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

M.M. Mekonnen
A.Y. Hoekstra

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M.M. Mekonnen¹
A.Y. Hoekstra¹,²

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¹ Twente Water Centre, University of Twente, Enschede, The Netherlands
² Contact author: Arjen Hoekstra, a.y.hoekstra@utwente.nl

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Summary

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 (Hoekstra et al., 2009).

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 m³/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 Gm³/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; 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 1995-99 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 and data

2.1. 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 (Chapter 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 steps followed in the calculation framework are schematically shown in Figure 1.

![Figure 1. Simplified representation of the model to calculate the water footprint of a crop.](image-url)
Under conditions in which water is not a limiting factor, the maximum crop evapotranspiration (the crop water requirement) is expressed as:

\[ CWR(t) = K_c[t] \times ET_o[t] \]  

(1)

where \( CWR(t) \) is the crop water requirement, \( K_c \) the crop coefficient and \( ET_o[t] \) the reference evapotranspiration (mm/day). The crop coefficient varies in time, as a function of the plant growth stage as shown in Figure 2. 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.

\[ K_c[t] = K_{c,ini} + (K_{c,mid} - K_{c,ini}) \times \frac{J(t) - J_{dev}}{L_{dev}} \]  

(2)

For the late stage:

\[ K_c[t] = K_{c,mid} + (K_{c,end} - K_{c,mid}) \times \frac{J(t) - J_{late}}{L_{late}} \]  

(3)

where \( J \) is the day number within the growing season, \( J_{dev} \) the day number at the beginning of the development period, \( J_{late} \) the day number at the beginning of the late season stage. \( L_{dev} \) and \( L_{late} \) represent the length of the development and late season stages respectively.

The actual crop evapotranspiration (\( ET_a \), mm/day) depends on soil water availability. The effect of soil water stress on the crop evapotranspiration is expressed as (Allen et al, 1998):
\[ ET_a[t] = K_s[t] \times CWR[t] \]  

with:

\[
K_s[t] = \begin{cases} 
\frac{S[t]}{(1-p) \times S_{\text{max}}[t]} & \text{if } S[t] < (1-p) \times S_{\text{max}}[t] \\ 
1 & \text{Otherwise} 
\end{cases}
\]  

where \( K_s[t] \) is a dimensionless transpiration reduction factor dependent on available soil water [0-1]; \( S[t] \) the actual available soil moisture at time \( t \) [mm]; \( S_{\text{max}}[t] \) the maximum available soil water in the root zone, i.e., the available soil water in the root zone when soil water content is at field capacity [mm] (represented by the symbol TAW in Allen et al., 1998); and \( p \) the fraction of \( S_{\text{max}} \) that a crop can extract from the root zone without suffering water stress [-].

Following heavy rainfall and irrigation, all the pores of soil will be filled with water until the saturation point is reached. During dry days, water will drain out of the root zone until the field capacity is reached. Field capacity (\( \theta_{\text{FC}} \)) refers to the amount of water that a well-drained soil can hold against the gravitational forces. Unless there is an additional water supply, the water content in the root zone will decrease due to water uptake by the crops. As evapotranspiration progresses the remaining water is held to the soil particles at increasingly greater suctions and it is more difficult for the plants to extract it. Eventually, the point is reached where water is tightly held in very fine pores and is no longer available to plants. This point is defined as the permanent wilting point (\( \theta_{\text{WP}} \)). The maximum available soil water in the root zone (\( S_{\text{max}} \)) at a certain point in time is the amount of water held in a soil between the limits of field capacity and permanent wilting point (Figure 3). The maximum available water (\( S_{\text{max}} \)) is expressed as:

\[
S_{\text{max}}[t] = 1000 \times (\theta_{\text{FC}} - \theta_{\text{WP}}) \times Z_r[t] = TAWC \times Z_r[t] 
\]

in which \( \theta_{\text{FC}} \) is the water content at field capacity [m$^3$/m$^3$]; \( \theta_{\text{WP}} \) the water content at wilting point [m$^3$/m$^3$]; \( Z_r \) the time-dependent rooting depth [m]; and \( TAWC \) the total available water capacity in 1 m soil, i.e. the available soil water in the root zone when soil water content is at field capacity [mm/m]. Not all \( S_{\text{max}} \) is available to plants. Under sufficient soil moisture, the soil will supply water at the rate the crop takes up water in order to meet its atmospheric demand, and water uptake equals the crop water requirement (CWR). As the soil moisture drops below the stress threshold value, the plant will come under water-stress and wilt. The fraction of \( S_{\text{max}} \) that a crop can extract from the root zone without suffering water stress is the readily available soil water (\( RAW \), mm) and is expressed as:

\[
RAW[t] = p[t] \times S_{\text{max}}[t] 
\]
Figure 3. Water balance of the root zone and water stress coefficient (Ks) as a function of the actual available soil moisture (S) in case of a rooting depth Zr (based on Allen et al., 1998).

The depletion fraction p depends on the crop type and the maximum crop evapotranspiration and is expressed as:

\[ p(t) = p_{std} + 0.04 \times (5 - CWR(t)) \]  

(8)

where \( p_{std} \) is the standard depletion fraction for crop water requirement \( CWR[t] \approx 5 \text{ mm/day} \) and is obtained from Allen et al (1998). The adjusted p should be within the range \( 0.1 \leq p \leq 0.8 \).

For annual crops the effective root depth varies in time, as a function of the plant growth stage as shown in Figure 4. During the initial stages of the crop development, \( Z_r \) is assumed to be constant and equals \( Z_{r,\text{min}} \). During the crop development season stage, \( Z_r \) increases in proportion to the increase in \( K_r \) and reaches a maximum by the beginning of the midseason (Allen et al., 1998).
Figure 4. Development of effective root depth ($Z_r$) during the crop growing season.

The effective root zone depth on day $t$ is calculated as follows:

$$
Z_r[t] = \begin{cases} 
Z_{r,\min} + (Z_{r,\max} - Z_{r,\min}) \times \frac{(K_c - K_{c,\text{ini}})}{(K_{c,\text{mid}} - K_{c,\text{ini}})} & \text{if } J < J_{\text{mid}} \\
Z_{r,\max} & \text{if } J \geq J_{\text{mid}} 
\end{cases}
$$

(9)

where $K_{c,\text{ini}}$ is the initial crop coefficient; $K_{c,\text{mid}}$ the mid-season crop coefficient; $K_c$ the crop coefficient at Julian date $J$; $J_{\text{mid}}$ the mid-season Julian date; $Z_{r,\min}$ the initial effective depth of the root zone (at the beginning of the initial stage, i.e. planting date); and $Z_{r,\max}$ the maximum effective depth of the root zone during the mid-season stage obtained from Allen et al. (1998). For many annual crops, $Z_{r,\min}$ is assumed to be 0.15 to 0.20 (ibid.). For perennial crops, the effective root depth is kept constant at the maximum root depth.

A daily calculation of the root zone soil water balance is required in order to estimate $K_c$. The daily water balance, expressed in terms of depletion at the end of the day is:

$$
$$

(10)

where $D_r[t]$ is the root zone depletion at the end of day $t$ [mm]; $D_r[t-1]$ the water content in the root zone at the end of the previous day $t-1$ [mm]; $P[t]$ precipitation on day $t$ [mm]; $RO[t]$ runoff on day $t$ [mm]; $I[t]$ the net irrigation depth on day $t$ that infiltrates the soil [mm]; $CR[t]$ the capillary rise from the groundwater table on day $t$ [mm]; $ET_a[t]$ the actual evapotranspiration [mm]; and $DP[t]$ the deep percolation [mm]. The calculated $D_r[t]$ should be within the range $0 \leq D_r[t] \leq S_{\text{max}}$.

During the planting stage, the root zone soil moisture is assumed to be near field capacity. Therefore, the initial depletion $D_r[t-1]$ is assumed to be equal to zero.
The daily water balance can also be expressed in terms of soil moisture at the end of the day:


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

\[ RO[t] = (P[t] + IR[t]) \times \left( \frac{S[t-1]}{S_{\text{max}}[t-1]} \right)^\gamma \] (12)

The value of the parameter \( \gamma \) is adopted from Siebert and Döll (2008) and was set to 3 for irrigated land and to 2 for rain-fed areas.

The ground water table is assumed to be more than 1 meter below ground level, therefore, the water transported upward by capillary rise (\( CR \)) can be assumed to be nil (Allen et al. 1998).

The irrigation requirement is determined based on the root zone depletion. Irrigation requirement exists when the root zone depletion is greater than or equal to the readily available soil moisture (\( RAW \)) and the amount of irrigation is equal to the depletion level as expressed below:

\[ IR[t] = \begin{cases} D_r[t-1] & \text{if } D_r[t-1] \geq RAW \\ 0 & \text{otherwise} \end{cases} \] (13)

The actual irrigation \( I[t] \) depends on the extent to which the irrigation requirement is met:

\[ I[t] = \alpha \times IR[t] \] (14)

where \( \alpha \) 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 \( \alpha = 0 \) (no application of irrigation, i.e. rain-fed conditions) and the other with \( \alpha = 1 \) (full irrigation). In the second scenario we have assumed that the amount of actual irrigation is sufficient to meet the irrigation requirement.

The water lost through deep percolation (\( DP \)) will be larger than zero if the soil water content is at field capacity. As long as the soil is under water stress (\( S[t] < S_{\text{max}}[t] \)) the soil will not drain and deep percolation is expressed as:
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):

\[
\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{\sum ET_a[t]}{CWR[t]}\right)
\]

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], \(ET_a\) the actual crop evapotranspiration in mm/period and \(CWR\) the crop water requirement in mm/period. \(K_y\) 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 resulting yield map is shown in Appendix II.

The green and blue water use for irrigated crops is calculated by running two scenarios: one for rain-fed (\(\alpha = 0\)) and the other for irrigated agriculture (\(\alpha = 1\)). The green and blue crop water use are calculated following Hoekstra et al. (2009):

Rain-fed scenario (\(\alpha = 0\)):

\[
CWU(\alpha = 0) = CWU_g(\alpha = 0)
\]

\[
CWU_g(\alpha = 0) = 10 \times \sum ET_g(\alpha = 0)
\]

\[
CWU_b(\alpha = 0) = 0
\]

Irrigated scenario (\(\alpha = 1\)):

\[
CWU(\alpha = 1) = 10 \times \sum ET_a(\alpha = 1)
\]

\[
CWU_g(\alpha = 1) = CWU_g(\alpha = 0)
\]

\[
CWU_b(\alpha = 1) = CWU(\alpha = 1) - CWU_g(\alpha = 0)
\]
where $CWU_g$ is the green crop water use (m$^3$/ha) and $CWU_b$ the blue crop water use (m$^3$/ha). For both cases ($\alpha = 0$ and $\alpha = 1$), the green and blue water footprints are calculated as:

$$WF_g = \frac{CWU_g}{Y_a}$$

$$WF_b = \frac{CWU_b}{Y_a}$$

where $Y_a$ is the actual crop yield (ton/ha), $WF_g$ the green water footprint and $WF_b$ the blue water footprint (m$^3$/ton).

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:

$$WF = \beta \times WF(\alpha = 1) + (1 - \beta) \times WF(\alpha = 0)$$

where $\beta$ 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. Nitrate is essential for the growth of plants and high yields. But it is considered as a threat to both public health and natural waters once it leached to the water bodies (Addiscott, 1996). In this study we have quantified the grey water footprint related to nitrogen use only. The grey component of the water footprint of wheat ($WF_{gy}$, m$^3$/ton) is calculated by multiplying the fraction of nitrogen that leached ($\delta$, %) by the nitrogen application rate ($AR$, kg/ha) and dividing this by the difference between the maximum acceptable concentration of nitrogen ($c_{\text{max}}$, kg/m$^3$) and the natural concentration of nitrogen in the receiving water body ($c_{\text{nat}}$, kg/m$^3$) and by the actual wheat yield ($Y_a$, ton/ha):

$$WF_{gy} = \left(\frac{\delta \times AR}{c_{\text{max}} - c_{\text{nat}}}\right) \times \frac{1}{Y_a}$$

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:

$$\overline{WF} = \frac{\sum WF[x, y] \times A[x, y]}{\sum A[x, y]}$$

where $\overline{WF}$ is the average water footprint in the country or river basin in m$^3$/ton, $WF[x,y]$ the water footprint in grid cell $(x,y)$ in m$^3$/ton and $A[x,y]$ the wheat cultivation area in grid cell $(x,y)$ in hectare.
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 (m³/yr) related to trade in wheat products were calculated by multiplying the trade volumes (tons/yr) by their respective water footprint (m³/ton). The virtual water flow $V$ (m³/yr) from exporting country $n_e$ to importing country $n_i$ as a result of export of a wheat product $p$ has been calculated as:

$$V[n_e, n_i, p] = T[n_e, n_i, p] \times WF[n_e, p]$$

(28)

in which $T$ represents the international commodity trade (ton/yr) while $WF$ is the exporting country’s product water footprint (m³/ton) of exported commodity $p$.

The national water saving $S_n$ (m³/yr) of a country $n$ as a result of trade in product $p$ is:

$$S_n[n_e, n_i, p] = (T[n_e, n_i, p] - T_e[n_e, p]) \times WF[n_e, p]$$

(29)

where $WF$ is the water footprint (m³/ton) of the product $p$ in importing country $n_i$, $T_i$ the volume of product $p$ imported (ton/yr) and $T_e$ the volume of the product exported (ton/yr). $S_n$ can have a negative sign, which means a net water loss instead of a saving. The global water saving $S_g$ (m³/yr) through trade in wheat products from an exporting country $n_e$ to an importing country $n_i$ can be calculated as follows:

$$S_g[n_e, n_i, p] = T[n_e, n_i, p] \times (WF[n_e, p] - WF[n_i, p])$$

(30)

where $T$ is the volume of trade (ton/yr) between the two countries.

The virtual water budget ($V_b$) of a country is the sum of the water footprint related to production within the country ($WF_p$) and the virtual water import $V_i$ (Hoekstra and Chapagain, 2008). Based on the water footprint accounting scheme as shown in Figure 5, one can calculate the water footprint related to consumption in the country ($WF_c$). The water footprint of national consumption can be distinguished into an internal ($WF_i$) and external component ($WF_e$). The internal water footprint ($WF_i$) 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 can be estimated based on the relative share of virtual-water import to the total virtual water budget:

$$WF_e = \frac{V_i}{WF_p + V_i} \times WF_e$$

(31)
2.2. Data

Average monthly reference evapotranspiration data at 10 arc minute resolution were obtained from FAO (2008b). The 10 minute data were converted to 5 arc minute resolution by assigning the 10 minute data to each of the four 5 minute 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). Countries such as Angola, Chad, Cyprus, Mauritania, Namibia, Qatar, Thailand, United Arab Emirates and Venezuela have wheat production according to FAOSTAT, but Monfreda et al. (2008) do not show data for these countries. For these countries, 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). The national averages of harvested wheat area, wheat production, wheat yield and irrigated wheat area as reckoned with in this study are provided in Appendix I.
Crop coefficients ($K_c$) 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). National average data on fertilizer application rates are provided in Appendix I. 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 ($\text{NO}_3$) per litre and the standard recommended by US-EPA is 10 mg per litre measured as nitrate-nitrogen ($\text{NO}_3\text{-N}$). In this study we have used the standard of 10 mg/litre of nitrate-nitrogen ($\text{NO}_3\text{-N}$), 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.
3. The global picture

3.1. The water footprint of wheat from the production perspective

The global water footprint of wheat production for the period 1996-2005 is 1088 Gm³/year (70% green, 19% blue, and 11% grey). Data per country are shown in Table 1 for the largest producers. Appendices V and VII provide data for all countries in the world in global maps and in a table, respectively. The global green water footprint related to wheat production was 760 Gm³/yr. At a country level, large green water footprints can be found in the USA (112 Gm³/yr), China (83 Gm³/yr), Russia (91 Gm³/yr), Australia (44 Gm³/yr), and India (44 Gm³/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 Gm³/yr), Saskatchewan in Canada (18 Gm³/yr), Western Australia (15 Gm³/yr), and North Dakota in the USA (15 Gm³/yr). The global blue water footprint was estimated to be 204 Gm³/yr. The largest blue water footprints were calculated for India (81 Gm³/yr), China (47 Gm³/yr), Pakistan (28 Gm³/yr), Iran (11 Gm³/yr), Egypt (5.9 Gm³/yr) and the USA (5.5 Gm³/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 Gm³/yr) and Madhya Pradesh (21 Gm³/yr) in the India and Punjab in Pakistan (20 Gm³/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 Gm³/yr. The largest grey water footprint was observed for China (32 Gm³/yr), India (20 Gm³/yr) the USA (14 Gm³/yr) and Pakistan (8 Gm³/yr).

The calculated global average water footprint per ton of wheat was 1830 m³/ton. The results show a great variation, however, both within a country and among countries (Figure 6). 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 m³/ton.

The global average blue water footprint per ton of wheat amounts to 343 m³/ton. For a few countries, including Pakistan, India, Iran and Egypt, the blue water footprint is much higher, up to 1478 m³/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 m³/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 Gm³/yr), Indus (42 Gm³/yr), Hwang Ho (13 Gm³/yr), Tigris-Euphrates (10 Gm³/yr), Amur (3.1 Gm³/yr) and Yangtze river basins (2.7 Gm³/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. Appendices VI and VIII provide data for the major river basins of the world in maps and a table, respectively.

<table>
<thead>
<tr>
<th>Country</th>
<th>Contribution to global wheat production (%)</th>
<th>Total water footprint of production (Mm³/yr)</th>
<th>Water footprint per ton of wheat (m³/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Green</td>
<td>Blue</td>
</tr>
<tr>
<td>Argentina</td>
<td>2.5</td>
<td>25905</td>
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<td>Australia</td>
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<td>Canada</td>
<td>3.9</td>
<td>32320</td>
<td>114</td>
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<tr>
<td>China</td>
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<td>47370</td>
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<tr>
<td>World</td>
<td></td>
<td>760301</td>
<td>203744</td>
</tr>
</tbody>
</table>

The global average water footprint of rain-fed wheat production is 1805 m³/ton, while in irrigated wheat production it is 1868 m³/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 under irrigation, yields are higher, but water consumption (evapotranspiration) as well.
### Table 2. The water footprint of wheat production for some selected river basins (1996-2005).

<table>
<thead>
<tr>
<th>River basin</th>
<th>Total water footprint of production (Mm³/yr)</th>
<th>Water footprint per ton of wheat (m³/ton)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>2339</td>
</tr>
<tr>
<td>Indus</td>
<td>22897</td>
<td>42145</td>
</tr>
<tr>
<td>Ob</td>
<td>51984</td>
<td>225</td>
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</tr>
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<td>Tigris-Euphrates</td>
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<td>13127</td>
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</tr>
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<td>World</td>
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### Table 3. The global water footprint of wheat production in rain-fed and irrigated lands (1996-2005).

<table>
<thead>
<tr>
<th>Farming system</th>
<th>Yield (ton/ha)</th>
<th>Total water footprint of production (Mm³/yr)</th>
<th>Water footprint per ton of wheat (m³/ton)</th>
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<tr>
<td></td>
<td>Green</td>
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<td>Grey</td>
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<td>World average</td>
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</table>
Figure 6. The green, blue, grey and total water footprint of wheat production per ton of wheat. Period: 1996-2005.
3.2. 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 Tables 4 and 5 for the largest virtual water exporters and importers, respectively, and in Appendix IX for all countries of the world. The largest net virtual water flows related to international wheat trade are shown in Figure 7.

<table>
<thead>
<tr>
<th>Country</th>
<th>Green</th>
<th>Blue</th>
<th>Grey</th>
<th>Total</th>
<th>Contribution to the global export (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>25841</td>
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<tr>
<td>Argentina</td>
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<tr>
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<td>200</td>
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</tr>
<tr>
<td>Germany</td>
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<tr>
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<td>249</td>
<td>1534</td>
<td>0.8</td>
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<tr>
<td>Others</td>
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<td>2204</td>
<td>2840</td>
<td>19186</td>
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<tr>
<td>Global flow</td>
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<td>7789</td>
<td>17807</td>
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</table>
Table 5. Gross virtual water import related to the import of wheat products in the period 1996-2005.

<table>
<thead>
<tr>
<th>Country</th>
<th>Virtual water import (Mm³/yr)</th>
<th>Contribution to the global import (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Blue</td>
</tr>
<tr>
<td>Brazil</td>
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<tr>
<td>Japan</td>
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<tr>
<td>Italy</td>
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<td>174</td>
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<td>Egypt</td>
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<td>Korea, Rep</td>
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<tr>
<td>Philippines</td>
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<tr>
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<tr>
<td>Global flow</td>
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</table>

Figure 7. 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 Gm³/yr) are shown.
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 8 illustrates the concept of global water saving through an example of the trade in durum wheat from France to Morocco.

3.3. 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 (Figure 9). 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 6 for the major wheat consuming countries and in Figure 10 and Appendix X for 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 6, 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).
Grey water footprint 9.8%
Blue water footprint 18.1%
Green water footprint 54.6%
Internal water footprint 82%
External water footprint 18%

Total water footprint = 1088 Gm³/yr
Per capita water footprint = 177 m³/cap/yr


<table>
<thead>
<tr>
<th>Countries</th>
<th>Internal water footprint (Mm³/yr)</th>
<th>External water footprint (Mm³/yr)</th>
<th>Water footprint</th>
<th>WF per capita</th>
<th>Wheat consumption per capita</th>
<th>WF of wheat products</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Grey</td>
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<td>810</td>
<td>13</td>
<td>120</td>
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<td>196690</td>
<td>106972</td>
<td>166703</td>
<td>7147</td>
<td>16586</td>
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</tbody>
</table>

Figure 10. Water footprint per capita related to consumption of wheat products in the period 1996-2005.
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 Figure 11.

Figure 11. The extent to which countries rely on external water resources for their wheat consumption. Period: 1996-2005.
4. Case studies

4.1. 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 (Figure 12). It covers an area of approximately 451,000 km², 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).

Figure 12. The area of the Ogallala (High Plains) Aquifer in the USA.

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 meters 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 7). The total water footprint in the Ogallala area was 21 Gm$^3$/yr (85% green, 5% blue, and 10% grey).

Table 7. Water footprint of wheat production and virtual water export from the Ogallala area (1996-2005).

<table>
<thead>
<tr>
<th>States in the Ogallala area*</th>
<th>Water footprint related to wheat production (Mm$^3$/yr)</th>
<th>Virtual water export related to export of wheat products (Mm$^3$/yr)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Green</td>
<td>Blue</td>
</tr>
<tr>
<td>Kansas</td>
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</tr>
<tr>
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<td>417</td>
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<tr>
<td>Nebraska</td>
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<td>78</td>
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<td>Wyoming</td>
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<td>6</td>
</tr>
<tr>
<td>Ogallala area total</td>
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<td>1056</td>
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<tr>
<td>USA total</td>
<td>111926</td>
<td>5503</td>
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</table>

* Values in the table refer to the part of the states within the Ogallala area only.

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 (Appendix XI).

Figure 13. 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.
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 7). Figure 13 shows the major foreign destinations of wheat-related virtual water exports from the area of the Ogallala Aquifer.

4.2. 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 the 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%) (Figure 14). 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; Alcamo et al., 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 (Figure 15). 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%).

4.3. 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 Gm³/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 Figure 13. Italy also imports virtual water from the water-scarce countries of the Middle East, such as Syria (58 Mm³/yr) and Iraq (36 Mm³/yr). The global water footprint of Italian wheat consumption is shown in Figure 16.

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 Figure 13. The water footprint in Australia largely lies in Southern Australia where most of the wheat is produced and water scarcity is high. Japan’s global water footprint related to wheat consumption is mapped in Figure 17.
Figure 16. The global water footprint of wheat products consumed by Italy's citizens (Mm$^3$/yr). The arrows show the largest virtual water import flows to Italy. Period:1996-2005.
Figure 17. The global water footprint of wheat products consumed by Japan’s citizens (Mm$^3$/yr). The arrows show the largest virtual water import flows to Japan. Period: 1996-2005.
5. Discussion

The results of the current study can be compared to results from earlier studies as shown in Table 8. 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 (Appendix XII).

Table 8. Comparison between the results from the current study with the results from previous studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Period</th>
<th>Global average water footprint of wheat</th>
<th>Global water footprint related to wheat production</th>
<th>International virtual water flows related to wheat trade</th>
<th>Global water saving due to wheat trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang et al. (2006)</td>
<td>1997-2001</td>
<td>-</td>
<td>-</td>
<td>188</td>
<td>130</td>
</tr>
<tr>
<td>Liu et al. (2007), Liu et al. (2009)</td>
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<td>1253</td>
<td>688</td>
<td>159</td>
<td>77</td>
</tr>
<tr>
<td>Siebert and Döll (2010)</td>
<td>1998-2002</td>
<td>1469</td>
<td>858</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hanasaki et al. (2010)</td>
<td>2000</td>
<td>-</td>
<td>-</td>
<td>122</td>
<td>-</td>
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<tr>
<td>Current study, green &amp; blue only</td>
<td>1996-2005</td>
<td>1622</td>
<td>964</td>
<td>182</td>
<td>57</td>
</tr>
<tr>
<td>Current study incl. grey water *</td>
<td>1996-2005</td>
<td>1830</td>
<td>1088</td>
<td>200</td>
<td>65</td>
</tr>
</tbody>
</table>

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

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 GEPI 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) 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 (m³/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 a 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 Gm³/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.
6. 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 Gm³/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 (as shown in Figure 5) 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.
References


Appendix I: Wheat cultivated area, yield and production average for the period 1996-2005 and fertilizer application rate and maximum yield.

<table>
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<th></th>
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$^1$ Source: FAO (2008a).

$^2$ Source: Portman et al. (2008) with adjustment to the period of study.


Appendix III: Crop and irrigation water requirements for wheat production in the world (1996-2005).

Irrigation water requirement
m³/ha

- < 1,000
- 1,000 - 2,000
- 2,000 - 3,000
- 3,000 - 5,000
- 5,000 - 14,000

Crop water requirement
m³/ha

- < 2,000
- 2,000 - 4,000
- 4,000 - 6,000
- 6,000 - 8,000
- 8,000 - 14,000
Appendix IV: Green and blue water footprint per hectare for wheat production in the world (1996-2005).
Appendix V: The water footprint of wheat production on a 5 by 5 arc minute grid in a global map showing country borders (1996-2005).
Appendix VI: The water footprint of wheat production on a 5 by 5 arc minute grid in a global map showing major river basins (1996-2005).

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A global and high-resolution assessment of the water footprint of wheat / 63

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Appendix IX: Virtual water import and export per country related to trade in wheat products (1996-2005).

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Appendix XI: Wheat production and associated blue water footprint in the USA, showing the Ogallala Aquifer (1996-2005).
## Appendix XII: Comparison of computed water footprint values with measured values from the literature.

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\(^a\) Measured water productivity values from Zwart and Bastiaanssen (2004). Estimated water footprint values as inverse of measured water productivity values from literature

\(^b\) Y indicate the simulated water footprint lies in between the minimum and maximum measured values from literature, while N indicates the simulated value outside these ranges.
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