The water footprint of humanity

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This study quantifies and maps the water footprint (WF) of humanity at a high spatial resolution. It reports on consumptive use of rainwater (green WF) and ground and surface water (blue WF) and volumes of water polluted (gray WF). Water footprints are estimated per nation from both a production and consumption perspective. International virtual water flows are estimated based on trade in agricultural and industrial commodities. The global annual average WF in the period 1996–2005 was 9,087 Gm^3/y (74% green, 11% blue, 15% gray). Agricultural production contributes 92%. About one-fifth of the global WF relates to production for export. The total volume of international virtual water flows related to trade in agricultural and industrial products was 2,320 Gm^3/y (68% green, 13% blue, 19% gray). The WF of the global average consumer was 1,385 m^3/y. The average consumer in the United States has a WF of 2,842 m^3/y, whereas the average citizens in China and India have WFs of 1,071 and 1,089 m^3/y, respectively. Consumption of cereal products gives the largest contribution to the WF of the average consumer (27%), followed by meat (22%) and milk products (7%). The volume and pattern of consumption and the WF per ton of product of the products consumed are the main factors determining the WF of a consumer. The study illustrates the global dimension of water consumption and pollution by showing that several countries heavily rely on foreign water resources and that many countries have significant impacts on water consumption and pollution elsewhere.

globalization | sustainable consumption | virtual water trade | water pollution

The Earth's freshwater resources are subject to increasing pressure in the form of consumptive water use and pollution (1–4). 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 has led a number of researchers to argue for the importance of putting freshwater issues in a global context (5–9). Appreciating the global dimension of freshwater resources can be regarded as a key to solving some of today's most urgent water problems (10).

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. 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 (WF) 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 (11–13). National WF accounts extend these statistics by including data on rainwater 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 (14) (Fig. S1). The WF is a measure of humans' appropriation of freshwater resources and has three components: blue, green, and gray (8, 14). The blue WF refers to consumption of blue water resources (surface and ground water), whereby consumption refers to the volume of water that evaporates or is incorporated into a product. The blue WF is thus often smaller than the water withdrawal, because generally part of a water withdrawal returns to the ground or surface water. The green WF is the volume of green water (rainwater) consumed, which is particularly relevant in crop production. The gray WF 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.

Quantifying and mapping national WFs has been an evolving field of study since the introduction of the WF concept in the beginning of this century (15). An earlier global study on the WFs of nations was carried out by Hoekstra and Hung (16); another, much more comprehensive study, was done by Hoekstra and Chapagain and reported in a number of subsequent publications (8, 17–20). The current study is the third global assessment of national WFs, 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 WF of humanity by quantifying the WFs of nations from both a production and consumption perspective. First, we quantify and map at a high spatial resolution the green, blue, and gray WFs 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. Finally, we quantify the WF of consumption for all countries of the world, distinguishing for each country between the internal and the external WF of national consumption. Throughout the study, we explicitly distinguish between green, blue, and gray WFs. We estimate annual averages for the period 1996–2005, which was the most recent 10-y period for which all required datasets could be collected at the time of execution of the calculations.

The current study is more comprehensive and detailed than the earlier two global WF studies (8, 16). The study improves

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upon the previous global WF study (8) in a number of respects. First, we apply a spatial resolution of $5 \times 5'$ in estimating the WF in crop production, industrial production and domestic water supply, whereas the earlier studies included estimates for countries as a whole, without considering the heterogeneity within countries. Second, in the case of crop production, we make an explicit distinction between the green and blue WF (which has not been done in the previous global WF studies) and we now include the gray WF in a global assessment. Third, we make use of better estimates of the feed composition of farm animals and distinguished three different animal production systems (grazing, mixed, and industrial) in each country, accounting for the relative presence of those three systems. Fourth, we explicitly distinguish between the blue and gray WF in industrial production and domestic water supply and account for wastewater treatment coverage per country. Finally, we apply the bottom-up approach in estimating the WF of national consumption of agricultural products, which is less sensitive to trade data than the top-down approach that was applied in the earlier studies (8, 16). Besides, taking the bottom-up approach enables us to assess the WF per country in a detailed way per consumption category, which was not possible in the earlier study that took the top-down approach. The current article builds on two earlier studies by the same authors. We have reported the green, blue, and gray WFs of crops and derived crop products in refs. 21 and 22, and have documented the green, blue, and gray WFs of farm animals and animal products in ref. 23.

Results

The WF of National Production. Fig. 1 shows the water footprint of humanity at a high spatial resolution. China, India, and the United States are the countries with the largest total WFs within their territory, with total WFs of 1,207; 1,182; and 1,053 Gm^3/y, respectively. About 38% of the WF of global production lies within these three countries. The next country in the ranking is Brazil, with total WF within its territory of 482 Gm^3/y. India is the country with the largest *blue* WF within its territory: 243 Gm^3/y, which is 24% of the global blue WF. Irrigation of wheat is the process that takes the largest share (33%) in India's blue WF, followed by irrigation of rice (24%) and irrigation of sugarcane (16%). China is the country with the largest *gray* WF within its borders: 360 Gm^3/y, which is 26% of the global gray WF. Fig. S2 shows world maps with the green, blue, and gray WFs within nations in the period 1996–2005.

In all countries, the WF related to agricultural production takes the largest share in the total WF within the country. China and the United States have the largest WFs in their territory related to industrial production; 22% of the global WF related to industrial production lies in China and 18% in the United States. Belgium is the country in which industrial production takes the largest share in the total WF in the country. The WF of industries in Belgium contributes 41% to the total WF in the country; agricultural production still contributes 53% here. Fig. S3 shows world maps with the WFs of agricultural production, industrial production, and related to domestic water supply.

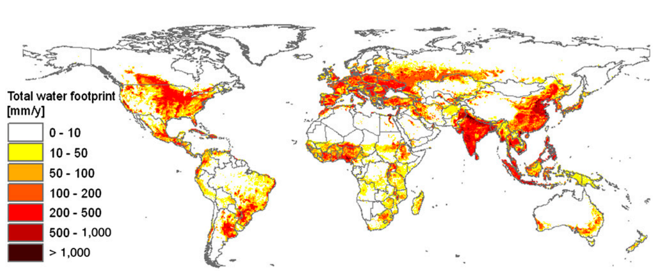

Fig. 1. The water footprint of humanity in the period 1996–2005. The data are shown in millimeter per year on a $5 \times 5'$ grid.

The global annual average WF related to agricultural and industrial production and domestic water supply for the period 1996–2005 was 9,087 Gm^3/y (74% green, 11% blue, 15% gray; see Table 1). Agricultural production takes the largest share, accounting for 92% of the global WF. Industrial production contributes 4.4% to the total WF and domestic water supply 3.6%.

The global WF related to producing goods for export is 1,762 Gm^3/y. In the agricultural sector, 19% of the total WF relates to production for export; in the industrial sector this is 41%. The WF 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 WF is not for domestic consumption but for export.

International Virtual Water Flows. The global sum of international virtual water flows related to trade in agricultural and industrial products in the period 1996–2005 was 2,320 Gm^3/y on average (68% green, 13% blue, and 19% gray). 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 1,762 Gm^3/y. The gross international virtual water flows are presented in Table 2.

As a global average, the blue and gray shares in the total WF of internationally traded products are slightly larger than in the case of domestically consumed products, meaning that export goods are more strongly related to water consumption from and pollution of surface and groundwater than nonexport goods. The green component in the total WF of internationally traded products is 68%, whereas 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 United States (314 Gm^3/y), China (143 Gm^3/y), India (125 Gm^3/y), Brazil (112 Gm^3/y), Argentina (98 Gm^3/y), Canada (91 Gm^3/y), Australia (89 Gm^3/y), Indonesia (72 Gm^3/y), France (65 Gm^3/y), and Germany (64 Gm^3/y). The United States, 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 (24–26), which 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 issue 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 United States (234 Gm^3/y), Japan (127 Gm^3/y), Germany (125 Gm^3/y), China (121 Gm^3/y), Italy (101 Gm^3/y), Mexico (92 Gm^3/y), France (78 Gm^3/y), the United Kingdom (77 Gm^3/y), and The Netherlands (71 Gm^3/y).

Fig. 2 shows the virtual water balance per country and the largest international gross virtual water flows. The countries shown in green 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 United States, 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.

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

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

	Agricultural production					
	Crop production	Pasture	Water supply in animal raising	Industrial production	Domestic water supply	Total
Global water footprint of production, Gm^3/y						
Green	5,771*	913†	—	—	—	6,684
Blue	899*	—	46†	38	42	1,025
Gray	733*	—	—	362	282	1,378
Total	7,404	913	46	400	324	9,087
Water footprint for export, Gm^3/y	———	1,597	———	165	0	1,762
Water footprint for export compared to total, %	———	19	———	41	0	19

*Mekonnen and Hoekstra (21, 22).
†Mekonnen and Hoekstra (23).

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%), coffee, tea, and cocoa (7.9%), and beef cattle products (6.7%).

The WF of National Consumption. The global annual average WF related to consumption was 1,385 m^3/y per capita over the period 1996–2005. Consumption of agricultural products largely determines the global WF related to consumption, contributing 92% to the total WF. 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 WF (27%), followed by meat (22%) and milk products (7%).

The WF of consumption in a country depends on two factors: what and how much do consumers consume and the WFs 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 WF in each place.

In total terms, China is the country with the largest WF of consumption in the world, with a total footprint of 1,368 Gm^3/y, followed by India and the United States with 1,145 and 821 Gm^3/y, respectively. Obviously, countries with large populations have a large WF. Therefore it is more interesting to look at the WF per capita.

The ranking of countries in Fig. 3 shows that industrialized countries have WFs per capita in the range of 1,250–2,850 m^3/y. The United Kingdom, with a WF of 1,258 m^3/y, is at the low end of this range, whereas the United States, with a footprint of 2,842 m^3/y, is at the high end. The differences can be partially explained by differences in consumption pattern. In the United States, for example, average consumption of bovine meat—one of the highly water-intensive commodities—was 43 kg/y per capita, about 4.5 times the global average, whereas in the United Kingdom the average was 18 kg/y per capita, about two times the global average. Another factor behind the differences in the WFs is the water consumption and pollution per unit of product per country.

Table 2. Gross international virtual water flows (giga cubic meter per year) (1996–2005)

	Related to trade in agricultural products	Related to trade in industrial products	Total
Related to export of domestically produced goods	1,597	165	1,762
Related to reexport of imported goods	441	117	558
Total	2,038	282	2,320

In the United States, the average WF of 1 kg of consumed bovine meat is 14,500 m^3/ton, whereas in the United Kingdom the average is 9,900 m^3/ton. A general trend is that industrialized countries have a larger WF related to consumption of industrial products than developing countries. The green, blue, gray, and total WFs per capita for all countries are mapped in Fig. S4.

The WF per capita for developing countries varies much more than for industrialized countries. We find values in a range 550–3,800 m^3/y per capita. At the low end is the Democratic Republic (DR) of Congo, with 552 m^3/y per capita. At the high end, we find Bolivia (3,468 m^3/y per capita), Niger (3,519 m^3/y per capita), and Mongolia (3,775 m^3/y per capita). 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 WFs of the products consumed on the other hand. What the ranking in Fig. 3 shows is that in the range of relatively large WFs per capita we find both industrialized 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 WFs per ton of product consumed. In Bolivia, for example, consumption of meat is 1.3 times the global average, but the WF 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 WF of cereals per ton is six times the world average.

When we look at the blue WF per capita, countries in Central and Southwest Asia and North Africa appear on top. Consumers in Turkmenistan have the largest blue WF of all countries, namely 740 m^3/y per capita on average. Other countries with a large blue WF are (in descending order): Iran (589), the United Arab Emirates (571), Egypt (527), Libya (511), Tajikistan (474), Saudi Arabia (447), and Pakistan (422 m^3/y per capita). The global average blue WF of consumption is 153 m^3/y per capita, which is 11% of the total WF. The variation in blue WF per capita across countries is huge (Fig. S5), much larger than the variation in total WF per capita (Fig. 3). Whereas the largest total WF per capita (Mongolia) is about seven times the smallest total WF per capita (DR Congo), the difference in the case of the blue WF is more than a factor hundred.

External Water Dependency of Countries. All external WFs of nations together constitute 22% of the total global WF. The share of external WF, however, varies from country to country. Some European countries, such as Italy, Germany, the United Kingdom, and The Netherlands have external WFs contributing 60–95% to the total WF. On the other hand, some countries, such as Chad, Ethiopia, India, Niger, DR Congo, Mali, Argentina, and Sudan have very small external WFs, smaller than 4% of the total footprint.

Countries with a large external WF apparently depend upon freshwater resources in other countries. Highly water-scarce countries that have a large external water dependency are for

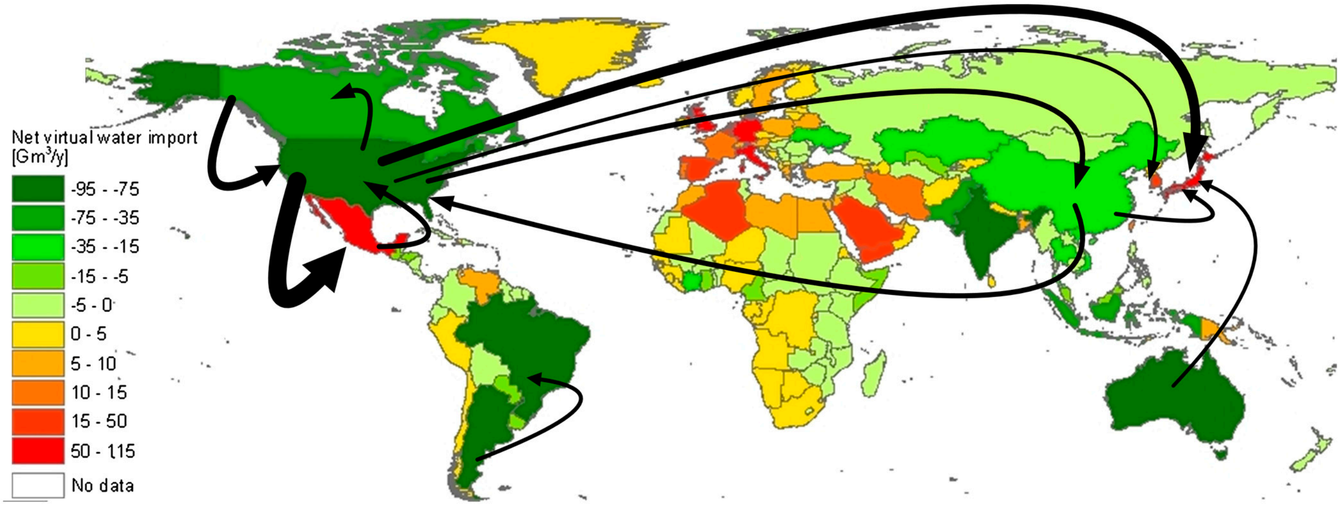

Fig. 2. Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996–2005. Only the biggest gross flows (>15 Gm^3/y) are shown.

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 WF, however, are water scarce. In this category are many Northern European countries like The Netherlands and the United Kingdom. They depend upon freshwater resources elsewhere, but the high dependence is not by necessity because these countries have ample room for expanding agricultural production and thus reduce their external water dependency. For the United States, the external water dependency is 20% (Figs. S6–S8)

Discussion

Inherent to the comprehensive nature of this study, it has a number of limitations. One limitation 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 WF 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 WF. 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 reexported. Tracing of products by more than one step has been done for example in ref. 27 for the United Kingdom, 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.

The gray WF estimates in this study are to be considered as conservative. In the case of agricultural production, the gray WF

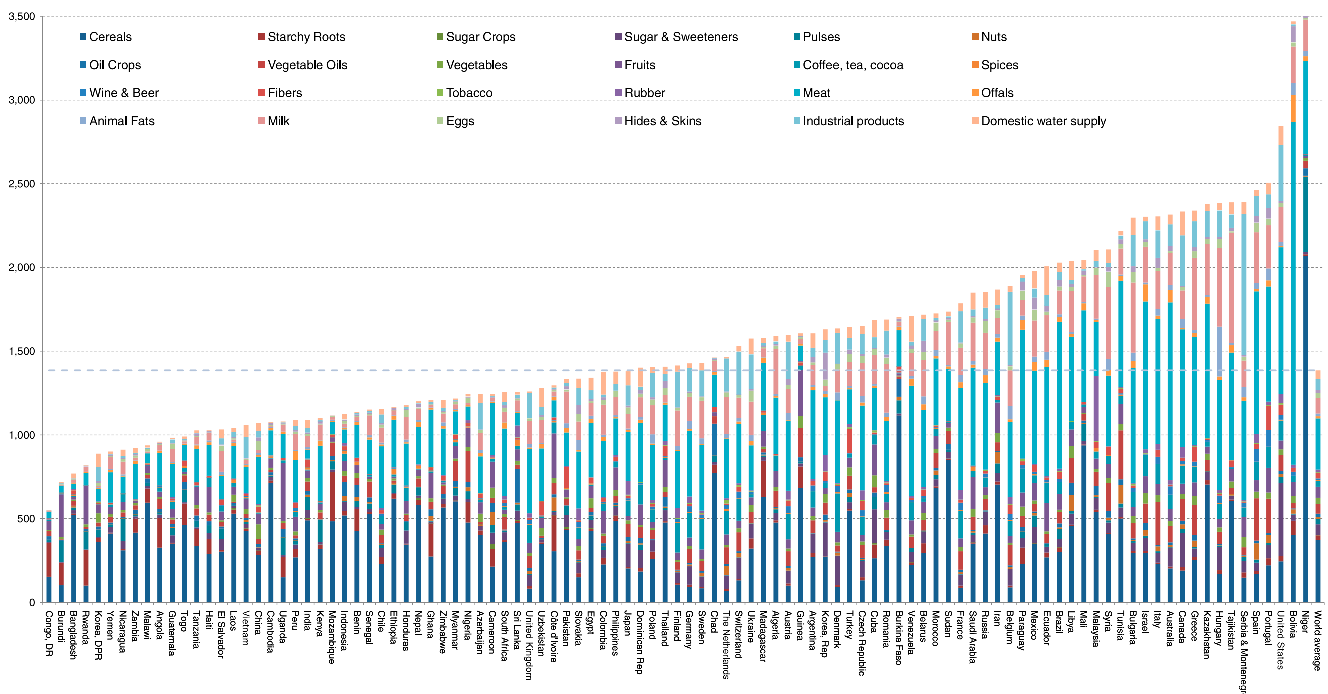

Fig. 3. Water footprint of national consumption for countries with a population larger than 5 million, shown by product category (cubic meter per year per capita) (1996–2005).

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estimates are based on leaching and runoff of nitrogen fertilizers, excluding the potential effect of other fertilizer components and pesticides (21, 22). 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.

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

We have analyzed a 10-y 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 10-y 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 WFs of agricultural products are necessarily 10-y averages, because they have been based on climate data, which are by definition multiyear averages (21, 22). Even if we would have been able to estimate WFs by year, a trend analysis over a 10-y period would have been difficult because of the natural interannual variability of rainfall and temperature.

The data presented in this paper are derived on the basis of a great number of underlying statistics, maps, and assumptions. Because all basic sources include uncertainties and possible errors, the presented WF data should be taken and interpreted with extreme caution, particularly when zooming in on specific locations on a map or when focusing 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 on which we relied. 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 WFs of industrial production and domestic water supply are geographically spread according to population densities. The reporting about uncertainties in the basic datasets that we had to rely on is very poor, particularly if we want to get a quantitative picture of the uncertainties. The basic datasets we have used together with our own assumptions do not give rise to the expectation that our data include a specific bias in some direction. Our estimates of global crop water consumption (21, 22) are in the middle of the range that one gets if considering different studies (28–32). For consumption and international trade data, there are no alternative global databases than the ones we used (33, 34); these databases do not yet include uncertainly information. Despite the uncertainties, we think that the current study forms a good basis for rough comparisons and to guide further analysis.

Conclusion

The study shows that about one-fifth of the global WF in the period 1996–2005 was not meant for domestic consumption but for export. The relatively large volume of international virtual water flows and the associated external water dependencies strengthen the argument to put the issue of water scarcity in a global context (8, 10). For governments in water-scarce countries such as in North Africa and the Middle East, it is crucial to recognize the dependency on external water resources and to develop foreign and trade policies such that they ensure a sustainable and secure import of water-intensive commodities that cannot be grown domestically. The water footprint of Chinese consumption is still relatively small and largely internal (90%), but given the country's rapid growth and the growing water stress (particularly in North China), the country is likely to increasingly rely on water resources outside its territory, evidenced by China's policy already today to buy or lease lands in Africa to secure their food supply (35).

The global average WF related to consumption is 1,385 m^3/y per capita over the period 1996–2005. Industrialized countries have WFs in the range of 1,250–2,850 m^3/y per capita, whereas developing countries show a much larger range of 550–3,800 m^3/y per capita. Two factors determine the magnitude of the WF of national consumption: (*i*) the volume and pattern of consumption and (*ii*) the WF per ton of consumed products. The latter, in the case of agricultural products, depends on climate, irrigation, and fertilization practice and crop yield. The small WF values for developing countries relate to low consumption volumes; the large values refer to very large WFs per unit of consumption. Detailed water footprint data as provided in this paper will help national governments understand to which extent the water footprint of national consumption relates to inefficient water use in production and to which extent it is inherent to the existing national consumption pattern. Thus it helps governments that strive toward more sustainable water use to prioritize production policies (aimed to increase water use efficiency) versus consumption policies (aimed to influence consumption patterns so that inherently water-intensive commodities are replaced by commodities that require less water).

The study provides important information on the WFs of nations, disaggregated into the type of WF (green, blue, or gray) and mapped at a high spatial resolution. This paper 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 localized WFs 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 take and share responsibilities to reduce the WFs where most necessary.

Methods

Accounting Framework. In this study, we follow the Global Water Footprint Standard developed by the Water Footprint Network (14). The method is presented in detail in *SI Methods*.

WFs of National Production. The WF of national production is 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 WFs 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. The WFs within nations related to crop production were obtained from Mekonnen and Hoekstra (21, 22, 36), who estimated the global WF of crop production with a crop water use model at a $5 \times 5'$ spatial resolution. The WFs within nations related to water use in livestock farming were obtained from Mekonnen and Hoekstra (23). The WFs within nations related to industrial production and domestic water supply were estimated using water withdrawal data from the AQUASTAT database (13) and EUROSTAT (37). We have assumed that 5% of the water withdrawn for industrial purposes is actual consumption (blue WF) and that the remaining fraction is return flow; for the domestic water supply sector, we assumed a consumptive portion of 10% (13). The part of the return flow that is disposed into the environment without prior treatment has been taken as a measure of the gray WF, thus assuming a dilution factor of 1. Data on the wastewater treatment coverage per country were obtained from the United Nations Statistical Division database (38).

International Virtual Water Flows. International virtual water flows are calculated by multiplying, per trade commodity, the volume of trade by the respective average WF per ton of product as in the exporting nation. Data on international trade in agricultural and industrial products have been taken from the Statistics for International Trade Analysis database available from the International Trade Centre (34).

Country-specific estimates on the green, blue, and gray WFs of 146 crops and more than 200 derived crop products per ton of product were taken from ref. 21. Estimates on the WFs of farm animals and animal products per ton of product were taken from ref. 23. The national average WF per dollar of industrial product was calculated per country by dividing the total national WF in the industrial sector by the value added in industrial sector. The latter was obtained from the United Nations Statistical Division database (39).

WFs of National Consumption. For agricultural commodities, the WF 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 WF. 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 of the Food and Agriculture Organization of the United Nations (33).

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

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Supporting Information

Hoekstra and Mekonnen 10.1073/pnas.1109936109

SI Text

SI Methods. ***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 (1). The water footprint (WF) 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 WF has three components: green, blue, and gray. The blue WF refers to consumption of blue water resources (surface and ground water). Consumptive water use is generally smaller than water withdrawal, because water withdrawals partly return to the catchment. Water consumption is a better indicator of water use than water withdrawal when one is interested in the effect of water use at the scale of the catchment as a whole (2). The green WF is the volume of green water (rainwater) consumed, which is particularly relevant in crop production. The gray WF 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 WF is a geographically explicit indicator, showing not only volumes of water consumption and pollution, but also the locations.

The framework for national WF accounting is shown in Fig. S1. One can see that "the WF of national consumption" is different from "the WF within the area of the nation." The latter is the WF 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 WFs 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. Water use in energy production is included in the figures for water use in the industrial sector. Water use in the services sector is included in the figures for the domestic water supply sector. WFs related to industrial production and domestic water supply were mapped using the global population density map from Center for International Earth Science Information Network and International Center for Tropical Agriculture (3). The WF 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 WF of national consumption. The internal WF is defined as the use of domestic water resources to produce goods and services consumed by the national population. It is the sum of the WF within the nation minus the volume of virtual water export to other nations insofar as related to the export of products produced with domestic water resources. The external WF is defined as the volume of water resources used in other nations to produce goods and services consumed by the population in the nation considered. 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 reexport of imported products. The virtual water export from a nation consists of exported water of domestic origin and reexported water of foreign origin. The virtual water import into a nation will partly be consumed, thus constituting the external WF of national consumption, and partly be reexported. The sum of the virtual water import into a country and the WF within the area of the nation is equal to the sum of the virtual water export from the nation and the WF of national consumption. This sum is called the virtual water budget of a nation.

WFs of national consumption. The WF of national consumption (in cubic meters per year) is calculated by adding the direct WF of consumers and two indirect WF components:

$$\mathrm{WF_{cons}} = \mathrm{WF_{cons,dir}} + \mathrm{WF_{cons,indir}}(\text{agricultural commodities}) + \mathrm{WF_{cons,indir}}(\text{industrial commodities}). \quad \textbf{[S1]}$$

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

The WF of national consumption of agricultural and industrial commodities can be calculated through either the top-down or the bottom-up approach (1). In the top-down approach, the WF of national consumption is calculated as the WF 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 WF 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 WF. In the bottom-up approach, the WF of national consumption is calculated by adding the direct and indirect WFs of consumers within the nation.

For agricultural commodities, the WF 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 WF:

$$\mathrm{WF_{cons,indir}}(\text{agricultural commodities}) = \sum_p \left(C[p] \times \mathrm{WF}^*_{\mathrm{prod}}[p]\right). \quad \textbf{[S2]}$$

$C[p]$ is consumption of agricultural product p by consumers within the nation (ton/y) and $\mathrm{WF}^*_{\mathrm{prod}}[p]$ the WF 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 of the Food and Agriculture Organization of the United Nations (4). 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 partly originate from the nation itself and partly from other nations. The average WF of a product p consumed in a nation is

$$\mathrm{WF}^*_{\mathrm{prod}}[p] = \frac{P[p] \times \mathrm{WF_{prod}}[p] + \sum_{n_e} \left(T_i[n_e,p] \times \mathrm{WF_{prod}}[n_e,p]\right)}{P[p] + \sum_{n_e} T_i[n_e,p]} \quad \textbf{[S3]}$$

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 WF of product p when produced in the nation considered, and $WF_{prod}[n_e,p]$ the WF 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 WFs of agricultural products were taken from Mekonnen and Hoekstra (5, 6).

For industrial commodities, the WF of national consumption is calculated based on the top-down approach as the WF 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 WF of national consumption ($WF_{cons,ext}$) is estimated based on the relative share of the virtual water import to the total water budget:

$$WF_{cons,ext} = \frac{V_i}{WF_{area} + V_i} \times WF_{cons} \qquad \textbf{[S4]}$$

in which WF_{area} is the WF 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 WF of national consumption ($WF_{cons,int}$) is calculated as

$$WF_{cons,int} = \frac{WF_{area}}{WF_{area} + V_i} \times WF_{cons}. \qquad \textbf{[S5]}$$

For mapping the global WF of the consumption of a certain country at a high spatial resolution, we distinguish between mapping the internal and the external WF. The internal WF is mapped by taking the shares of the WFs within the different grid cells in the country that contribute to the WF of national consumption. Mapping the external WF is done in two steps. First, we quantify the external WF 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 WF by taking the shares of the WFs within the different grid cells in the trade partner country that contribute to the WF of consumption in our country under consideration. We could not trace the external WF of imported animal products at grid level because of data limitations.

In a case study for the United States, 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 WFs 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 WF is slightly improved this way, but more importantly, it enabled us to trace the external WF not only by location but also by crop.

SI Results. ***Mapping the global WF of national consumption: an example from the United States.*** The WF statistics presented in the main paper section hide the fact that WFs have a spatial dimension. In this section we illustrate this spatial dimension with an example from the United States. The global WF of US citizens related to the consumption of agricultural products is mapped at a fine spatial resolution ($5 \times 5'$ grid) in Fig. S6. The map shows the WF of crops consumed directly by US consumers and the WF of animal feed crops (domestic and imported) used to produce the animal products that are both produced and consumed within the United States. It excludes the WF of imported animal products consumed within the United States, 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 WF of US consumption of industrial products is mapped in Fig. S7. The WF of US domestic water consumption is fully within the United States itself and shown in Fig. S8. We ignore here the WF 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 (7). Most of the US WF lies within the United States, mainly in the Mississippi basin (more than 50%). About 20% of the WF of US citizens lies outside the United States. The largest WF outside the United States is in the Yangtze basin (China).

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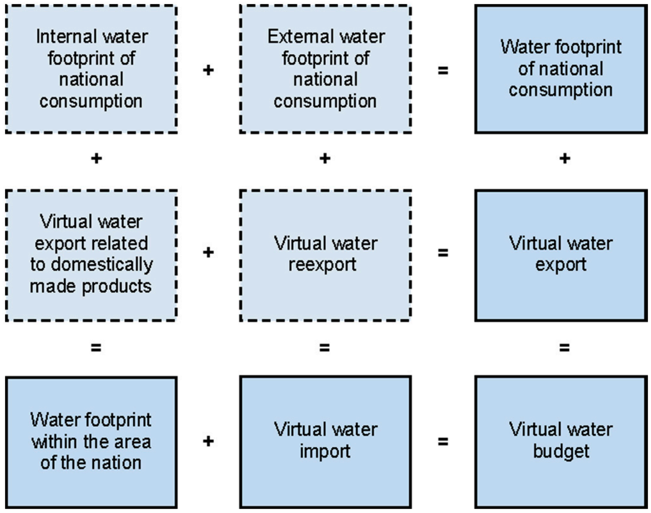

Fig. S1. The national water footprint accounting scheme (1).

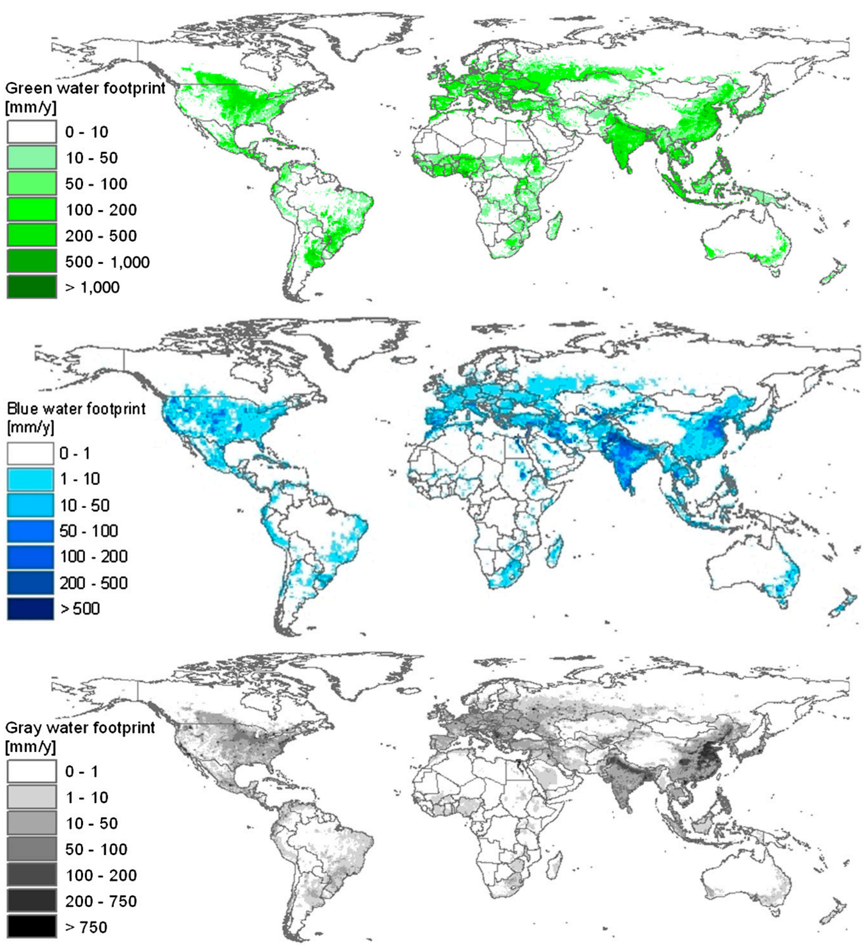

Fig. S2. The green, blue, and gray water footprints within nations in the period 1996–2005. The data are shown in millimeter per year on a $5 \times 5'$ grid. Data per grid cell have been calculated as the water footprint within a grid cell (in cubic meters per year) divided by the area of the grid cell (in 10^3 m^2).

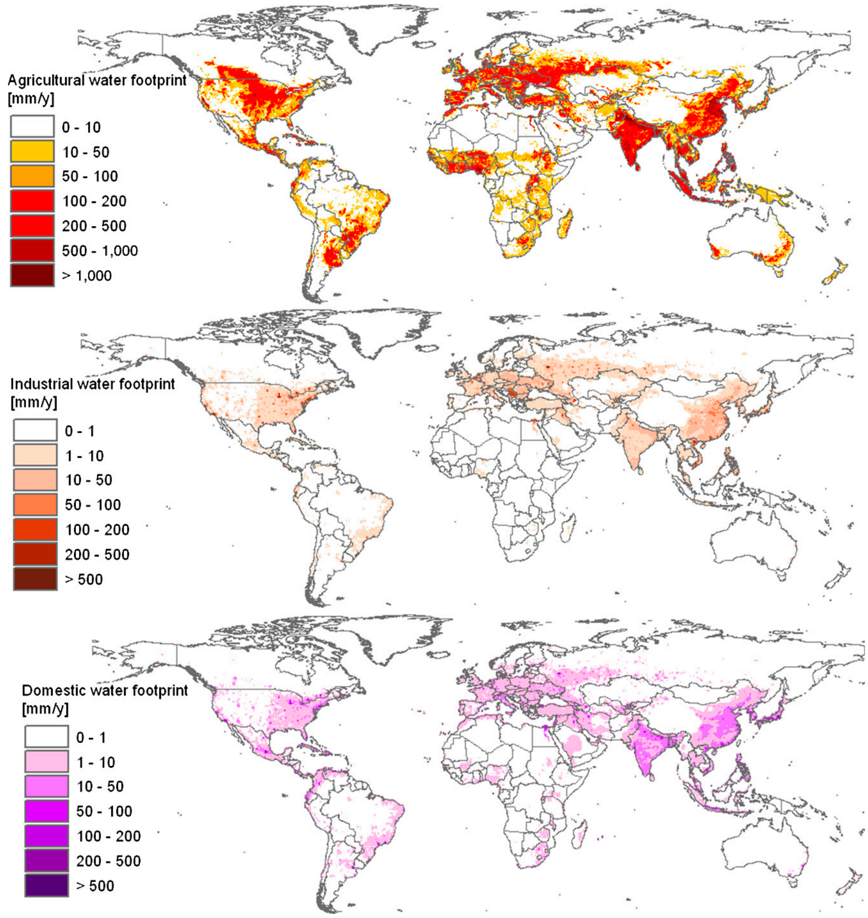

Fig. S3. The water footprint within nations in the period 1996–2005, shown by sector: the total water footprint of agricultural production (above), the total water footprint of industrial production (mid), and the total water footprint related to domestic water supply (below). The data are shown in millimeter per year on a $5 \times 5'$ grid. Data per grid cell have been calculated as the water footprint within a grid cell (in cubic meters per year) divided by the area of the grid cell (in 10^3 m^2).

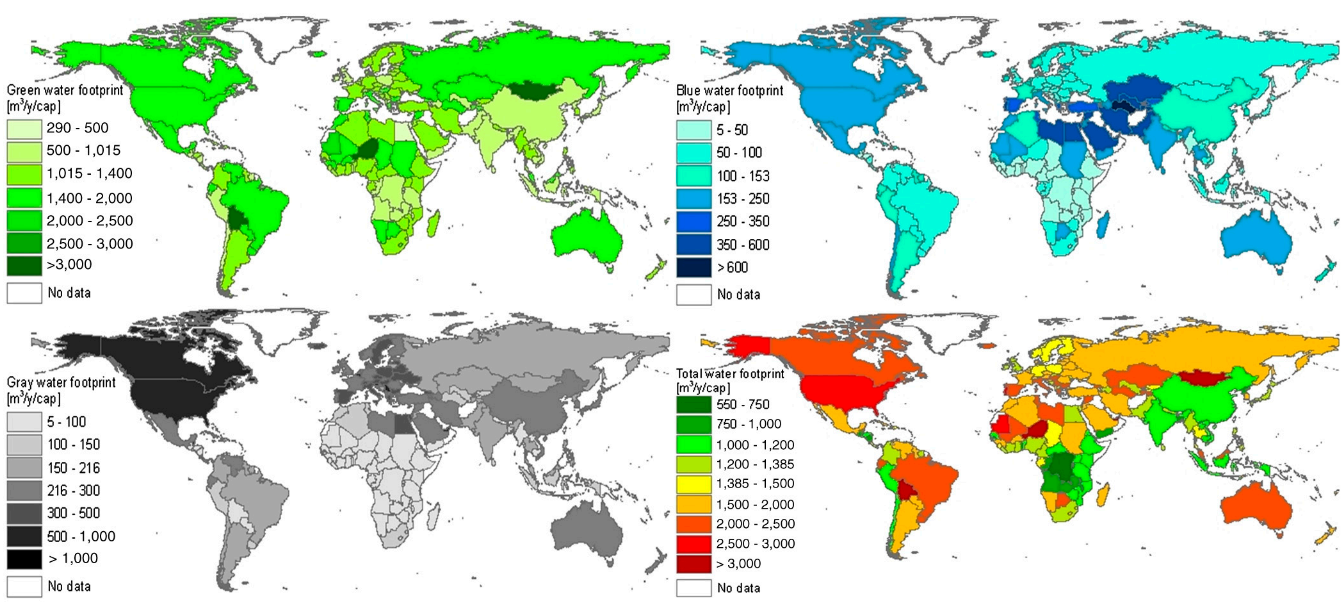

Fig. S4. The green, blue, gray and total water footprint of consumption per country in the period 1996–2005 (cubic meter per year per capita). In the map showing the total water footprint of consumption per country (*Lower Right*), countries shown in green have a water footprint that is smaller than the global average; countries shown in yellow-red have a water footprint larger than the global average.

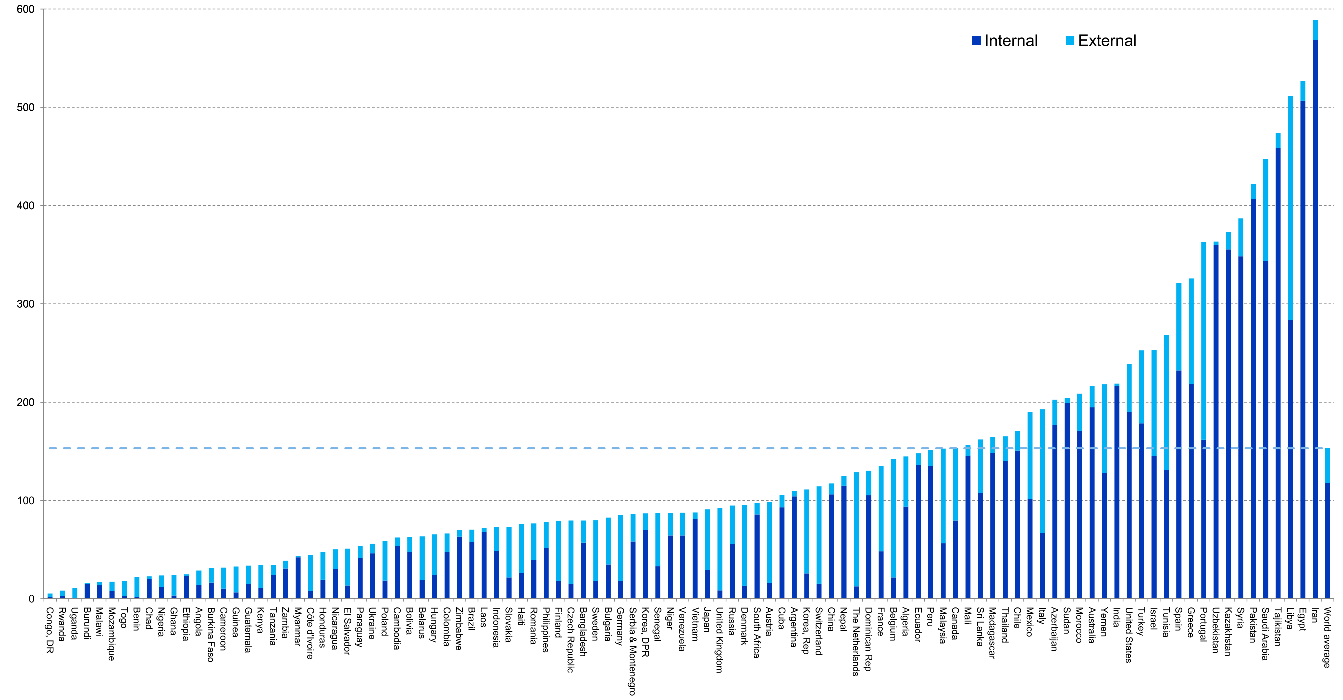

Fig. S5. Blue water footprint of national consumption for countries with a population larger than 5 million, shown by internal and external component (cubic meter per year per capita) (1996–2005).

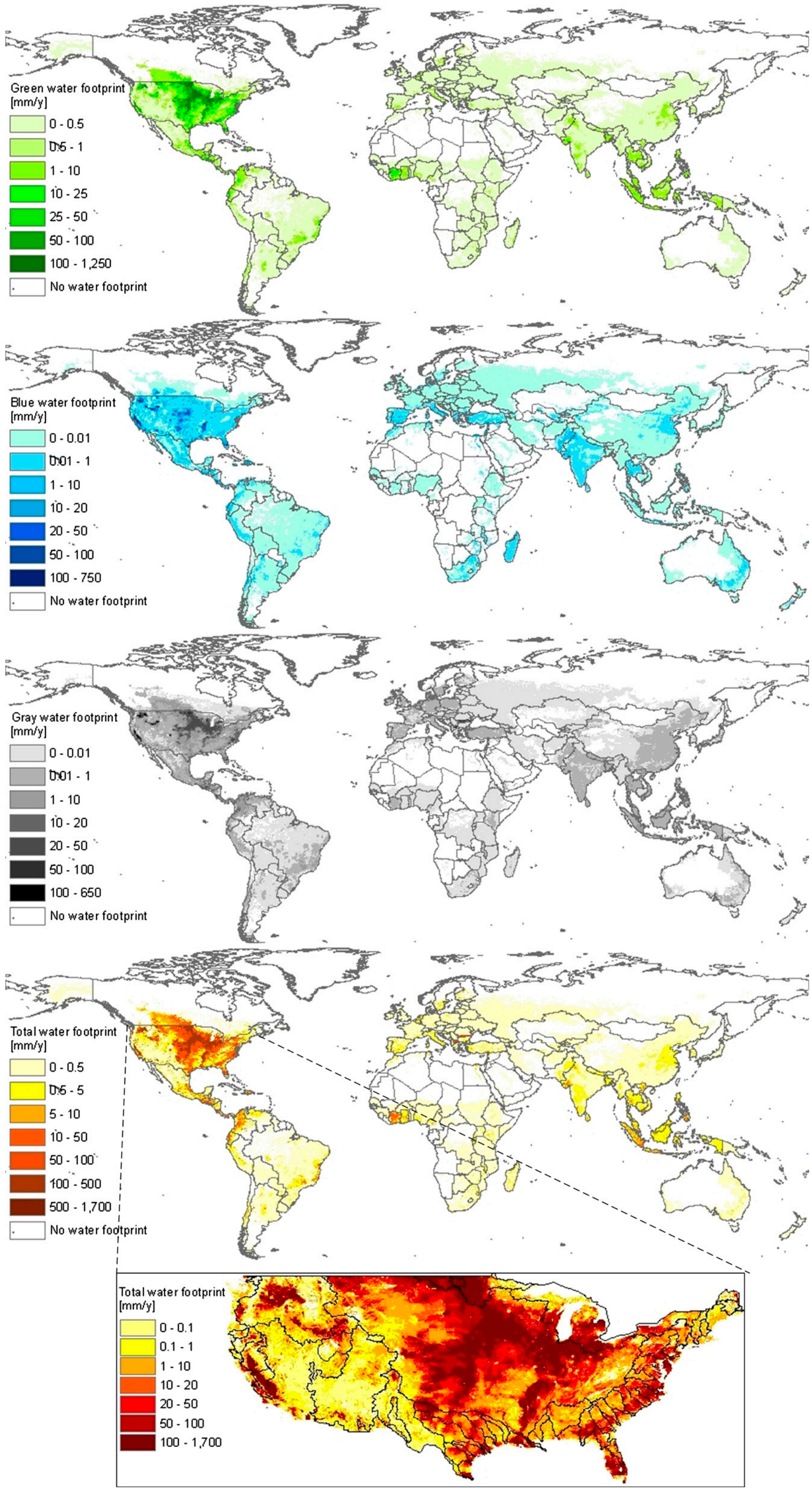

Fig. S6. The global water footprint of US citizens related to the consumption of crop and animal products (1996–2005).

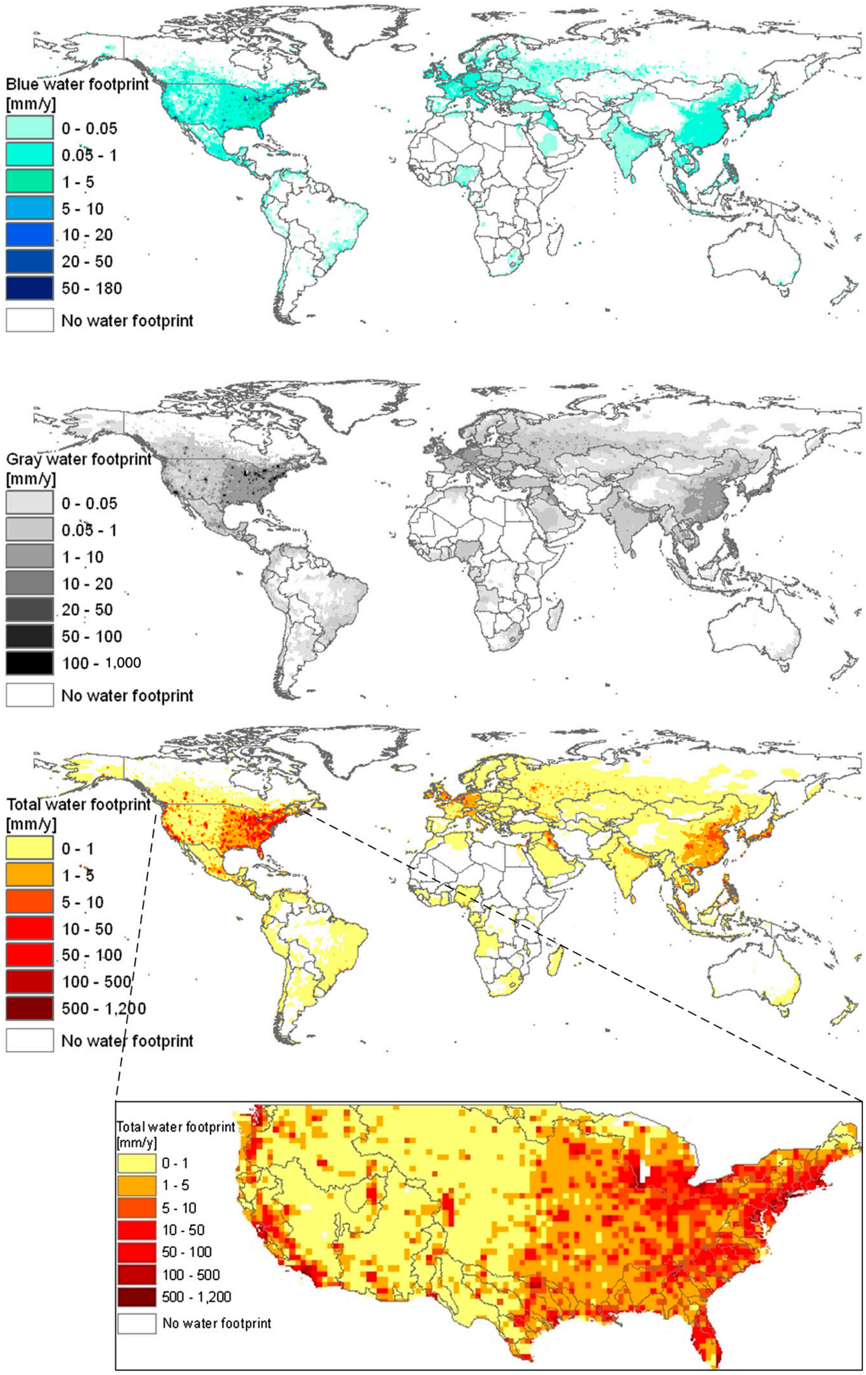

Fig. S7. The global water footprint of US citizens related to the consumption of industrial products (1996–2005).

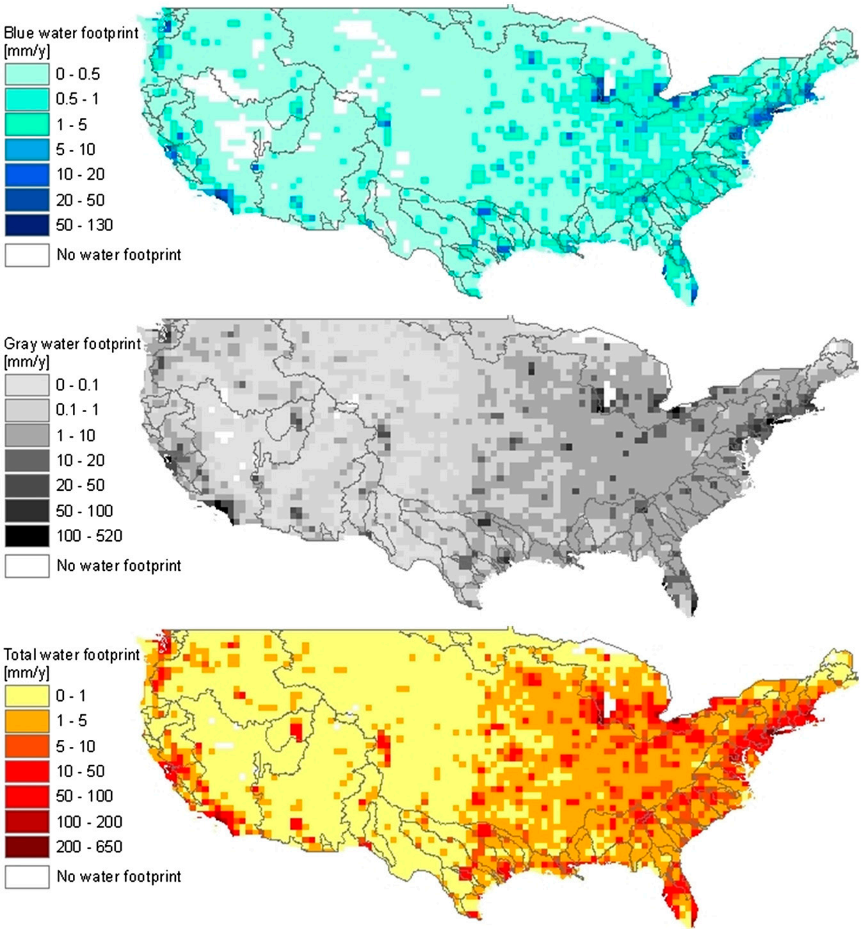

Fig. S8. The water footprint of US citizens related to domestic water supply (1996–2005). The boundaries shown are river basin boundaries.