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National water footprint accounts: The green, blue and grey water footprint of production and consumption

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NATIONAL WATER FOOTPRINT ACCOUNTS: THE GREEN, BLUE AND GREY WATER FOOTPRINT OF PRODUCTION AND CONSUMPTION

VOLUME 1: MAIN REPORT

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Summary

This study quantifies and maps the water footprints of nations from both a production and consumption perspective and estimates international virtual water flows and national and global water savings as a result of trade. The entire estimate includes a breakdown of water footprints, virtual water flows and water savings into their green, blue and grey components. The main finding of the study can be summarized as:

- The global water footprint in the period 1996-2005 was 9087 Gm^3/yr (74% green, 11% blue, 15% grey). Agricultural production contributes 92% to this total footprint.
- About one fifth of the global water footprint relates to production for export.
- The total volume of international virtual water flows related to trade in agricultural and industrial products was 2320 Gm^3/yr (68% green, 13% blue, 19% grey). Trade in crop products contributes 76% to the total volume of international virtual water flows; trade in animal and industrial products contribute 12% each. As a global average, the blue and grey shares in the total water footprint of internationally traded products are slightly larger than in the case of domestically consumed products.
- Mexico and Spain are the two countries with the largest national blue water savings as a result of trade.
- The global water saving as a result of trade in agricultural products in the period 1996-2005 was 369 Gm^3/yr (59% green, 27% blue, 15% grey), which is equivalent to 4% of the global water footprint related to agricultural production. The global *blue* water saving is equivalent to 10% of the global blue water footprint related to agricultural production, which indicates that virtual water importing countries generally depend more strongly on blue water for crop production than the virtual water exporting countries. The largest global water saving (53%) is due to trade in cereal crops, followed by oil crops (22%) and animal products (15%).
- International trade in industrial products can be associated with an increased global water footprint that is equivalent to 4% of the global water footprint related to industrial production.
- The water footprint of the global average consumer in the period 1996-2005 was 1385 m^3/yr. About 92% of the water footprint is related to the consumption of agricultural products, 5% to the consumption of industrial goods, and 4% to domestic water use.
- The average consumer in the US has a water footprint of 2842 m^3/yr, while the average citizens in China and India have water footprints of 1071 m^3/yr and 1089 m^3/yr respectively.
- Consumption of cereal products gives the largest contribution to the water footprint of the average consumer (27%), followed by meat (22%) and milk products (7%). The contribution of different consumption categories to the total water footprint varies across countries.
- The volume and pattern of consumption and the water footprint per ton of product of the products consumed are the main factors determining the water footprint of a consumer.

The study illustrates the global dimension of water consumption and pollution by showing that several countries heavily rely on water resources elsewhere (for example Mexico depending on virtual water imports from the US) and that many countries have significant impacts on water consumption and pollution elsewhere (for example Japan and many European countries due to their large external water footprints).

1. Introduction

The earth's freshwater resources are subject to increasing pressure in the form of consumptive water use and pollution (Postel, 2000; WWAP, 2003, 2006, 2009). Until recently, issues of freshwater availability, use and management have been addressed at a local, national and river basin scale. The recognition that freshwater resources are subject to global changes and globalization have led a number of researchers to argue for the importance of putting freshwater issues in a global context (Postel et al., 1996; Vörösmarty et al., 2000; Hoekstra and Hung, 2005; Hoekstra and Chapagain, 2008; Hoff, 2009). Appreciating the global dimension of freshwater resources can be regarded as a key to solving some of today's most urgent water problems (Hoekstra, 2011).

In formulating national water plans, governments have traditionally taken a purely national perspective, aiming at matching national water supplies to national water demands. Governments have looked for ways to satisfy water users without questioning the total amount of water demands. Even though governments nowadays consider options to reduce water demands, in addition to options to increase supplies, they generally do not consider the global dimension of water demand patterns. Since production processes in a global economy can shift from one place to another, water demands can be met outside the boundaries of a nation through the import of commodities. All countries trade water-intensive commodities, but few governments explicitly consider options to save water through import of water-intensive products or to make use of relative water abundance to produce water-intensive commodities for export. In addition, by looking at water use within only their own country, governments do not have a comprehensive view of the sustainability of national consumption. Many countries have significantly externalized their water footprint without looking at whether the imported products are related to water depletion or pollution in the producing countries. Knowledge of the dependency on water resources elsewhere is relevant for a national government, not only when evaluating its environmental policy but also when assessing national food security.

Understanding the water footprint of a nation is highly relevant for developing well-informed national policy. Conventional national water use accounts are restricted to statistics on water withdrawals within their own territory (Van der Leeden et al., 1990; Gleick, 1993; FAO, 2010b). National water footprint accounts extend these statistics by including data on green water use and volumes of water use for waste assimilation and by adding data on water use in other countries for producing imported products as well as data on water use within the country for making export products (Hoekstra et al., 2011).

Quantifying and mapping 'national water footprints' is an evolving field of study since the introduction of the water footprint concept in the beginning of this century (Hoekstra, 2003). The first global study on the water footprints of nations was carried out by Hoekstra and Hung (2002); a second, much more comprehensive study, was done by Hoekstra and Chapagain and reported in a number of subsequent publications: Chapagain and Hoekstra (2004, 2008), Chapagain et al. (2006) and Hoekstra and Chapagain (2007a, 2008). The current study is the third global assessment of national water footprints, which improves upon the previous assessments in a number of respects as will be elaborated below.

The objective of this study is to estimate the water footprints of nations from both a production and consumption perspective. First, we quantify and map at a high spatial resolution the green, blue and grey water footprints within countries associated with agricultural production, industrial production and domestic water supply. Second, we estimate international virtual water flows related to trade in agricultural and industrial commodities. Based on these flows, we estimate national and global water savings that can be associated with these trade flows. Finally, we quantify and map the water footprint of consumption for all countries of the world distinguishing for each country between the internal and the external water footprint of national consumption. Throughout the study we explicitly distinguish between green, blue and grey water footprints.

The current study is more comprehensive and detailed than the earlier two global water footprint studies (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2008). It is also more comprehensive than the contemporary study by Fader et al. (2011), who estimate the global green and blue water footprint of consumption showing the internal and external water footprint per country. This study excludes the grey water footprint component and is restricted to an analysis of the water footprint of consuming crop products, leaving out the water footprints of farm animal products, industrial products and domestic water supply.

Apart from the global water footprint studies mentioned, several water footprint studies with a focus on a specific country were published in the past few years: Vincent et al. (2011) for Belgium; Ma et al. (2006), Liu and Savenije (2008), Hubacek et al. (2009) and Zhao et al. (2009) for China; Sonnenberg et al. (2009) for Germany; Kampman et al. (2008) for India; Bulsink et al. (2009) for Indonesia; Hoekstra and Chapagain (2007b) for Morocco; Hoekstra and Chapagain (2007b) and Van Oel et al. (2009) for the Netherlands; Aldaya et al. (2010) and Garrido et al. (2010) for Spain; Sonnenberg et al. (2010) for Switzerland; Chahed et al. (2008) for Tunisia; and Chapagain and Orr (2008), Yu et al. (2010) and Feng et al. (2011) for the UK. The scope, assumptions and data sources in these country studies vary widely, so these studies cannot be used to make comparisons between countries.

The current study is a global study that allows a comparison of the water footprints of different countries, because the same method, assumptions and databases are applied for all countries. The study improves upon the previous global water footprint study – Hoekstra and Chapagain (2008) – in a number of respects:

- We apply a high spatial resolution in estimating the water footprint in crop production, industrial production and domestic water supply.
- In the case of crop production, we make an explicit distinction between the green and blue water footprint. In addition, we include the grey water footprint in the estimation of the water footprint in agricultural production.
- We account for actual irrigation, so we do not take irrigation requirements as a proxy for blue water consumption.
- We make use of better estimates of the feed composition of farm animals (which is relevant for the estimation of the water footprint of farm animal products).

- We distinguish three different animal production systems (grazing, mixed and industrial) in each country, accounting for the relative presence of those three systems.
- We explicitly distinguish between the blue and grey water footprint in industrial production and domestic water supply and account for wastewater treatment coverage per country.
- We apply the bottom-up approach in estimating the water footprint of national consumption of agricultural products, which is less sensitive to trade data than the top-down approach.
- We add calculations of national and global water savings related to trade in industrial products.
- We consider a ten-year period (1996-2005), while the earlier study analysed a five-year period (1997-2001).

The current report builds on two earlier studies by the same authors. In Mekonnen and Hoekstra (2010b, 2011) we have reported the green, blue and grey water footprints of crops and derived crop products. In Mekonnen and Hoekstra (2010c) we documented the green, blue and grey water footprints of farm animals and animal products.

2. Method and data

2.1. Accounting framework

In this study we adopt the terminology and calculation methodology as set out in *The Water Footprint Assessment Manual*, which contains the global standard for water footprint assessment developed by the Water Footprint Network (Hoekstra et al., 2011). The 'water footprint' is a measure of human's appropriation of freshwater resources. Freshwater appropriation is measured in terms of water volumes consumed (evaporated or incorporated into a product) or polluted per unit of time. A water footprint has three components: green, blue and grey. The blue water footprint refers to consumption of blue water resources (surface and ground water). The green water footprint is the volume of green water (rainwater) consumed, which is particularly relevant in crop production. The grey water footprint is an indicator of the degree of freshwater pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. The water footprint is a geographically explicit indicator, showing not only volumes of water consumption and pollution, but also the locations.

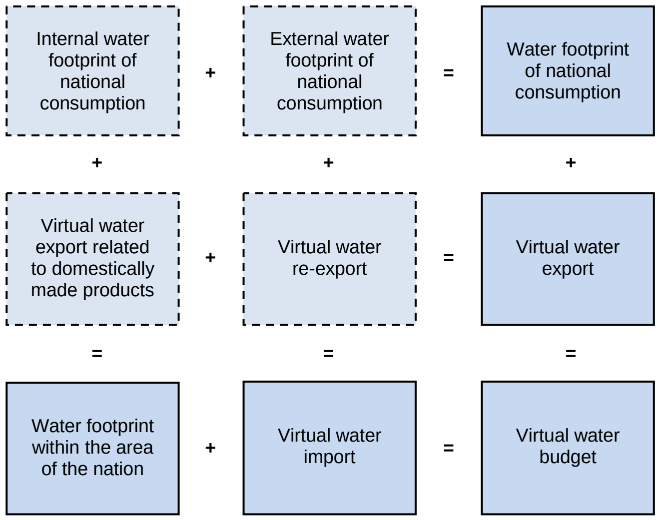

Figure 1. The national water footprint accounting scheme. Source: Hoekstra et al. (2011).

The framework for national water footprint accounting is shown in Figure 1. One can see that 'the water footprint of national consumption' is different from 'the water footprint within the area of the nation'. The latter is the water footprint of national production, defined as the total freshwater volume consumed or polluted within the territory of the nation as a result of activities within the different sectors of the economy. It can be calculated by summing the water footprints of all water consuming or polluting processes taking place in the nation. Generally, one can distinguish three main water using sectors: the agricultural sector, the industrial sector and the domestic water supply sector. On the other hand, the water footprint of national consumption is defined as the total volume of freshwater that is used to produce the goods and services consumed by the inhabitant of the nation. It consists of two components: the internal and external water footprint of national consumption. The internal water footprint is defined as the use of domestic water resources to produce goods and services consumed by the nation's population. It is the sum of the water footprint within the nation minus the volume of virtual-water export to other nations related to the export of products produced with domestic water resources. The external water footprint is defined as the volume of water resources used in other nations to produce goods and services consumed by the population in the nation under consideration. It is equal to the virtual-water import into the nation minus the volume of virtual-water export to other nations as a result of re-export of imported products. The virtual-water export from a nation consists of exported water of domestic origin and re-exported water of foreign origin. The virtual-water import into a nation will partly be consumed, thus constituting the external water footprint of national consumption, and may partly be re-exported. The sum of the virtual water import into a country and the water footprint within the area of the nation is equal to the sum of the virtual water export from the nation and the water footprint of national consumption. This sum is called the virtual-water budget of a nation.

2.2. Water footprints of national production

The water footprints within nations related to crop production were obtained from Mekonnen and Hoekstra (2010a, 2010b, 2011), who estimated the global water footprint of crop production with a crop water use model at a 5 by 5 arc minute spatial resolution. The water footprints within nations related to water use in livestock farming, were obtained from Mekonnen and Hoekstra (2010c). The water footprints within nations related to industrial production and domestic water supply were estimated in this study using water withdrawal data from the AQUASTAT database (FAO, 2010b). For some countries, water withdrawal data were taken from EUROSTAT (2011). We have assumed that 5% of the water withdrawn for industrial purposes is actual consumption (blue water footprint) and that the remaining fraction is return flow; for the domestic water supply sector we assumed a consumptive portion of 10% (FAO, 2010b). The part of the return flow which is disposed into the environment without prior treatment has been taken as a measure of the grey water footprint, thus assuming a dilution factor of 1. Data on the wastewater treatment coverage per country were obtained from the United Nations Statistical Division database (UNSD, 2010a). For countries for which we could not find data, we assumed zero wastewater treatment coverage. Domestic wastewater treatment coverage data are generally specified for urban areas only; we used data on urban populations per country from FAO (2010a) to estimate the grey water footprint from domestic water supply in urban areas. For rural areas we assumed zero treatment. For treatment coverage in the industrial sector per country we used data on municipal treatment coverage in urban areas as an indicator. Water footprints related to industrial production and domestic water supply were mapped using the global population density map from CIESIN and CIAT (2005).

2.3. International virtual water flows

International virtual-water flows are calculated by multiplying, per trade commodity, the volume of trade by the respective average water footprint per ton of product in the exporting nation. When a product is exported from a country that does not produce the product we have assumed the global average product water footprint for that trade flow.

Data on international trade in agricultural and industrial 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. Country-specific estimates on the green, blue and grey water footprints of 146 crops and more than two hundred derived crop products per ton of product were taken from Mekonnen and Hoekstra (2010b). Estimates on the water footprints of farm animals (beef cattle, dairy cattle, pig, sheep, goat, broiler chicken, layer chicken and horses) and animal products per ton of product were taken from Mekonnen and Hoekstra (2010c). The national average water footprint per dollar of industrial product was calculated per country by dividing the total national water footprint in the industrial sector by the value added in industrial sector. The latter was obtained from the United Nations Statistical Division database (UNSD, 2010b).

2.4. National and global water savings related to international trade

The national water saving of a country as a result of trade in a certain commodity is calculated as the net import volume of this commodity times the water footprint of the commodity per commodity unit in the country considered. Obviously, the calculated saving can have a negative sign, which means a net national water loss instead of a saving. The global water saving through trade in a commodity between two countries is calculated as the trade volume times the difference between the water footprints of the commodity per unit of the commodity in the importing and the exporting country. The total global water saving is obtained by summing up the global savings of all international trade flows. By definition, the total global water saving is equal to the sum of the national savings of all nations.

2.5. Water footprints of national consumption

The water footprint of national consumption (in m^3/yr) is calculated by adding the direct water footprint of consumers and two indirect water footprint components:

$$WF_{cons} = WF_{cons,dir} + WF_{cons,indir}(agricultural\ commodities) + WF_{cons,indir}(industrial\ commodities) \qquad (1)$$

The direct water footprint of consumers within the nation ($WF_{cons,dir}$) refers to consumption and pollution of water related to domestic water supply. The indirect water footprint of consumers ($WF_{cons,indir}$) refers to the water use by others to make the commodities consumed, whereby we distinguish between agricultural and industrial commodities.

The water footprint of national consumption of agricultural and industrial commodities can be calculated through either the top-down or the bottom-up approach (Hoekstra et al., 2011). In the top-down approach, the water footprint of national consumption is calculated as the water footprint within the nation plus the virtual-water import minus the virtual-water export. The gross virtual-water import is calculated by multiplying import volumes of various products by their respective product water footprint in the nation of origin. The gross virtual-water export is found by multiplying the export volumes of the various export products by their respective product water footprint. In the bottom-up approach, the water footprint of national consumption is calculated by adding the direct and indirect water footprints of consumers within the nation.

For agricultural commodities, the water footprint of national consumption is calculated in this study based on the bottom-up approach. It is calculated by multiplying all agricultural products consumed by the inhabitants of the nation by their respective product water footprint:

$$WF_{cons,indir}(agricultural\ commodities) = \sum_{p} (C[p] \times WF^{*}_{prod}[p]) \qquad (2)$$

$C[p]$ is consumption of agricultural product p by consumers within the nation (ton/yr) and $WF^{*}_{prod}[p]$ the water footprint of this product (m^3/ton). We consider the full range of final agricultural goods. Data on national consumption of agricultural products per country for the period 1996-2005 were taken from the Supply and Utilization Accounts (SUA) of the Food and Agriculture Organization of the United Nations (FAO, 2010a). For edible products, we have taken the “food” column multiplied by a certain factor representing seed and waste. For fibre, hide and skin products, we took the “other utilization” column, again multiplied by a certain factor representing seed and waste. The multiplication factor was calculated per product as the global production divided by the difference between the global production and volume of seed and waste.

The volume of agricultural product p consumed in a nation will generally originate in part from the nation itself and in part from other nations. The average water footprint of a product p consumed in a nation is:

$$WF^{*}_{prod}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e} \left(T_i[n_e, p] \times WF_{prod}[n_e, p] \right)}{P[p] + \sum_{n_e} T_i[n_e, p]} \qquad (3)$$

in which $P[p]$ represents the production quantity of product p in the nation, $T_i[n_e,p]$ the imported quantity of product p from exporting nation n_e, $WF_{prod}[p]$ the water footprint of product p when produced in the nation considered and $WF_{prod}[n_e,p]$ the water footprint of product p as in the exporting nation n_e. The assumption made here is that the total consumption volume originates from domestic production and imports according to their relative volumes. The water footprints of agricultural products were taken from Mekonnen and Hoekstra (2010b, 2010c).

For industrial commodities, the water footprint of national consumption is calculated based on the top-down approach as the water footprint of industrial processes taking place within the nation plus the virtual-water import related to import of industrial commodities minus the virtual-water export.

The external water footprint of national consumption ($WF_{cons,ext}$) is estimated based on the relative share of the virtual water import to the total water budget:

$$WF_{cons,ext} = \frac{V_i}{WF_{area} + V_i} \times WF_{cons} \tag{4}$$

in which WF_{area} is the water footprint within a nation and V_i the virtual water import. We apply this formula separately for the category of agricultural products (crop and animal products) and for the category of the industrial products. The internal water footprint of national consumption ($WF_{cons,int}$) is calculated as:

$$WF_{cons,int} = \frac{WF_{area}}{WF_{area} + V_i} \times WF_{cons} \tag{5}$$

For mapping the global water footprint of the consumption of a certain country at a high spatial resolution, we distinguish between mapping the internal and the external water footprint. The internal water footprint is mapped by taking the shares of the water footprints within the different grid cells in the country that contribute to the water footprint of national consumption. Mapping the external water footprint is done in two steps. First, we quantify the external water footprint per product category per trade partner country based on the relative import from different trade partners. Second, within each trade partner country we map the external water footprint by taking the shares of the water footprints within the different grid cells in the trade partner country that contribute to the water footprint of consumption in our country under consideration. We could not trace the external water footprint of imported animal products at grid level because of data limitations.

In a case study for the US, we applied the above approach but took a more refined, though laborious, approach by applying the whole procedure separately for each crop type and animal type. For (domestically produced and consumed) animal products we identify the feed volumes from the country itself and from abroad, and for each feed crop we map the internal and external water footprints using the same approach as for food crops. The category of the industrial products was still treated as one category. The mapping of the external water footprint is slightly improved this way, but more importantly, it enabled us to trace the external water footprint not only by location but also by crop.

3. Results

3.1. The water footprint of national production

Figure 2 shows world maps with the green, blue and grey water footprints within nations in the period 1996-2005. China, India and the US are the countries with the largest total water footprints within their territory, with total water footprints of 1207, 1182 and 1053 Mm^3/yr, respectively. About 38% of the water footprint of global production lies within these three countries. The next country in the ranking is Brazil, with a total water footprint within its territory of 482 Mm^3/yr. India is the country with the largest *blue* water footprint within its territory: 243 Mm^3/yr, which is 24% of the global blue water footprint. Irrigation of wheat is the process that takes the largest share (33%) in India's blue water footprint, followed by irrigation of rice (24%) and irrigation of sugarcane (16%). China is the country with the largest *grey* water footprint within its borders: 360 Mm^3/yr, which is 26% of the global grey water footprint.

Figure 3 shows world maps with the water footprints of agricultural production, industrial production and related to domestic water supply. In all countries of the world, the water footprint related to agricultural production takes the largest share in the total water footprint within the country. China and the US have the largest water footprints in their territory related to industrial production; 22% of the global water footprint related to industrial production lies in China and 18% in the US. Belgium is the country in which industrial production takes the largest share in the total water footprint in the country. The water footprint of industries in Belgium contributes 41% to the total water footprint in the country; agricultural production still contributes 53% here. Full statistics on the green, blue and grey water footprints related to agricultural and industrial production and domestic water supply per country are provided in Appendix I.

The global water footprint related to agricultural and industrial production and domestic water supply for the period 1996-2005 was 9087 Gm^3/yr (74% green, 11% blue, 15% grey; see Table 1). Agricultural production takes the largest share, accounting for 92% of the global water footprint. Industrial production contributes 4.4% to the total water footprint and domestic water supply 3.6%.

The global water footprint related to producing goods for export is 1762 Gm^3/yr. In the agricultural sector, 19% of the total water footprint relates to production for export; in the industrial sector this is 41%. The water footprint related to domestic water supply does not relate to export at all. Taken as an average over the three water-using sectors, we find that 19% of the global water footprint is not for domestic consumption but for export.

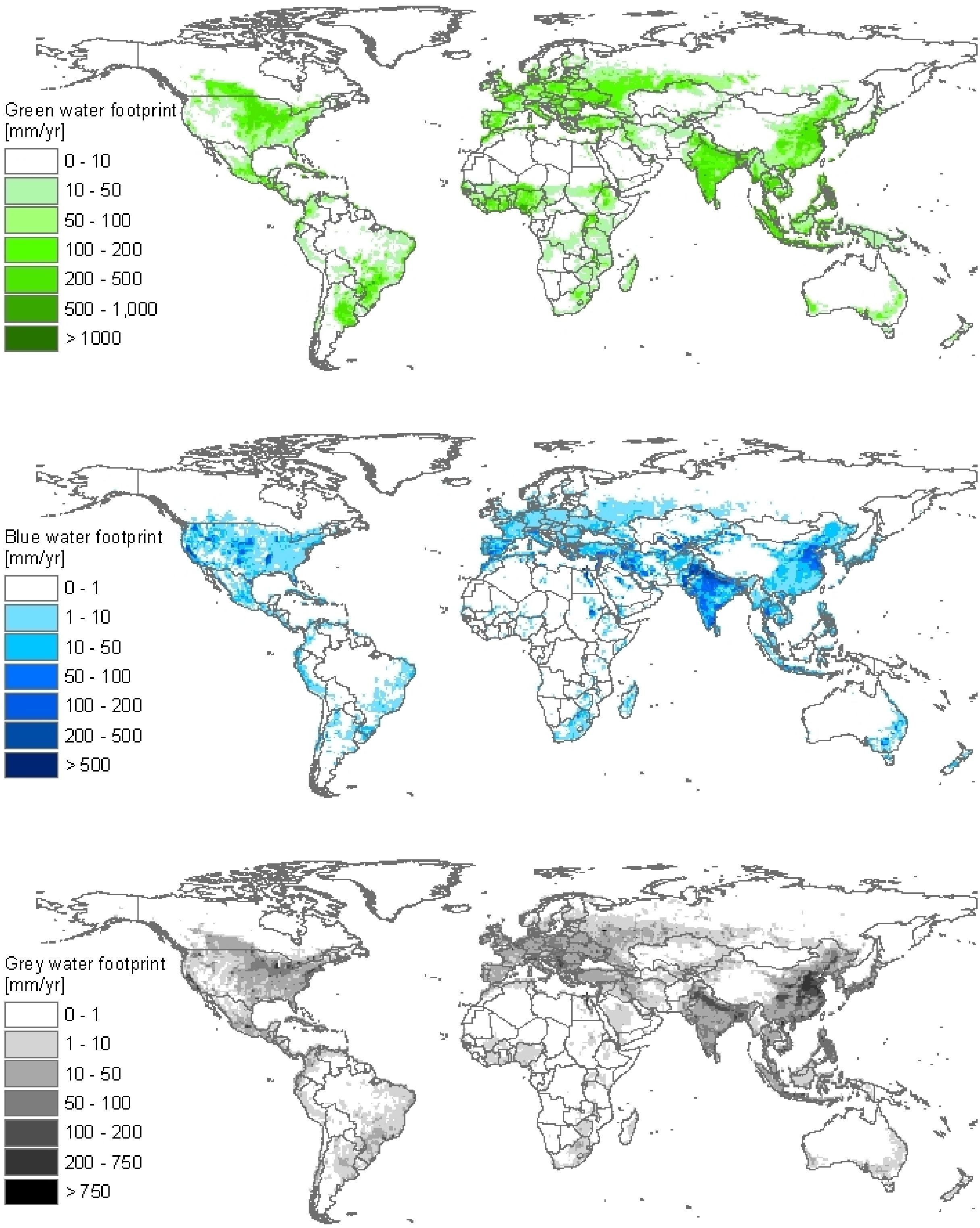

Figure 2. The green, blue and grey water footprints within nations in the period 1996-2005. The data are shown in mm/yr on a 5 by 5 arc minute grid. Data per grid cell have been calculated as the water footprint within a grid cell (in m^3/yr) divided by the area of the grid cell (in 10^3 m^2).

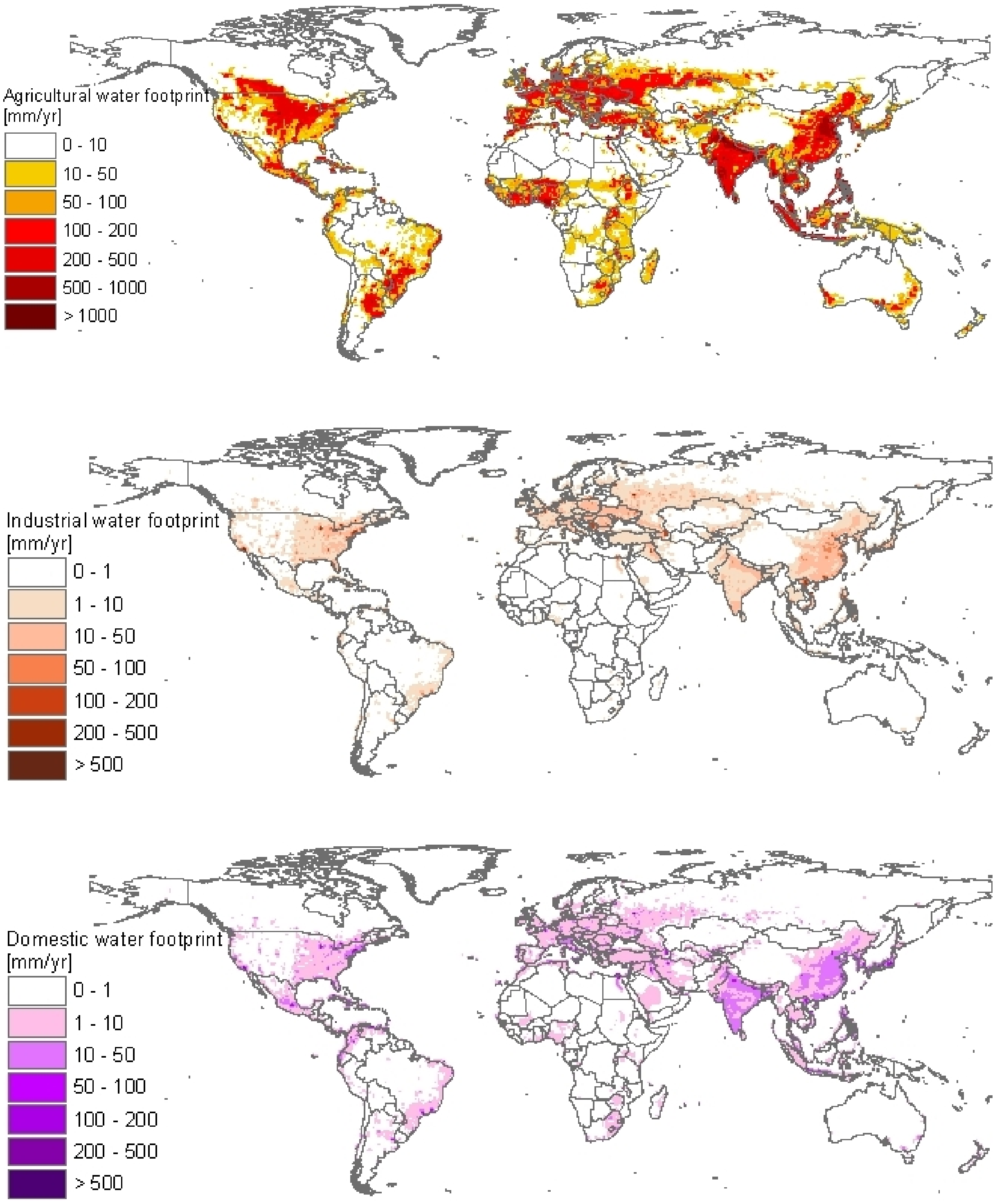

Figure 3. The water footprint within nations in the period 1996-2005, shown by sector: the total water footprint of agricultural production (above), the total water footprint of industrial production (middle) and the total water footprint related to domestic water supply (below). The data are shown in mm/yr on a 5 by 5 arc minute grid. Data per grid cell have been calculated as the water footprint within a grid cell (in m^3/yr) divided by the area of the grid cell (in 10^3 m^2).

Table 1. Global water footprint of production (1996-2005).

	Agricultural production			Industrial production	Domestic water supply	Total
	Crop production	Pasture	Water supply in animal raising			
Global water footprint of production (Gm^3/yr)						
- Green	5771*	913**	-	-	-	6684
- Blue	899*	-	46**	38	42	1025
- Grey	733*	-	-	363	282	1378
- Total	7404	913	46	400	324	9087
Water footprint for export (Gm^3/yr)	----------------1597----------------			165	0	1762
Water footprint for export compared to total (%)	------------------19-----------------			41	0	19

* Source: Mekonnen and Hoekstra (2010b; 2011).

** Source: Mekonnen and Hoekstra (2010c).

3.2. International virtual water flows related to trade in agricultural and industrial products

The global sum of international virtual water flows for the period 1996-2005 was 2320 Gm^3/yr (68% green, 13% blue and 19% grey). The largest share (76%) of the virtual water flows between countries is related to international trade in crops and derived crop products. Trade in animal products and industrial products contributed 12% each to the global virtual water flows. The volume of global virtual water flows related to domestically produced products was 1762 Gm^3/yr. The gross international virtual water flows are presented in Table 2. Appendix II tabulates the virtual water flows per country.

Table 2. Gross international virtual water flows (Gm^3/yr). Period 1996-2005.

	Related to trade in agricultural products	Related to trade in industrial products	Total
Related to export of domestically produced goods	1597	165	1762
Related to re-export of imported goods	441	117	558
Total	2038	282	2320

As a global average, the blue and grey shares in the total water footprint of internationally traded products are slightly larger than in the case of domestically consumed products. This means that export goods are more strongly related to water consumption from and pollution of surface and groundwater than non-export goods. The green component in the total water footprint of internationally traded products is 68%, while it is 74% for total global production.

The major gross virtual water exporters, which together account for more than half of the global virtual water export, are the US (314 Gm^3/yr), China (143 Gm^3/yr), India (125 Gm^3/yr), Brazil (112 Gm^3/yr), Argentina (98 Gm^3/yr), Canada (91 Gm^3/yr), Australia (89 Gm^3/yr), Indonesia (72 Gm^3/yr), France (65 Gm^3/yr) and Germany

(64 Gm^3/yr). The US, Pakistan, India, Australia, Uzbekistan, China and Turkey are the largest blue virtual water exporters, accounting for 49% of the global blue virtual water export. All of these countries are partially under water stress (Alcamo and Henrichs, 2002; Alcamo et al. 2003; Smakhtin et al., 2004). This raises the question whether the implicit or explicit choice to consume the limited national blue water resources for export products is sustainable and most efficient. Closely related to this is the question to what extent the scarcity is reflected in the price of water in these countries. Given the fact that all the externalities and a scarcity rent are seldom included in the price of water, most particular in agriculture, one cannot expect that production and trade patterns automatically account for regional water scarcity patterns.

The major gross virtual water importers are the US (234 Gm^3/yr), Japan (127 Gm^3/yr), Germany (125 Gm^3/yr), China (121 Gm^3/yr), Italy (101 Gm^3/yr), Mexico (92 Gm^3/yr), France (78 Gm^3/yr), the UK (77 Gm^3/yr) and the Netherlands (71 Gm^3/yr).

Figure 4 shows the virtual water balance per country and the largest international gross virtual water flows. The countries shown in green colour have a negative balance, which means that they have net virtual water export. The countries shown in yellow to red have net virtual water import. The biggest net exporters of virtual water are found in North and South America (the US, Canada, Brazil and Argentina), Southern Asia (India, Pakistan, Indonesia, Thailand) and Australia. The biggest net virtual water importers are North Africa and the Middle East, Mexico, Europe, Japan and South Korea.

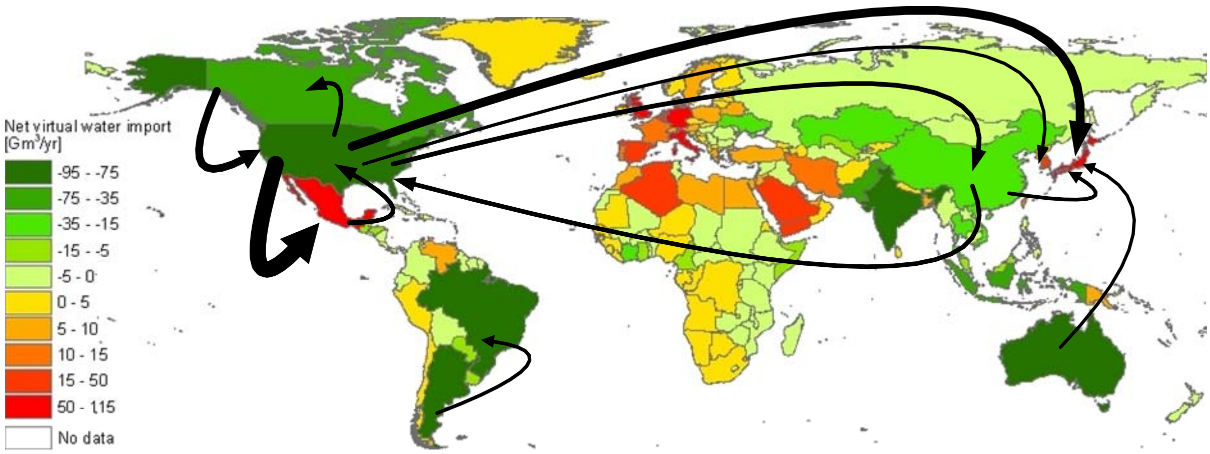

Figure 4. Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996-2005. Only the biggest gross flows (> 15 Gm^3/yr) are shown; the fatter the arrow, the bigger the virtual water flow.

The largest share of the international virtual water flows relates to trade in oil crops (including cotton, soybean, oil palm, sunflower, rapeseed and others) and derived products. This category accounts for 43% of the total sum of international virtual water flows. More than half of this amount relates to trade in cotton products; about one fifth relates to trade in soybean. The other products with a large share in the global virtual water flows are cereals (17%), industrial products (12.2%), stimulants (7.9%) and beef cattle products (6.7%). Figure 5 shows the contribution of different product categories to the global sum of international virtual water flows. Virtual water flows per product category are presented in Appendix III.

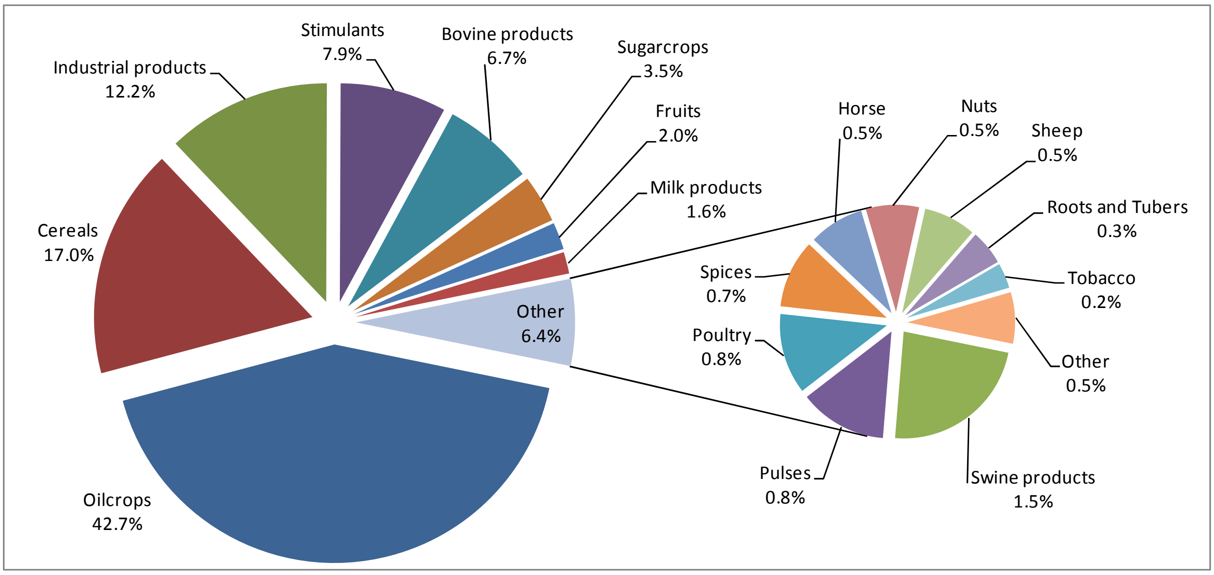

Figure 5. Contribution of different product categories to the global virtual water flows

3.3. National water saving per country as a result of trade

A number of countries reduce the use of their national water resources through the import of agricultural products. Japan saves 134 Gm^3/yr (80% green, 9% blue, 12% grey) of its domestic water resources, Mexico 83 Gm^3/yr (69% green, 26% blue, 6% grey), Italy 54 Gm^3/yr (83% green, 10% blue, 7% grey), the UK 53 Gm^3/yr (75% green, 15% blue, 9% grey) and Germany 50 Gm^3/yr (83% green, 14% blue, 3% grey). In terms of blue water saved, Mexico, Spain, Japan, the UK and a number of countries in the Middle East come on top of the list. Appendix IV presents green, blue and grey water savings per country as a result of trade in crop, animal and industrial products. The figures on ‘national water saving’ presented here should be merely understood as ‘volumes of domestic water resources not necessary to be used for production because the commodities are imported’. The term ‘saving’ is used in a physical, not economic sense. Besides, the ‘water saving’ does not necessarily imply that the water saved is allocated to other beneficial uses (De Fraiture et al. 2004). In water-scarce countries, however, ‘water saving’ is likely to have positive environmental, social and economic implications.

From a water resources point of view, one would expect that countries facing water stress adopt a trade strategy that alleviates their water scarcity problem. However, international trade in agricultural goods is driven largely by factors other than water. Therefore, import of virtual water is often unrelated to relative water scarcity in a country (Yang et al., 2003; De Fraiture et al., 2004; Oki and Kanae, 2004; Chapagain and Hoekstra, 2008; Yang and Zehnder, 2008). As shown by Yang et al. (2003), only below a certain threshold in water availability can a relationship be established between the country’s per capita water availability and its cereal import. For most relatively water-scarce countries – like in North Africa, Middle East, Southern Europe and Mexico – we find indeed net virtual water imports and related national water savings. The national water savings found for Northern European countries, however, cannot be understood from a water scarcity perspective.

3.4. Global water saving related to trade in agricultural and industrial products

The global water saving related to trade in agricultural products in the period 1996-2005 was 369 Gm^3/yr (58.7% green, 26.6% blue and 14.7% grey). This volume is equivalent to 4% of the global water footprint related to agricultural production (which is 8363 Gm^3/yr, see Table 1). Looking only at the blue water saving, it would have required an additional 98 Gm^3/yr of blue water to produce the same amount of goods without virtual water trade. This volume is equivalent to 10% of the global blue water footprint related to agricultural production (which is 945 Gm^3/yr, see again Table 1). More than a quarter (98/369=27%) of the global water saving related to agricultural trade is blue water, which indicates that virtual water importing countries generally depend more strongly on blue water for crop production than the virtual water exporting countries. Figure 6 shows trade flows that save more than 5 Gm^3/yr. Export of agricultural products (mainly maize and soybean products) from the US to Mexico and Japan comprise the biggest global water savings, contributing over 11% toward the total global water saving.

The largest water saving is due to trade in cereal crops with a global water saving of 196 Gm^3/yr, followed by oil crops (82 Gm^3/yr, mainly soybean) and animal products (56 Gm^3/yr). Among the cereal crops, trade in maize has resulted in the largest saving (71 Gm^3/yr), followed by wheat (67 Gm^3/yr), rice (27 Gm^3/yr), barley (21 Gm^3/yr) and other cereals (10 Gm^3/yr). In the case of rice, there is net global water saving if we look at the sum of green, blue and grey, but when we focus on the blue component we find a global blue water loss associated with trade in rice. Among the animal products, international trade in poultry products (25 Gm^3/yr), dairy products (16 Gm^3/yr), bovine products (16 Gm^3/yr) and pig products (2 Gm^3/yr) result in significant global water savings, but trade flows in horse, sheep and goat products are accompanied with a total global water loss of 3 Gm^3/yr. Figure 7 shows the contribution of different product groups to the total global water saving.

Trade in industrial products has resulted in a net global water loss of 16.4 Gm^3/yr (2% blue and 98% grey). This volume is equivalent to 4% of the global water footprint related to industrial production (which is 400 Gm^3/yr, see Table 1). Exports of industrial products from China and Russia are the major trade flows contributing to this global water loss related to industrial product trade. This is mainly due to the large grey water footprints per unit of value added in the industrial sectors in those two countries, which in turn relate to the low wastewater treatment coverage in those countries.

When we consider the global water saving related to trade in both agricultural and industrial products, we come to a net saving of 353 Gm^3/yr (61.5% green, 27.7% blue and 10.8% grey). The global water saving related to trade in agricultural and industrial products is presented in Appendix V. Global water savings due to international trade in crop products are specified by crop type; global water savings related to trade in animal products are given by animal type.

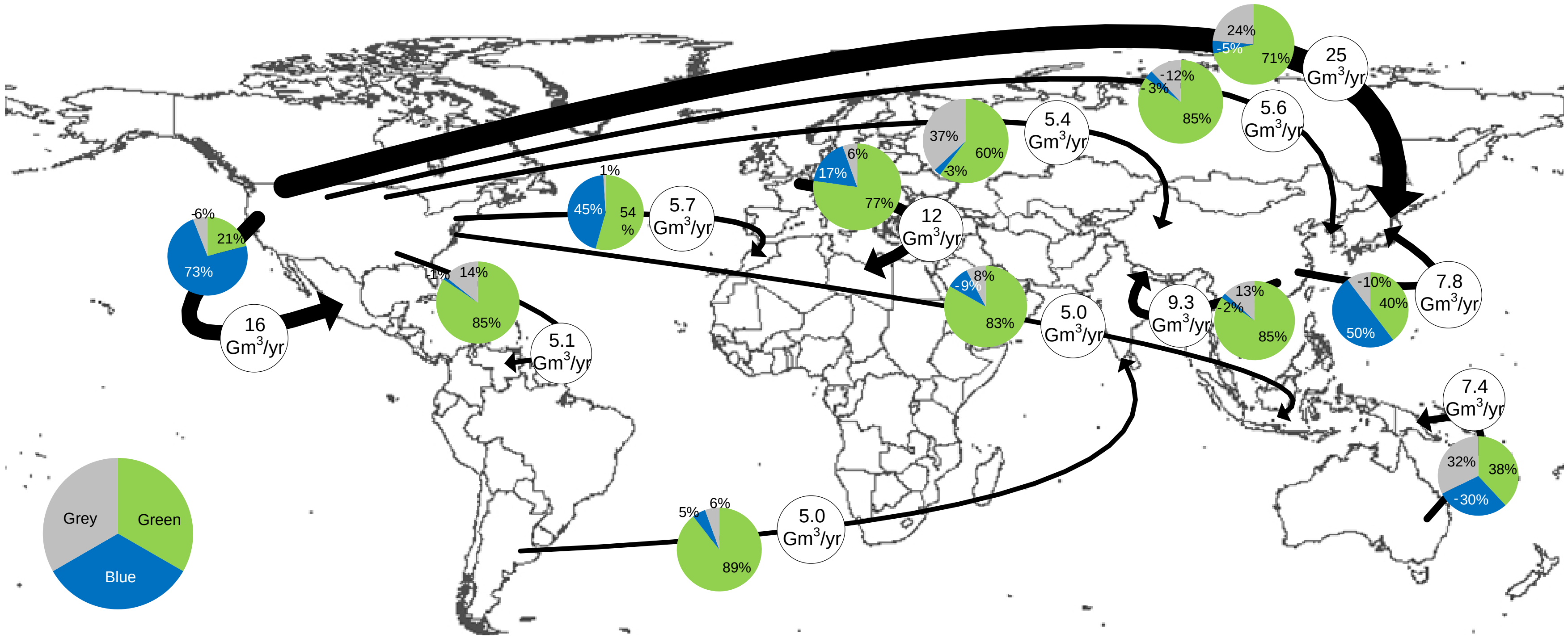

Figure 6.Global water savings associated with international trade in agricultural products (1996-2005). Only the biggest water savings (> 5 Gm^3/yr) are shown.

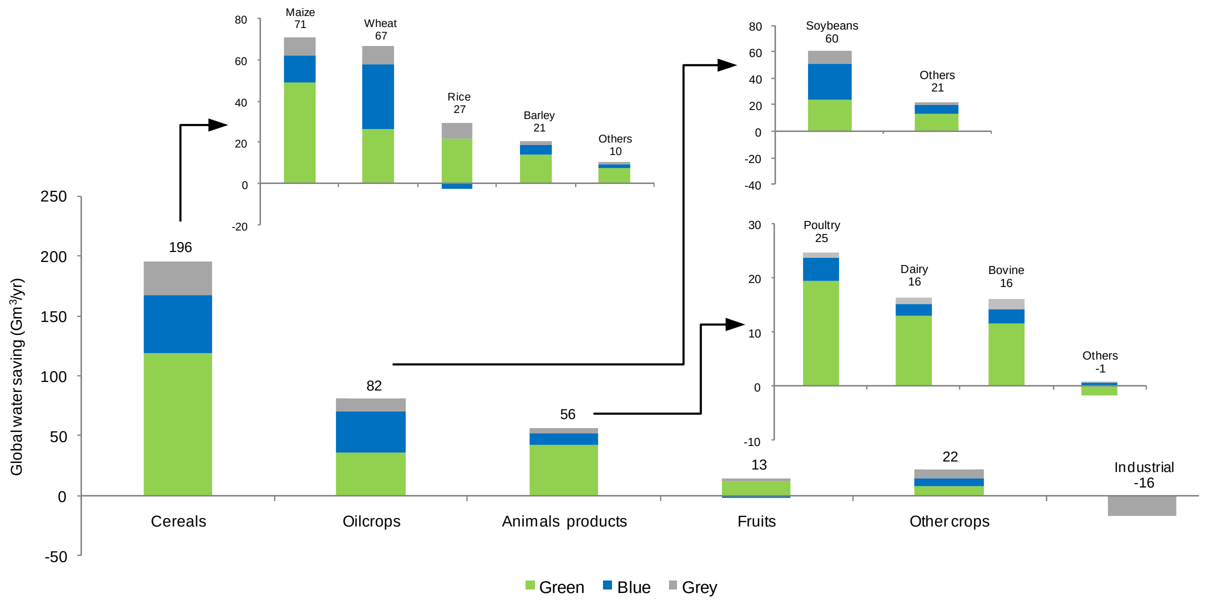

Figure 7. Contribution of different product categories to the total global water saving (1996-2005).

The calculated trade-related water savings are based on the crop yields and corresponding water footprints as they currently exist in the exporting and importing countries. One should therefore be careful in extrapolating water savings when trade flows would intensify. Water scarcity will stimulate countries to improve their water productivities, particularly in countries with low yields (Appelgren and Klohn, 1999; Keller et al., 1998; Molle, 2003; Ohlsson, 2000). Current global water savings resulting from trade in water-intensive products from countries with high water productivity to countries with low water productivity will diminish once the latter countries have increased their water productivity.

The presented global water saving related to international trade may seem significant: the global water footprint of agricultural and industrial production would be 4% higher if countries would produce all commodities within their own territory based on existing domestic productivities instead of partially import them from other countries. The potential of optimising international trade for further global water savings is probably small once the most important importing countries with low water productivities increase their productivity. The global water footprint can be reduced more significantly by achieving high water productivities across the globe than by optimising trade from high to low productivity regions. Supported by the assessment by Falkenmark et al. (2009), we estimate that the potential global water saving by increasing water productivities in regions that currently still have low productivities will be of an order of magnitude larger than the current global water saving achieved by trade. Therefore, for water scarce countries the first priority should be to raise their water productivity as much as possible before turning to virtual water import as an option to address their water scarcity problem.

3.5. The water footprint of national consumption

The global average water footprint related to consumption is 1385 m^3/yr per capita over the period 1996-2005. Consumption of agricultural products largely determines the global water footprint related to consumption, contributing 92% to the total water footprint. Consumption of industrial products and domestic water use contribute 4.7% and 3.8% respectively. When we look at the level of product categories, cereals consumption contribute the largest share to the global water footprint (27%), followed by meat (22%) and milk products (7%). The contribution of different product categories to the global average water footprint of consumption is presented in Figure 8.

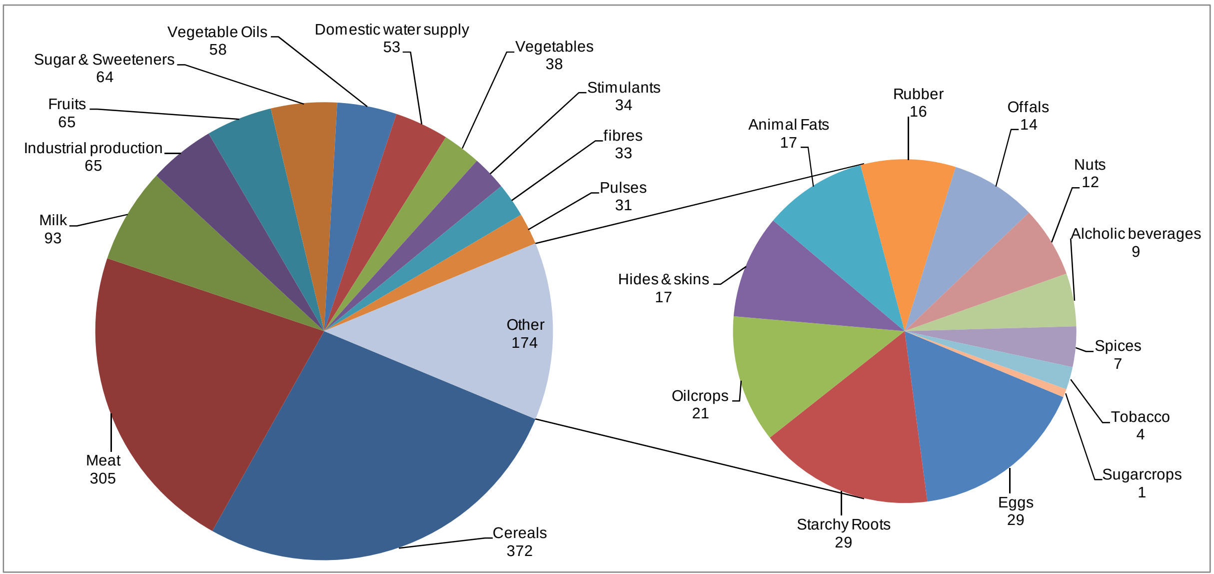

Figure 8. Contribution of different product categories to the global water footprint of consumption (in m^3/yr/cap).

The water footprint of consumption in a country depends on two factors: what and how much do consumers consume and what are the water footprints of the commodities consumed. The latter depends on the production circumstances in the places of origin of the various commodities. A certain product as available on the shelves within a country generally comes from different places, with different production circumstances and thus a different water footprint in each place. To calculate the average water footprint of a product in a country, the water footprints for all locations the product originates from are multiplied by the proportional share of the product coming from those locations. Appendix VI provides the average water footprint per ton of commodity per country weighted based on origin. As an example, consider the water footprint of tomatoes as consumed by German consumers. In the period 1996-2005, German tomato production was 47,000 ton/yr with an average total water footprint of 36 m^3/ton. Germany imported 667,000 ton/yr in the same period, amongst which 252,000 ton/yr was from the Netherlands with a water footprint of 10 m^3/ton, 244,000 ton/yr from Spain with a water footprint of 83 m^3/ton and 72,000 ton/yr from Italy with a water footprint of 109 m^3/ton. Weighting the water footprints of the different tomatoes on the German consumer market gives an average water footprint of tomatoes in Germany of 57 m^3/ton.

The relative contribution of different countries to the total water footprint of consumption is given in Figure 9. The green, blue, grey and total water footprint per capita for all countries are mapped in Figure 10. The water footprint of national consumption by product category for countries with a population size above 5 million is shown in Figure 11. Full details of the water footprint of national consumption per country are tabulated in

Appendices VII-IX. Appendix VII shows the water footprint of the average consumer per country by commodity. Appendix VIII summarizes the water footprint of the average consumer per country by consumption category and also specifies the water footprint by its internal and external components. Appendix IX, finally, shows the total water footprint of national consumption summed over all inhabitants of the country.

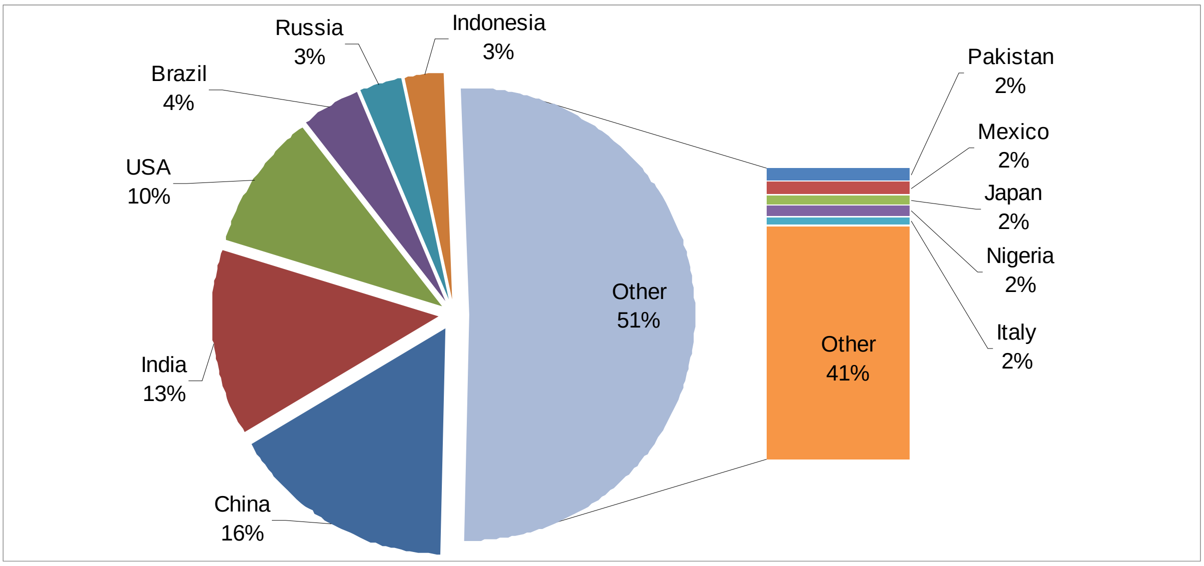

Figure 9. Contribution of different countries to the global water footprint of consumption.

In total terms, China is the country with the largest water footprint of consumption in the world, with a total footprint of 1368 Gm^3/yr, followed by India and the US with 1145 Gm^3/yr and 821 Gm^3/yr respectively. Obviously, countries with large populations have a large water footprint. Therefore it is more interesting to look at the water footprint per capita.

The ranking of countries in Figure 11 shows that industrialised countries have water footprints per capita in the range of 1250-2850 m^3/yr. The UK, with a water footprint of 1258 m^3/yr, is at the low end of this range, while the USA, with a footprint of 2842 m^3/yr, is at the high end. The differences can be partially explained by differences in consumption pattern. In the USA, for example, average consumption of bovine meat – one of the highly water-intensive commodities – was 43 kg/yr per capita, about 4.5 times the global average, while in the UK this was 18 kg/yr per capita, about two times the global average. Another factor behind the differences in the water footprints is the water consumption and pollution per unit of product per country. In the USA, the average water footprint of one kg of consumed bovine meat is 14500 m^3/ton, while in the UK this is 9900 m^3/ton.

The water footprint per capita for developing countries varies much more than for industrialised countries. We find values in a range 550-3800 m^3/yr per capita. At the low end is the Democratic Republic of Congo, with 552 m^3/yr per capita. At the high end we find Bolivia (3468 m^3/yr/cap), Niger (3519 m^3/yr/cap) and Mongolia (3775 m^3/yr/cap). With the disclaimer that the extreme values can also partially relate to weak basic data on consumption and water productivity in those countries, the differences can be traced back to differences in consumptions patterns on the one hand and differences in the water footprints of the products consumed on the other hand. What the ranking in Figure 11 shows is that in the range of relatively large water footprints per capita we find both industrialised and developing countries. The latter are in that range generally not because of their relative large consumption – although a relative large meat consumption can play a role – but because of their low water productivities, i.e. large water footprints per ton of product consumed. In Bolivia, for example, consumption of meat is 1.3 times the global average, but the water footprint per ton of meat is five times the global average. For Niger, the consumption of cereals per capita is 1.4 times the global average, but the water footprint of cereals per ton is six times the world average.

When we look at the blue water footprint per capita, countries in Central and Southwest Asia and North Africa appear on top. Consumers in Turkmenistan have the largest blue water footprint of all countries, namely 740 m^3/yr per capita on average. Other countries with a large blue water footprint are (in descending order): Iran (589 m^3/yr/cap), the United Arab Emirates (571), Egypt (527), Libya (511), Tajikistan (474), Saudi Arabia (447) and Pakistan (422). The global average blue water footprint of consumption is 153 m^3/yr per capita, which is 11% of the total water footprint. As can be seen in Figure 12, the variation in blue water footprint per capita across countries is huge, much larger than the variation in total water footprint per capita (Figure 11). Whereas the largest total water footprint per capita (Mongolia) is about seven times the smallest total water footprint per capita (DR Congo), the difference in case of the blue water footprint is more than a factor hundred.

3.6. External water dependency of countries

All external water footprints of nations together constitute 22% of the total global water footprint (Figure 13). The share of external water footprint, however, varies from country to country. Some European countries, such as Italy, Germany, the UK and the Netherlands have external water footprints contributing 60% to 95% to the total water footprint. On the other hand, some countries such as Chad, Ethiopia, India, Niger, DR Congo, Mali, Argentina and Sudan have very small external water footprints, smaller than 4% of the total footprint.

Countries with a large external water footprint apparently depend upon freshwater resources in other countries. Highly water-scarce countries that have a large external water dependency are for example: Malta (dependency 92%), Kuwait (90%), Jordan (86%), Israel (82%), United Arab Emirates (76%), Yemen (76%), Mauritius (74%), Lebanon (73%) and Cyprus (71%). Not all countries that have a large external water footprint, however, are water scarce. In this category are many Northern European countries like the Netherlands and the UK. They depend upon freshwater resources elsewhere, but the high dependence is not by necessity, since these countries have ample room for expanding agricultural production and thus reduce their external water dependency.

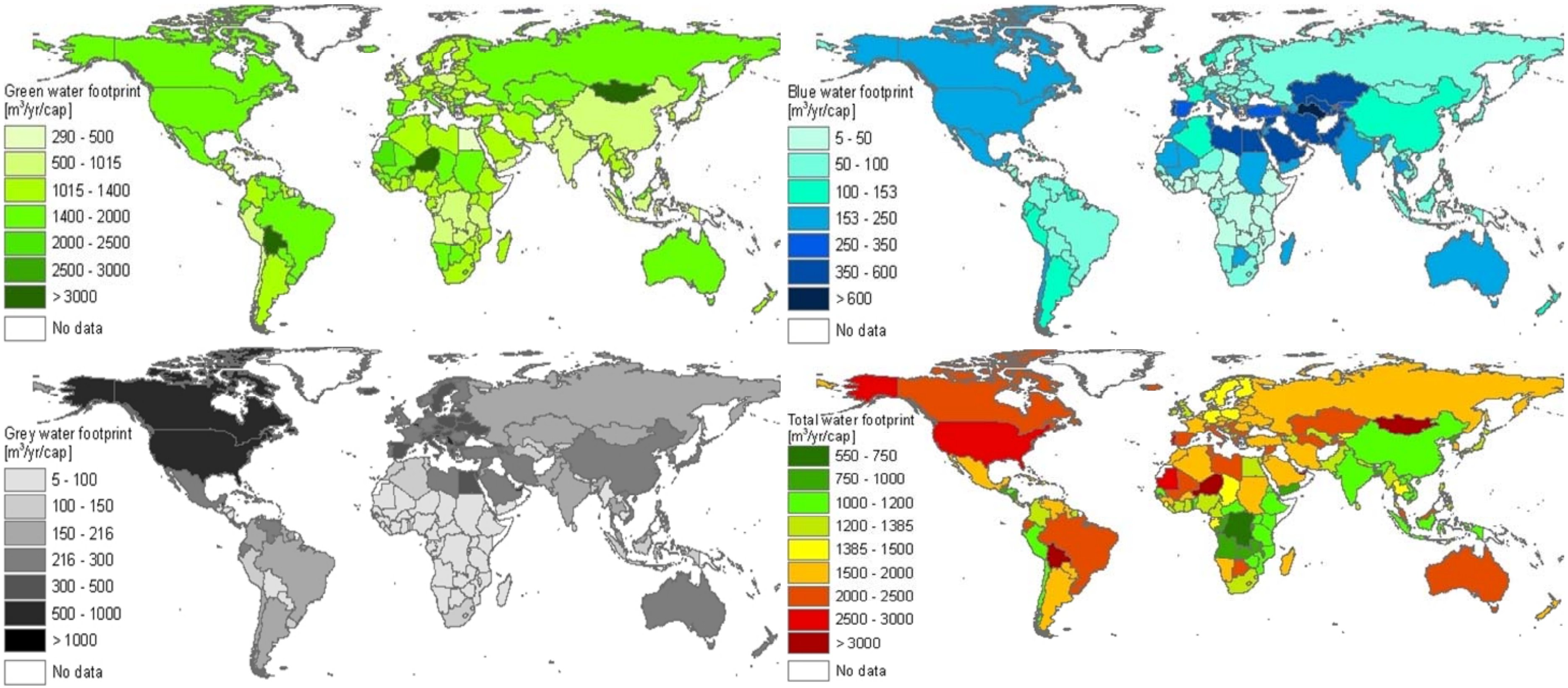

Figure 10. The green, blue, grey and total water footprint of consumption per country in the period 1996-2005 (m^3/yr per capita). In the map showing the total water footprint of consumption per country (bottom-right), countries shown in green have a water footprint that is smaller than the global average; countries shown in yellow-red have a water footprint larger than the global average.

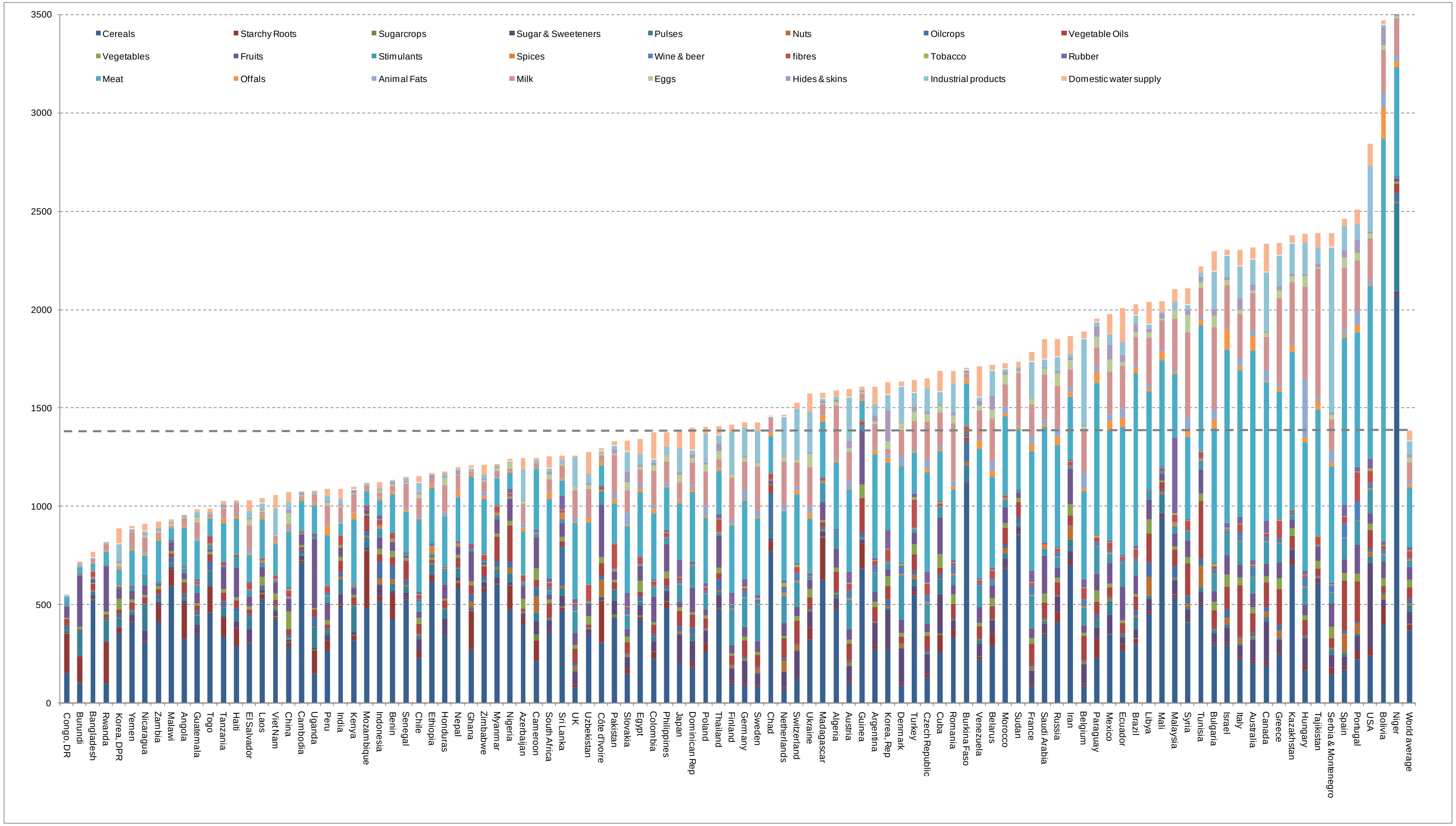

Figure 11. Water footprint of national consumption for countries with a population larger than 5 million, shown by product category (m^3/yr/cap) (1996-2005).

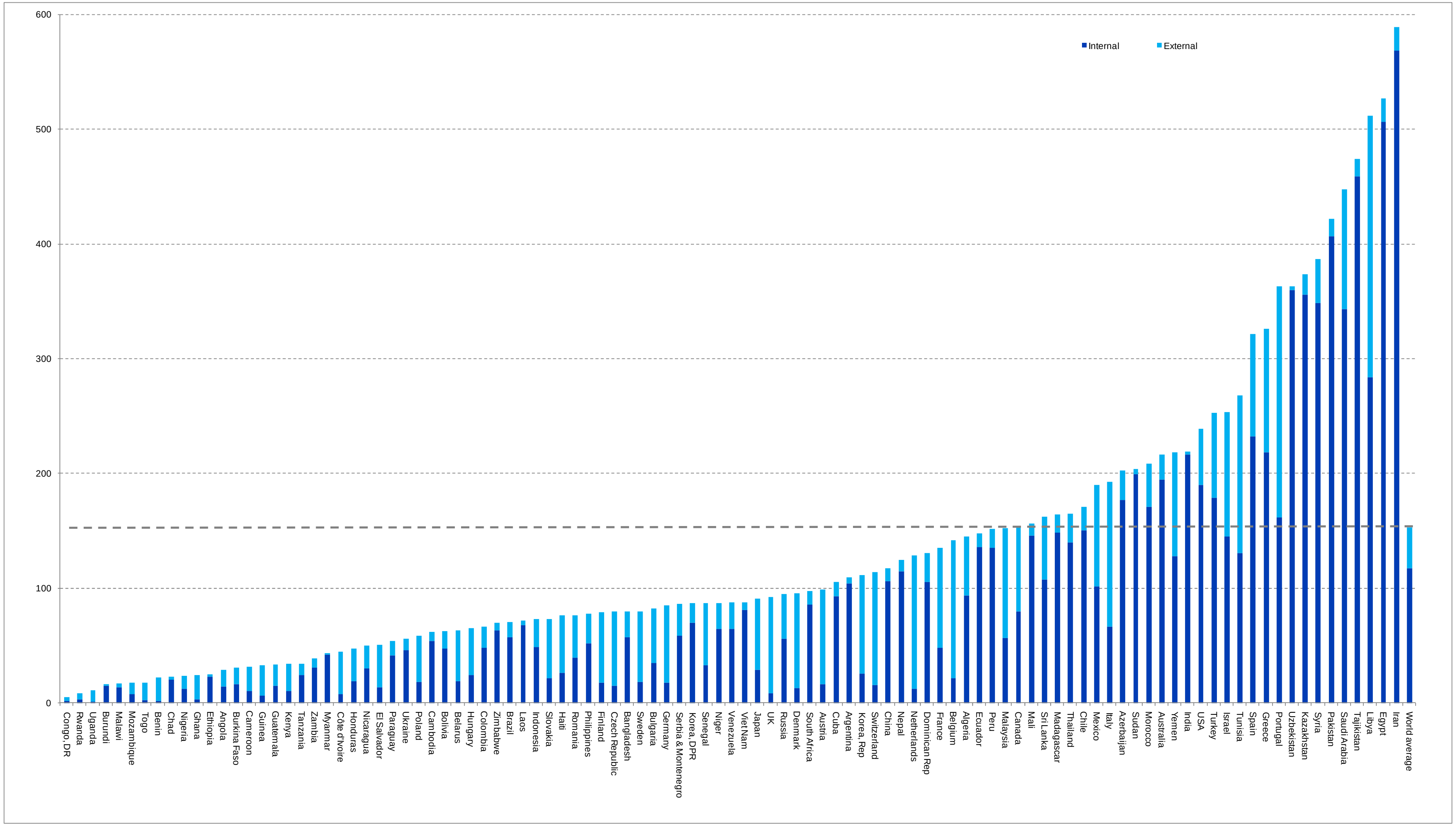

Figure 12. Blue water footprint of national consumption for countries with a population larger than 5 million, shown by internal and external component (m^3/yr/cap) (1996-2005).

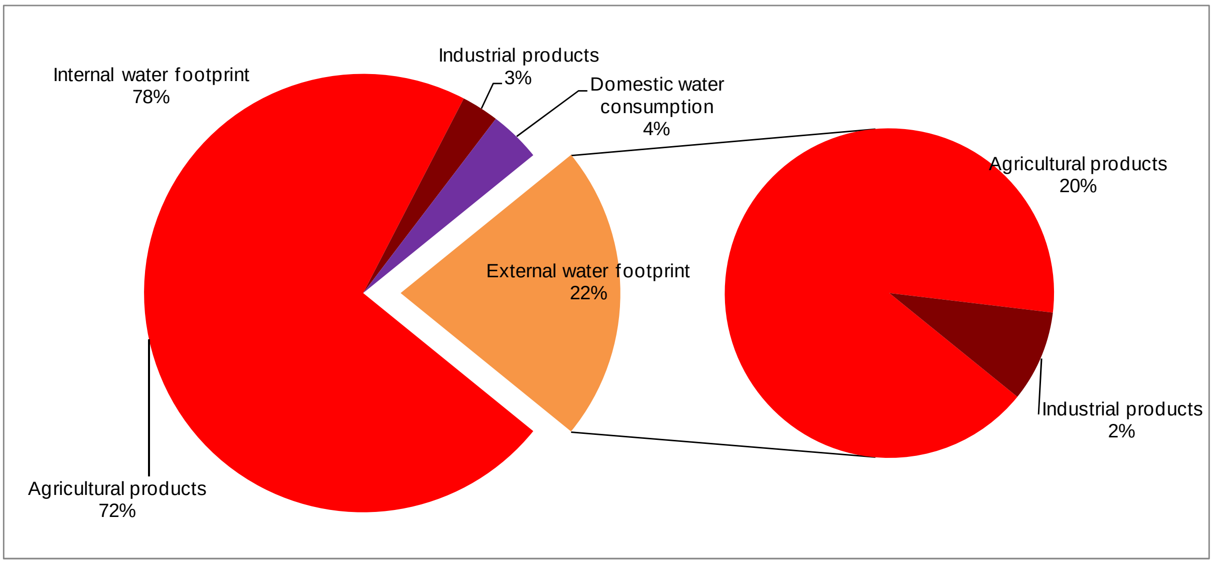

Figure 13. Contribution of different consumption categories to the global water footprint, split into internal and external water footprint.

3.7. Mapping the global water footprint of national consumption: an example from the US

The water footprint statistics presented in the previous section hide the fact that water footprints have a spatial dimension. In this section we illustrate this spatial dimension with an example from the US.

The global water footprint of US citizens related to the consumption of agricultural products is mapped at a fine scale resolution (5 by 5 arc minute grid) in Figure 14. The map shows the water footprint of crops consumed directly by US consumers and the water footprint of animal feed crops (domestic and imported) used to produce the animal products that are both produced and consumed within the US. It excludes the water footprint of imported animal products consumed within the US because tracing the origin of the feed of imported animal products on grid level would require a very laborious additional step of analysis.

The global water footprint of US consumption of industrial products is mapped in Figure 15. The water footprint of US domestic water consumption is fully within the US itself and shown in Figure 16. We ignore here the water footprint of imported bottled water, but in terms of volumes this is very small compared to the water volumes consumed in households from domestic water supply (Gleick, 2010).

Most of the US water footprint lies within the US, mainly in the Mississippi basin (more than 50%). About 20% of the water footprint of US citizens lies outside the US. The largest water footprint outside the US is in the Yangtze basin (China). In Appendix X we tabulate the water footprint of US consumption per river basin for the 250 basins where the water footprint is largest.

Appendix XI provides maps of the global water footprint of consumption for eight selected countries other than the US: Australia, Canada, Germany, Italy, Japan, Mexico, the Netherlands, Spain and the UK.

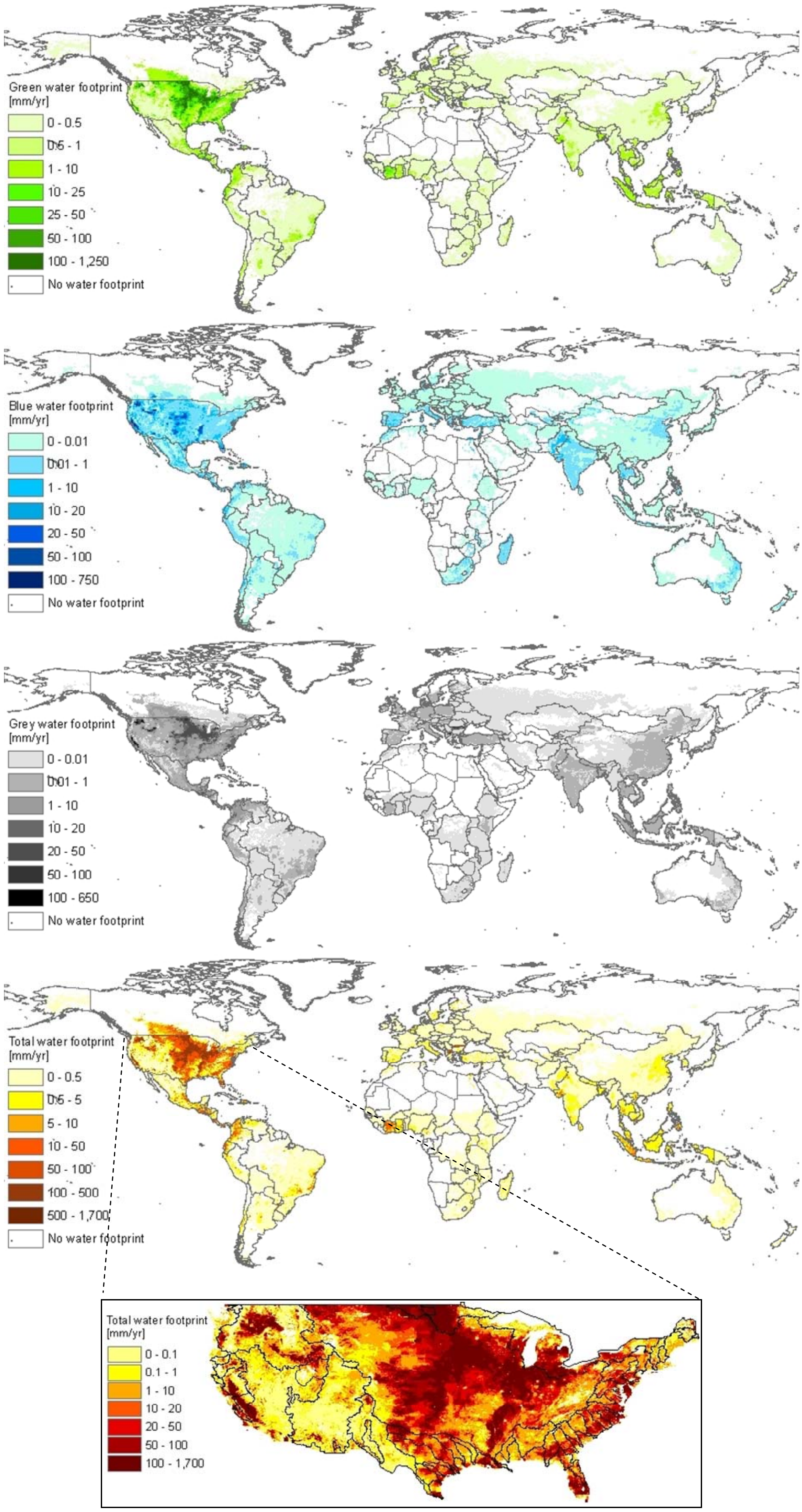

Figure 14. The global water footprint of US citizens related to the consumption of crop and animal products (1996-2005).

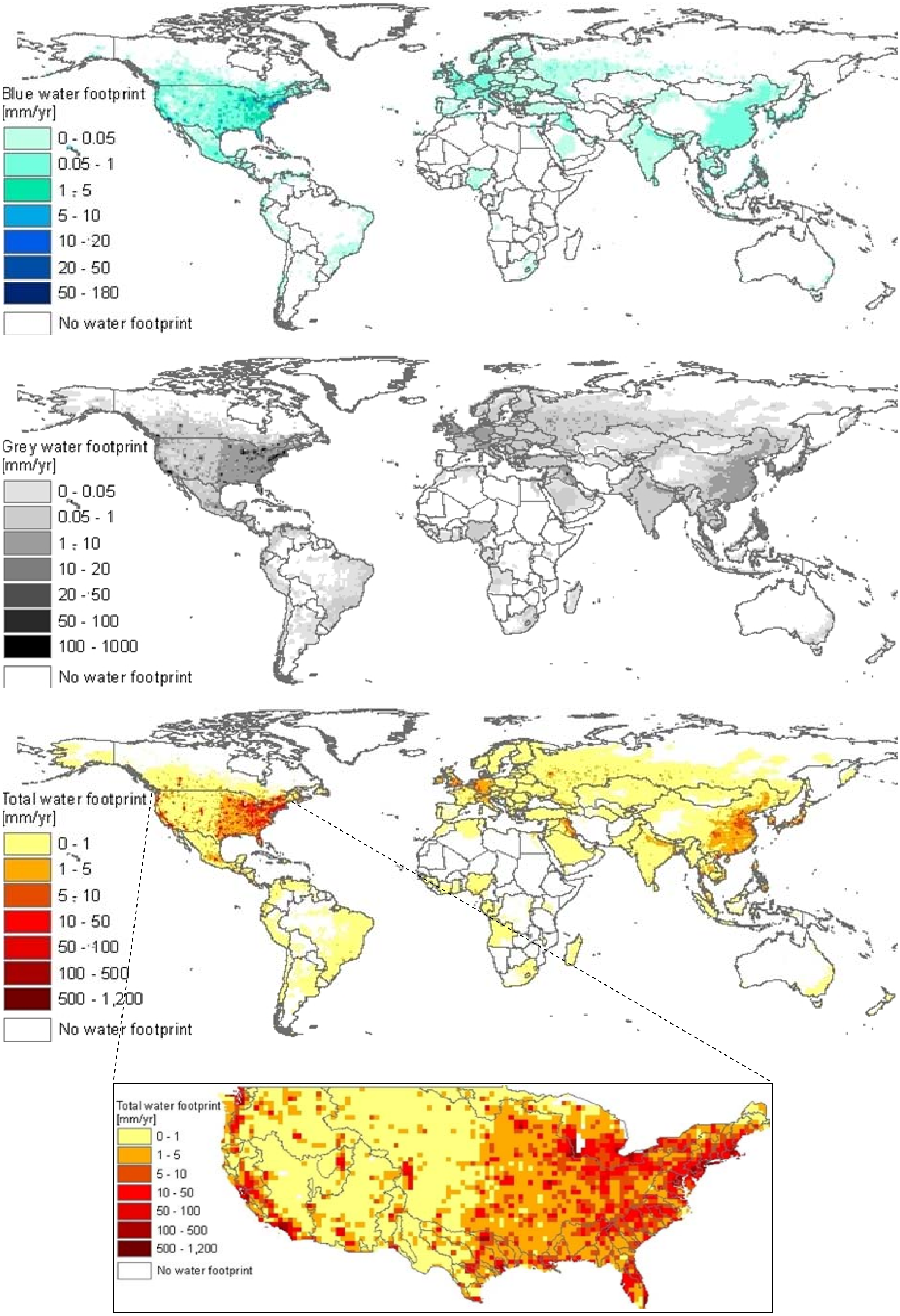

Figure 15. The global water footprint of US citizens related to the consumption of industrial products (1996-2005).

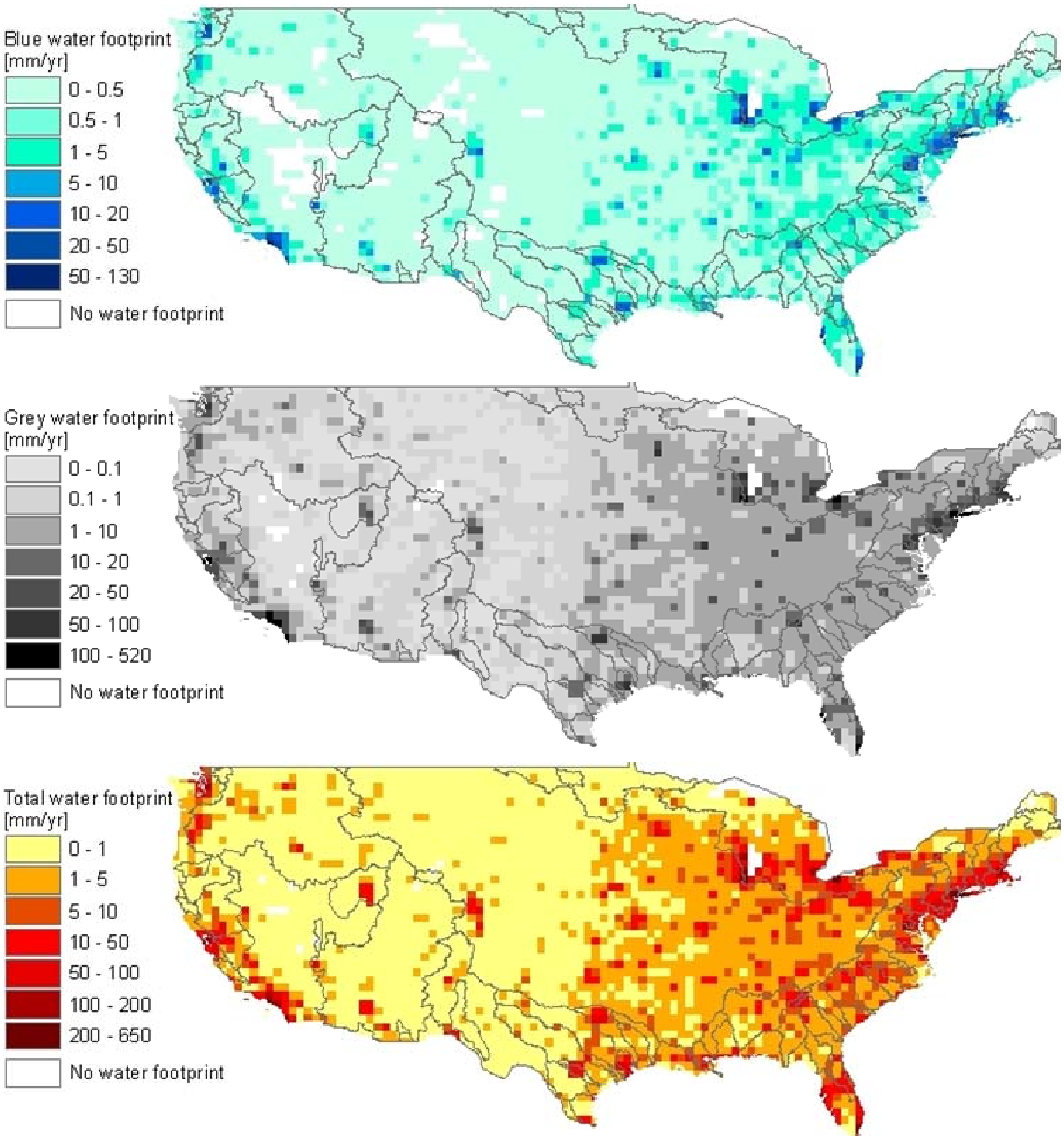

Figure 16. The water footprint of US citizens related to domestic water supply (1996-2005). The boundaries shown are river basin boundaries.

4. Discussion

The global water footprint related to agricultural and industrial production and domestic water supply for the period 1996-2005 was found to be 9087 Gm^3/yr (Section 3.1). If we calculate the global sum of estimated national water footprints of consumption (Section 3.5), we arrive at a 6% lower figure, namely 8525 Gm^3/yr. An explanation is that the latter figure is conservative, because in the estimation of the water footprint of national consumption of agricultural products based on the bottom-up approach we only partially accounted for the water footprint of waste and seeds. We multiplied all consumption figures by a certain factor to account for waste and seeds where applicable (see method and data section) for all crop and animal products consumed but we could not account for the water footprint of waste and seeds in the production of animal feed. Another reason for the difference between the two global water footprint estimates is that in the water footprint of global production we could account for all countries, while in the estimation of the water footprint of national consumption we had to exclude a few countries due to the absence of consumption data (most notably Iraq and Afghanistan). Another explanation of the difference is that in the estimation of the national water footprint related to consumption we could not include all consumer categories (like for example some alcoholic beverages). When it was not clear which crops underlie certain products, we could not calculate the water footprint per ton of those products. A final explanation for differences between the two global water footprint figures could be that stock changes reported in the Supply and Utilization Accounts of the Food and Agriculture Organization (FAO, 2010a) create a difference between 'production plus imports' and 'utilization' in a certain period.

This study is the first to use the bottom-up approach to estimate the water footprint of national consumption of agricultural commodities at a global scale. As shown by Van Oel et al. (2009), the advantage of using the bottom-up approach is that it is more stable. The bottom-up approach depends on the quality of consumption data, while the top-down-approach relies on the quality of production and trade data. The outcome of the top-down approach can be vulnerable to relatively small errors in the trade data when the import and export of a country are large relative to its domestic production. Relatively small errors in the estimates of virtual-water import and export can then translate into a relatively large error in the water footprint estimate. In such a case, the bottom-up approach yields a more reliable estimate than the top-down approach. Another advantage of the bottom-up approach is that it allows for showing the composition of the water footprint by commodity or product category in a very straightforward manner (because this is the way the overall estimate is built up), which in the top-down approach is difficult to achieve.

A limitation in the study is that the origin of products has been traced only by one step. If a product is imported from another country, we assume that the product has been produced in that country and we take the water footprint of the imported product accordingly. If the trade partner country does not produce that commodity, we do not trace further back but assume a global average water footprint. But even if the country produces the product, it could have been the case that the product was in part imported from somewhere else and re-exported. Tracing of products by more than one step has been done for example by Chapagain and Orr (2008) for the UK but this was too laborious for this global study. Besides, such continued tracing effort is necessarily based on assumptions because export data in trade statistics are not connected to import data, therefore the added value of tracing can be questioned. Finally, in a global study, tracing back more than one step would create the problem of circularity in the calculations. Common products are traded in all directions between all countries, so that a strategy of tracing products will soon lead to the situation in which a small fraction of a product imported to a country X is estimated to originate, through a detour, from the same country X. This leads to a mathematical circularity in the calculation of the average water footprint of the product in country X – see equation (3).

The grey water footprint estimates in this study are to be considered as conservative. In the case of agricultural production, the grey water footprint estimates are based on leaching and runoff of nitrogen fertilisers, excluding the potential effect of other fertiliser components and pesticides (Mekonnen and Hoekstra, 2010b, 2011). In the cases of industrial production and domestic water supply, a very conservative dilution factor of 1 has been applied for all untreated return flows.

While in the estimation of the water footprint of consumer products we considered a huge amount of different agricultural commodities separately, industrial commodities were treated as one whole category. Although in this way the study shows no detail within the estimation of the water footprint of production and consumption of industrial products, we justify the choice in this global study based on the fact that most of the water footprint of humanity is within the agricultural sector.

We have analysed a ten-year period, but we do not show annual variations or trends in time. The reason is that the data do not allow for that. Many of the databases that we used show data for every individual year within our ten-year period (e.g. production, consumption, trade, rainfall and yield data), but not all global databases show year-specific data (e.g. reference evapotranspiration, crop growing area and irrigation data). The estimated water footprints of agricultural products are necessarily ten-year averages, because they have been based on climate data, which are by definition multi-year averages (Mekonnen and Hoekstra, 2010b, 2011). Even if we would have been able to estimate water footprints by year, a trend analysis over a ten-year period would have been difficult due to the natural inter-annual variability of rainfall and temperature.

The data presented in this report are derived on the basis of a great number of underlying statistics, maps and assumptions. Since all basic sources include uncertainties and possible errors, the presented water footprint data should be taken and interpreted with extreme caution, particularly when zooming in on specific locations on a map or when focussing on specific products. Basic sources of uncertainties are for example the global precipitation, temperature, crop and irrigation maps that we have used and the yield, production, consumption, trade and wastewater treatment statistics that we had to rely on. Underlying assumptions refer, for example, to planting and harvesting dates per crop per region and feed composition per farm animal type per country and production system. Another assumption has been that water footprints of industrial production and domestic water supply are geographically spread according to population densities. Despite the plethora of uncertainties, we think that the current study forms a good basis for rough comparisons and to guide further analysis.

5. Conclusion

The study shows that about one fifth of the global water footprint in the period 1996-2005 was not related to production for domestic consumption but for export. The global volume of water saving from international trade in agricultural products was equivalent to 4% of the global water footprint for agricultural production. The relatively large volume of international virtual water flows and the associated national water savings and external water dependencies strengthen the argument to consider issues of local water scarcity in a global context (Hoekstra and Chapagain, 2008; Hoekstra, 2011).

Two factors determine the magnitude of the water footprint of national consumption: (1) the volume and pattern of consumption and (2) the water footprint per ton of consumed products. The latter, in the case of agricultural products, depends on climate, irrigation and fertilization practice and crop yield. The global average water footprint related to consumption is 1385 m^3/yr per capita over the period 1996-2005. Industrialised countries have water footprints in the range of 1250-2850 m^3/yr/cap, while developing countries show a much larger range of 550-3800 m^3/yr/cap. The low values for developing countries relate to low consumption volumes; the large values refer to very large water footprints per unit of consumption.

The study provides important information on the water footprints of nations, disaggregated into the type of water footprint (green, blue or grey) and mapped at a high spatial resolution. The report shows how different products and national communities contribute to water consumption and pollution in different places. The figures can thus form an important basis for further assessment of how products and consumers contribute to the global problem of increasing freshwater appropriation against the background of limited supplies and to local problems of overexploitation and deterioration of freshwater bodies or conflict over water. Once one starts overlaying localised water footprints of products or consumers with maps that show environmental or social water conflict, a link has been established between final products and consumers on the one hand and local water problems on the other hand. Establishing such links can help the dialogue between consumers, producers, intermediates (like food processors and retailers) and governments about how to share responsibility for reducing water footprints where most necessary.

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