fig. 9. The external water footprint of rice consumption in the EU27. Period 2000–2004.

(runoff) or ground water bodies (leaching). All these three processes are intertwined and it is hard to study them in isolation. A systematic analysis of fate of nitrogen should be carried out at field level to reveal any specific impacts on the system.

7. Conclusion

The water footprint of rice production and consumption is quite significant in south Asian countries. However, in these countries most of the water footprint is rooted in the wet season, so that the contribution to water scarcity is relatively low in contrast to our general perception. Globally, there is nearly an equal share of green and blue water use in the total water footprint of rice. The green water footprint (rain) has a relatively low opportunity cost compared to the blue water footprint (irrigation water evaporated from the field). The environmental impact of the blue water footprint in rice production depends on the timing and location of the water use. It would need a dedicated analysis to estimate where and when blue water footprints in rice production constitute significant environmental problems, but from our results it is obvious that rice from the USA and Pakistan, where rice production heavily depends on blue water, will generally cause larger impacts per unit of product than rice from Vietnam. From a sustainable consumption perspective, for countries or regions that import a lot of rice for own consumption, it may be relevant to compare the local impacts of different rice sources. Besides, in international context one may address the question why rice consumers like in the EU do not cover the actual water cost (costs of water scarcity and water pollution) that occurs in the countries from where the rice is obtained. Since irrigation systems are generally heavily subsidized and water scarcity is never translated into a price, the economic or environmental costs of water are not contained in the price of rice. The water cost may actually largely vary from place to place, depending on whether the rice comes from, e.g., India, Thailand, the USA, Pakistan or Egypt, and depending on whether the rice is produced in the dry or the wet period.

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