Hydrol. Earth Syst. Sci. Discuss., 7, 2499–2542, 2010
www.hydrol-earth-syst-sci-discuss.net/7/2499/2010/
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Hydrology and Earth System Sciences Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

A global and high-resolution assessment of the green, blue and grey water footprint of wheat

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Received: 10 April 2010 – Accepted: 13 April 2010 – Published: 22 April 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The aim of this study is to estimate the green, blue and grey water footprint of wheat in a spatially-explicit way, both from a production and consumption perspective. The assessment is global and improves upon earlier research by taking a high-resolution approach, estimating the water footprint of the crop at a 5 by 5 arc minute grid. We have used a grid-based dynamic water balance model to calculate crop water use over time, with a time step of one day. The model takes into account the daily soil water balance and climatic conditions for each grid cell. In addition, the water pollution associated with the use of nitrogen fertilizer in wheat production is estimated for each grid cell. We have used the water footprint and virtual water flow assessment framework as in the guideline of the Water Footprint Network.

The global wheat production in the period 1996–2005 required about 1088 billion cubic meters of water per year. The major portion of this water (70%) comes from green water, about 19% comes from blue water, and the remaining 11% is grey water. The global average water footprint of wheat per ton of crop was 1830 m^3/ton. About 18% of the water footprint related to the production of wheat is meant not for domestic consumption but for export. About 55% of the virtual water export comes from the USA, Canada and Australia alone. For the period 1996–2005, the global average water saving from international trade in wheat products was 65 Gm^3/yr.

A relatively large total blue water footprint as a result of wheat production is observed in the Ganges and Indus river basins, which are known for their water stress problems. The two basins alone account for about 47% of the blue water footprint related to global wheat production. About 93% of the water footprint of wheat consumption in Japan lies in other countries, particularly the USA, Australia and Canada. In Italy, with an average wheat consumption of 150 kg/yr per person, more than two times the word average, about 44% of the total water footprint related to this wheat consumption lies outside Italy. The major part of this external water footprint of Italy lies in France and the USA.

1 Introduction

Fresh water is a renewable but finite resource. Both freshwater availability and quality vary enormously in time and space. Growing populations coupled with continued socio-economic developments put pressure on the globe's scarce water resources. In many parts of the world, there are signs that water consumption and pollution exceed a sustainable level. The reported incidents of groundwater depletion, rivers running dry and worsening pollution levels form an indication of the growing water scarcity (Gleick, 1993; Postel, 2000; WWAP, 2009). Authors of the Comprehensive Assessment of Water Management in Agriculture (2007) argue that to meet the acute freshwater challenges facing humankind over the coming fifty years requires substantial reduction of water use in agriculture.

The concept of "water footprint" introduced by Hoekstra (2003) and subsequently elaborated by Hoekstra and Chapagain (2008) provides a framework to analyse the link between human consumption and the appropriation of the globe's freshwater. The water footprint of a product is defined as the total volume of freshwater that is used to produce the product (Hoekstra et al., 2009). The *blue* water footprint refers to the volume of surface and groundwater consumed (evaporated) as a result of the production of a good; the *green* water footprint refers to the rainwater consumed. The *grey* water footprint of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. The water footprint of national consumption is defined as the total amount of freshwater that is used to produce the goods consumed by the inhabitants of the nation. The water footprint of national consumption always has two components: the internal and the external footprint. The latter refers to the appropriation of water resources in other nations for the production of goods and services that are imported into and consumed within the nation considered. Externalising the water footprint reduces the pressure on domestic water resources, but increases the pressure on the water resources in other countries. Virtual water transfer in the form of international trade in agricultural

goods is increasingly recognized as a mechanism to save domestic water resources and achieve national water security (Allan, 2003; Hoekstra, 2003; De Fraiture et al., 2004; Liu et al., 2007; Oki and Kanae, 2004; Chapagain et al., 2006a; Yang et al., 2006; Hoekstra and Chapagain, 2008). Virtual water import is an instrument that enables nations to save scarce domestic water resources by importing water-intensive products and exporting commodities that require less water. On the other hand, water-abundant countries can profit by exporting water-intensive commodities.

In this report, we focus on the water footprint of wheat, which is one of the most widely cultivated cereal grains globally. It is grown on more land area than any other commercial crop and is the second most produced cereal crop after maize and a little above rice. It is believed to originate in Southwest Asia and the most likely site of its first domestication is near Diyarbakir in Turkey (Dubcovsky and Dvorak, 2007). About 90 to 95 percent of the wheat produced is the common wheat or bread wheat followed by durum wheat which accounts less than 5% of world wheat production (Pena, 2002; Ekboir, 2002). For trading purposes, wheat is classified into distinct categories of grain hardness (soft, medium-hard and hard) and colour (red, white and amber). Based on the growing period, it may be further subdivided into spring and winter wheat.

A number of previous studies on global water use for wheat are already available. Hoekstra and Hung (2002, 2005) were the first to make a global estimate of the water use in wheat production. They analysed the period 1995–1999 and looked at total evapotranspiration, not distinguishing between green and blue water consumption. Hoekstra and Chapagain (2007, 2008) improved this first study in a number of respects and studied the period 1997–2001. Still, no distinction between green and blue water consumption was made. Liu et al. (2007) made a global estimate of water consumption in wheat production for the period 1998–2002 without making the green-blue water distinction, but for the first time grid-based. Liu et al. (2009) and Liu and Yang (2010) present similar results, but now they show the green-blue water distinction. Siebert and Döll (2008, 2010) have estimated the global water consumption for wheat production for the same period as Liu et al. (2007, 2009), showing the green-blue water distinction

and applying a grid-based approach as well. Gerbens et al. (2009) estimated the green and blue water footprint for wheat in the 25 largest producing countries. Aldaya et al. (2010) have calculated the green and blue water components for wheat in four major producing countries and also estimate international virtual water flows related to wheat trade. Aldaya and Hoekstra (2010) made an assessment of the water footprint of wheat in different regions of Italy, for the first time specifying not only the green and blue, but the grey water footprint as well.

The aim of this study is to estimate the green, blue and grey water footprint of wheat in a spatially-explicit way, both from a production and consumption perspective. We quantify the green, blue and grey water footprint of wheat production by using a grid-based dynamic water balance model that takes into account local climate and soil conditions and nitrogen fertilizer application rates and calculates the crop water requirements, actual crop water use and yields and finally the green, blue and grey water footprint at grid level. The model has been applied at a spatial resolution of 5 arc minutes by 5 arc minutes. The model's conceptual framework is based on the FAO CROPWAT approach (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Allen et al., 1998). The water footprint of wheat consumption per country is estimated by tracing the different sources of wheat consumed in a country and considering the specific water footprints of wheat production in the producing regions.

2 Method

In this study the global green, blue and grey water footprint of wheat production and consumption and the international virtual water flows related to wheat trade were estimated following the calculation framework of Hoekstra and Chapagain (2008) and Hoekstra et al. (2009). The computations of crop evapotranspiration and yield, required for the estimation of the green and blue water footprint in wheat production, have been done following the method and assumptions provided by Allen et al. (1998) for the case of crop growth under non-optimal conditions (Sect. 8). The grid-based dynamic water

balance model developed in this study for estimating the crop evapotranspiration and yield computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields. The model is applied at a global scale using a resolution level of 5 by 5 arc minute grid size (about 10 km by 10 km around the Equator). The water balance model is largely written in Python language and embedded in a computational framework where input and output data are in grid-format. The input data available in grid-format (like precipitation, reference evapotranspiration, soil, crop parameters) are converted to text-format to feed the Python code. Output data from the Python code are converted back to grid-format.

The actual crop evapotranspiration ($\boldsymbol{ET}_a$, mm/day) depends on climate parameters (which determine potential evapotranspiration), crop characteristics and soil water availability (Allen et al., 1998):

$$\boldsymbol{ET}_a[t] = K_c[t] \times K_s[t] \times \boldsymbol{ET}_o[t] \quad (1)$$

where K_c is the crop coefficient, $K_s[t]$ a dimensionless transpiration reduction factor dependent on available soil water and $\boldsymbol{ET}_o[t]$ the reference evapotranspiration (mm/day). The crop coefficient varies in time, as a function of the plant growth stage. During the initial and mid-season stages of the crop development, K_c is a constant and equals $K_{c,ini}$ and $K_{c,mid}$, respectively. During the crop development and late season stages, K_c varies linearly and linear interpolation is applied for days within the development and late growing seasons. The value of K_s is calculated on a daily basis as a function of the maximum and actual available soil moisture in the root zone.

Following the approach as in the HBV model (Bergström, 1995; Lidén and Harlin, 2000) the amount of rainfall lost through runoff is computed as:

$$\boldsymbol{RO}[t] = (P[t] + I[t]) \times \left(\frac{S[t-1]}{S_{max}[t-1]} \right)^{\gamma} \quad (2)$$

in which RO[t] is runoff on day t [mm]; $P[t]$ precipitation on day t [mm]; $I[t]$ the net irrigation depth on day t that infiltrates the soil [mm]. The value of the parameter γ is

adopted from Siebert and Döll (2010) and was set to 3 for irrigated land and to 2 for rain-fed areas.

The irrigation requirement is determined based on the root zone depletion. The actual irrigation $I[t]$ depends on the extent to which the irrigation requirement is met:

$$I[t] = \alpha \times \boldsymbol{IR}[t] \tag{3}$$

where α is the fraction of the irrigation requirement that is actually met. Following the method as proposed in Hoekstra et al. (2009) and also applied by Siebert and Döll (2010), we run two scenarios, one with α=0 (no application of irrigation, i.e. rain-fed conditions) and the other with α=1 (full irrigation). In the second scenario we have assumed that the amount of actual irrigation is sufficient to meet the irrigation requirement. In the case of rain-fed wheat production, blue crop water use is zero and green crop water use (m^3/ha) is calculated by summing up the daily values of $\boldsymbol{ET}_a$ (mm/day) over the length of the growing period. In the case of irrigated wheat production, the green crop water use is assumed to be equal to the green crop water use as was calculated for the rain-fed case. The blue crop water use is then equal to the total $\boldsymbol{ET}_a$ over the growing period as simulated under the case α=1 (full irrigation) minus the green crop water use.

The crop growth and yield are affected by the water stress. To account for the effect of water stress, a linear relationship between yield and crop evapotranspiration was proposed by Doorenbos and Kassam (1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{\sum \boldsymbol{ET}_a[t]}{\sum \boldsymbol{CWR}[t]}\right) \tag{4}$$

where K_y is a yield response factor (water stress coefficient), Y_a the actual harvested yield [kg/ha], Y_m the maximum yield [kg/ha], $\boldsymbol{ET}_a$ the actual crop evapotranspiration in mm/period and CWR the crop water requirement in mm/period (which is equal to $K_c \times \boldsymbol{ET}_o$). K_y values for individual periods and the complete growing period are given in Doorenbos and Kassam (1979). The K_y values for the total growing period for winter

wheat and spring wheat are 1.0 and 1.15, respectively. The maximum yield value for a number of countries is obtained from Ekboir (2002) and Pingali (1999). For countries with no such data the regional average value is taken. The actual yields which are calculated per grid cell are averaged over the nation and compared with the national average yield data (for the period 1996–2005) obtained from FAO (2008a). The calculated yield values are scaled to fit the national average FAO yield data.

The green and blue water footprints (m^3/ton) are calculated by dividing the green and blue crop water use (m^3/ha), respectively, by the actual crop yield (t/ha). Both the total green and the total blue water footprint in each grid cell are calculated as the weighted average of the (green, respectively blue) water footprints under the two scenarios:

$$\boldsymbol{WF} = \beta \times \boldsymbol{WF}(\alpha = 1) + (1 - \beta) \times \boldsymbol{WF}(\alpha = 0) \tag{5}$$

where β refers to the fraction of wheat area in the grid cell that is irrigated.

The grey water footprint of wheat production is calculated by quantifying the volume of water needed to assimilate the fertilisers that reach ground- or surface water. Nutrients leaching from agricultural fields are the main cause of non-point source pollution of surface and subsurface water bodies. In this study we have quantified the grey water footprint related to nitrogen use only. The grey component of the water footprint of wheat ($\boldsymbol{WF}_{gy}$, m^3/ton) is calculated by multiplying the fraction of nitrogen that leached (δ, %) by the nitrogen application rate ($\boldsymbol{AR}$, kg/ha) and dividing this by the difference between the maximum acceptable concentration of nitrogen (c_{max}, kg/m^3) and the natural concentration of nitrogen in the receiving water body (c_{nat}, kg/m^3) and by the actual wheat yield (Y_a, ton/ha):

$$\boldsymbol{WF}_{gy} = \left(\frac{\delta \times \boldsymbol{AR}}{c_{max} - c_{nat}}\right) \times \frac{1}{Y_a} \tag{6}$$

The average green, blue and grey water footprints of wheat in a whole nation or river basin were estimated by taking the area-weighted average of the water footprint (m^3/ton) over the relevant grid cells.

The water footprints of wheat as harvested (unmilled wheat) have been used as a basis to calculate the water footprints of derived wheat products (wheat flour, wheat groats and meal, wheat starch and gluten) based on product and value fractions following the method as in Hoekstra et al. (2009).

International virtual water flows (m^3/yr) related to trade in wheat products were calculated by multiplying the trade volumes (tons/yr) by their respective water footprint (m^3/ton). The global water saving (m^3/yr) through international trade in wheat products is calculated by multiplying the volume of trade (ton/yr) between two countries by the difference between the water footprint of the traded product in the importing country and the water footprint of the product in the exporting country.

The water footprint of national wheat consumption can be distinguished into an internal and external component. The internal water footprint is defined as the use of domestic water resources to produce goods and services consumed by inhabitants of the country. It is the water footprint related to production within the country minus the volume of virtual water export to other countries insofar as related to export of domestically produced products. The external water footprint is the part of the water footprint of national consumption that falls outside the nation considered. It refers to the appropriation of water resources in other nations for the production of goods and services that are imported into and consumed within the nation considered

3 Data

Average monthly reference evapotranspiration data at 10 arc minute resolution were obtained from FAO (2008b). The 10 min data were converted to 5 arc minute resolution by assigning the 10 min data to each of the four 5 min grid cells. Following the CROPWAT approach, the monthly average data were converted to daily values by curve fitting to the monthly average through polynomial interpolation.

Monthly values for precipitation, wet days and minimum and maximum temperature with a spatial resolution of 30 arc minute were obtained from CRU-TS-2.1 (Mitchell

and Jones, 2005). The 30 arc minute data were assigned to each of the thirty-six 5 arc minute grid cells contained in the 30 arc minute grid cell. Daily precipitation values were generated from these monthly average values using the CRU-dGen daily weather generator model (Schuol and Abbaspour, 2007).

Wheat growing areas on a 5 arc minute grid cell resolution were obtained from Monfreda et al. (2008). For countries missing grid data in Monfreda et al. (2008) the MICRA grid database as described in Portmann et al. (2008) was used to fill the gap. The harvested wheat areas as available in grid format were aggregated to a national level and scaled to fit national average wheat harvest areas for the period 1996–2005 obtained from FAO (2008a). Grid data on irrigated wheat area per country were obtained from Portmann et al. (2008).

Crop coefficients (K_c's) for wheat were obtained from Chapagain and Hoekstra (2004). Wheat planting dates and lengths of cropping seasons for most wheat producing countries and regions were obtained from Sacks et al. (2009) and Portmann et al. (2008). For some countries, values from Chapagain and Hoekstra (2004) were used. We have not considered multi-cropping practices.

Grid based data on total available water capacity of the soil (TAWC) at a 5 arc minute resolution were taken from ISRIC-WISE (Batjes, 2006). An average value of TAWC of the five soil layers was used in the model.

Country-specific nitrogen fertilizer application rates for wheat have been based on Heffer (2009), FAO (2006, 2009) and IFA (2009). Globally, wheat accounts for about 17% of total fertilizer use and 19% of the total nitrogen fertilizer consumption. A number of authors show that about 45–85% of the applied nitrogen fertilizer is recovered by the plant (Addiscot, 1996; King et al., 2001; Ma et al., 2009; Noulas et al., 2004). On average, about 16% of the applied nitrogen is presumed to be lost either by denitrification or leaching (Addiscot, 1996). The reported value of nitrogen leaching varies between 2–13% (Addiscot, 1996; Goulding et al., 2000; Riley et al., 2001; Webster et al., 1999). In this study we have assumed that on average 10% of the applied nitrogen fertilizer is lost through leaching, following Chapagain et al. (2006b). The recommended standard

value of nitrate in surface and groundwater by the World Health Organization and the European Union is 50 mg nitrate (NO_3) per litre and the standard recommended by US-EPA is 10 mg per litre measured as nitrate-nitrogen (NO_3-N). In this study we have used the standard of 10 mg/l of nitrate-nitrogen (NO_3-N), following again Chapagain et al. (2006b). Because of a lack of data, the natural nitrogen concentrations were assumed to be zero.

Data on international trade in wheat products have been taken from the SITA database (Statistics for International Trade Analysis) available from the International Trade Centre (ITC, 2007). This database covers trade data over ten years (1996–2005) from 230 reporting countries disaggregated by product and partner countries. We have taken the average for the period 1996–2005 in wheat products trade.

4 The water footprint of wheat from the production perspective

The global water footprint of wheat production for the period 1996–2005 is 1088 Gm^3/year (70% green, 19% blue, and 11% grey). Data per country are shown in Table 1 for the largest producers. The global green water footprint related to wheat production was 760 Gm^3/yr. At a country level, large green water footprints can be found in the USA (112 Gm^3/yr), China (83 Gm^3/yr), Russia (91 Gm^3/yr), Australia (44 Gm^3/yr), and India (44 Gm^3/yr). About 49% of the global green water footprint related to wheat production is in these five countries. At sub-national level (state or province level), the largest green water footprints can be found in Kansas in the USA (21 Gm^3/yr), Saskatchewan in Canada (18 Gm^3/yr), Western Australia (15 Gm^3/yr), and North Dakota in the USA (15 Gm^3/yr). The global blue water footprint was estimated to be 204 Gm^3/yr. The largest blue water footprints were calculated for India (81 Gm^3/yr), China (47 Gm^3/yr), Pakistan (28 Gm^3/yr), Iran (11 Gm^3/yr), Egypt (5.9 Gm^3/yr) and the USA (5.5 Gm^3/yr). These six countries together account for 88% of the total blue water footprint related to wheat production. At sub-national level, the largest blue water footprints can be found in Uttar Pradesh (24 Gm^3/yr) and Madhya Pradesh (21 Gm^3/yr) in

the India and Punjab in Pakistan (20 Gm^3/yr). These three states in the two countries alone account about 32% of the global blue water footprint related to wheat production. The grey water footprint related to the use of nitrogen fertilizer in wheat cultivation was 124 Gm^3/yr. The largest grey water footprint was observed for China (32 Gm^3/yr), India (20 Gm^3/yr) the USA (14 Gm^3/yr) and Pakistan (8 Gm^3/yr).

The calculated global average water footprint per ton of wheat was 1830 m^3/ton. The results show a great variation, however, both within a country and among countries (Fig. 1). Among the major wheat producers, the highest total water footprint per ton of wheat was found for Morocco, Iran and Kazakhstan. On the other side of the spectrum, there are countries like the UK and France with a wheat water footprint of around 560–600 m^3/ton.

The global average blue water footprint per ton of wheat amounts to 343 m^3/ton. For a few countries, including Pakistan, India, Iran and Egypt, the blue water footprint is much higher, up to 1478 m^3/ton in Pakistan. In Pakistan, the blue water component in the total water footprint is nearly 58%. The grey water footprint per ton of wheat is 208 m^3/ton as a global average, but in Poland it is 2.5 times higher than the global average.

Table 2 shows the water footprint related to production of wheat for some selected river basins. About 59% of the global water footprint related to wheat production is located in this limited number of basins. Large blue water footprints can be found in the Ganges-Brahmaputra-Meghna (53 Gm^3/yr), Indus (42 Gm^3/yr), Yellow (13 Gm^3/yr), Tigris-Euphrates (10 Gm^3/yr), Amur (3.1 Gm^3/yr) and Yangtze river basins (2.7 Gm^3/yr). The Ganges-Brahmaputra-Meghna and Indus river basins together account for about 47% of the global blue and 21% of the global grey water footprint.

The global average water footprint of rain-fed wheat production is 1805 m^3/ton, while in irrigated wheat production it is 1868 m^3/ton (Table 3). Obviously, the blue water footprint in rain-fed wheat production is zero. In irrigated wheat production, the blue water footprint constitutes 50% of the total water footprint. Although, on average, wheat yields are 30% higher in irrigated fields, the water footprint of wheat from irrigated lands

is higher than in the case of rain-fed lands. The reason is that, although yields are higher under irrigation, water consumption (evapotranspiration) is higher as well. Under rain-fed conditions, the actual evapotranspiration over the growing period is lower than the potential evapotranspiration, while under irrigated conditions there is more water available to meet crop water requirements, leading to an actual evapotranspiration that will approach or equal potential evapotranspiration.

5 International virtual water flows related to trade in wheat products

The total global virtual water flow related to trade in wheat products averaged over the period 1996–2005 was 200 Gm^3/year. This means that an estimated 18% of the global water footprint was related to wheat production for export. About 87% of this amount comes from green water and only 4% from blue water and the remaining 9% is grey water. Wheat exports in the world are thus basically from rain-fed agriculture. The world's largest 26 wheat producers, which account for about 90% of global wheat production (Table 1), were responsible for about 94% of the global virtual water export. The USA, Canada and Australia alone were responsible for about 55% of the total virtual water export. China, which is the top wheat producer accounting for 17.4% of the global wheat production, was a net virtual water importer. India and the USA were the largest exporters of blue water, accounting for about 62% of the total blue water export. A very small fraction (4%) of the total blue water consumption in wheat production was traded internationally. Surprisingly, some water-scarce regions in the world, relying on irrigation, show a net export of blue water virtually embedded in wheat. Saudi Arabia had a net blue virtual water export of 21 Mm^3/yr and Iraq exported a net volume of blue water of 6 Mm^3/yr. The largest grey water exporters were the USA, Canada, Australia and Germany. Data per country are shown in Table 4 for the largest virtual water exporters and importers, respectively. The largest net virtual water flows related to international wheat trade are shown in Fig. 2.

The global water saving associated with the international trade in wheat products

adds up to 65 Gm^3/yr (39% green, 48% blue, and 13% grey). Import of wheat and wheat products by Algeria, Iran, Morocco and Venezuela from Canada, France, the USA and Australia resulted in the largest global water savings. Figure 3 illustrates the concept of global water saving through an example of the trade in durum wheat from France to Morocco.

6 The water footprint of wheat from the consumption perspective

The global water footprint related to the consumption of wheat products was estimated at 1088 Gm^3/yr, which is 177 m^3/yr per person on average (70% green, 19% blue, and 11% grey). About 82% of the total water footprint related to consumption was from domestic production while the remaining 18% was external water footprint (Fig. 4). In terms of water footprint per capita, Kazakhstan has the largest water footprint, with 1156 m^3/cap/yr, followed by Australia and Iran with 1082 and 716 m^3/cap/yr, respectively. Data per country are shown in Table 5 for the major wheat consuming countries and in Fig. 5 all countries of the world. When the water footprint of wheat consumption per capita is relatively high in a country, this can be explained by either one or a combination of two factors: (i) the wheat consumption in the country is relatively high; (ii) the wheat consumed has a high water footprint per kg of wheat. As one can see in Table 5, in the case of Kazakhstan and Iran, both factors play a role. In the case of Australia, the relatively high water footprint related to wheat consumption can be mostly explained by the high wheat consumption per capita alone. Germany has a large wheat consumption per capita – more than twice the world average – so that one would expect that the associated water footprint would be high as well, but this is not the case because, on average, the wheat consumed in Germany has a low water footprint per kg (43% of the global average).

The countries with the largest external water footprint related to wheat consumption were Brazil, Japan, Egypt, Italy, the Republic of Korea and Iran. Together, these countries account for about 28% of the total external water footprint. Japan's water

footprint related to wheat consumption lies outside the country for about 93%. In Italy, with an average wheat consumption of 150 kg/yr per person, more than two times the word average, this was about 44%. Most African, South-East Asian, Caribbean and Central American countries strongly rely on external water resources for their wheat consumption as shown in Fig. 6.

7 Case studies

7.1 The water footprint of wheat production in the Ogallala area (USA)

The Ogallala Aquifer, also known as the High Plains Aquifer, is a regional aquifer system located beneath the Great Plains in the United States in portions of the eight states of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. It covers an area of approximately 451 000 km^2, making it the largest area of irrigation-sustained cropland in the world (Peterson and Bernardo, 2003). Most of the aquifer underlies parts of three states: Nebraska has 65% of the aquifer's volume, Texas 12% and Kansas 10% (Peck, 2007). About 27 percent of the irrigated land in the United States overlies this aquifer system, which yields about 30 percent of the nation's ground water used for irrigation (Dennehy, 2000).

Water from the Ogallala Aquifer is the principal source of supply for irrigated agriculture. In 1995, the Ogallala Aquifer contributed about 81% of the water supply in the Ogallala area while the remainder was withdrawn from rivers and streams, most of it from the Platte River in Nebraska. Outside of the Platte River Valley, 92% of water used in the Ogallala area is supplied by ground water (Dennehy, 2000). Since the beginning of extensive irrigation using ground water, the water level of the aquifer has dropped by 3 to 15 m in most part of the aquifer (McGuire, 2007).

Within the Ogallala area, Kansas takes the largest share in wheat production (51%), followed by Texas and Nebraska (16% and 15%, respectively). In Kansas, 84% of the wheat production comes from rain-fed areas. In Nebraska, this is 86% and in Texas

47%. The Ogallala area accounts for about 14% of the total wheat production in the USA. Our study shows that 16% of the total water footprint of wheat production in the country lies in the Ogallala area. About 19% of the *blue* water footprint of wheat production in the USA is in the Ogallala area (Table 6). The total water footprint in the Ogallala area was 21 Gm^3/yr (85% green, 5% blue, and 10% grey).

Texas takes the largest share (39%) in the blue water footprint of wheat production in the Ogallala area, followed by Kansas (35%). There is a considerable variation in the blue water footprint per ton of wheat within the Ogallala area. Besides, the blue water footprint per ton of wheat in the Ogallala area is relatively high if compared to the average in the USA.

In the period 1996–2005, the virtual water export related to export of wheat products from the USA was 57 Gm^3/yr. About 98% (55.6 Gm^3/yr) of the virtual water export comes from domestic water resources and the remaining 2% (1.4 Gm^3/yr) is from re-export of imported virtual water related to import of wheat products. If we assume that wheat export from the USA comes from the different states proportional to their production, the virtual water export for the period 1996–2005 from the Ogallala area was 8.9 Gm^3/yr, which is 42% of the total water footprint related to wheat production in the Ogallala area (Table 6). Figure 7 shows the major foreign destinations of wheat-related virtual water exports from the area of the Ogallala Aquifer.

7.2 The water footprint of wheat production in the Ganges and Indus river basins

The Ganges river basin, which is part of the composite Ganges-Brahmaputra-Meghna river basin, is one of most densely populated river basins in the world. It covers about 1 million km^2 (Gleick, 1993). The Indus river basin, which extends over four countries (China, India, Pakistan and Afghanistan), is also a highly populated river basin. The area of the Indus basin is a bit smaller than the Ganges basin but covers nearly 1 million km^2 as well (Gleick, 1993).

The two river basins together account for about 90 percent of the wheat production

in India and Pakistan in the period 1996–2005. Almost all wheat production (98%) in Pakistan comes from the Indus river basin. About 89% of India's wheat is produced in the Ganges (62%) and the Indus basin (27%). About 87% of the total water footprint related to wheat production in India and Pakistan lies in these two river basins. The total water footprint of wheat production in the Indian part of the Ganges basin is 92 Gm^3/yr (32% green, 54% blue, 14% grey). The total water footprint of wheat production in the Pakistani part of the Indus basin is 48 Gm^3/yr (25% green, 58% blue, 17% grey).

In the period 1996–2005, India and Pakistan together had a virtual water export related to wheat export of 5.1 Gm^3/yr (29% green water, 56% blue, 15% grey), which is a small fraction (3%) of the total water footprint of wheat production in these two countries. About 55% of this total virtual water export comes from the Ganges basin and 45% from the Indus basin. The blue water export to other countries from the Ganges and Indus river basins was 1304 Mm^3/yr and 1077 Mm^3/yr, respectively.

Based on the water withdrawal-to-availability ratio, which is an indicator of water stress (Alcamo et al., 2003a, 2007; Cosgrove and Rijsberman, 2000), most parts of Pakistan and India are highly water stressed (Alcamo et al., 2003b). Both the Ganges and Indus river basins are under severe water stress, in particular the Indus river basin. About 97% of the water footprint related to wheat production in the two basins is for domestic consumption within the two countries. Since the two basins are the wheat baskets of the two countries, there are substantial virtual water transfers from the Ganges and Indus basins to other areas within India and Pakistan. By looking at the virtual flows both within the country and to other countries, it is possible to link the impacts of wheat consumption in other places to the water stress in the Ganges and Indus basins. For the case of India, Kampman et al. (2008) have shown that the states which lie within the Indus and Ganges river basins, such as Punjab, Uttar Pradesh and Haryana are the largest inter-state virtual water exporters within India. The highly subsidized irrigation water in these regions has led to an intensive exploitation of the available water resources in these areas compared to other, more water-abundant regions of India. In order to provide incentives for water protection, negative externalities such as water

overexploitation and pollution, and also scarcity rents should be included in the price of the crop. Both basins have a relatively high water productivity, which is shown by a smaller water footprint per ton of wheat, compared to other wheat producing areas in the two countries (Fig. 8). Since wheat is a low-value crop, one may question whether water allocation to wheat production for export in states such as Punjab, Uttar Pradesh and Haryana is worth the cost. A major destination of wheat exports from India's parts of the Indus and Ganges basins is East India, to states like Bihar. Major foreign destinations of India's virtual water export related to export of wheat products are Bangladesh (22%), Indonesia (11%), Philippines (10%) and Yemen (10%). Pakistan's export mainly goes to Afghanistan (56%) and Kenya (11%).

7.3 The external water footprint of wheat consumption in Italy and Japan

In the previous two sections we have looked into the water footprint of wheat production in specific areas of the world and analysed how this water footprints could be linked to consumers elsewhere. In this section we will do the reverse: we will consider the wheat consumers in two selected countries – Italy and Japan – and trace where their water footprint lies.

Italy's water footprint related to the consumption of wheat products for the period 1996–2005 was 17.4 Gm^3/yr. More than half (56%) of Italy's water footprint is pressing on domestic water systems. The rest of the water footprint of Italian wheat consumption lies in other countries, mainly the USA (20%), France (19%), Canada (11%) and Russia (10%). The water footprint of Italy's wheat consumers in the USA lies in different regions of that country, among others in the Ogallala area as earlier shown in Fig. 7. Italy also imports virtual water from the water-scarce countries of the Middle East, such as Syria (58 Mm^3/yr) and Iraq (36 Mm^3/yr).

About 93% of the water footprint of wheat consumption in Japan lies in other countries, mainly in the USA (59%), Australia (22%) and Canada (19%). About 87% of Japan's external water footprint is from green water. Japan's wheat-related water footprint in the USA partly presses on the water resources of the Ogallala area as shown

in Fig. 7. The water footprint in Australia largely lies in Southern Australia where most of the wheat is produced and water scarcity is high.

8 Discussion

The results of the current study can be compared to results from earlier studies as shown in Table 7. The global average water footprint of wheat in our study comes to 1622 m^3/ton (excluding grey water), while earlier studies gave estimates of 1334 m^3/ton (Chapagain and Hoekstra, 2004), 1253 m^3/ton (Liu et al., 2007) and 1469 m^3/ton (Siebert and Döll, 2010). A variety of factors differ in the various studies, so that it is difficult to identify the main reason for the different results. The model results with respect to the wheat water footprint per ton can also be compared for a number of specific locations to the inverse of the measured crop water productivity values as collected by Zwart and Bastiaanssen (2004). The comparison shows that out of 28 measured sites, for 17 sites (61% of the time) the simulated water footprint lies within the range of measured values.

The model results with respect to the total global water footprint of wheat production can be compared to three previous global wheat studies. The study by Chapagain and Hoekstra (2004) did not take a grid-based approach and also did not make the green-blue distinction, unlike the current study and the studies by Siebert and Döll (2010) and Liu et al. (2009), therefore we will compare here only with the latter two. When we compare the computed green and blue water footprints to the computation by Siebert and Döll (2010), we find that their estimate of the total water footprint of global wheat production is 11% lower, which is completely due to their lower estimate of the green water footprint component. The estimate of the total water footprint by Liu et al. (2009) is 29% lower than our estimate, again due to the difference in the estimate of the green component. The relatively low value presented by Liu et al. (2009) is not a surprise given the fact that their estimate is based on the GEPIC model, which has been shown to give low estimates of evapotranspiration compared to other models

(Hoff et al., 2010). Our estimate of the total green water footprint in global wheat production is 760 Gm^3/yr (period 1996–2005), whereas Siebert and Döll (2010) give an estimation of 650 Gm^3/yr (period 1998–2002) and Liu et al. (2009) 540 Gm^3/yr (1998–2002). Our estimate of the total blue water footprint in global wheat production is 204 Gm^3/yr, whereas Siebert and Döll (2010) give an estimation of 208 Gm^3/yr and Liu et al. (2009) 150 Gm^3/yr.

Liu et al. (2009) use another water balance model than applied in the current study. As a basis, they use the EPIC model (Williams et al., 1989), whereas we apply the model of Allen et al. (1998). Although both models compute the same variables, EPIC has been developed as a crop growth model, whereas the model of Allen et al. (1998) has been developed as a water balance model, which makes that the two models have a different structure and different parameters. One of the differences is the runoff model applied, which affects the soil water balance and thus soil water availability and finally the green water footprint. Besides, Liu et al. (2009) estimate water footprints (m^3/ton) based on computed yields, whereas we use computed yields, but scale them according to FAO statistics. Siebert and Döll (2010) basically apply the same modelling approach as in the current study. Both studies have the same spatial resolution, carry out a soil water balance with a daily time step, use the same CRU TS-2.1 climate data source to generate the daily precipitation and use the same crop, soil and irrigation maps. Although there are many similarities, the studies differ in some respects. For estimating daily reference evapotranspiration data, Siebert and Döll (2010) applied the cubic splin method to generate daily climate data from the monthly data as provided in the available database. In contrast, we have used long-term monthly average reference evapotranspiration global spatial data obtained from FAO (2008b) and converted these data to daily values by polynomial interpolation. Further, Siebert and Döll (2010) have considered multi-cropping based on a number of assumptions and generated their own cropping calendar based on climatic data, while in our study we have neglected multi-cropping and adopted cropping calendars as provided in literature at country level. Siebert and Döll (2010) compute local yields and scale them later on, like in the current

study, but scaling is done in different manner. Finally, in our study we include the grey water footprint and study international virtual water flows, which is not done by Siebert and Döll (2010).

It is difficult to make a conclusion about the accuracy or reliability of our estimates vice versa the quality of the data presented in the other two modelling studies cited. All studies depend on a large set of assumptions with respect to modelling structure, parameter values and datasets used. For the time being, it is probably best to conclude that the divergence in outcomes is a reflection of the uncertainties involved. It implies that all estimates – both from the current and the previous studies – should be interpreted with care. Assuming that the different study periods are comparable, the three studies together give an estimation of the total water footprint of wheat production of about 830 Gm^3/yr±17%. This uncertainty range is probably still a conservative estimate, because it is based on the central estimates of three different modelling studies only. Furthermore, locally, differences and uncertainty ranges can be larger.

The green water footprint estimate is sensitive to a variety of assumptions, including: (a) the daily rain pattern (b) the modelling of runoff, (c) the rooting depth, (d) the soil type, which determines the soil water holding capacity, (e) the planting and harvesting dates and thus the length of the growing period, (f) the moisture content in the soil at the moment of planting, (g) the modelling of yield. The blue water footprint estimate depends on the same assumptions, plus it depends on data on actual irrigation. In a global study, given the limitations in global databases, it seems very difficult in this stage to reduce the uncertainties. Higher resolution maps of all input parameters and variables, based on either local measurements or remote sensing (Romaguera et al., 2010) may finally help to reduce the uncertainties in a global assessment like this one. In local studies, it will generally be less time-consuming to find better estimates for the various parameters and data involved and better be able to validate the model used for the specific local conditions, so that uncertainties can be reduced more easily.

9 Conclusion

Estimating water footprints of crops at national level and estimating international virtual water flows based on those national estimates – as done in all previous global water footprint studies until date – hides the existing variation at sub-national level in climatic conditions, water resources availability and crop yields. Therefore, the present study is an attempt to improve water footprint accounting through implementing the calculations at a grid basis, which takes into account the existing heterogeneity at grid level. Such approach has the advantage of being able to pinpoint precisely in space where the water footprint of wheat consumption is located. We have combined the water footprint assessment framework as provided in Hoekstra and Chapagain (2008) and Hoekstra et al. (2009) with a grid-based approach to estimating crop evapotranspiration as applied by for example Liu et al. (2009) and Siebert and Döll (2010).

The study showed that the global water footprint of wheat production for the period 1996–2005 was 1088 Gm^3/yr (70% green, 19% blue, 11% grey). Since about 18% of the global water footprint related to wheat production is for making products for export, the importance of mapping the impact of global wheat consumption on local water resources with the help of the water footprint and virtual water trade accounting framework is quite clear. Quantifying the water footprint of wheat consumption and visualizing the hidden link between wheat consumers and their associated appropriation of water resources elsewhere (in the wheat producing areas) is quite relevant. The study shows that countries such as Italy and Japan, with high external water footprints related to wheat consumption, put pressure on the water resources of their trading partners. Including a water scarcity rent and the external costs of water depletion and pollution in the price of the wheat traded is crucial in order to provide an incentive within the global economy to enhance the efficiency and sustainability of water use and allocation.

The model result was compared with measured water productivity values found in the literature and outputs of previous studies. It appears very difficult to attribute differences in estimates from the various studies to specific factors; also it is difficult to assess the

quality of our new estimates relative to the quality of earlier estimates. Our grid-based estimates of the water footprint of wheat production are better than the earlier national estimates as provided by Chapagain and Hoekstra (2004), but it is not possible to claim that they are better than the results from similar grid-based estimates as presented by Liu et al. (2009) and Siebert and Döll (2010). The quality of input data used defines the accuracy of the model output; all studies suffer the same sorts of limitations in terms of data availability and quality and deal with that in different ways. It has been observed that the model output is sensitive for example to the soil data and crop calendar, which are parameters about which no accurate data are available. A slight change in the planting date and length of cropping has a significant impact on the crop water footprint. In future studies it would be useful to spend more effort in structurally studying the sensitivity of the model outcomes to assumptions and parameters and assessing the uncertainties in the final outcome.

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Table 1. Water footprint of wheat production for the major wheat producing countries. Period: 1996–2005.

Country	Contribution to global wheat production (%)	Total water footprint of production (Mm^3/yr)				Water footprint per ton of wheat (m^3/ton)			
		Green	Blue	Grey	Total	Green	Blue	Grey	Total
Argentina	2.5	25 905	162	1601	27 668	1777	11	110	1898
Australia	3.6	44 057	363	2246	46 666	2130	18	109	2256
Canada	3.9	32 320	114	4852	37 286	1358	5	204	1567
China	17.4	83 459	47 370	31 626	162 455	820	466	311	1597
Czech Republic	0.6	2834	0	900	3734	726	0	231	957
Denmark	0.8	2486	30	533	3049	530	6	114	651
Egypt	1.1	1410	5930	2695	10 034	216	907	412	1536
France	6.0	21 014	48	199	21 261	584	1	6	591
Germany	3.5	12 717	0	3914	16 631	602	0	185	787
Hungary	0.7	4078	8	1389	5476	973	2	331	1306
India	11.9	44 025	81 335	20 491	145 851	635	1173	296	2104
Iran	1.8	26 699	10 940	3208	40 847	2412	988	290	3690
Italy	1.2	8890	120	1399	10 409	1200	16	189	1405
Kazakhstan	1.7	33 724	241	1	33 966	3604	26	0	3629
Morocco	0.5	10 081	894	387	11 362	3291	292	126	3710
Pakistan	3.2	12 083	27 733	8000	47 816	644	1478	426	2548
Poland	1.5	9922	4	4591	14 517	1120	0	518	1639
Romania	0.9	9066	247	428	9741	1799	49	85	1933
Russian Fed.	6.5	91 117	1207	3430	95 754	2359	31	89	2479
Spain	1.0	8053	275	1615	9943	1441	49	289	1779
Syria	0.7	5913	1790	842	8544	1511	457	215	2184
Turkey	3.3	40 898	2570	3857	47 325	2081	131	196	2408
UK	2.5	6188	2	2292	8482	413	0	153	566
Ukraine	2.5	26 288	287	1149	27 724	1884	21	82	1987
USA	10.2	111 926	5503	13 723	131 152	1879	92	230	2202
Uzbekistan	0.7	3713	399	0	4112	939	101	0	1039
World		760 301	203 744	123 533	1 087 578	1279	343	208	1830

Table 2. The water footprint of wheat production for some selected river basins (1996–2005).

River basin	Total water footprint of production (Mm^3/yr)				Water footprint per ton of wheat (m^3/ton)			
	Green	Blue	Grey	Total	Green	Blue	Grey	Total
Ganges-Brahmaputra-Meghna	30 288	53 009	12 653	95 950	665	1164	278	2107
Mississippi	79 484	2339	9413	91 236	1979	58	234	2271
Indus	22 897	42 145	13 326	78 368	604	1111	351	2066
Ob	51 984	225	511	52 721	2680	12	26	2718
Nelson-Saskatchewan	38 486	118	5691	44 294	1275	4	189	1468
Tigris-Euphrates	29 219	10 282	2670	42 170	2893	1018	264	4175
Yellow	17 012	13 127	7592	37 731	695	536	310	1541
Danube	27 884	273	3579	31 735	1298	13	167	1477
Volga	25 078	272	955	26 305	2315	25	88	2429
Don	24 834	384	927	26 144	2658	41	99	2799
Yangtze	17 436	2700	4855	24 991	1112	172	310	1594
Murray-Darling	20 673	343	987	22 003	2061	34	98	2193
La Plata	17 127	73	1070	18 271	2039	9	127	2175
Amur	8726	3136	2355	14 216	985	354	266	1604
Dnieper	13 219	68	813	14 100	1732	9	107	1847
Columbia	7238	1877	1122	10 236	1852	480	287	2620
Oral	9338	94	192	9624	2542	26	52	2620
World	760 301	203 744	123 533	1 087 578	1279	343	208	1830

Table 3. The global water footprint of wheat production in rain-fed and irrigated lands (1996–2005).

Farming system	Yield (t/ha)	Total water footprint of production (Mm^3/yr)				Water footprint per ton of wheat (m^3/ton)			
		Green	Blue	Grey	Total	Green	Blue	Grey	Total
Rain-fed	2.5	611	0	66	676	1629	0	175	1805
Irrigated	3.3	150	204	58	411	679	926	263	1868
World average	2.7	760	204	124	1088	1279	343	208	1830

Table 4. Gross virtual water export and import related to the international trade of wheat products in the period 1996–2005.

Largest virtual water exporters (Mm^3/yr)					Largest virtual water importers (Mm^3/yr)				
	Green	Blue	Grey	Total		Green	Blue	Grey	Total
USA	48 603	2389	5959	56 952	Brazil	11 415	88	801	12 304
Canada	24 144	85	3625	27 854	Japan	10 393	320	1147	11 860
Australia	24 396	201	1244	25 841	Italy	7345	174	760	8279
Argentina	15 973	100	987	17 060	Egypt	6838	274	633	7745
Kazakhstan	16 490	118	0	16 608	Korea, Rep	6511	398	685	7594
France	9347	21	89	9457	Indonesia	6512	364	577	7453
Russian Fed	7569	100	285	7954	Iran	6105	60	504	6670
Ukraine	4587	50	200	4837	Malaysia	5616	185	636	6437
Germany	3537	0	1090	4626	Algeria	5330	323	696	6350
India	1266	2338	589	4193	Mexico	5155	205	660	6020
Turkey	2208	139	208	2555	Russian Fed	5334	69	92	5495
UK	1189	0	441	1630	Philippines	3923	426	538	4887
Spain	1242	42	249	1534	Spain	4161	80	493	4734
Hungary	1035	2	352	1389	China	4087	98	453	4638
Others	13 107	2202	2488	17 797	Others	85 967	4725	9131	99 823
Global flow	174 693	7789	17 807	200 289	Global flow	174 693	7789	17 807	200 289

Table 5. Water footprint of wheat consumption for the major wheat consuming countries (1996–2005).

Countries	Internal water footprint (Mm^3/yr)			External water footprint (Mm^3/yr)			Water footprint		WF per capita	Wheat consumption per capita	WF of wheat products
	Green	Blue	Grey	Green	Blue	Grey	Total WF (Mm^3/yr)	WF per capita (m^3/yr)	Fraction of world average	Fraction of world average	Fraction of world average
China	82 990	47 091	31 442	4064	97	450	166134	133	0.75	0.86	0.88
India	42 786	78 997	19 903	931	17	64	142 699	135	0.76	0.66	1.15
Russia	83 967	1112	3152	4915	63	85	93 295	635	3.59	2.67	1.33
USA	64 508	3124	7941	1612	15	244	77 444	270	1.53	1.32	1.17
Pakistan	11 900	27 218	7856	2752	90	259	50 075	345	1.95	1.42	1.37
Iran	26 693	10 937	3208	6104	60	504	47 505	716	4.04	2.32	1.74
Turkey	38 810	2434	3659	2238	54	181	47 376	691	3.90	2.98	1.30
Ukraine	21 905	239	955	1021	12	30	24 163	496	2.80	2.78	1.01
Australia	19 671	162	1005	8	1	3	20 851	1082	6.11	5.47	1.16
Brazil	6901	3	469	11 224	88	788	19 472	111	0.63	0.58	1.08
Egypt	1409	5924	2692	6837	274	633	17 768	264	1.49	1.62	0.92
Kazakhstan	17 312	124	1	83	1	7	17 529	1156	6.53	3.92	1.85
Italy	8274	114	1284	6837	165	697	17 372	300	1.69	2.35	0.70
Poland	9687	4	4478	572	7	94	14 841	386	2.18	2.48	0.87
Morocco	9923	877	383	3230	68	306	14 786	505	2.85	2.21	1.29
Germany	9459	0	2868	810	13	120	13 270	161	0.91	2.07	0.43
World	593 599	196 690	106 972	166 703	7147	16 586	1 087 696	177			

Table 6. Water footprint of wheat production and virtual water export from the Ogallala area (1996–2005).

States in the Ogallala area[a]	Water footprint related to wheat production (Mm^3/yr)				Virtual water export related to export of wheat products (Mm^3/yr)			
	Green	Blue	Grey	Total	Green	Blue	Grey	Total
Kansas	9136	368	1077	10 581	3872	156	456	4484
Texas	1981	417	301	2699	839	177	128	1144
Nebraska	2952	78	345	3375	1251	33	146	1430
Colorado	2108	67	281	2456	893	29	119	1041
Oklahoma	693	26	91	809	293	11	38	343
New Mexico	317	94	45	455	134	40	19	193
South Dakota	211	0	24	235	90	0	10	100
Wyoming	299	6	34	338	127	2	14	143
Ogallala area total	17 696	1056	2196	20 949	7499	448	931	8877
USA total	111 926	5503	13 723	131 152	48 603	2389	5959	56 952

[a] Values in the table refer to the part of the states within the Ogallala area only.

Table 7. Comparison between the results from the current study with the results from previous studies.

Study	Period	Global average water footprint of wheat m^3/ton	Global water footprint related to wheat production Gm^3/yr	International virtual water flows related to wheat trade Gm^3/yr	Global water saving due to wheat trade Gm^3/yr
Hoekstra and Hung (2002, 2005)	1995–1999	–	–	210	–
Chapagain and Hoekstra (2004), Chapagain et al. (2006a), Hoekstra and Chapagain (2008)	1997–2001	1334	793	114	103
Oki and Kanae (2004)	2000	–	–	271	193
Yang et al. (2006)	1997-2001	–	–	188	130
Liu et al. (2007, 2009)	1998–2002	1253	688	159	77
Siebert and Döll (2010)	1998–2002	1469	858	–	–
Hanasaki et al. (2010)	2000	–	–	122	–
Current study, green & blue only	1996–2005	1622	964	182	57
Current study incl. grey water[a]	1996–2005	1830	1088	200	65

[a] None of the previous studies included grey water, so these figures are for information only, not for comparison.

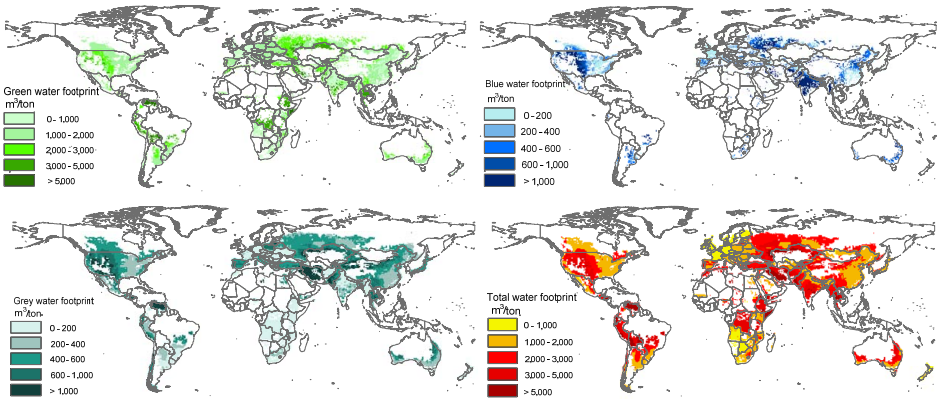


Fig. 1. The green, blue, grey and total water footprint of wheat production per ton of wheat. Period: 1996–2005.

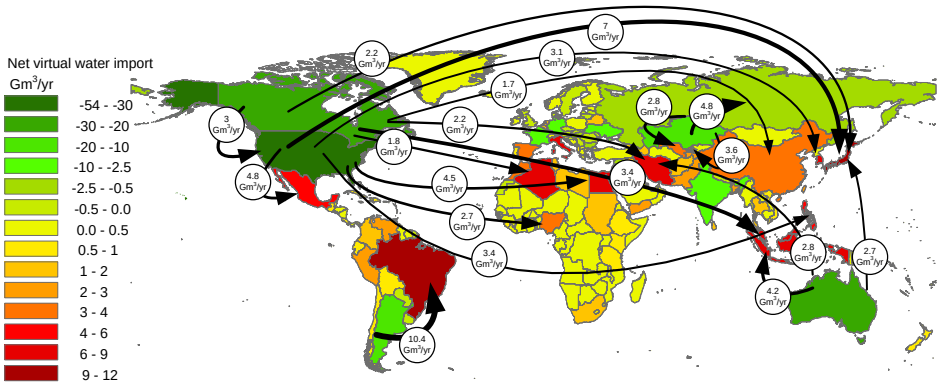


Fig. 2. National virtual water balances and net virtual water flows related to trade in wheat products in the period 1996–2005. Only the largest net flows (>2 Gm^3/yr) are shown.

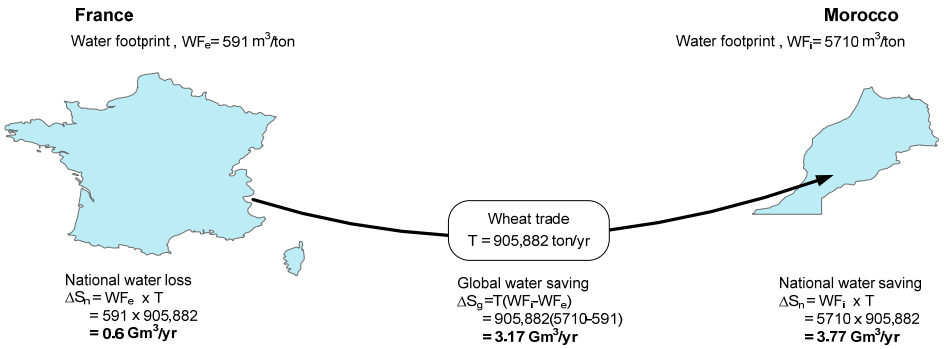


Fig. 3. Global water saving through the trade in durum wheat from France to Morocco. Period: 1996–2005.

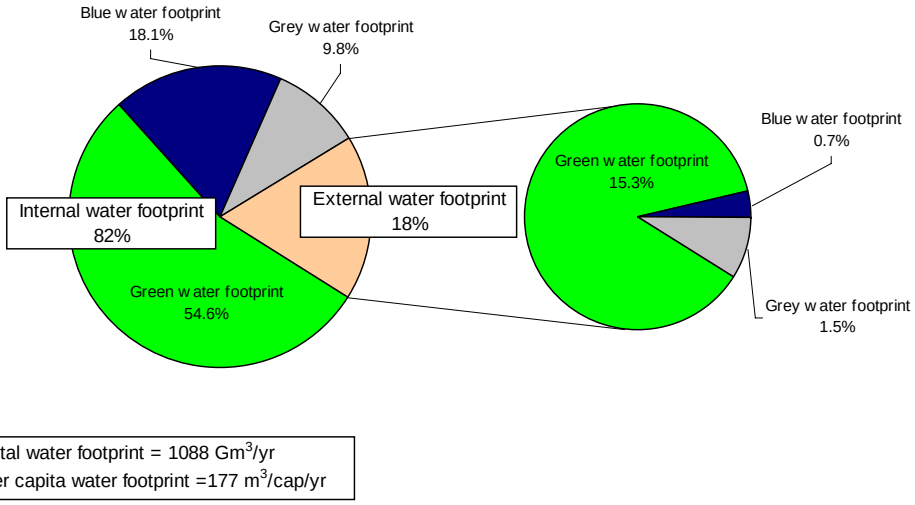


Fig. 4. Global water footprint related the consumption of wheat products. Period: 1996–2005.

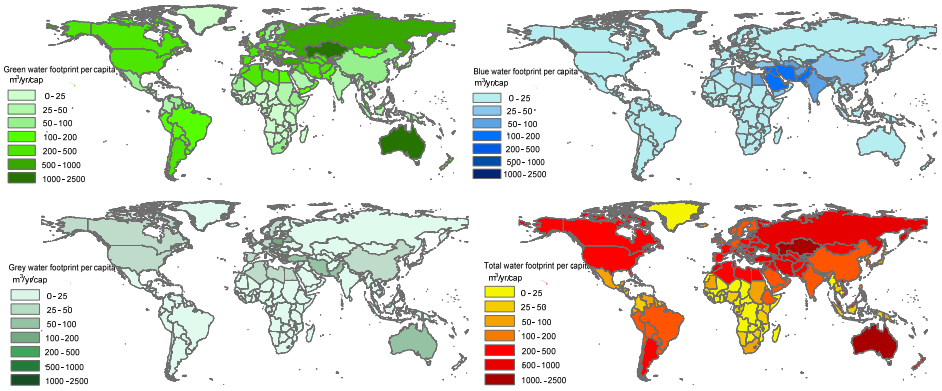


Fig. 5. Water footprint per capita related to consumption of wheat products in the period 1996–2005.

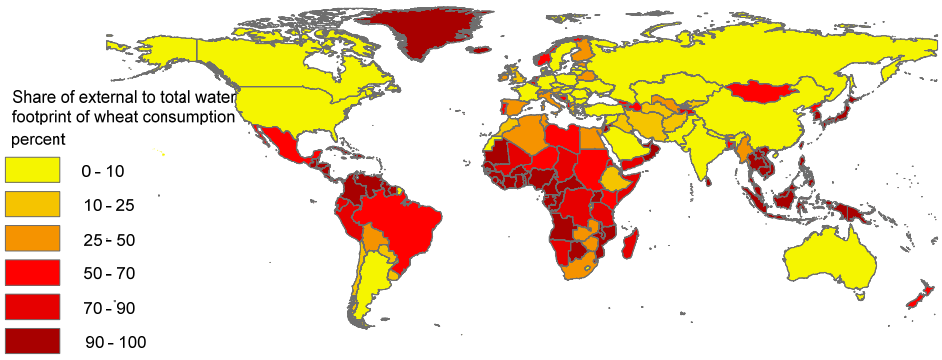


Fig. 6. The extent to which countries rely on external water resources for their wheat consumption. Period: 1996–2005.

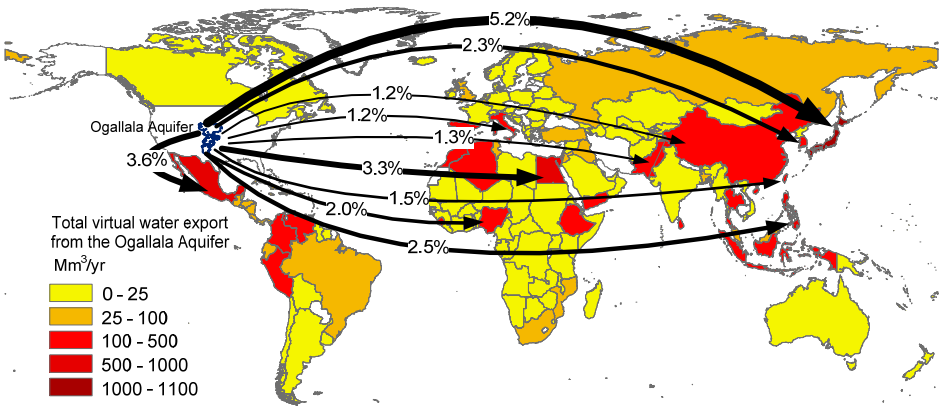


Fig. 7. Major destinations of wheat-related virtual water exports from the Ogallala area in the USA (1996–2005). About 58% of the total water footprint of wheat production in the area is for wheat consumption in the USA and 42% is for export to other nations. Only the largest exports (>1%) are shown.

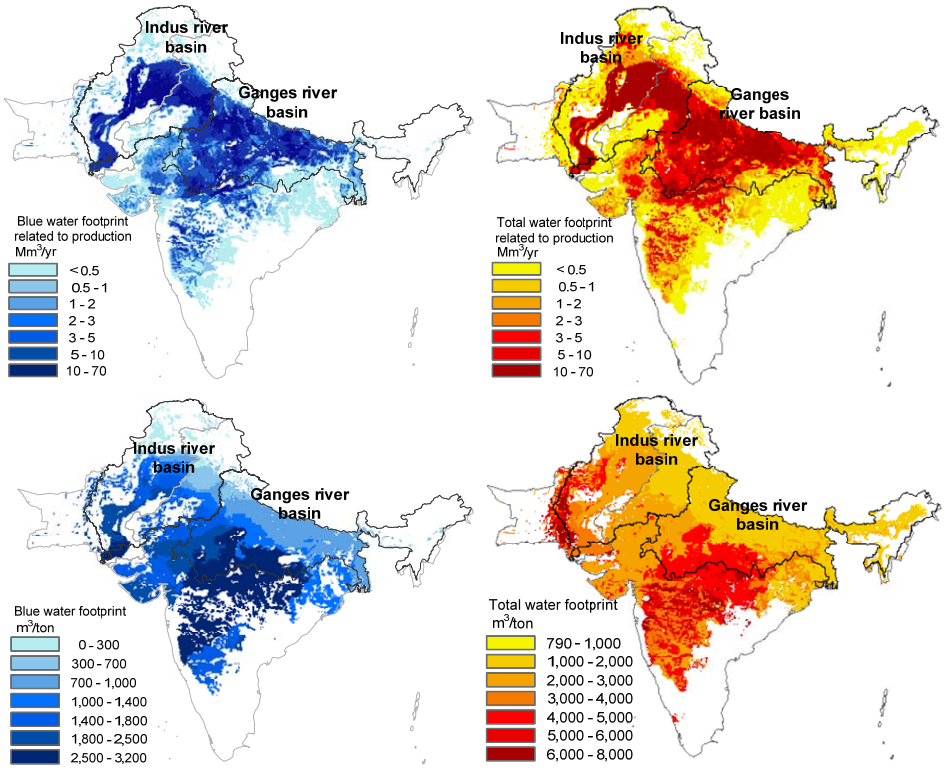


Fig. 8. The total and blue water footprint related to wheat production in India and Pakistan, both expressed as a total (Mm^3/yr) and per ton of wheat (m^3/ton). Period: 1996–2005.