SUSTAINABILITY

Four billion people facing severe water scarcity

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10.1126/sciadv.1500323

Freshwater scarcity is increasingly perceived as a global systemic risk. Previous global water scarcity assessments, measuring water scarcity annually, have underestimated experienced water scarcity by failing to capture the seasonal fluctuations in water consumption and availability. We assess blue water scarcity globally at a high spatial resolution on a monthly basis. We find that two-thirds of the global population (4.0 billion people) live under conditions of severe water scarcity at least 1 month of the year. Nearly half of those people live in India and China. Half a billion people in the world face severe water scarcity all year round. Putting caps to water consumption by river basin, increasing water-use efficiencies, and better sharing of the limited freshwater resources will be key in reducing the threat posed by water scarcity on biodiversity and human welfare.

INTRODUCTION

During the last few decades, it has become evident that because of a steadily increasing demand, freshwater scarcity is becoming a threat to sustainable development of human society. In its most recent annual risk report, the World Economic Forum lists water crises as the largest global risk in terms of potential impact (*1*). The increasing world population, improving living standards, changing consumption patterns, and expansion of irrigated agriculture are the main driving forces for the rising global demand for water (*2*, *3*). At the global level and on an annual basis, enough freshwater is available to meet such demand, but spatial and temporal variations of water demand and availability are large, leading to water scarcity in several parts of the world during specific times of the year. The essence of global water scarcity is the geographic and temporal mismatch between freshwater demand and availability (*4*, *5*), which can be measured in physical terms or in terms of social or economic implications based on adaptation capability (*6*, *7*). Various studies have assessed global water scarcity in physical terms at a high spatial resolution on a yearly time scale (*2*, *8*–*11*). Annual assessments of water scarcity, however, hide the variability within the year and underestimate the extent of water scarcity (*12*–*15*). The usually large intra-annual variations of both consumption and availability of blue water (fresh surface water and groundwater) lead to a large variation of water scarcity within the year. Wada *et al.* (*13*, *14*) studied global water scarcity at a high spatial resolution on a monthly basis but did not account for environmental water needs, thus underestimating water scarcity. Hoekstra *et al.* (*15*) accounted for environmental flow requirements in estimating global water scarcity on a monthly basis but did not cover the whole globe and used a rather coarse resolution level, namely, the level of river basins, failing to capture the spatial variation within basins.

Here, we assess global water scarcity on a monthly basis at the level of grid cells of 30 × 30 arc min. Water scarcity as locally experienced is calculated as the ratio of the blue water footprint in a grid cell to the total blue water availability in the cell. Blue water footprint refers to "blue water consumption" or "net water withdrawal" and is equal to the volume of fresh surface water and groundwater that is withdrawn and not returned because the water evaporated or was incorporated into a product. Total blue water availability is calculated as the sum of the runoff generated within the grid cell plus the runoff generated in all upstream grid cells minus the environmental flow requirement and minus the blue water footprint in upstream grid cells. We thus account for the effect of upstream water consumption on the water availability in downstream grid cells. Monthly blue water scarcity (WS) is classified as low if the blue water footprint does not exceed blue water availability (WS < 1.0); in this case, environmental flow requirements are met. Monthly blue water scarcity is said to be moderate if it is in the range 1.0 < WS < 1.5, significant if it is in the range 1.5 < WS < 2.0, and severe if WS > 2.0.

Geographic and temporal spread of blue water scarcity

Quarterly averaged monthly blue water scarcities at a spatial resolution of 30 × 30 arc min are presented in Fig. 1; annual average monthly blue water scarcity is shown in Fig. 2. The 12 monthly water scarcity maps are provided in fig. S1 of the Supplementary Materials. Figure 3 shows the number of months per year in which water scarcity exceeds 1.0. The maps in Figs. 2 and 3 show a striking correspondence (with a correlation coefficient of 0.99) even if the indicators used are different, implying that averaging monthly blue water scarcities over the year suffices to capture water scarcity variability within the year.

Year-round low blue water scarcity can be found in the forested areas of South America (notably the Amazon basin), Central Africa (the Congo basin), and Malaysia-Indonesia (Sumatra, Borneo, New Guinea) and in the northern forested and subarctic parts of North America, Europe, and Asia. Other places with low water scarcity throughout the year can be found in the eastern half of the United States, in large parts of Europe, and in parts of South China. Africa shows a band roughly between 5° and 15° northern latitude with low water scarcity from May or June to January but moderate to severe water scarcity from February to April. A similar picture is found for the areas between 10° and 25° northern latitude, with moderate to severe water scarcity from February to May or June in Mexico (Central America) and India (South Asia). At higher latitudes, in the western part of the United States, Southern Europe, Turkey, Central Asia, and North China, there are many areas experiencing moderate to severe water scarcity in the spring-summer period. Regions with moderate to severe water scarcity during more than half of the year include northern Mexico and parts of the western United States, parts of Argentina and northern Chile, North Africa and Somalia, Southern Africa, the Middle East, Pakistan, and Australia.

High water scarcity levels appear to prevail in areas with either high population density (for example, Greater London area) or the presence of much irrigated agriculture (High Plains in the United States), or both (India, eastern China, Nile delta). High water scarcity levels also occur in areas without dense populations or intense irrigated agriculture but

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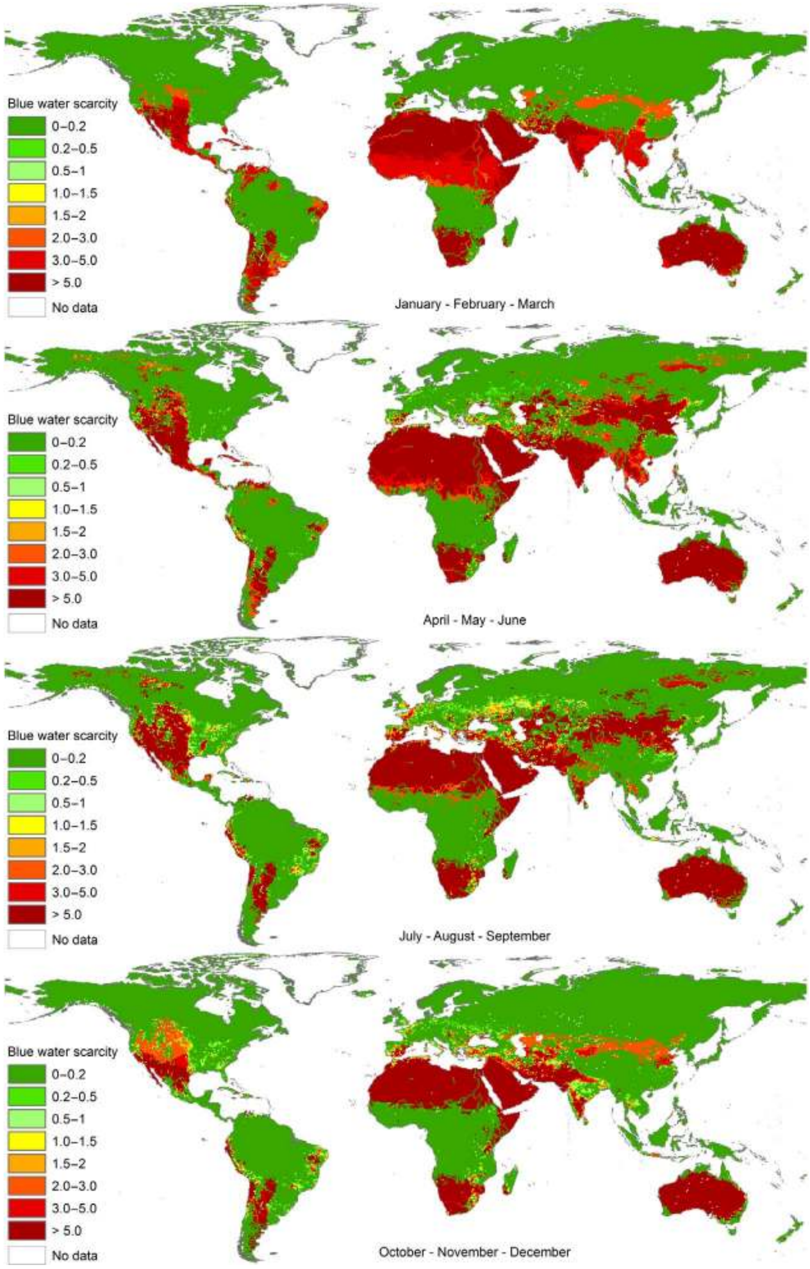

Fig. 1. Quarterly averaged monthly blue water scarcity at 30 × 30 arc min resolution. Water scarcity at the grid cell level is defined as the ratio of the blue water footprint within the grid cell to the sum of the blue water generated within the cell and the blue water inflow from upstream cells. Period: 1996–2005.

with very low natural water availability, such as in the world's arid areas (for example, Sahara, Taklamakan, Gobi, and Central Australia deserts). Water scarcity in the Arabian Desert is worse than that in other deserts because of the higher population density and irrigation intensity. In many river basins, for instance, the Ganges basin in India, the Limpopo basin in Southern Africa, and the Murray-Darling basin in Australia, blue water consumption and blue water availability are countercyclical, with water consumption being highest when water availability is lowest.

Large water consumption relative to water availability results in decreased river flows, mostly during the dry period, and declining lake water and groundwater levels. Notable examples of rivers that are fully or nearly depleted before they reach the end of their course include the Colorado River in the western United States and the Yellow River in North China (*16*, *17*). The most prominent example of a disappearing lake as a result of reduced river inflow is the Aral Sea in Central Asia (*18*, *19*), but there are many other smaller lakes suffering from upstream water consumption, including, for example, Chad Lake in Africa (*19*, *20*). Groundwater depletion occurs in many countries, including India, Pakistan, the United States, Iran, China, Mexico, and Saudi Arabia (*21*, *22*). Direct victims of the overconsumption of water resources are the users themselves, who increasingly suffer from water shortages during droughts, resulting in reduced harvests and loss of income for farmers, threatening the

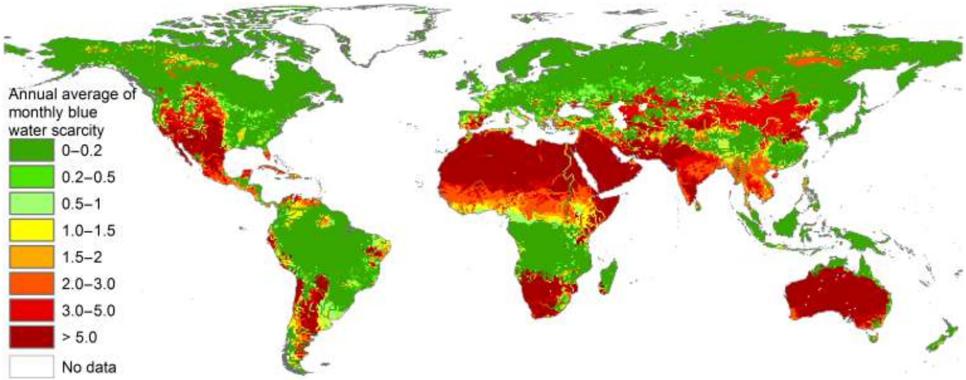

Fig. 2. Annual average monthly blue water scarcity at 30 × 30 arc min resolution. Period: 1996–2005.

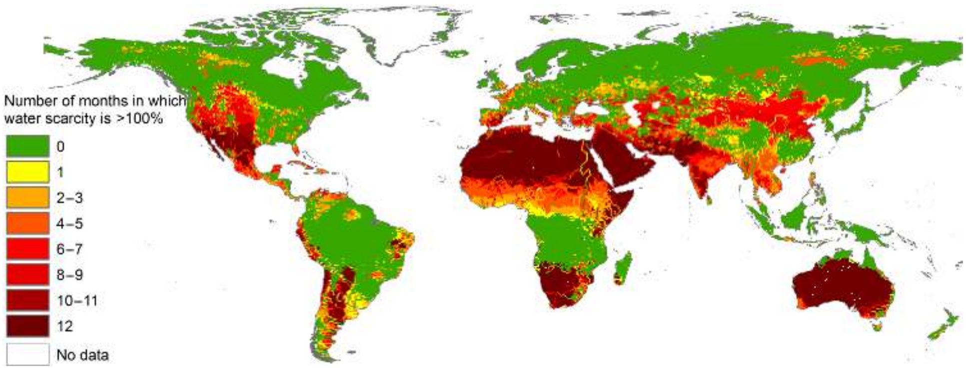

Fig. 3. The number of months per year in which blue water scarcity exceeds 1.0 at 30 × 30 arc min resolution. Period: 1996–2005.

livelihoods of whole communities (*2*, *23*). Businesses depending on water in their operations or supply chain also face increasing risks of water shortages (*1*, *24*). Other effects include biodiversity losses, low flows hampering navigation, land subsidence, and salinization of soils and groundwater resources (*17*, *19*, *25*, *26*).

People facing different levels of water scarcity

The number of people facing low, moderate, significant, and severe water scarcity during a given number of months per year at the global level is shown in Table 1. We find that about 71% of the global population (4.3 billion people) lives under conditions of moderate to severe water scarcity (WS > 1.0) at least 1 month of the year. About 66% (4.0 billion people) lives under severe water scarcity (WS > 2.0) at least 1 month of the year. Of these 4.0 billion people, 1.0 billion live in India and another 0.9 billion live in China. Significant populations facing severe water scarcity during at least part of the year further live in Bangladesh (130 million), the United States (130 million, mostly in western states such as California and southern states such as Texas and Florida), Pakistan (120 million, of which 85% are in the Indus basin), Nigeria (110 million), and Mexico (90 million).

The number of people facing severe water scarcity for at least 4 to 6 months per year is 1.8 to 2.9 billion. Half a billion people face severe water scarcity all year round. Of those half-billion people, 180 million live in India, 73 million in Pakistan, 27 million in Egypt, 20 million in Mexico, 20 million in Saudi Arabia, and 18 million in Yemen. In the latter two countries, it concerns all people in the country, which puts those countries in an extremely vulnerable position. Other countries in which a very large fraction of the population experiences severe water scarcity year-round are Libya and Somalia (80 to 90% of the population) and Pakistan, Morocco, Niger, and Jordan (50 to 55% of the population).

DISCUSSION

The finding that 4.0 billion people, two-thirds of the world population, experience severe water scarcity, during at least part of the year, implies that the situation is worse than suggested by previous studies, which give estimates between 1.7 and 3.1 billion (see the Supplementary Materials) (*2*, *8*, *11*–*15*, *27*–*30*). Previous studies underestimated water scarcity and hence the number of people facing severe levels by assessing water scarcity (i) at the level of very large spatial units (river basins), (ii) on an annual rather than on a monthly basis, and/or (iii) without accounting for the flows required to remain in the river to sustain flow-dependent ecosystems and livelihoods. Measuring at a basin scale and on an annual basis hides the water scarcity that manifests itself in particular places and specific parts of the year. One or a few months of severe water scarcity will not be visible when measuring water scarcity annually, because of averaging out with the other, less scarce months. We find that the number of people facing severe water scarcity for at least 4 to 6 months is 1.8 to 2.9 billion, which is the range provided by earlier estimates. Thus, we show that measuring the variability of water scarcity within the year helps to reveal what is actually experienced by

Table 1. Number of people facing low, moderate, significant, and severe water scarcity during a given number of months per year, for the average year in the period 1996–2005.

Number of months per year (n)	Billions of people facing low, moderate, significant, and severe water scarcity during n months per year				Billions of people facing moderate or worse water scarcity during at least n months per year	Billions of people facing severe water scarcity during at least n months per year
	Low water scarcity	Moderate water scarcity	Significant water scarcity	Severe water scarcity		
0	0.54	4.98	5.22	2.07	6.04	6.04
1	0.12	0.81	0.66	0.31	4.26	3.97
2	0.12	0.19	0.13	0.37	3.95	3.66
3	0.35	0.05	0.03	0.37	3.55	3.28
4	0.33	0.01	0.001	0.59	3.15	2.91
5	0.30	0	0	0.55	2.56	2.32
6	0.33	0	0	0.27	2.09	1.78
7	0.47	0	0	0.21	1.76	1.50
8	0.59	0	0	0.29	1.46	1.30
9	0.40	0	0	0.30	1.13	1.01
10	0.40	0	0	0.12	0.78	0.71
11	0.30	0	0	0.09	0.66	0.59
12	1.78	0	0	0.50	0.54	0.50
Total	6.04	6.04	6.04	6.04		

people locally. More than a billion people experience severe water scarcity "only" 1 to 3 months per year, a fact that definitely affects the people involved but gets lost in annual water scarcity evaluations.

The results are not very sensitive to the assumption on the level of environmental flow requirements. With the current assumption of environmental flow requirements at 80% of natural runoff, we find 4.3 billion people living in areas with WS > 1.0 at least 1 month in a year. If we would assume environmental flow requirements at 60% of natural runoff, this number would still be 4.0 billion.

The results are also barely sensitive to uncertainties in blue water availability and blue water footprint. We tested the sensitivity of the estimated number of people facing severe water scarcity to changes in blue water availability and blue water footprint. When we increase water availability estimates worldwide and for each month by 20%, the number of people facing severe water scarcity during at least 1 month of the year reduces by 2% (from 4.0 to 3.9 billion). Reducing water availability by 20% gives 4.1 billion. Changing water footprints in the ±20% range results in the number of people facing severe water scarcity to be between 3.9 and 4.1 billion as well. Changing water availability in the ±50% range yields 3.8 to 4.3 billion people facing severe water scarcity during at least part of the year, whereas changing water footprints in the ±50% range yields 3.6 to 4.2 billion people. The reason for the low sensitivity is the huge temporal mismatch between water demand and availability: Demand is generally much lower than availability or the other way around. Only in times wherein water demand and availability are of the same magnitude can changes in one or the other flip the situation from one scarcity level to another.

The current study sets the stage for intra-annual water scarcity measurement. Future improvements in assessing water scarcity can possibly be achieved by better accounting for the effect of artificial reservoirs in modifying the seasonal runoff patterns and alleviating scarcity. Besides, future water scarcity studies should include water consumption related to the evaporation from artificial reservoirs and interbasin water transfers, factors that have not been included in the current study. Future studies need to consider scarcity of green water (rainwater that is stored in the soil) as well (*5*, *6*, *31*–*33*), assess the interannual variability of scarcity (*13*), develop better procedures to estimate environmental flow requirements per catchment (*34*), and take into account the effect of climate change, which most likely will worsen the extent of water scarcity (*2*).

CONCLUSION

Meeting humanity's increasing demand for freshwater and protecting ecosystems at the same time, thus maintaining blue water footprints within maximum sustainable levels per catchment, will be one of the most difficult and important challenges of this century (*35*). Proper water scarcity assessment, at the necessary detail, will facilitate governments, companies, and investors to develop adequate response strategies. Water productivities in crop production will need to be increased by increasing yields and reducing nonproductive evaporation (*36*, *37*). An important part of a strategy to reduce the pressure on limited blue water resources will be to raise productivity in rain-fed agriculture (*31*). It will be important that governments and companies formulate water footprint benchmarks based on best available technology and practice (*38*). Assessing the sustainability of the water footprint along the supply chain of products and disclosing relevant information will become increasingly important for investors (*39*).

MATERIALS AND METHODS

Blue water scarcity is calculated per month per grid cell, at a 30 × 30 arc min resolution, as the ratio of the local blue water footprint (WF_{loc}) to the total blue water availability (WA_{tot}) in the month and grid cell (*32*)

$$WS = \frac{WF_{loc}}{WA_{tot}} \tag{1}$$

Blue water scarcity is time-dependent; it varies within the year and from year to year. Blue water footprint and blue water availability are expressed in cubic meters per month. For each month of the year, we considered the 10-year average for the period 1996–2005. Blue water scarcity values were classified into four ranges (*15*, *32*): low ($WS < 1.0$), moderate ($1.0 < WS < 1.5$), significant ($1.5 < WS < 2.0$), and severe ($WS > 2.0$). WS = 1.0 means that the available blue water has been fully consumed; at WS > 1.0, environmental flow requirements are not met.

Total monthly blue water availability in a grid cell (WA_{tot}) is the sum of locally generated blue water in the grid cell (WA_{loc}) and the blue water flowing in from upstream grid cells. Because there are economic activities consuming water in the upstream grid cells, the blue water generated upstream is not fully available to the downstream cell. Therefore, the blue water available from upstream grid cells is estimated by subtracting the blue water footprint in the upstream cells (WF_{up}) from the blue water generated in the upstream cells (WA_{up})

$$WA_{tot} = WA_{loc} + \sum_{i=1}^{n} (WA_{up,i} - WF_{up,i}) \tag{2}$$

where the subscript i denotes the cells upstream of the cell under consideration. If the upstream blue water footprint is larger than the upstream available blue water, the total available blue water will be equal to the locally available blue water in the grid cell (that is, $WA_{tot} = WA_{loc}$). Monthly blue water availability per grid cell was calculated as the natural runoff minus the environmental flow requirement. Natural runoff per grid cell was estimated by adding the actual runoff and the blue water footprint within the grid cell.

To avoid unrealistic water scarcity values, in particular in the northern hemisphere, we have set a condition that when the average monthly maximum temperature is equal to or below 10°C, water scarcity is set to be equal to zero. These conditions occur when precipitation and thus runoff are very small (sometimes zero or near zero), such that the WF/WA ratio can become very large. In practice, this is not experienced as high water scarcity, because under these circumstances, water use is generally small as well (no crop growth in this period) and can be made available through small temporary water storage or melting of snow.

Average monthly blue water footprints at a 5 × 5 arc min resolution for the period 1996–2005 were derived from Mekonnen and Hoekstra (*40*, *41*) and were aggregated to a 30 × 30 arc min resolution. These data show the aggregated blue water footprint per grid cell from the agricultural (crop and livestock), industrial, and municipal sectors. The blue water footprint of crop production was estimated by considering blue water consumption per crop per grid cell, based on crop maps, data on growing periods, estimated irrigation requirements, and data on actual irrigation. The blue water footprints of the industrial and municipal sectors were estimated per grid cell based on water consumption data per country and population densities.

Monthly actual runoff data at a 30 × 30 arc min resolution were obtained from the Composite Runoff V1.0 database of Fekete *et al.* (*42*). Regarding environmental flow requirements, we adopted the presumptive environmental flow standard, according to which 80% of the natural runoff is allocated as environmental flow requirement; the remaining 20% can be considered as blue water available for human use without affecting the integrity of downstream water-dependent ecosystems and livelihoods (*32*, *43*). The "flow accumulation" function of ArcGIS was used to calculate (rout) blue water availability and blue water footprint from upstream to downstream grid cells. The flow direction raster at a spatial resolution of 30 × 30 arc min was obtained from the World Water Development Report II Web site (*44*, *45*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/2/e1500323/DC1

Supplementary Discussion

Fig. S1. Average monthly blue water scarcity at a spatial resolution of 30 × 30 arc min.

Table S1. Comparison of results between the current study and previous studies.

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Acknowledgments: The work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences. **Funding:** The work was fully funded by the University of Twente. **Author contributions:** A.Y.H. and M.M.M. designed the study. M.M.M. performed the modeling work. A.Y.H. and M.M.M. analyzed the results and wrote the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors. The data used in the current study are from cited references. The monthly blue water footprint and scarcity data are available from the authors upon request.

Submitted 12 March 2015
Accepted 30 November 2015
Published 12 February 2016
10.1126/sciadv.1500323

Citation: M. M. Mekonnen, A. Y. Hoekstra, Four billion people facing severe water scarcity. *Sci. Adv.* **2**, e1500323 (2016).

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Supplementary Materials for

Four billion people facing severe water scarcity

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Published 12 February 2016, *Sci. Adv.* **2**, e1500323 (2016)
DOI: 10.1126/sciadv.1500323

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Supplementary Discussion

The assumptions behind previous studies that estimated the number of people facing severe water scarcity are summarised in Table S1. The first two studies listed in the table measure water scarcity as the natural runoff available per capita, with 1000 m^3/cap/y as a threshold for severe water scarcity. The disadvantage of this measure is that it tells little about actual water scarcity, since the water footprint of a population is not necessarily in the same basin as in which it lives (*40*). In all studies, with the exception of Wada et al. (*13, 14*), Hanasaki et al. (*12*) and Hoekstra et al. (*15*), water scarcity was estimated on annual basis. The latter two studies are the only ones that account for environmental flow requirements. Hanasaki et al. (*12*), however, do not really measure water scarcity but measure the extent to which crop water requirement are met.

Previous studies underestimated water scarcity and hence the number of people facing severe levels by evaluating water scarcity (a) at the level of too large spatial units (per river basin), (b) at annual rather than monthly basis, and/or (c) excluding environmental flow requirements. Measuring at too large spatial scale or at annual basis hides the water scarcity that manifests itself in specific parts of river basins and specific parts of the year. In order to account for that shortcoming, the traditional threshold value for severe water scarcity has been, rather arbitrarily, set at 0.4, meaning that annual withdrawal in a river basin should not exceed 40% of annual runoff. Assuming that, on average, water consumption is 60% of total water withdrawal, this is equivalent to requiring that annual water consumption should not exceed 24% of annual runoff. This threshold contains implicit assumptions regarding environmental flow requirements and fails to capture variability within the year and within a basin. By taking the presumptive standard on environmental flow requirements, we require that monthly water consumption remains below 20% of monthly runoff, but we speak about severe water scarcity only if monthly water consumption exceeds 40% of monthly runoff. By estimating water scarcity at a high spatial and temporal resolution we thus have been able to better capture true water scarcity, and by considering environmental flow requirements and water consumption rather than gross abstraction, we were also able to use a water scarcity measure that has a straightforward interpretation: in the current study, WS reflects the fraction of water available for consumptive activities that has been consumed.

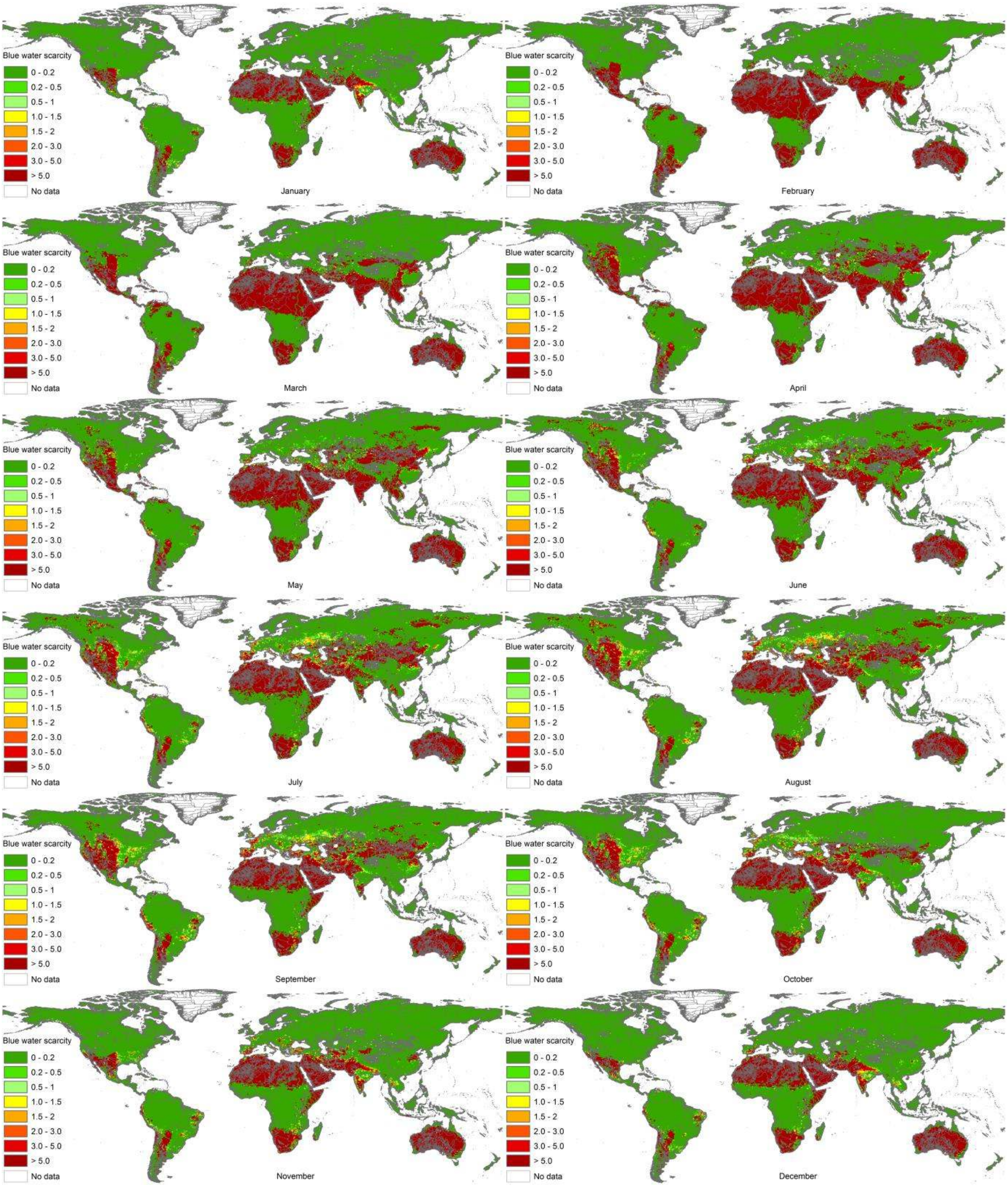

Fig. S1. *Average monthly blue water scarcity at a spatial resolution of 30 × 30 arc min. Period 1996-2005.*

Table S1. *Comparison of results between the current study and previous studies.*

Study	Year	Coverage	Spatial resolution	Temporal resolution	Measure of water use*	Measure of water availability**	Threshold for severe water scarcity	Population under severe water scarcity (billions)	Remark
Kummu et al. (*28*)	2005	Global	Sub-basins	Annual	Population size	Natural runoff	< 1000 m^3/cap/y	2.3	
Islam et al. (*27*)	2000	Global	30 arc minute	Annual	Population size	Natural and actual runoff	< 1000 m^3/cap/y	1.8 - 3.1	Lower estimate refers to case where all water from upstream grid cells is fully available; the upper estimate to when it is fully consumed.
Hanasaki et al. (*12*)	1995	Global	60 arc minute	Monthly	Withdrawal	Actual runoff minus environmental flow requirement	Cumulative water withdrawal to demand ratio < 0.5	2.4-2.5	
Alcamo et al. (*29*)	1995	Global	Basin	Annual	Withdrawal	Natural runoff	Water withdrawal / availability > 0.4	2.1	
Alcamo et al. (*30*)	1995	Global	Basin	Annual	Withdrawal	Natural runoff	Water withdrawal / availability > 0.4	2.3	
Oki et al. (*8*)	1995	Global	30 arc minute and basin	Annual	Withdrawal	Actual runoff	Water withdrawal / availability > 0.4	1.7-2.7	The lower estimate for the grid level assessment, the higher estimate for the basin assessment
Oki and Kanae (*11*)	1995	Global	30 arc minute	Annual	Withdrawal	Actual runoff	Water withdrawal / availability > 0.4	2.4	
Vörösmarty et al. (*2*)	1995	Global	30 arc minute	Annual	Withdrawal	Actual runoff	Water withdrawal / availability > 0.4	1.8	
Wada et al. (*13*), (*14*)	2000	Global	30 arc minute	Monthly	Consumption	Actual runoff	Water consumption / availability > 0.4	1.7-1.8	
Hoekstra et al. (*15*)	1996-2005	405 major river basins	Basin	Monthly	Consumption	Natural runoff minus environmental flow requirement	Water consumption / availability > 2	2.7	People facing severe water scarcity at least one month / year
Current study	1996-2005	Global	30 arc minute	Monthly	Consumption	Actual runoff minus environmental flow requirement	Water consumption / availability > 2	4.0	People facing severe water scarcity at least one month / year

* Water withdrawal refers to gross water abstraction; water consumption refers to net water abstraction, also called blue water footprint.

** Actual runoff refers to natural runoff minus upstream water consumption.