The number of people exposed to water stress in relation to how much water is reserved for the environment: a global modelling study

Davy Vanham, Lorenzo Alfieri, Martina Flörke, Stefania Grimaldi, Valerio Lorini, Ad de Roo, Luc Feyen

Summary

Background Increasing human demand for water and changes in water availability due to climate change threatens water security worldwide. Additionally, exploitation of water resources induces stress on freshwater environments, leading to biodiversity loss and reduced ecosystem services. We aimed to conduct a spatially detailed assessment of global human water stress for low to high environmental flow (EF) protection.

Methods In this modelling study, we used the LISFLOOD model to generate daily natural flows without anthropogenic water use for 1980–2018. On the basis of these flows, we selected three EF methods (EF with high ecological protection [EF_{PROT}], EF with minimum flow requirements [EF_{MIN}], and variable monthly flow [EF_{VMF}]) to calculate monthly EFs. We assessed monthly consumptive water use for industry, agricultural crops, livestock, municipalities, and energy production for 2010. We then estimated the corresponding number of people under water stress per month on a global and national level using a spatially detailed population database for 2010.

Findings We estimate that 3·2 billion (EF_{PROT}), 2·4 billion (EF_{VMF}), and 2·2 billion (EF_{MIN}) people lived under water stress for at least 1 month per year, corresponding to 46%, 35%, and 32% of the world's population in 2010, respectively. Around 80% of people living under water stress lived in Asia; in particular, India, Pakistan, and northeast China. Compared with EF_{MIN}, imposing EF_{PROT} globally would have put between 710 million (March) to 1 billion (June) additional people under water stress on a monthly basis, whereas this would have been 72 million (August) to 218 million (April) additional people if EF_{VMF} were imposed.

Interpretation Ensuring high ecological protection would put nearly half of the world's population (3·2 billion people) under water stress for at least 1 month per year. Policy makers and water managers have to make an important trade-off when allocating limited water resources between direct human needs and the environment. A better understanding of local ecosystem needs is crucial to alleviating current and future human water stress, while sustaining healthy ecosystems.

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European Commission, Joint Research Centre, Directorate for Sustainable Resources, Ispra, Italy (D Vanham PhD, Prof A de Roo PhD)**; Directorate for Space, Security and Migration, Ispra, Italy** (L Alfieri PhD, S Grimaldi PhD, V Lorini MSc)**; CIMA Research Foundation, Hydrology and Hydraulics Department, Savona, Italy** (L Alfieri)**; Ruhr-University Bochum, Institute of Engineering Hydrology and Water Resources Management, Bochum, Germany** (Prof M Flörke PhD)**; European Commission, Joint Research Centre, Directorate for Energy, Transport and Climate, Sevilla, Spain** (L Feyen PhD)

Correspondence to: Dr Davy Vanham, European Commission, Joint Research Centre, Directorate for Sustainable Resources, Ispra 21027, Italy **davy.vanham@yahoo.de**

Introduction

Human demand for water worldwide has increased six times over the past century and continues to rise at a rate of around 1% per year due to growing population and economies.[1] Scarcity of water supplies poses severe risks to people, notably through food security, energy security, and conflict.[1,2] Therefore, reducing the number of people living with water scarcity is a target of the Sustainable Development Goal (SDG) on clean water and sanitation.[3] Furthermore, water is essential to sustain healthy freshwater[4] and terrestrial[5] ecosystems, and subsequently the human livelihoods and wellbeing that depend on these ecosystems. As water supplies are threatened by climate change,[1] there is increasing need to balance competing human and environmental demands.

Water stress reflects the ratio between human water use (ie, water abstraction or consumption)[6] and environmentally available water resources.[3,6] The latter equals total available water resources minus the environmental flows (EFs) that are required to maintain ecosystem integrity in streams, rivers, wetlands, riparian zones, and estuaries.[7] This definition is also used in the globally accepted SDG indicator 6.4.2 on water stress,[6] which measures water abstraction as water use. This indicator is one of two indicators that measure the progress in reaching SDG target 6.4 by 2030, which aims to reduce the number of people under water stress. As EFs are an integral part of this indicator, their quantification is high on the research and policy agenda.[7–9]

EFs are key for various ecosystem services linked to several SDGs, such as SDG 2 of "zero hunger" by providing fish for nutrition, or SDG 15 of "life on land" by sustaining habitats.[6,7,10] EF needs are still unknown for most freshwater and estuarine ecosystems.[8] With currently more than 200 EF methods, there is consequently large variability and uncertainty in how much water is allowed for the environment within a river basin and how much can be made available for human use. Locally, empirical quantitative relationships between

Research in context

Evidence before this study

Water stress is generally defined as the ratio between water use (ie, abstraction or consumption) and environmentally available water resources. The latter equals total available water resources minus environmental flows (EFs). This definition is also used in the Sustainable Development Goal (SDG) indicator 6.4.2 on water stress, one of two indicators used to measure progress towards SDG target 6.4, which aims to reduce the number of people facing water stress by 2030. Scientific literature has previously quantified the number of people under water stress by use of one EF. However, to date, this quantification has not yet been done for different EFs, despite how different methods exist.

Added value of this study

In this modelling study, we selected three commonly used EF methods and computed the related number of people under water stress. We used an EF with high ecological protection (EF_{PROT}), an EF with minimum flow recommendations (EF_{MIN}) and high ecological risk, and the variable monthly flow method (EF_{VMF}) representing in-between ecological risk. We found that the resulting number of people under water stress differed substantially, both globally and nationally. We estimate that 3·2 billion (EF_{PROT}), 2·4 billion (EF_{VMF}), and 2·2 billion (EF_{MIN}) people lived under water stress for at least 1 month per year in 2010, corresponding to 46%, 35%, and 32% of the world's population at the time, respectively. 1916 million (EF_{PROT}), 1154 million (EF_{VMF}), and 964 million (EF_{MIN}) people lived with water stress for at least 6 months per year, and 496 million (EF_{PROT}), 174 million (EF_{VMF}), and 149 million (EF_{MIN}) people faced these conditions for all 12 months of the year.

Implications of all the available evidence

Our assessment shows that an important trade-off exists in allocating water between the environment and human use. Freshwater biodiversity has declined rapidly the past five decades, and EFs provide many essential ecosystem benefits for humanity. Nevertheless, water use for economic activities might be hampered when allocating water for EFs. The number of people facing water stress on a national and global level depend strongly on EF choices, emphasising the need to invest in research (including field studies) of local ecosystem needs. This study hopes to inform SDG monitoring efforts and existing guidelines for incorporating EFs into the SDG indicator 6.4.2 on water stress. Achieving SDG target 6.4 requires careful balancing between human and ecosystem needs.

various kinds of flow alteration and ecological responses have been derived, but their transferability to other sites and larger scales is limited.[7] A global understanding of the trade-offs between water stress for people and freshwater environments is essential to achieve long-term water resilience of our societies, while maintaining or restoring healthy ecosystems.

In this modelling study, we aimed to conduct a spatially detailed assessment of global water stress, selecting three commonly used EF methods that vary in the amount of water made available to ecosystems. Additionally, we aimed to quantify the corresponding number of people who live under water stress conditions on a global and national level.

Methods

Hydrological model

We computed global water stress at the spatial resolution of 0·1° (equivalent to 11·1 km at the equator), with a monthly time step. To generate daily natural flows without anthropogenic water use for 1980–2018, we used LISFLOOD,[11] a distributed, semi-physically based hydrological model, which is open-source, well established, and used in different studies from a local to global level.[12] To compute natural flows, we used LISFLOOD accounts for rainfall runoff routing in the river network, as well as several surface and subsurface hydrological processes, including plant interception, evapotranspiration, soil freezing, snow accumulation and melting, surface runoff, lakes and reservoirs, water use, infiltration, preferential flow, redistribution of soil moisture within the soil profile, drainage to the groundwater system, groundwater storage, and base flow. Surface runoff is produced at every grid cell and routed through the river network with a kinematic wave approach.[13]

High-quality spatial datasets in hydrological modelling are crucial to avoid over-parameterisation and to reduce the dimensionality of the model calibration. Such spatial datasets used in LISFLOOD include topography maps (eg, digital elevation model, local drainage direction, slope gradient, and elevation range), land use (eg, land use classes, forest fraction, and fraction of urban area), soil (eg, soil texture classes and soil depth), and channel geometry (eg, roughness coefficient, bankfull channel depth, channel gradient, length, bottom width, and side slope). Various parameter maps necessary for the model were estimated from available datasets, such as the Shuttle Radar Topography Mission[14] for elevation, GlobCover 2009[15] for land use, SoilGrids1km[16] for soil information, the global river network database[17] for river network and flow direction, the Global Width Database of Large Rivers[18] for river widths, and the SPOT-VGT data[19] for monthly maps of Leaf Area Index.

We used the LISFLOOD setup and parameterisation of the GloFAS-Reanalysis (version 3.0),[12] a state-of-the-art global streamflow reanalysis with median scores at 1226 calibration stations within 66 countries, with a Kling-Gupta efficiency of 0·67 and correlation (*r*) of 0·8. Further details of the GloFAS-Reanalysis are discussed by Alfieri and colleagues.[12] All atmospheric variables used to run the model were extracted from the ERA5 reanalysis[20] and re-gridded from the original resolution of 31·0 km to the model resolution (11·1 km), with nearest neighbour interpolation. As input, LISFLOOD requires near surface air temperature, precipitation, and potential evapotranspiration. Potential evapotranspiration was estimated with the Penman-Monteith equation, as described in Supit and colleagues,[21] using daily average temperature, wind speed, relative humidity, and solar radiation as input.

We ran a 40-year simulation for 1979–2018, excluding all human influences (ie, without the effect of reservoirs and of all water use). Resulting daily discharges of natural or pristine flows were aggregated at monthly resolution and the first year of data was discarded to allow for model warm-up. These flows incorporated surface water flows and base flows (ie, renewable groundwater).

EF methods

Based on the unregulated pristine flows, we computed monthly EFs and the corresponding environmentally available water resources (ie, water resources minus EFs) for human use. We chose three commonly used EF methods to quantify EF requirements: an EF with high ecological protection (EF_{PROT}), the variable monthly flow method (EF_{VMF}), and an EF with minimum flow requirements (EF_{MIN}). As a measure representing EF_{PROT}, we used the presumptive standard for EFs by Richter and colleagues,[8] which attributes 80% of natural monthly river flows as EF. The remaining 20% is considered to be water available for human use. EF_{VMF} is the variable monthly flow method described by Pastor and colleagues.[22] During low-flow months (when long-term mean monthly streamflow is ≤40% the long-term mean annual flow), 60% of mean monthly streamflow is allocated to EFs. In high-flow months (when mean monthly streamflow is >80% of mean annual flow), the EF share is 30% of mean monthly streamflow. Otherwise, EF is 45% of mean monthly streamflow. This method was tested by means of case studies of locally assessed EFs; therefore, it is accepted as a standard method by various authors (appendix p 2). As a measure representing EF_{MIN} and high ecological risk, we used the daily flow exceeded for 95% of the month (Q_{95}).[23] Q_{95} is often used as a low-flow index.

All three selected methods are hydrological methods that are widely used in different water management studies (appendix p 2).[10] With the choice of EF_{PROT} and EF_{MIN}, we identified a wide range between minimum and maximum EF quantifications. EF methods can be classified into four types: hydrological methods, hydraulic rating methods, habitat simulation methods, and holistic methods. Hydraulic rating methods, habitat simulation methods, and holistic methods require large amounts of data that are not available at the global level. As such, we chose to use hydrological methods only.

Consumptive water use

We computed monthly consumptive water use for industry, agricultural crops, livestock, municipalities, and energy production for 2010 at a spatial resolution of 5×5 arc mins or 0·083×0·083°. Data on domestic and industrial (ie, manufacturing industry and thermoelectric production) water consumption were obtained from Flörke and colleagues.[24] Domestic global water consumption amounted to 64 km³/year, and industrial global water consumption amounted to 93 km³/year.

Irrigation water consumption was calculated, according to the methodology of aus der Beek and colleagues,[25] as the long-term monthly mean (1981–2010) driven by WATCH Forcing Data methodology applied to ERA-Interim data meteorological forcing. The following crops and crop classes were included: rice, wheat, winter wheat, barley, cotton, fodder, maize, potato, sugar beet, sunflower, millet, sorghum, pulses, soy, olives, fruits, vegetables, sugarcane, coffee, tobacco, cassava, and sweet potato. In the irrigation model, net and gross irrigation water requirements were computed on the area equipped for irrigation, which was based on the digital global map of irrigated areas around 2005.[26] The model simulates cropping patterns, growing seasons, and net and gross irrigation requirements. The model also establishes irrigation water withdrawals as the ratio of irrigation water consumption to irrigation project efficiency (country-specific);[27] however, these values are not used in our assessment. Crop patterns were used from MIRCA2000.[28] Global irrigation water consumption amounted to 1032 km³/year.

Livestock water consumption was calculated by means of the global database on livestock distribution for 2010,[29] and unit water consumption amount for drinking and service water was described by Mekonnen and Hoekstra.[30]

The resulting monthly sectoral water consumption datasets, all with a 0·083° spatial resolution, were then summed to a raster of total water use. This raster was resampled to a 0·1° raster, the same as the output of LISFLOOD.

Water stress

See Online for appendix

We calculated water stress, as locally experienced, as the ratio of total consumptive water use to environmentally available water resources:[3,6]

$$\text{Water stress} = \frac{WC}{WA}$$

where WC is consumptive water use and WA is environmentally available water resources. WA was calculated by:

$$WA = WR - EF$$

where WR is total water resources and EF is environmental flow.

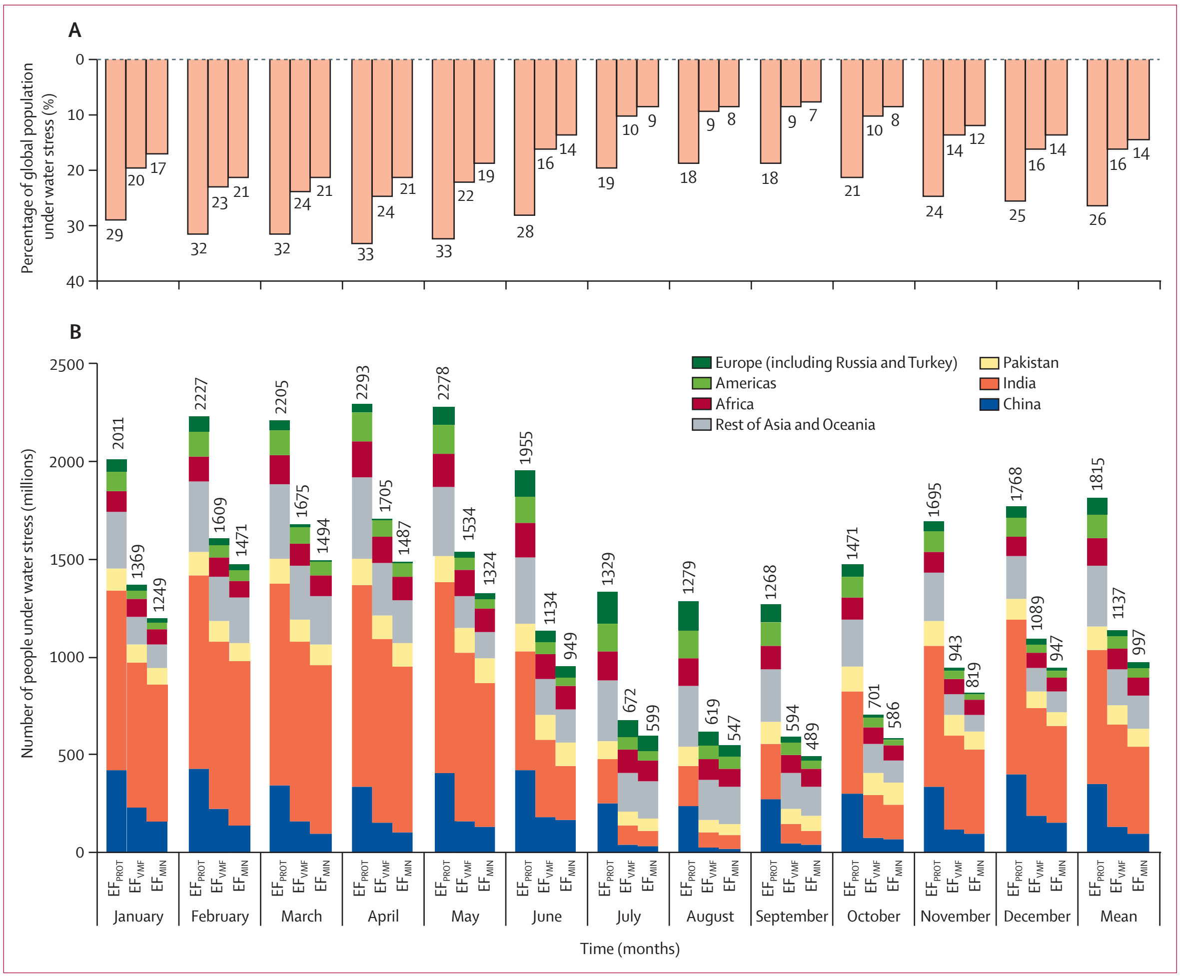

Figure 1: **Proportions of the global population under water stress per month in 2010**
Percentages (A) and absolute numbers in millions (B) of the global population under water stress per month for EF_{PROT}, EF_{VMF}, and EF_{MIN}. EF_{PROT}=environmental flow with high ecological protection. EF_{VMF}=variable monthly flow method. EF_{MIN}=environmental flow with minimum flow requirements.

Values from 0–1 indicated low water stress. Values exceeding the threshold of 1 suggested that more water was used than was environmentally available and that EF requirements were violated. This ratio is in line with the definition of water stress as in SDG indicator 6.4.2,[3,6] although this indicator uses water abstraction. Nevertheless, Vanham and colleagues[6] pointed out that both water abstraction and consumption are relevant for water stress. These authors recommend that the SDG indicator 6.4.2 should be measured with both of these factors. In its 2020 edition monitoring report on progress towards the SDGs, Eurostat also applied water consumption and not abstraction, with reference to SDG indicator 6.4.2.[31]

To quantify grid cell water stress, we used the same equation as Mekonnen and Hoekstra:[32]

$$\text{Water stress} = \frac{WC_{loc}}{WA_{tot}}$$

where WC_{loc} is local consumptive water use in a grid cell and WA_{tot} is total environmentally available water resources in the grid cell. WA_{tot} is the sum of locally produced, environmentally available water resources in the grid cell (WA_{loc}) and the water flowing in from upstream grid cells:

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

where $_i$ denotes the cells upstream of the cell under consideration. If the upstream consumptive water use is larger than the upstream environmentally available water, the total environmentally available water will be equal to the locally available water in the grid cell (WA_{tot}=WA_{loc}).

For some grid cells where there was no or little water availability, generally in northern zones during winter or in desert areas, no meaningful values for water stress could be computed. These grid cells are indicated as

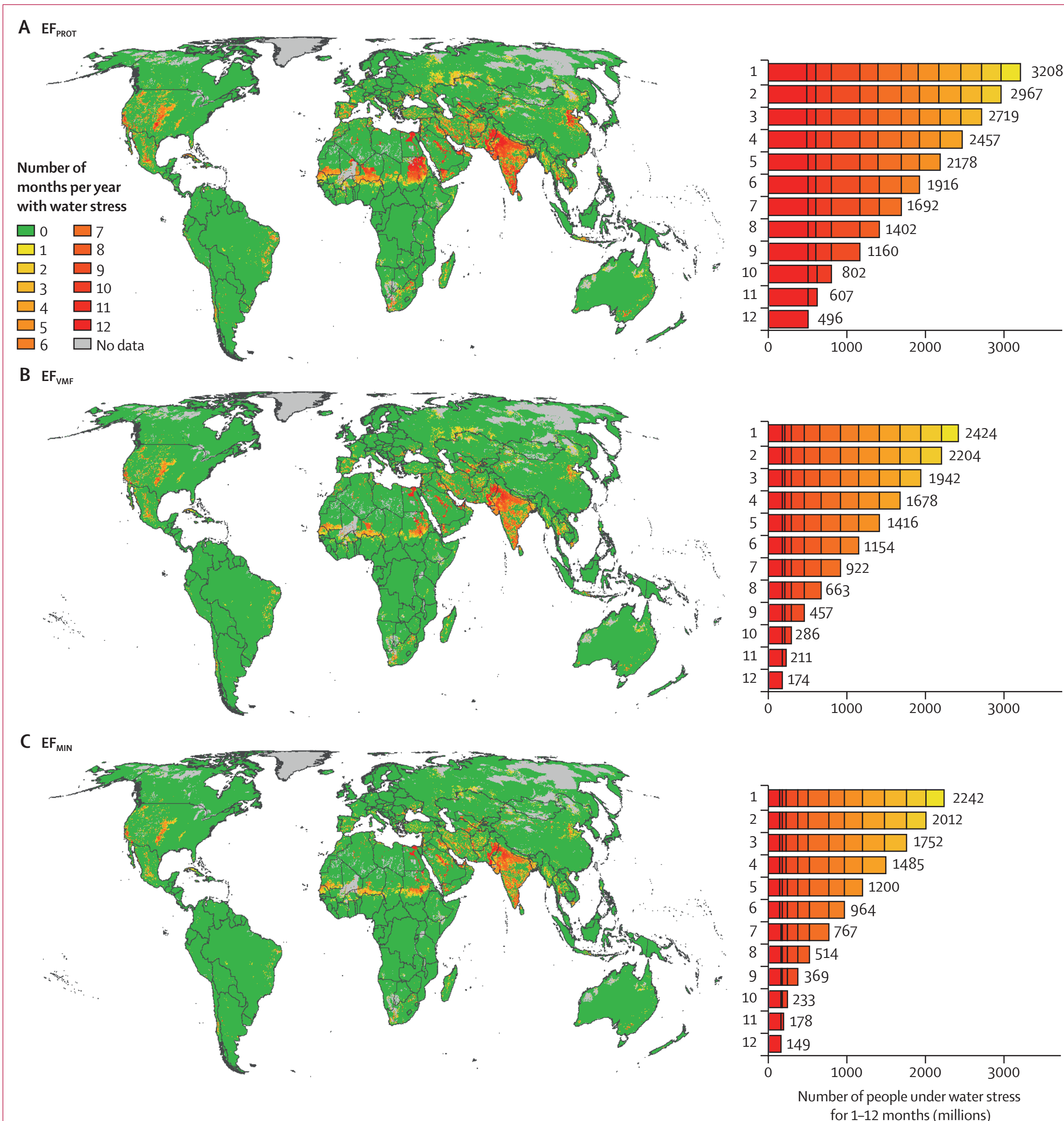

Figure 2: **Proportions of the global population under water stress for 1–12 months per year in 2010**
Number of months per year and related number of people (millions) under water stress for EF_{PROT} (A), EF_{VMF} (B), and EF_{MIN} (C). EF_{PROT}=environmental flow with high ecological protection. EF_{VMF}=variable monthly flow method. EF_{MIN}=environmental flow with minimum flow requirements.

having no data on the figures. Additionally, no water stress amounts were computed for Greenland, given that there is almost no water use.

In our analysis, we did not take water supply infrastructure into account. Thus, water stress was computed on the basis of topographically routed water availability. In reality, infrastructure influences local water stress (eg, by means of reservoirs, irrigation infrastructure, drinking water supply pipes, water transfers, desalination plants). Water transfers can exist over hundreds of kilometres.[6] However, information on infrastructure is scattered and incomplete, and can be outdated or unreliable. Although some detailed infrastructure data exist on a local level, no reliable, comprehensive, and updated database on water infrastructure exists on a continental or global level. Therefore, to be consistent in our analysis for all global regions, we did not account for water supply infrastructure. Our decision to omit reservoirs was made on the basis that only a small fraction of reservoirs was included in global models and, for most, no operating rules were known. Reservoir construction and management are also constantly

	National population, millions	EF_{PROT}	EF_{VMF}	EF_{MIN}
Bangladesh	150·8	120·5 (79·9%)	107·8 (71·5%)	111·8 (74·2%)
Brazil	195·7	44·3 (22·6%)	20·8 (10·6%)	19·1 (9·7%)
China	1337·7	624·1 (46·7%)	339·2 (25·4%)	283·2 (21·2%)
India	1234·3	1066·0 (86·4%)	991·6 (80·3%)	952·4 (77·2%)
Iran	73·8	59·4 (80·5%)	51·3 (69·5%)	51·5 (69·8%)
Iraq	30·6	24·4 (79·9%)	16·1 (52·6%)	14·9 (48·6%)
Israel	8·0	7·9 (98·9%)	7·2 (89·7%)	7·1 (88·8%)
Jordan	7·3	6·3 (86·3%)	6·2 (84·9%)	6·0 (82·2%)
Lebanon	5·0	3·5 (70·4%)	1·3 (26·8%)	1·7 (34·3%)
Libya	6·2	6·0 (96·8%)	5·8 (93·6%)	5·4 (87·1%)
Malta	0·4	0·4 (100·0%)	0·4 (100·0%)	0·4 (100·0%)
Mauritania	3·6	3·2 (88·9%)	3·0 (83·3%)	2·8 (77·8%)
Niger	16·5	12·9 (78·2%)	11·8 (71·5%)	10·7 (64·8%)
Pakistan	179·4	144·3 (80·4%)	134·1 (74·8%)	132·6 (73·9%)
Qatar	1·9	1·7 (89·5%)	1·7 (89·5%)	1·7 (89·5%)
Russia	142·8	51·6 (36·1%)	33·7 (23·6%)	23·3 (16·3%)
Saudi Arabia	27·4	24·1 (88·0%)	21·5 (78·5%)	22·7 (82·9%)
Syria	21·0	17·4 (82·9%)	11·7 (57·1%)	11·9 (56·7%)
The Gambia	1·7	1·4 (82·4%)	1·4 (82·4%)	1·3 (76·5%)
Turkmenistan	5·1	4·3 (84·3%)	3·8 (74·5%)	3·8 (74·5%)
USA	309·3	61·3 (19·8%)	44·5 (14·4%)	35·1 (11·3%)

Data are n (%). EF_{PROT}=environmental flow with high ecological protection. EF_{VMF}=monthly environmental flow method. EF_{MIN}=environmental flow with minimum flow requirements.

Table: **Countries with a high proportion of the national population (millions) living under water stress for at least 1 month per year in 2010**

evolving worldwide. In Europe and North America, there is a tendency to rethink and even remove large reservoirs, given that they have a high environmental and social cost. Additionally, many older large reservoirs are gradually losing storage volume due to sedimentation.[33] Furthermore, modern strategies on water storage call for a new integrated approach, which moves beyond large built storage and includes various options (eg, large reservoirs, small reservoirs, ponds and tanks, aquifers, natural wetlands, constructed wetlands).[34]

We accounted for renewable groundwater in our simulations (baseflow entering discharge) and, thereby, water use from groundwater. Due to a scarcity of respective spatial datasets on fossil groundwater, we did not account for this resource.

We used the HYDE 3.2 database,[35] a spatially detailed population database for 2010, to quantify the number of people living under water stress within a grid cell. We divided the world by four regions: Africa; the Americas; Asia and Oceania; and Europe, Russia, and Turkey (including Azerbaijan, Georgia, and Armenia).

Sensitivity analysis

For a sensitivity analysis, we conducted an additional water stress analysis, accounting for the influence of 687 large reservoirs in LISFLOOD[12] to compute regulated monthly water resources (WR in equation 2). These findings are presented in the appendix (p 6).

Role of the funding source

There was no funding source for this study.

Results

Overall, we generated global monthly water stress maps for EF_{PROT} (appendix p 3), EF_{VMF} (appendix p 4), and EF_{MIN} (appendix p 5), resulting in a total of 42 maps in this paper. Considering the presumptive standard for EF_{PROT}, the number of people under monthly water stress in 2010 varied globally between 1·3 billion and 2·3 billion throughout the year, with an annual mean of 1·8 billion (SD 402 million; figure 1). This finding corresponded to 18% and 33% of the world's population (in 2010), and an annual mean of 26%. Imposing EF_{MIN}, between 0·5 billion (7%) and 1·5 billion (21%) people faced water stress, or an annual mean of 1·0 billion (SD 391 million; 14%). For EF_{VMF}, the monthly number of people ranged between 0·6 billion (9%) and 1·7 billion (24%), with an annual mean of 1·1 billion (432 million; 16%). Compared with EF_{MIN}, imposing EF_{PROT} globally would have put between 710 million (March) to 1 billion (June) additional people under water stress on a monthly basis, whereas this would have been 72 million (August) to 218 million (April) additional people if EF_{VMF} were imposed.

For all levels of ecological protection, the majority of people under water stress lived in Asia and Oceania (60–89%), with high proportions in India (maximum 701 million [58% of globally affected people] in January), northeast China (401 million [22%] in December), and Pakistan (111 million [19%] in October). The highest proportion of the population living under water stress was observed from January to May, during which Asia (including Oceania) accounted for 80–90% of the affected people. During the Indian summer monsoon, lasting from June to September, and the Chinese rainy season, lasting from May to September, the global number of people under water stress decreased substantially. In July and August, which are summer months or dry season in Europe, Russia, and North America, the proportion of the Asian population under water stress was less than 70% of the global total. From October to December, the global population under water stress increased again, mainly due to increases in numbers across India and China.

Due to the large number of people facing water scarcity in Asia (including Oceania), the trade-off between the degree of ecological protection and population under water stress is highest in absolute terms in this region. The difference in the number of people exposed to monthly water stress between high (EF_{PROT}) and low (EF_{MIN}) EF protection in Asia (including Oceania) varied throughout the year, from 516 million to 776 million people per month. On a monthly basis, this difference varied between 61 million and 94 million people in the Americas, 25 million and 60 million people in Africa, and 35 million to 91 million people in Europe (including Russia and Turkey).

The effect of comparing EF_{VMF} with EF_{MIN} on human water stress was much less pronounced than the effect of comparing EF_{PROT} with EF_{MIN}, in all regions of the world. Throughout 2010, 37–192 million additional people faced water stress in Asia (including Oceania), 6–20 million in the Americas, 6–17 million in Africa, and 450 000 to 11 million in Europe (including Russia and Turkey).

Regions can be affected by water stress between 1 and 12 months of the year (figure 2). We estimate that 3·2 billion (EF_{PROT}), 2·4 billion (EF_{VMF}), and 2·2 billion (EF_{MIN}) people lived under water stress for at least 1 month per year. These estimates corresponded to 46% (EF_{PROT}), 35% (EF_{VMF}), and 32% (EF_{MIN}) of the world's population in 2010, respectively. Hence, high EF_{PROT} would have placed an additional 1 billion people under water stress for at least 1 month, compared with EF_{MIN}. The population under water stress decreased consistently as the number of months increased. We estimate that 1916 million (EF_{PROT}), 1154 million (EF_{VMF}), and 964 million (EF_{MIN}) people lived under water stress for at least 6 months of the year, whereas 496 million (EF_{PROT}), 174 million (EF_{VMF}), and 149 million (EF_{MIN}) people lived under these conditions for all 12 months of the year. Areas under water stress for multiple months during the year were concentrated in India, the northeast of China, Pakistan, the Middle East, the Mediterranean, the Sahel, South Africa, central and southwestern USA, Mexico, the northeast of Brazil, and along the Pacific Coast of South America.

High proportions of the national population living under water stress for at least 1 month of the year could be found in India, Pakistan, Bangladesh, Turkmenistan, Iran, Iraq, Jordan, Israel, Lebanon, Qatar, Saudi Arabia, Syria, Libya, Mauritania, Niger, The Gambia, and Malta (table; figure 3). Although accounting for high absolute numbers, China had a lower proportion of the national population facing water stress overall because these proportions were concentrated in the northeastern region of the country, whereas the southern population only faced low water stress. Other countries with high absolute numbers but lower proportions included Russia and the USA, where the densely populated eastern region of the USA generally only faced low water stress. Additionally, Brazil had high absolute numbers but relatively low percentages, with populations facing water stress concentrated in the north-eastern region of the country, whereas the densely populated southern regions faced low water stress.

In the sensitivity analysis, which accounted for the influence of 687 large reservoirs, we found similar quantities (deviations from main analyses of 0–7%) in the number of people facing water stress for 1–12 months per year globally (appendix p 6). The values for the number of people facing water stress for 6 months per year are 1·94 billion instead of 1·92 billion (EF_{PROT}), 1·16 billion instead of 1·15 billion (EF_{VMF}), and 0·95 billion instead of 0·96 billion (EF_{MIN}) people.

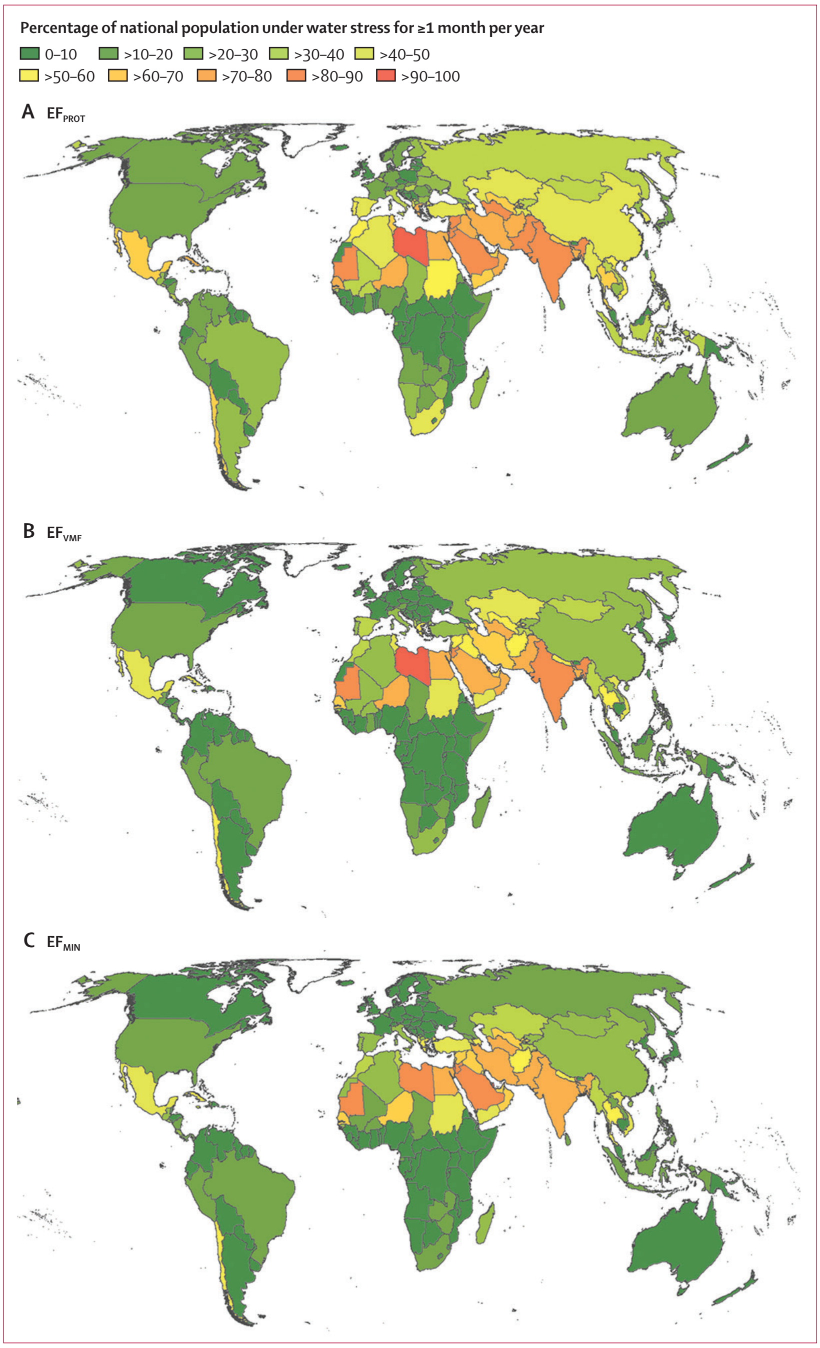

Figure 3: **Percentage of the national population under water stress for at least 1 month per year in 2010**
Percentages of population provided for EF_{PROT} (A), EF_{VMF} (B), and EF_{MIN} (C). EF_{PROT}=environmental flow with high ecological protection. EF_{VMF}=variable monthly flow method. EF_{MIN}=environmental flow with minimum flow requirements.

Discussion

The large uncertainty in EF needs and the multiple methods used to define them provide uncertainty in how much water is available for human use from most streams and rivers worldwide. Our analysis of the global population under water stress for different levels of environmental protection shows that—even when applying minimum flow requirements—32% of the world's population faced water stress for at least 1 month per year and 14% did so for at least 6 months per year. Sustaining a minimum flow is important for the survival of many aquatic species, yet does not guarantee the benefits of high flows for sediment flushing,[36] the maintenance of wetlands,[37] and resistance against invasive species.[7] The EF_{VMF} method[22] was developed to increase the protection of freshwater ecosystems, with a reserve of 60% of the mean monthly flow allocated to EFs during low-flow season and a reserve of 30% during high-flow season. Its global application would result in an increase in the number of people exposed to water stress, which could range from 10% to 30% compared with minimum flow requirements, depending on timing in the year and the number of months under water stress. For the presumptive standard of high environmental flow protection, in 2010, 46% of the world's population would have been under water stress for at least 1 month per year, whereas 27% would have faced water scarcity for at least 6 months per year.

Balancing future water needs of ecosystems and humans will become even more challenging as changes in climate, demography, and socioeconomic systems drive both the availability and use of water.[1] Leaving sufficient water for ecosystems and alleviating human water stress will require great efforts to save water to reduce consumption intensities.[38] Irrigated agriculture is particularly water intensive, accounting for approximately 70% of global withdrawals and around 90% of global consumption.[1] There are many options to increase the sustainability of food systems with respect to water, such as augmenting the water productivity of crops and livestock (as partly captured by SDG indicator 6.4.1),[39,40] growing stress-resistant crops to improve yield stability under water stress conditions,[41] or applying solutions at the end of the supply chain (eg, diversifying human diet and reducing meat consumption).[42]

Our analysis is a first-pass global assessment, which should be complemented by regional or local river basin and sub-basin assessments that incorporate databases (eg, water supply infrastructure, groundwater databases,[43] and fossil groundwater[44]) and knowledge on regional and actual water management, preferably involving local stakeholders and expertise. Countries should apply this procedure to the best of their capacities to monitor and report SDG indicator 6.4.2. We expect that our assessment is on the conservative side, given that LISFLOOD is on the higher end of the multi-model range of water availability computations.[45] Furthermore, in many countries where population size has increased since 2010, the number of people facing water stress is also likely to increase. The omission of fossil groundwater might have led to a slight underestimation of current water availability and use in some regions, such as northern Africa and the Middle East, northern India, and the western region of the USA, subsequently resulting in a local overestimation of the pressure on river flows and EF requirements. Nevertheless, all EF methods are similarly affected by this restriction.

The UN Millennium Development Goals campaign, which ran from 2002 to 2015, defined water stress as the ratio between water use and total available water resources. The Millennium Development Goals were succeeded by the SDGs for the period between 2016 and 2030. For the SGDs, water stress was redefined as water use as a fraction of environmentally available water. Compared with the Millennium Development Goals, the SDGs explicitly recognise the importance of water requirements for the environment. This understanding is an essential evolution, given that the number of globally monitored freshwater species has declined by 84% between 1970 and 2016.[46] Accelerating the implementation of EFs is essential in improving the current situation of global freshwater biodiversity loss.[47] In view of these developments, water managers and policy makers will need to make balanced choices and trade-offs in the allocation of available water resources between human use and the environment, in which water for the environment also serves humans due to multiple services provided by healthy aquatic ecosystems. Further investigation of environmental needs through sophisticated EF assessment methodologies is required to decide which EFs are best attributed in specific locations, such as habitat simulation methods and holistic methods supported by local field measurements campaigns.

Contributors

DV and LF conceptualised the study and drafted the paper. LA conducted the hydrological model analysis, with support from SG and VL. MF provided data on water use. DV conducted the water stress assessment and produced all figures. All authors contributed to the reviewing and editing of the paper. DV and LA verified the underlying data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

All authors declare no competing interests.

Data sharing

Data for all countries can be found in the appendix and are available for reuse, following proper citation to this Article. Requests for additional data should be sent to the corresponding author. Our estimates rely on multiple datasets complying with terms and conditions, or licensing.

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