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Global Environmental Flow Information for the Sustainable Development Goals

Aditya Sood, Vladimir Smakhtin, Nishadi Eriyagama, Karen G. Villholth, Nirosha Liyanage, Yoshihide Wada, Girma Ebrahim and Chris Dickens



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IWMI Research Report 168

Global Environmental Flow Information for the Sustainable Development Goals

*Aditya Sood, Vladimir Smakhtin, Nishadi Eriyagama, Karen G. Villholth, Nirosha Liyanage, Yoshihide Wada, Girma Ebrahim
and Chris Dickens*

International Water Management Institute (IWMI)
P O Box 2075, Colombo, Sri Lanka

The authors: Aditya Sood, Senior Researcher – Integrated Hydrological Modelling, International Water Management Institute (IWMI), Colombo, Sri Lanka; Vladimir Smakhtin, Director, United Nations University - Institute for Water, Environment and Health (UNU-INWEH), Ontario, Canada; Nishadi Eriyagama is Water Resources Engineer, IWMI, Colombo, Sri Lanka; Karen G. Villholth, Sub-theme Leader (Groundwater and Underground Solutions), IWMI, Pretoria, South Africa; Nirosha Liyanage, Consultant, IWMI, Colombo, Sri Lanka; Yoshihide Wada: (i) Research Scientist, Department of Physical Geography, Faculty of Geosciences, Utrecht University, the Netherlands; and (ii) Deputy Program Director, Water, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; Girma Ebrahim, Postdoctoral Fellow, Hydrogeology and Water Resources, IWMI, Pretoria, South Africa; and Chris Dickens, Principal Researcher and Head of Office, IWMI, Pretoria, South Africa.

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Front cover photograph: A wooded stream in Zumicom, Switzerland.

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Acronyms and Abbreviations

BF	Baseflow
EF	Environmental Flows
EMC	Environmental Management Class
FDC	Flow Duration Curve
GEFC	Global Environmental Flow Calculator
GHM	Global Hydrological Model
GRACE	Gravity Recovery and Climate Experiment
GRanD	Global Reservoir and Dam Database
GRDC	Global Runoff Data Centre
HydroSHEDS	Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
MAWA	Mean Annual Water Availability
NGO	Nongovernmental organization
NWCI	Natural Water Capital Index
PCR-GLOBWB	PCRaster Global Water Balance
SDG	Sustainable Development Goal
SR	Surface Runoff
TRWR	Total Renewable Freshwater Resources
TWS	Terrestrial Water Storage
TWW	Total Freshwater Withdrawn
UN	United Nations

Summary

Water is a crosscutting issue across many of the Sustainable Development Goals (SDGs). However, there is one goal that is focused explicitly on water - Goal 6. Sustainable management of water implies that, as part of water resources management activities, sufficient water is left for ecosystems so that they can continue to provide services to society into the future. This, essentially, points to the need to ensure environmental flows (EF) in order to meet the SDGs. However, in most countries, there is a lack of awareness of EF at multiple stakeholder levels, and a lack of consistent, easy-to-use, readily available EF data to feed into the SDG process. If countries are to implement EF-related SDG targets over the next 15 years, baseline EF information is a prerequisite, and a process to incorporate such information into the targets needs to be developed.

This research study focused on making data on EF, and sustainable surface water (SR) and groundwater (BF) abstractions available at a global, regional and subregional level. The first EF assessment at global scale, carried out by the International Water Management Institute (IWMI) in 2004, was modified to provide EF information for the calculation of SDG target indicators. The spatial resolution of the analysis was improved from 0.5 to 0.1 degrees, and environmental

water 'needs' were estimated for both surface runoff and groundwater. The desired flow and environmental conditions of rivers are defined by four environmental management classes (EMCs). The percentage of flow required relative to pristine conditions, and the volume of groundwater and surface water that may be withdrawn without impacting EF are calculated for each EMC globally. The EF for each EMC are based on modifying synthetic, pre-development natural flows derived from the global hydrological model PCR-GLOBWB. Since the actual river flow and environmental condition of rivers vary across the world, the study also provides an estimate of the most likely current EMC for each grid cell globally, based on a modified "Incident Biodiversity Threat".

Finally, an online, publicly available, interactive tool, the 'Global Environmental Flow Information System' developed by IWMI, enables users to select areas either at a country or river basin level (or any area of choice), identify existing and/or desired EMC, and get estimates of associated EF, baseflow (BF) contribution, and corresponding sustainable surface water and groundwater abstractions. These estimates can then be compared either directly with the information on actual water withdrawals in the selected area or fed into the SDG target indicators.

Global Environmental Flow Information for the Sustainable Development Goals

Aditya Sood, Vladimir Smakhtin, Nishadi Eriyagama, Karen G. Villholth, Nirosha Liyanage, Yoshihide Wada, Girma Ebrahim and Chris Dickens

Introduction

One of the main events of 2015 was the adoption of the 17 Sustainable Development Goals (SDGs) by world leaders of the 193 United Nations (UN) member countries (United Nations 2015). Between now and 2030, the SDGs aim *“to end poverty and hunger everywhere; to combat inequalities within and among countries; to build peaceful, just and inclusive societies; to protect human rights and promote gender equality and the empowerment of women and girls; and to ensure the lasting protection of the planet and its natural resources. ... also to create conditions for sustainable, inclusive and sustained economic growth, shared prosperity and decent work for all, taking into account different levels of national development and capacities”* (United Nations 2015). The 17 SDGs have 169 targets. The goals and their targets have been developed after extensive negotiations between the 193 UN member countries. As such, they reflect the results of a political, rather than a scientific, process. Water is a crosscutting theme across many of the SDGs with direct or indirect impacts related to: ending poverty (Goal 1), ending hunger (sustainable agriculture, improved nutrition) (Goal 2), sustainable economic growth (Goal 8), sustainable cities (Goal 11), sustainable consumption and production patterns (Goal 12), climate change mitigation (Goal 13), and protecting and restoring ecosystems (Goal 15). There is, notably, also one SDG that focuses explicitly on water - Goal 6 (*“Ensure availability and sustainable management of water and sanitation for all”*). Sustainable management of water implies that, as part of water resources management activities, sufficient water is left for ecosystems so that they can continue to provide services to society into the future. This, essentially, points to the need to

ensure environmental flows (EF) in order to meet the SDGs.

The EF concept entered water management discussions in the mid to late twentieth century after extensive dam construction led to large-scale obstruction of free flowing rivers and significant loss of ecosystem services. Initial concerns were related to the impact of dams on game fish species, such as salmon, in rivers, leading to the concept of minimum flows in the rivers (or minimum instream flows). Over subsequent decades, the concept of EF has evolved to encompass river flow variability, river connectivity (longitudinal and lateral), ecosystem services and human well-being, and many methods have been developed to quantify EF. Acreman and Dunbar (2004) classified methods for evaluating and ensuring EF into four main categories of increasing complexity: (i) lookup tables – methods that define EF by rule-of-thumb, based on simple indices; (ii) desktop analysis – methods that are based on statistical analysis of time series of available data (either hydrological data only or hydrological data with ecological data); (iii) functional analysis – methods that link aspects of hydrology with ecology (i.e., direct response of species); and (iv) hydraulic habitat analysis and modeling – methods that link hydraulic characteristics with ecology.

It is difficult to provide definitive evidence in support of the performance of different methods for evaluating and ensuring EF, as there are many factors that guide the selection of a particular methodology. These include the scale and objective of the study; the level and quality of data available; and the resources available to carry out the study. While lookup tables and desktop analysis tend to be more

suitable for quick assessments or large-scale studies with low involvement of stakeholders, the other two methods (financial analysis, and hydraulic habitat analysis and modeling) are more suited to local and regional studies, where there is more interaction with local experts and stakeholders. In general, the latter two methods can be regarded as producing outputs of higher confidence, as they normally require site-specific field investigations.

Poff and Matthews (2013) divided the history of EF theory and methodology development into four eras: (i) pre-1980s - defined as reductionist, where the goal was to have minimum flows to protect a single species of interest; (ii) late 1980s to mid-1990s - defined as the “emergence and synthesis” period, where ecological theory became part of the discourse on EF; (iii) mid-1990s to mid-2000s - defined as the “consolidation and expansion” period, when ecosystems were considered on par with human needs and EF moved out of the realm of academics to become tools for ensuring and implementing environmental policies espoused by local and regional nongovernmental organizations (NGOs); and (iv) post mid-2000s - defined as “globalization”, where the concept of EF has been taken up at a regional and global scale, supported by tools for their implementation, due to emergence and increasing popularity of regional- and global-scale hydrological models (e.g., Smakhtin et al. 2004a; Pastor et al. 2014), and with greater awareness of threats to global ecosystems (Vörösmarty et al. 2004; Döll et al. 2009; Vörösmarty et al. 2010).

The first attempt to calculate EF requirement at a global scale was undertaken by Smakhtin et al. (2004a, 2004b). Their proposed methodology was a desktop approach based on ecological hypotheses and hydrological data simulated by the global WaterGAP model (Döll et al. 2003) with a 0.5 degree spatial grid. Their approach focused only on surface water and considered only a single ecosystem scenario - that of a “fair” ecosystems condition. The EF requirement was calculated for low and high flow conditions (defined as the environmental low flow requirement and environmental high flow requirement, respectively), which were aggregated

to represent the total EF requirement per annum. A similar approach was used by Hanasaki et al. (2008) to include EF in their assessment of global water resources. Hoekstra and Mekonnen (2011) used the “presumptive standard” methodology developed by Richter et al. (2012) to define EF requirement for major global rivers in their analysis of global water scarcity. Presumptive standards implied precautionary EF that may be used in areas where detailed analysis of EF had not been undertaken. The precautionary EF is based on precautionary principle to risk management, which states that, if an action is suspected of causing harm to the environment, in the absence of scientific consensus, the burden of proof that the action is not harmful falls on those taking action. Such an approach can help prevent irreversible damage to a river ecosystem until a more detailed, site-specific analysis of EF is conducted. The presumptive standards are calculated as a percentage-based range around historic flows. For global-scale studies on EF, Pastor et al. (2014) compared the performance of three existing and two newly developed EF methodologies in the context of 11 different case studies, where locally accessed, more detailed, estimates of EF were also available. Their analysis showed that the performance of EF methodologies depends upon the type of the flow regime (stable versus variable - stable being flows with less intra-annual variability compared to “variable” flows) and streamflow “condition” (low versus high).

There is no single ‘best’ EF methodology that can be universally applied under all circumstances. Many EF methods exist (e.g., http://waterdata.iwmi.org/applications/efm/efm_home.php - accessed on February 8, 2017), and each one of these methods has its pros and cons; the method selected must be determined by the needs and resources of the study.

From the perspective of the SDG process, it is important to offer countries some baseline data and tools to help with preliminary estimates of EF, which may be improved at a later stage when relevant capacity is developed. Naturally, for some “EF-advanced” countries, such estimates will not be required.

Most of the previous global EF studies have focused on required river flow, with little attention being given to the source of this flow (surface water or groundwater) and hence limited understanding of sustainable limits of water abstraction from these interconnected sources. Gleeson et al. (2012) calculated groundwater footprints for major global aquifers and included the environmental contribution of groundwater to streamflow. In the analysis, the authors arbitrarily considered monthly streamflow that exceeded 90% of the time (Q90) as a proxy for EF, which is met by groundwater. Contribution from groundwater is a crucial component of river flow, especially during the months without rainfall. If river flow can be conceptualized to be made up of surface runoff (SR) and contribution from groundwater (baseflow [BF]), and the same can be done for EF, the excess of each resource can

be translated into respective abstraction limits. Such an approach was developed by Ebrahim and Villholth (2016) to estimate sustainable groundwater abstraction based on recession flows in catchments in South Africa. Groundwater is moving up the development agenda, and explicit thresholds of sustainable withdrawals, from both surface water and groundwater, need to be incorporated into EF methodologies. The role of groundwater in future food security and climate change mitigation is well recognized (Famiglietti 2014), thus making it critical to explicitly consider groundwater within the EF discourse.

The next section of the report discusses the role of EF in the SDGs. This is followed by the methods and data used in this study. Results are discussed in the fourth section together with details of the web-based interface for calculating EF online.

Environmental Flows in the SDGs

The “SDG on water” (SDG 6) has six targets, of which at least three explicitly or implicitly cover the issues of sustainability of water resources development and freshwater ecosystem maintenance. These targets are as follows:

Target 6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity.

Target 6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.

Target 6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

Each SDG target has at least one measurable indicator, and many such indicators are still emerging in the ongoing global discourse on how to operationalize the targets (<http://www.unwater.org/news-events/news-details/en/c/428698/> - accessed on February 8, 2017). Target 6.4 promotes efficient use of water by different sectors of the economy. The associated indicator calculates the level of water stress in each country, thus quantifying the pressure on renewable national freshwater resources. The Water Stress Indicator (*Stress%*), calculated at annual time scale, is defined as the total freshwater withdrawn (TWW) by all sectors divided by the difference between the total renewable freshwater resources (TRWR) and environmental water requirements (*Env*), and multiplied by 100 (Equation [1]).

$$Stress\% = \frac{TWW}{TRWR-Env} * 100 \quad (1)$$

The indicator in this form was first proposed by Smakhtin et al. (2004b) for surface water resources. In Equation (1), TWW includes surface water and groundwater, and TRWR includes internal (generated within a country) and external (generated outside but made available within a country) renewable freshwater resources. *Env* is the environmental water requirements, established to protect the basic environmental services of freshwater ecosystems. In some versions of the Water Stress Indicator, *Env* is established separately for surface water and groundwater, where “surface *Env*” is essentially the EF and “groundwater *Env*” is the groundwater remaining in the aquifer to play its ecological role at subsurface level. Stress% should not exceed a certain desired threshold, which needs to be defined as a societal choice.

Although not yet explicit in indicators of Target 6.5 on integrated water resources management (IWRM), this target would have to consider EF as part of water resources management to make the latter truly holistic. To properly practice IWRM, each country (or basin authority) would need to know the EF, so that river water withdrawals and groundwater abstraction can be managed within sustainable limits.

Target 6.6 is developed with the intension of protecting water-related ecosystems, so that they can continue to provide ecosystem services for human well-being. This includes protecting wetlands, rivers, aquifers and lakes, which are

connected to each other through the flux of water, both on the surface and underground. While environmental flows naturally play an important part in protecting water-related ecosystems, the indicator for Target 6.6 relies on the Water Stress Indicator of Target 6.4 to provide that information. The indicator for Target 6.6 explicitly notes this connection.

Therefore, environmental flows need to become an integral part of the SDG discourse, but there is still lack of consistency and also awareness of EF in many countries. If countries are to accept and implement EF over the next 15 years in the context of achieving the SDG targets by 2030, some initial EF information needs to be provided. Countries can then make further decisions on what additional data, resources and capacity they will need to invest in, in order to improve assessments and be compliant with the SDGs.

This research study advances on the work conducted by Smakhtin et al. (2004a) (http://waterdata.iwmi.org/Applications/Global_Assessment_Environmental_Water_Requirements_Scarcity/ - accessed on February 8, 2017) on the first global EF assessment, together with a follow-up hydrology-based approach to estimate EF time series (Smakhtin and Eriyagama 2008) (<http://www.iwmi.cgiar.org/resources/models-and-software/environmental-flow-calculators/> - accessed on February 8, 2017), to help provide EF information which could be useful for the calculation of indicators for the SDG targets.

Data and Methods

To estimate EF globally, natural river flow at a global scale is required. Continuous and consistent observed hydrological time series at global scale are not available. Global hydrological models (GHMs) are used to obtain such data. Sood and Smakhtin (2015) provide a review of GHMs. This research study used PCRaster Global Water Balance (PCR-GLOBWB) model

(version 2.0) which was developed by Utrecht University (Wada et al. 2016). This model was selected for three reasons. First, it operates at 0.1 degree spatial resolution (compared to other models, which are mostly 0.5 degree resolution). Second, since the discharge components from surface water (SR) and groundwater (BF) act as incremental contributions to river flow, these

contributions can be added up as independent incremental contributions at the grid scale. The actual flow in the river may be a bit different to the aggregated runoff due to routing processes that take place in a stream channel, but there is a trade-off between the ability to aggregate at different landscape scales versus ignoring the impact of routing on streamflow. Third, the PCR-GLOBWB model has been used in many studies dealing with groundwater issues (e.g., Wada et al. 2010, 2012; Sutanudjaja et al. Forthcoming). Simulated monthly streamflow from 1960 to 2010 (51 years) for natural conditions (i.e., no human interventions such as abstractions, reservoirs and irrigation) was used. The 'Global Environmental Flow Calculator' (GEFC) software (Smakhtin and Eriyagama 2008) was then used with the simulated flow time series to calculate EF for different environmental management classes (EMCs) that relate to the current or desired condition of a river, and are perceived as scenarios of the environmental state of rivers. An attempt was also made to infer the most probable current EMC for rivers globally by linking EMCs with the "health" of rivers (e.g., Vörösmarty et al. 2010). The EF were then split, for each EMC, into surface water and groundwater contributions, which were subsequently used to estimate sustainable abstractions from surface water and groundwater. The details of these methodological components are summarized below.

Simulating Natural River Flow Time Series

Figure 1 shows a schematic diagram of the PCR-GLOBWB model (version 2.0) used in this study to simulate the natural flow time series. A detailed description of the hydrological model structure and water use calculation is given in van Beek et al. (2011) and Wada et al. (2016). A summary of the main features of the model and model parameterization over the land, excluding the Antarctic, are given below.

For each grid cell and daily time step, the PCR-GLOBWB model simulates the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the

water exchange between the layers (infiltration, percolation, recharge and capillary rise) and between the top layer and the atmosphere (rainfall, evapotranspiration and snowmelt). The model also calculates canopy interception and snow storage. Sub-grid variability is taken into account by considering separately tall and short vegetation, open water (lakes, reservoirs, floodplains and wetlands), different soil types based on the Food and Agriculture Organization of the United Nations (FAO) Digital Soil Map of the World (FAO 2003), and the area fraction of saturated soil calculated by the improved ARNO rainfall-runoff model (Todini 1996; Hagemann and Gates 2003). The groundwater layer represents the deeper part of the soil that is exempt from any direct influence of vegetation and constitutes an active groundwater reservoir fed by recharge and discharge to rivers. The groundwater store is explicitly parameterized based on lithology and topography assuming a linear reservoir model (Kraaijenhoff van de Leur 1958). The simulated local direct runoff, interflow (which collectively forms SR) and BF were routed along the drainage network based on channel characteristics at a 0.1° spatial resolution derived from the Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) dataset (<http://hydrosheds.cr.usgs.gov/index.php/> - accessed on February 8, 2017). The total flow generated in each grid is the sum of SR and BF. The drainage network above 60° N was supplemented using the Simulated Topological Network (STN) (Vörösmarty et al. 2000) and the topographic data from the HYDRO1k database (http://gcmd.nasa.gov/records/GCMD_HYDRO1k.html - accessed on February 8, 2017). The routing in the river network was based on the characteristic distances, where volumes of water are transported over a distance based on the channel width and depth, the gradient derived from the elevation and drainage network, and the Manning's roughness coefficient (Wada et al. 2014).

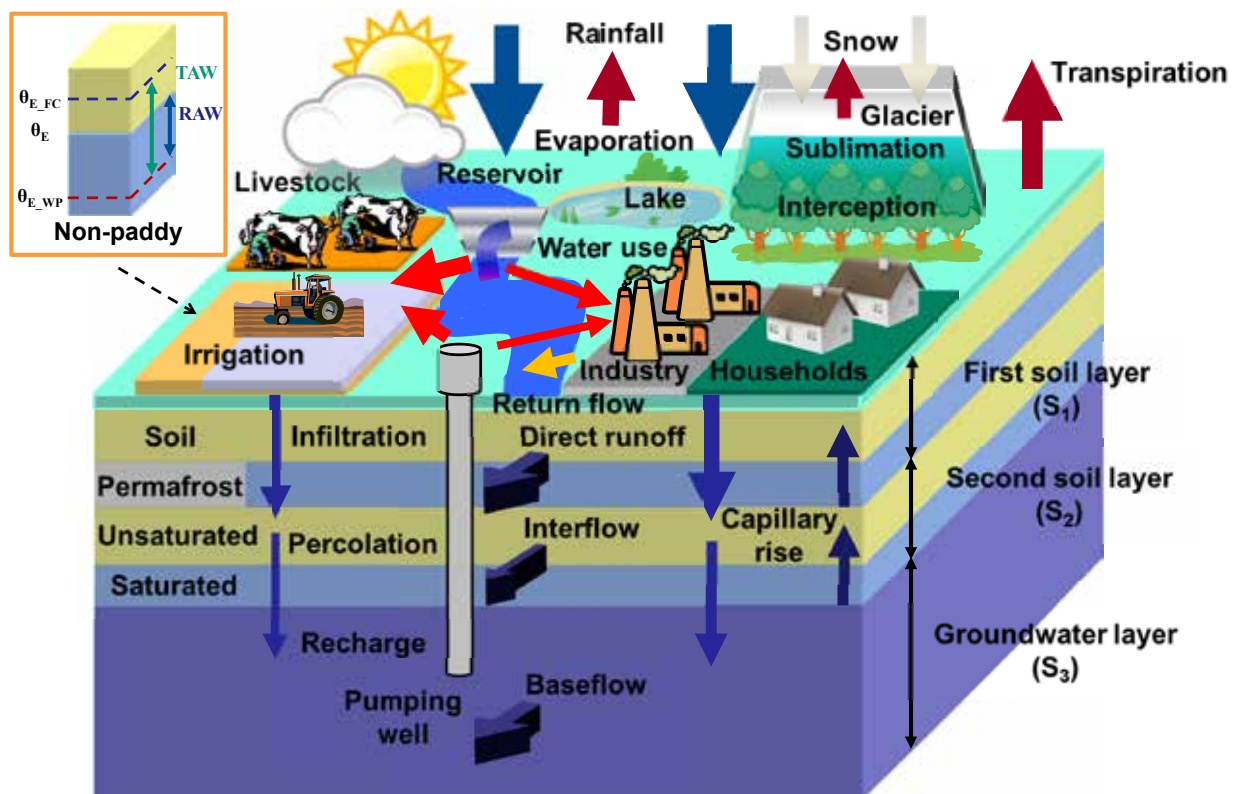
Reservoirs are located on the drainage or river network based on the newly available and extensive Global Reservoir and Dam Database (GRanD), which contains 6,862 reservoirs with a

total storage capacity of 6,197 km³. A dynamic irrigation scheme has been implemented that separately parameterizes paddy and non-paddy crops and dynamically links with the daily surface and soil water balance, taking into consideration the feedback between the application of irrigation water and the corresponding changes in surface and soil water balance. Other sectoral water demands include those from livestock, industry and households, taking into consideration the past changes in population, socioeconomic and technological development, and livestock densities.

Extensive validations of the PCR-GLOBWB model were performed in earlier work (e.g., van Beek et al. 2011; Wada et al. 2011, 2014) by comparing the simulated river discharge to observations from the Global Runoff Data Centre (GRDC), and the estimated actual

evapotranspiration to that of the European Reanalysis – 40 (ERA-40) as a proxy for observed rates. Comparisons with over 3,600 GRDC stations show that the coefficient of determination (R^2) is high (≈ 0.9) for most of the stations, but R^2 decreases when the mean minimum and maximum monthly discharge are considered instead of the mean annual discharge. Inter-annual variability is mostly well reproduced in major rivers, except for the Niger ($R^2 = 0.54$), Orange ($R^2 = 0.54$), Murray ($R^2 = 0.60$), Indus ($R^2 = 0.62$), Zambezi ($R^2 = 0.75$) and Nile ($R^2 = 0.87$) where the simulated river discharge is often overestimated. Simulated terrestrial water storage (TWS) anomalies were also compared with those of the Gravity Recovery and Climate Experiment (GRACE) observations and show good agreement ($R^2 > 0.8$) with these observations across the globe.

FIGURE 1. Schematic diagram of the PCR-GLOBWB model.



Source: Wada et al. 2014.

Notes: TAW - Total Available Water; RAW - Readily Available Water; θ_{E_FC} - Effective degree of saturation at field capacity; θ_{E_WP} - Effective degree of saturation at wilting point.

For this research study, natural river flow time series for the entire globe at a resolution of 0.1 degree spatial resolution and monthly temporal resolution were calculated as a sum of simulated monthly SR (i.e., contribution of surface runoff to river flow) and monthly BF (i.e., contribution of groundwater to river flow) from the model.

Estimating Environmental Flows from Simulated Flow Time Series

The GEFC (Smakhtin and Eriyagama 2008) is a simple tool to calculate EF from either simulated or user-defined flow time series (monthly time step). The method uses original flow time series to construct a long-term flow duration curve (FDC) - a cumulative probability distribution of flows. Each FDC is based on the entire 51-year (1960-2010) long, simulated monthly time step flow data. A FDC is then modified depending on the desired EMC of the river (Smakhtin and Anputhas 2006). The EMC concept originates from the EcoClassification approach developed by Kleynhans and Louw (2008). There are six EMCs (Table 1) that represent either the current or a prescribed/negotiated desired condition of a river ecosystem. The higher the EMC, the more water is needed for ecosystem maintenance and more flow variability needs to be preserved. Classes A and B represent the *unmodified and largely natural conditions*, where no or limited modification has occurred or should be allowed. Class C is defined as *moderately modified*, where the modifications are such that they generally have a limited impact on ecosystem integrity, although sensitive species are impacted. *Largely modified* ecosystems (Class D) show considerable modification from the natural state, where sensitive biota, in particular, are reduced in numbers and extent, and the community structure is substantially, but acceptably, changed. *Seriously and critically modified* ecosystems (Classes E and F) are normally in poor condition, where most of the ecosystem's functions and services are lost. Poor ecosystem conditions (classes E or F) are generally not considered acceptable from a management perspective and were thus excluded from further analysis in this study.

Monthly 'natural' flow time series from the PCR-GLOBWB model were converted into a FDC, represented by a table of flows corresponding to 17 fixed probabilities of exceedance: 0.01%, 0.1%, 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9% and 99.99%. These points ensure coverage of nearly the entire range of possible flow values at any location/grid cell. To generate EF FDCs for any EMC, this 'natural' or 'reference' FDC is shifted step-wise laterally to the left along the probability axis to generate flow regimes with progressively lower flows. An FDC shift by one step means that a flow which was exceeded 99.99% of the time in the original FDC will now be exceeded 99.9% of the time, the flow at 99.9% becomes the flow at 99%, the flow at 99% becomes the flow at 95%, etc. (Figure 2). A linear extrapolation is used to define the 'new low flows' at the lower tail (dry season) of a shifted curve. With each shift, a new EF regime (corresponding to an EMC) is defined, in which, although the peak flows are reduced, the natural flow pattern (considered vital for ecosystem health) still remains intact. Shift of a FDC to the left implies that the general pattern of flow variability is preserved, although with every shift part of the variability is 'lost'. This loss is due to the reduced assurance of monthly flows, i.e., the same flow will be occurring less frequently and the total amount of EF, expressed as the mean annual flow, is reduced. It is an arbitrary categorization, but it is assumed that each step of reduction in flow leads to a decline in the state of the health of the river, which warrants a change in its EMC. More details of the method are discussed in Smakhtin and Anputhas (2006).

Determining Probable Current Environmental Management Classes

If any one of the four EMCs (A to D) considered in this study is assumed for the entire world, it becomes a 'scenario' of environmental water management and EF for such a scenario can also be calculated. It is also possible to try and determine the most probable present EMC for rivers globally. One way of doing this is to relate

EMCs with some global dataset of ecosystem state indicators. In this study, the elements of the methodology proposed by Vörösmarty et al. (2010) were used. Vörösmarty et al. (2010) considered 23 drivers (grouped under four themes) to calculate an “Incident Biodiversity Threat” index for rivers. The four themes were *watershed disturbance*, *pollution*, *water resource development* and *biotic factors*. These four themes consider the aggregated impact on rivers due to direct anthropogenic drivers (such as pollution, dam development, etc.), as well as indirect drivers (such as land-use change, non-native fish, etc.). The scores for the individual drivers (normalized to a continuous 0-1 scale) presented in global maps

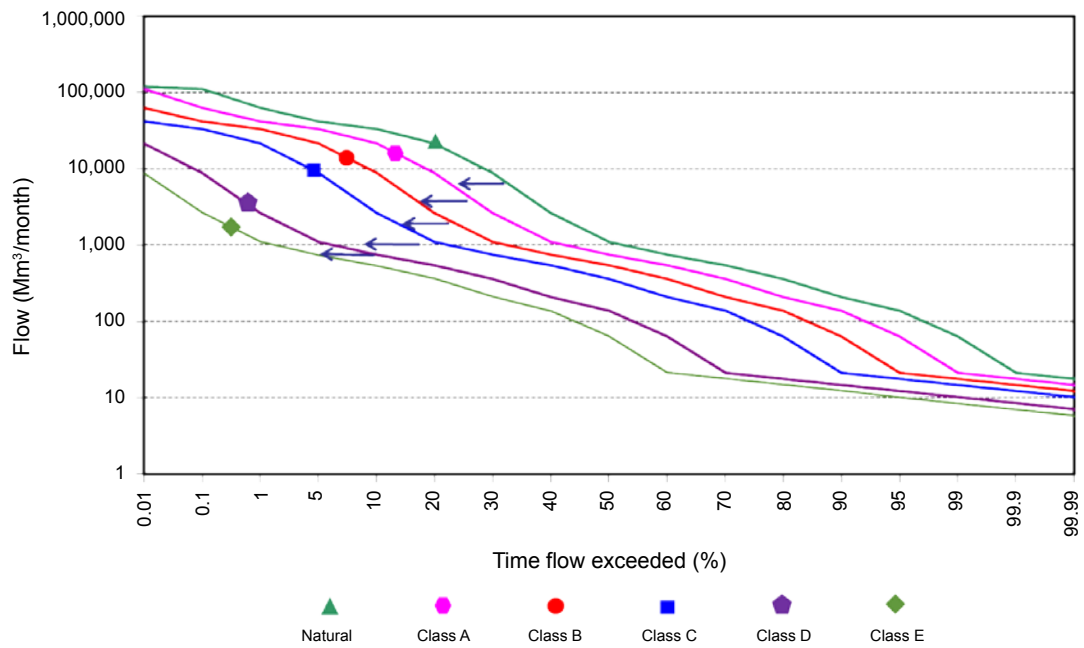
of 0.5 degree spatial resolution are available at <http://www.riverthreat.net/data.html> (accessed October 2015). Since, the EF methodology described above does not explicitly consider water pollution and land-use change, the “threat” index was recalculated with *water resource development* and *biotic factors* only, with new relative weights as shown in Table 2. The modified index was used as a proxy for the “health” of a river. Thus, the indicators considered are those that directly affect river flows (*water resource development*) or are affected by river flows (*biotic factors*). These weights were recalculated and rescaled to ensure that the ratio between them is the same as defined by Vörösmarty et al. (2010).

TABLE 1. Description of environmental management classes (EMC).

EMC	Most likely ecological condition	Management perspective
A: Natural	Natural rivers with minor modification of in-stream and riparian habitat.	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions) allowed.
B: Slightly modified	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Water supply schemes or irrigation development present and/or allowed.
C: Moderately modified	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socioeconomic development, e.g., dams, diversions, habitat modification and reduced water quality.
D: Largely modified	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail.	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation.
E: Seriously modified	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Generally, this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to move a river to a higher management category.
F: Critically modified	Modifications have reached a critical level and the ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible.	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern and river habitats (if still possible/feasible) - to ‘move’ a river to a higher management category.

Source: Smakhtin and Anpuhas 2006.

FIGURE 2. Estimation of EF using the FDC shifting method.



Source: Adapted from Smakhtin and Anputhas 2006.

TABLE 2. Selected themes and factors considered by Vörösmarty et al. (2010) to calculate an “Incident Biodiversity Threat” index for rivers, with adjusted relative weights.

Theme	Relative weight
Factor	
Water resource development	0.5
Dam density	0.25
River fragmentation	0.30
Consumptive water loss	0.22
Human water stress	0.04
Agricultural water stress	0.07
Flow disruption	0.12
Biotic factors	0.5
Non-native fish (%)	0.26
Non-native fish (#)	0.21
Fishing pressure	0.34
Aquaculture pressure	0.19

The modified index map was resampled to 0.1 degree spatial resolution (using ArcGIS software) to ensure it is compatible with the current study. The value of the index ranges from 0 to 1 (0 being no threat and 1 being the highest threat). The index was grouped into five classes 0-0.25, 0.25-0.5, 0.5-0.65, 0.65-0.6 and > 0.75 to represent EMCs A, B, C, D and E-F, respectively. This grouping is arbitrary but consistent with the analysis by Vörösmarty et al. (2010). According to these authors, a moderate threat level is reached when the index is above 0.5. This essentially corresponds to EMCs C and D in Table 1. Thus, below 0.5, the index represents EMCs A and B. The authors also suggest that a high threat level is represented by an index value of 0.75 or greater, which may correspond to EMCs E and F in Table 1.

It has to be noted that the four EMCs (considered in this study) are assumed applicable to the entire world, but this needs to be viewed from the perspective of an individual country. Similarly, the most probable present EMC scenario may be derived by more detailed, country-specific approaches, especially where pertinent local data are available.

Separating Environmental Flows into Groundwater and Surface Water Components

To provide an approximate estimate of the groundwater-related EF component, the study separated river flow into SR ('quick' component) and BF ('slow' component), the latter broadly representing flow from subsurface stores. Evapotranspiration from groundwater in the vicinity of the river channel was ignored. Many automated

techniques exist that facilitate this separation. Nathan and McMahon (1990) developed a recursive digital filter method to separate BF from a daily streamflow hydrograph using the following algorithm:

$$q_t = \beta q_{t-1} + \frac{1+\beta}{2} * (Q_t - Q_{t-1}) \quad (2)$$

and

$$b_t = Q_t - q_t \quad (3)$$

Where: q_t and b_t are the filtered SR and BF at time step t , respectively; Q_t is the total streamflow at time t , and β is the filter parameter.

Although the Nathan and McMahon (1990) approach was initially developed for separating BF from daily river flow time series, Smakhtin (2001) illustrated the application of the same algorithm to monthly streamflows by adjusting the value of the filter parameter.¹ According to Nathan and McMahon (1990), based on applications of daily data in catchments ranging from 4.2 to 210 km² in Australia, the value of β is in the range of 0.90 to 0.95. Smakhtin (2001) suggested that this value ranges between 0.91 and 0.94. Chapman (1991), however, argued that, since the β value represents the catchment characteristics, defining a single value for all catchments is unrealistic. This is especially true at the global scale. Therefore, a methodology was developed here to calculate the β value for each grid globally.

Using the aggregated hydrological model monthly output of SR and BF to natural river flow, equations (2) and (3) were run at grid level for multiple values (increments of 0.05) of β between 0.85 and 0.99. The value of β that provided the least mean squared error between

¹ Hughes et al. (2003) presented a slightly modified form of the Nathan and McMahon (1990) algorithm for monthly BF separation from monthly streamflow data:

$$q_t = \beta q_{t-1} + \alpha(1+\beta) * (Q_t - Q_{t-1}) \quad (4)$$

A new filter parameter, α , was introduced to better represent the shape of BF. This is a generalized form of the equation used by Nathan and McMahon (1990) and Smakhtin (2001), where the value of α is 0.5. Equation (4) was tested on 70 observed monthly streamflow time series and its output (where α was allowed to vary between 0 and 0.5) was compared with the Smakhtin (2001) algorithm (where α was fixed at 0.5). The introduction of a flexible parameter improved the shape of the BF by shifting the peak of the BF, although the total BF remains the same. Since the focus of this particular study is on annual BF values, introducing another variable adds complexity without major accuracy gains. Hence, the original algorithm of Nathan and McMahon (1990) modified by Smakhtin (2001) for monthly data was used.

the calculated BF and the BF derived from the hydrological model was selected as the β value for that grid. It was assumed that, for an individual grid cell, the value of β remains constant for all EMCs. Sustainable withdrawal of surface water and groundwater was calculated for the EF representing different EMCs using Equations (1) and (2) and the optimal β value. It was assumed that the groundwater aquifer is connected to the river channel, which might not always be true, especially in arid and semi-arid regions. The reduced (lower EMC) flow records were calculated by converting the FDCs for each EMC back into monthly time series (as described in Smakhtin and Eriyagama 2008, and Hughes and Smakhtin 1996), thus maintaining similar patterns of flow as the natural system. The difference between filtered SR (i.e., total flow minus BF) in natural conditions and the filtered SR contribution to EF for each EMC (i.e., total EF minus corresponding 'environmental' BF) was assumed to approximate a 'sustainable' surface water withdrawal for each EMC.

To calculate exploitable groundwater, BFs (under natural and EMC flow conditions) were converted into volumes of shallow groundwater storage (assuming linear storage) that generate these flows within the contributing catchment (Ebrahim and Villholth 2016). The assumption behind this analysis is that the BF component of EF determines or constrains the groundwater storage, which is necessary to maintain the BFs. It was assumed that the relationship between aquifer storage and BF is not impacted by water withdrawal. Also, it was assumed that the low flow is comprised entirely of BF: discharge from snowmelt, and natural lakes and wetlands was ignored. The time series of differences between natural (reference) aquifer volume (or similarly estimated present-day aquifer volume) and the 'EF-driven' aquifer volume, in principle, represent a time series of exploitable groundwater. This analysis considers a change in storage of aquifers and not necessarily abstraction of groundwater. However, the temporal and spatial scale of this analysis is not adequate

for a more detailed analysis. The difference between annual BF under natural conditions and the annual BF contribution to EF for each EMC provides an estimate of the acceptable change in BF (ΔBF) for that EMC. Sustainable groundwater abstraction can be calculated based on equation (5).

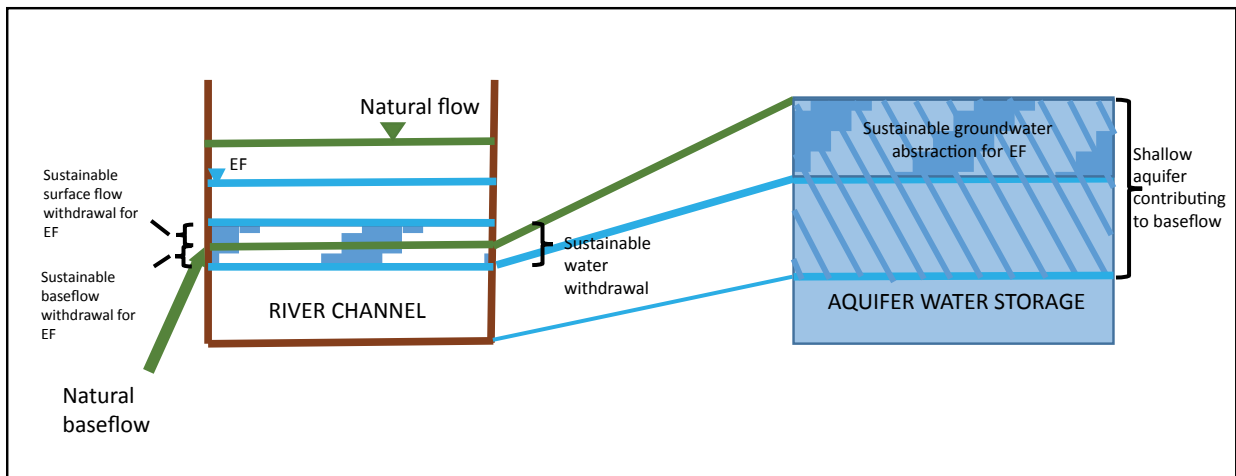
$$\Delta S = K \Delta BF \quad (5)$$

Where: K is the characteristic drainage time scale (T), which is the inverse of the recession constant. K values per grid were taken from the PCR-GLOBWB (version 2.0) model.

The overall methodology is illustrated in Figure 3. Corresponding to a given EMC, there is an acceptable reduction in streamflow that would preserve EF components. The new flow is shown in the figure as 'EF'. The shaded portion in the channel depicts the water that can be sustainably withdrawn from the channel for EF. It can be conceptually divided into SR and BF withdrawals. The rectangle on the right side represents the aquifer storage connected to the river channel that contributes to BF. The acceptable BF withdrawal for the EMC translates into an acceptable level of groundwater reduction in the aquifer storage. Thus, the shaded portions in the 'aquifer storage' represent the sustainable aquifer water withdrawals to maintain EF for the specific EMC.

The shaded portion within the stream channel can shift up or down (indicating smaller/larger portion of BF contribution to abstracted water), which will affect the amount of water that can be sustainably removed from the aquifer storage. In other words, if more river flow is abstracted (than estimated) as sustainable surface water abstraction, a corresponding reduction in groundwater abstraction will have to take place (using the linear aquifer approach), but only to the extent possible within the total sustainable water withdrawal for that EMC. In contrast, groundwater withdrawals may not replace allowable surface water withdrawals, because river flow may be comprised exclusively of BF during rainless periods, thereby compromising EF.

FIGURE 3. A schematic relationship between natural flows, EF, BF and aquifer storage for natural and different EMC conditions.



Results and Discussion

Environmental Flows Based on EMCs

Figures 4 to 7 show the global maps of the EF (total, i.e., groundwater plus surface water) derived for EMCs A to D, respectively, as a percentage of natural long-term discharge. Figure 4 shows the percentage of natural discharge required if all the rivers, globally, had an EMC of A; Figure 5 shows the same for EMC of B, etc. Arid and semi-arid regions with negligible streamflows have been excluded from calculations. To define regions with negligible flows, land use was used as

a proxy for arid regions. GlobCover 2009, developed by the European Space Agency (http://due.esrin.esa.int/page_globcover.php - accessed in October 2015), was used to obtain land use coverages. The following land use categories were excluded from the study: 'bare areas', 'water bodies', 'permanent snow and ice', 'closed to open grassland', 'closed to open shrubland' for North America and South America; and 'sparse vegetation' for Africa and Australia. The excluded areas are similar to the excluded areas in Vörösmarty et al. (2010).

FIGURE 4. EF as a percentage of total natural flow for EMC A.

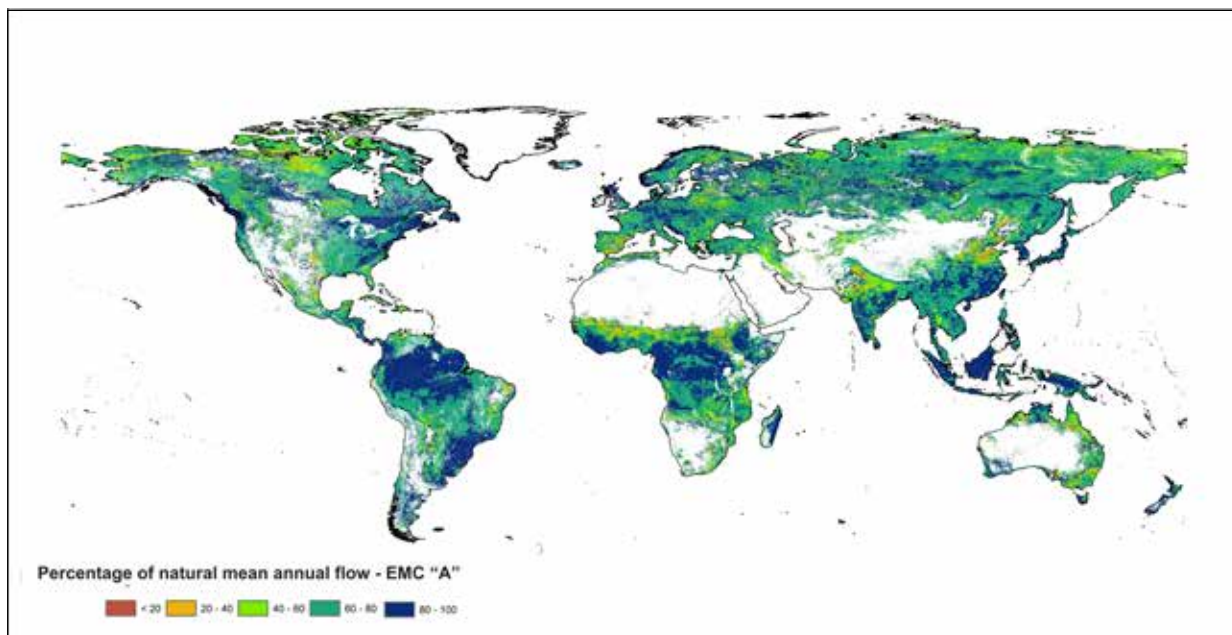


FIGURE 5. EF as a percentage of total natural flow for EMC B.

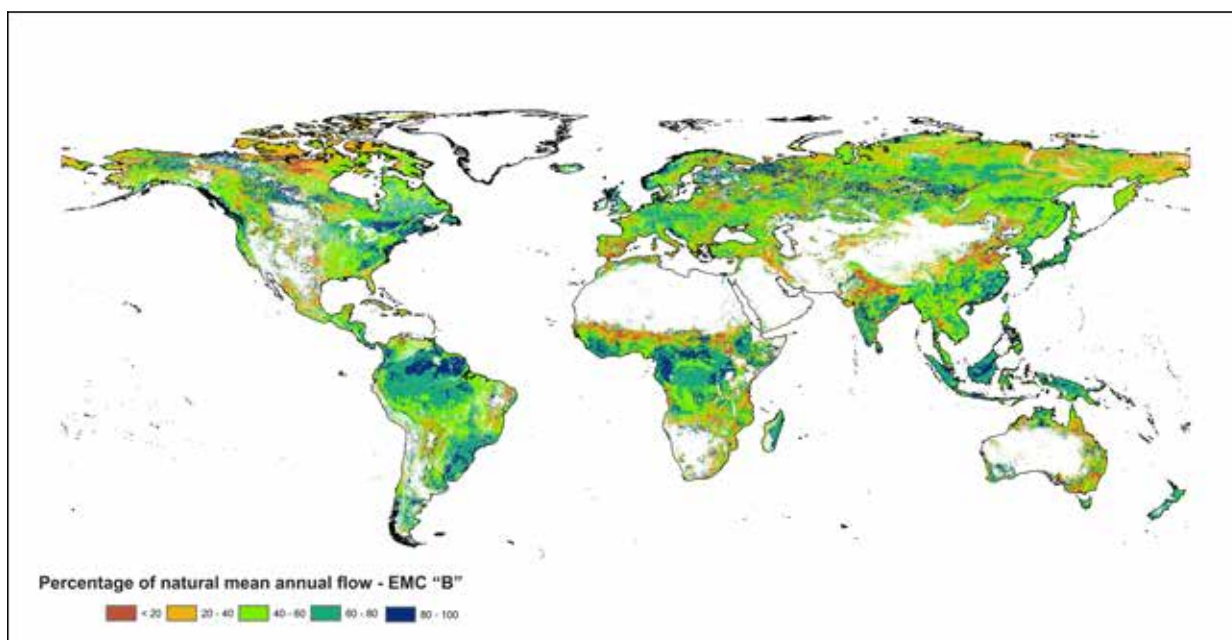


FIGURE 6. EF as a percentage of total natural flow for EMC C.

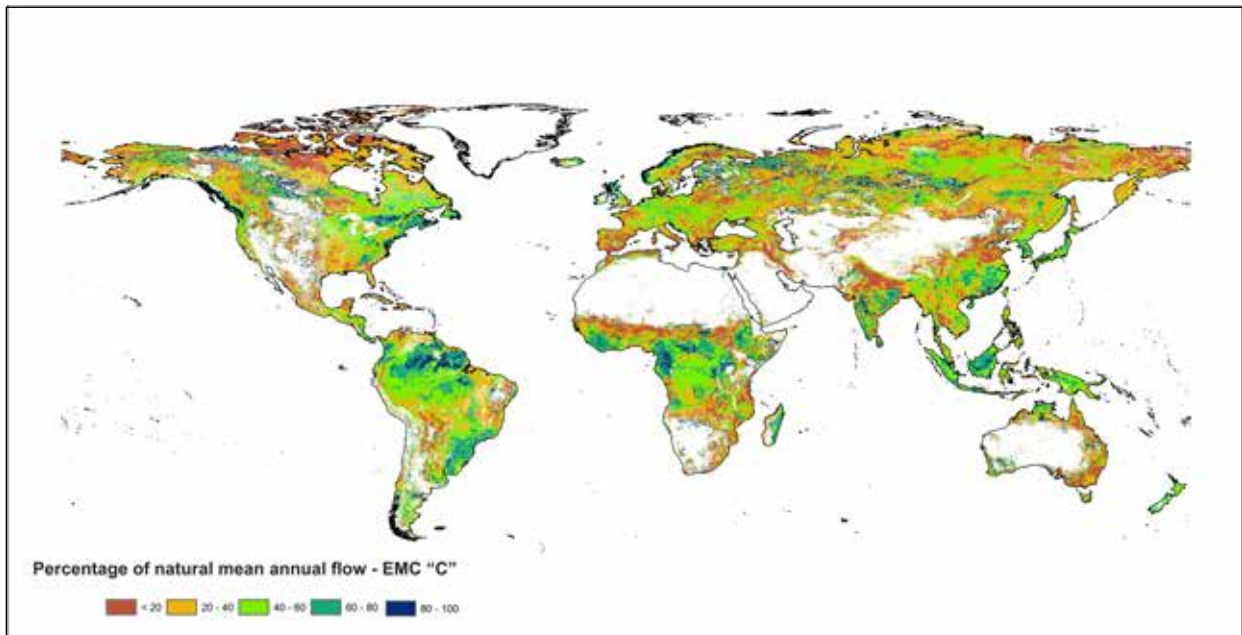
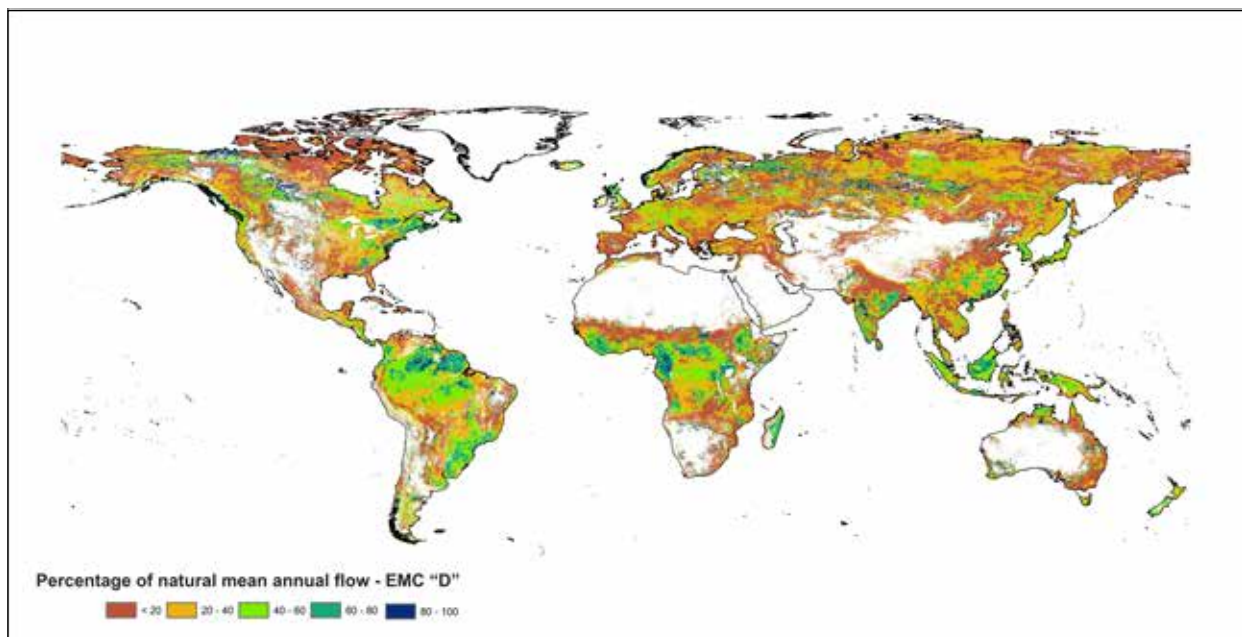


FIGURE 7. EF as a percentage of total natural flow for EMC D.



The total global annual runoff for natural conditions, simulated by the PCRGLOB-WB model, is 50,969 km³. Shiklomanov (2000) estimated the global annual river discharge to the ocean as 43,000 km³. van Beek et al. (2011) summarized discharges from other global studies and found that it ranged from 29,485 km³ to 44,560 km³. Oki and Kanae (2006) presented a value of 45,500 km³ as river discharge to the oceans. As discussed in the section above, for this analysis, runoff (i.e., SR and BF) is considered and not the river discharge. Thus, certain processes, such as evaporation in river channels, transmission losses, interactions between river channels and delta regions, and water draining into inland water bodies, are not considered and may be the reason for the higher runoff in this study compared to the river discharge calculated by other studies. Nijssen et al. (2001) also highlighted this with an example

of Niger River in West Africa, where the river discharge decreases even though the watershed area increases as one goes downstream. Thus, in some regions, flow routing can have a significant impact on the river discharge in comparison to the runoff generated. From the figures, it is clear that, for EMC A, the annual flow in the rivers, on average, needs to be 40,784 km³, which is about 80% of the annual flow in the rivers. Spatially, the percentage ranges from 72% in Australia to 83% in South America and Oceania for EMC A. This reduces as the EMC is lowered to Class D, where most of the rivers require, on average, about 42% of their natural flow, and significant parts of the globe can 'cope' with even less than 20%. For EMC D, the continental variation ranges from 33% for Australia to 48% for South America. Table 3 shows the long-term average annual river flow (51 years) per continent for natural flows and for EMCs A to D.

TABLE 3. Continent-level distribution of annual river flow for natural conditions and EF for the four EMCs (A to D) considered in this study.

Region	Annual flow (km ³) (percentage of natural flow [%])				
	Natural	EMC A	EMC B	EMC C	EMC D
Asia	17,850	14,042 (78.7)	11,035 (61.8)	8,704 (48.8)	6,898 (38.6)
North America	6,618	5,160 (78.0)	4,018 (60.7)	3,136 (47.4)	2,453 (37.1)
Europe	2,819	2,206 (78.3)	1,714 (60.8)	1,328 (47.1)	1,026 (36.4)
Africa	7,170	5,792 (80.8)	4,733 (66.0)	3,926 (54.8)	3,302 (46.1)
South America	15,309	12,644 (82.6)	10,488 (68.5)	8,754 (57.2)	7,347 (48.0)
Oceania	685	569 (83.1)	472 (68.9)	391 (57.1)	323 (47.2)
Australia	518	372 (71.8)	276 (53.3)	214 (41.3)	170 (32.8)
Global	50,969	40,785 (80.0)	32,736 (64.2)	26,453 (51.9)	21,519 (42.2)

Sustainable Groundwater Abstraction

The contribution of groundwater (or BF) to the annual discharge of the rivers in the considered

areas is highly variable. Figure 8 shows average annual groundwater contribution to total river flow for natural conditions as a percentage of total flow.

FIGURE 8. Estimated contribution of groundwater (BF) to mean annual natural river flow.

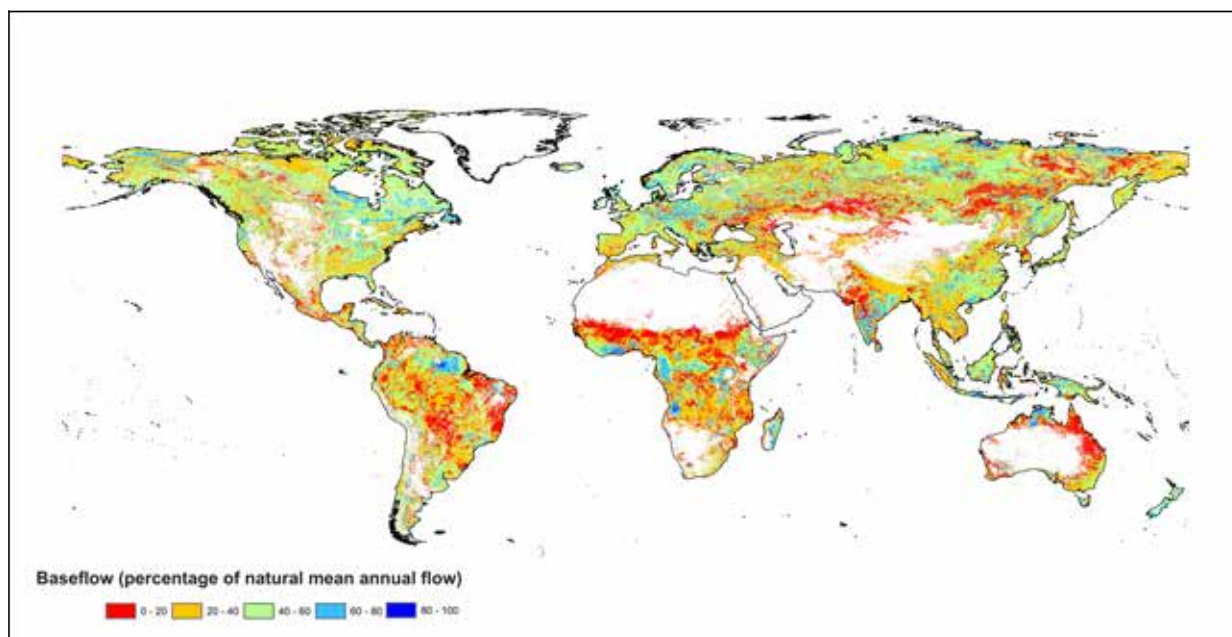


Table 4 provides the continent-level distribution of the annual contribution of groundwater (BF) to river flow - for natural flow and the four EMCs considered in this study. At a global level, and for the areas under consideration, BF constitutes about 41% of the total annual natural river flow. This is on the lower side compared to other global studies conducted

by, for example, Beck et al. (2013), where the BF component of total streamflow ranges from 49% to 77% (based on Köppen-Geiger climatic zones). When compared to the natural flows, about 76.5% of the natural BF is required to meet EMC A requirements. This goes down to 38.5% of the natural BF to meet EMC D requirements.

TABLE 4. Continent-level distribution of the annual contribution of BF to river flow for natural conditions and for EF for the four EMCs (A to D) considered in this study.

Region	Annual BF (km ³) (percentage of natural BF [%])				
	Natural	EMC A	EMC B	EMC C	EMC D
Asia	7,596	5,639 (74.2)	4,232 (55.7)	3,244 (42.7)	2,565 (33.8)
North America	2,962	2,204 (74.4)	1,645 (55.5)	1,246 (42.1)	967 (32.6)
Europe	1,287	944 (73.3)	692 (53.8)	509 (39.5)	382 (29.7)
Africa	2,867	2,313 (80.7)	1,902 (66.3)	1,604 (55.9)	1,391 (48.5)
South America	5,483	4,350 (79.3)	3,498 (63.8)	2,883 (52.6)	2,468 (45.0)
Oceania	340	264 (77.6)	206 (60.6)	164 (48.2)	133 (39.1)
Australia	217	165 (76.0)	128 (59.0)	102 (47.0)	84 (38.7)
Global	20,752	15,879 (76.5)	12,303 (59.3)	9,752 (47.0)	7,990 (38.5)

Figures 9 and 10 show groundwater that can be extracted ($10^{-3} \text{ Mm}^3 \text{ a}^{-1}$) sustainably from each 0.1 degree grid cell for EMCs A and D, respectively (the pattern of groundwater abstraction maps for classes B and C is broadly similar).

FIGURE 9. Sustainable annual groundwater abstraction for EMC A ($10^{-3} \text{ Mm}^3 \text{ a}^{-1}$).

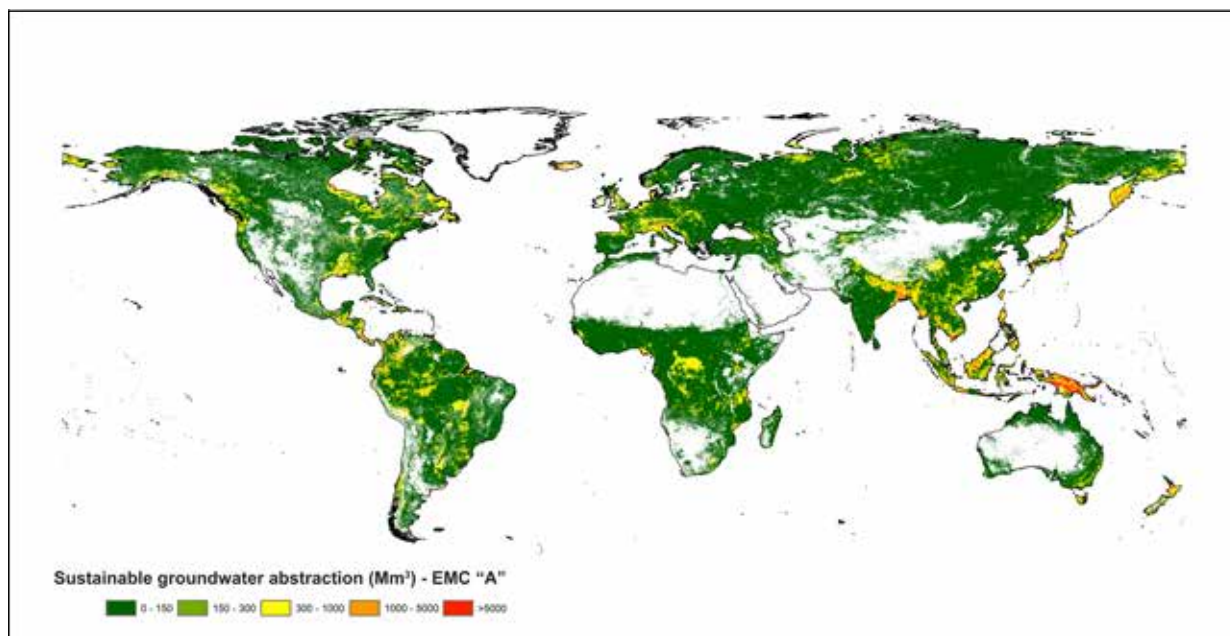
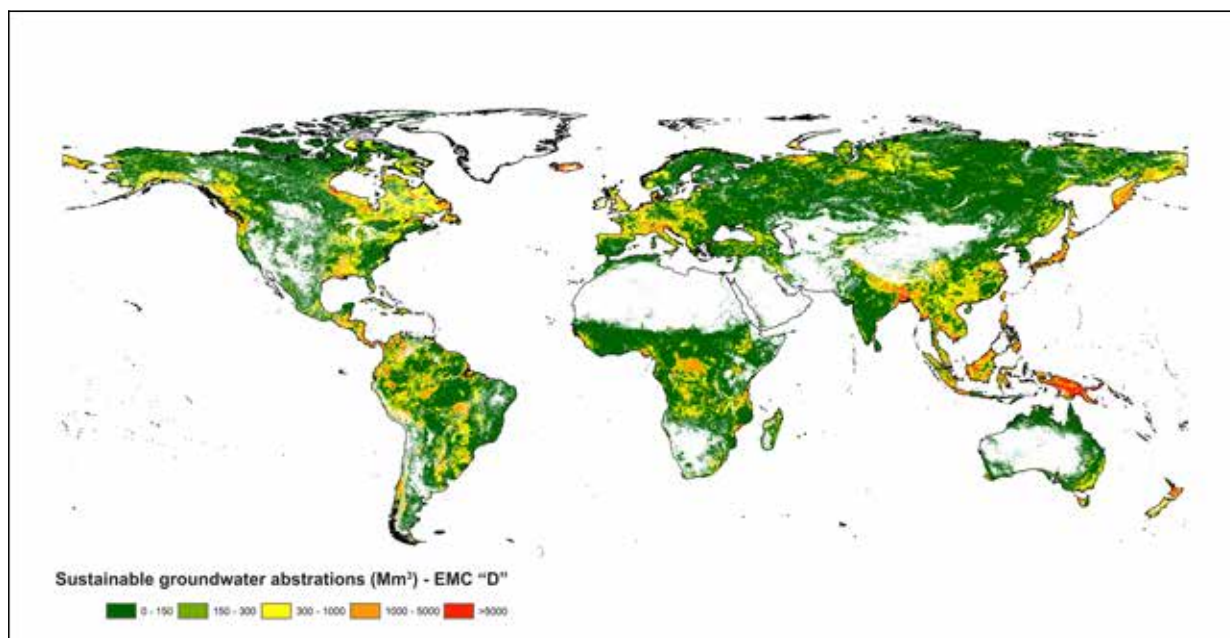


FIGURE 10. Sustainable annual groundwater abstraction for EMC D ($10^{-3} \text{ Mm}^3 \text{ a}^{-1}$).



Based on the required contribution of groundwater to the EF, the amount of groundwater that can be extracted sustainably in the major world regions is shown in Table 5. This calculation assumes that the contribution to the EF is being met by surface water and groundwater in the same proportion as it is in the natural flow. For EMC A, about 148.9 km³ a⁻¹ of groundwater, globally, can be abstracted sustainably. For EMCs B, C and D, these numbers are 255.5, 328.4 and 376.2 km³ a⁻¹, respectively. Giordano (2009) used data from FAO's AQUASTAT database to show total global groundwater abstraction as 658 km³ a⁻¹. From modelling, the global total and non-renewable groundwater abstractions in 2000 were estimated to be 734 and 234 km³ a⁻¹, respectively (Wada et al. 2012). The figure for renewable groundwater abstraction (the difference: 500 km³ a⁻¹) is larger than the

sustainable level for EMC D (376.2 km³ a⁻¹). While significant uncertainty relates to the estimation of groundwater abstraction from renewable and non-renewable resources (Döll et al. 2014), the finding that estimates of groundwater abstraction from renewable resources is significantly higher than the estimate of sustainable abstraction for all EMCs, as estimated in this study, highlights the fact that the PCR-GLOBWB model does not take into account EFs. As seen, streamflow is significantly impacted by levels of abstraction (streamflow depletion) in many regions of the world already. There is significant regional variation in withdrawals. Some regions, such as northwestern India, the northern parts of China and the western US, have much higher groundwater abstractions than the sustainable limits (as discussed above) and are now mining non-renewable groundwater.

TABLE 5. Continent-level distribution of sustainable groundwater abstraction to meet the requirements of the four EMCs (A to D) considered in this study.

Region	Sustainable groundwater abstraction (km ³ a ⁻¹)			
	EMC A	EMC B	EMC C	EMC D
Asia	77.9	133.0	170.0	194.0
North America	24.0	41.6	54.0	62.4
Europe	12.0	20.9	27.3	31.7
Africa	11.0	18.9	24.2	27.6
South America	17.1	29.4	37.8	43.1
Oceania	5.2	8.9	11.4	13.2
Australia	1.7	2.9	3.7	4.15
Global	148.9	255.6	328.4	376.15

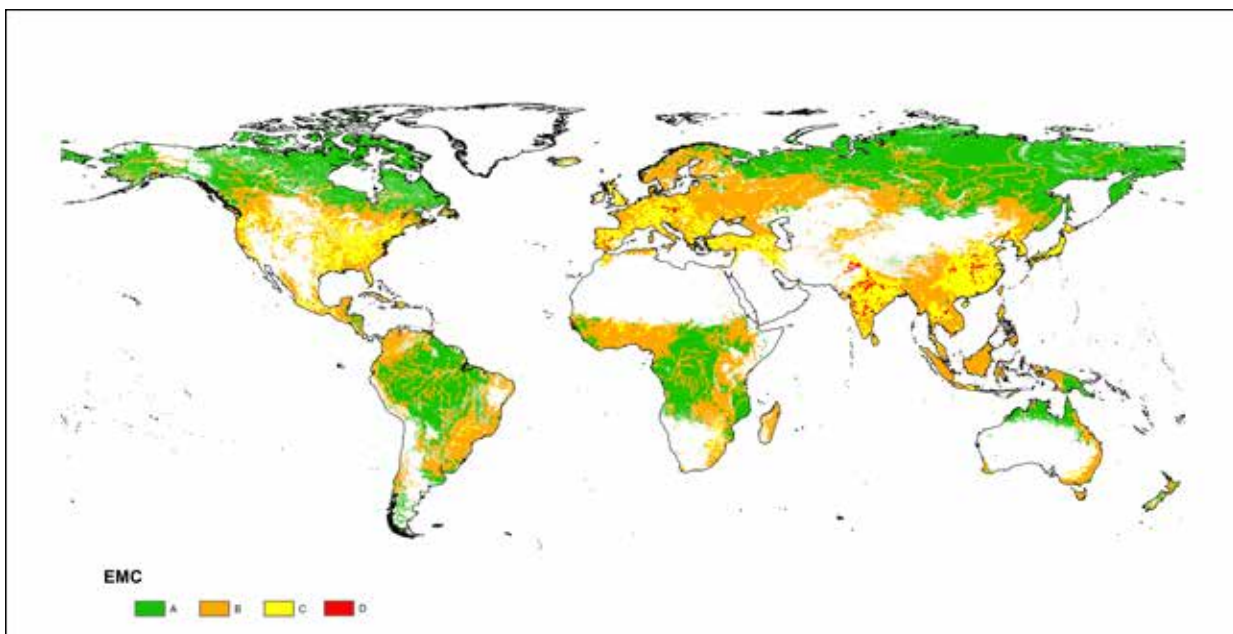
Current EF Requirements

All the above results are based on the assumption that all rivers, globally, are in the same class, e.g., EMC A or EMC B, etc. These are, as mentioned, simply scenarios. Certainly, different rivers are at various stages of development at present. In fact, even different sections of the same river can have different EMCs. For management practices in basins and countries, these EMCs should be defined based on development priorities, and involving specific local knowledge and stakeholders. These classes may be based on empirical relationships between flow and ecological status/condition that are described by clearly identifiable thresholds. However, at present, the evidence for such thresholds throughout the globe is not available. Therefore, these categories simply represent

a management ‘concept’ that has been developed and used to facilitate decisions under conditions of limited knowledge.

Alternatively, classes may be defined based on global river health indicators, such as those developed by Vörösmarty et al. (2010), as discussed in the *Methodology* section of this report. Figure 11 shows the probable distribution of current EMCs for rivers or sections of rivers based on the drivers from the *water resource development* and *biotic factors* themes of the “Incident Biodiversity Threat” index as calculated by Vörösmarty et al. (2010) (see Table 2). It is important to emphasize, again, that this is just one possible way of estimating current EMCs based on globally available data – done specifically for the purpose of creating an approximate global picture of the ‘state’ of rivers; and that local knowledge is imperative in determining EMCs more precisely.

FIGURE 11. Current EMCs estimated based on *water resource development* and *biotic factors* themes of the “Incident Biodiversity Threat” index as calculated by Vörösmarty et al. (2010).



In Figure 11, it can be seen that large parts of North America, Europe and Asia fall into EMC C. In these regions, the natural flows of the rivers have been substantially modified. Most of these regions also have high agricultural activity. These factors present poor levels of EMC, and correspondingly high levels of abstraction indicate that the residual potential for increasing abstractions is limited and would shift the EMC to even more degraded levels.

Based on the estimated existing EMCs for the globe, EF (Figure 12) and sustainable groundwater abstraction (Figure 13) have been

calculated. This assumes that surface water is abstracted sustainably, i.e., the surface water component of the EF is satisfied. Figures 12 and 13 show the percentage of EF required and sustainable groundwater abstraction limits, respectively, if the current EMC is to be maintained. Thus, if currently (partially) degraded rivers are to be kept in, at least, the same class, they need a smaller percentage of natural flow to maintain the current EMC than for higher EMCs. The information provided by these figures may be seen as the approximate threshold levels required to prevent rivers from degrading further.

FIGURE 12. EF as a percentage of mean total annual natural flow for present-day EMCs.

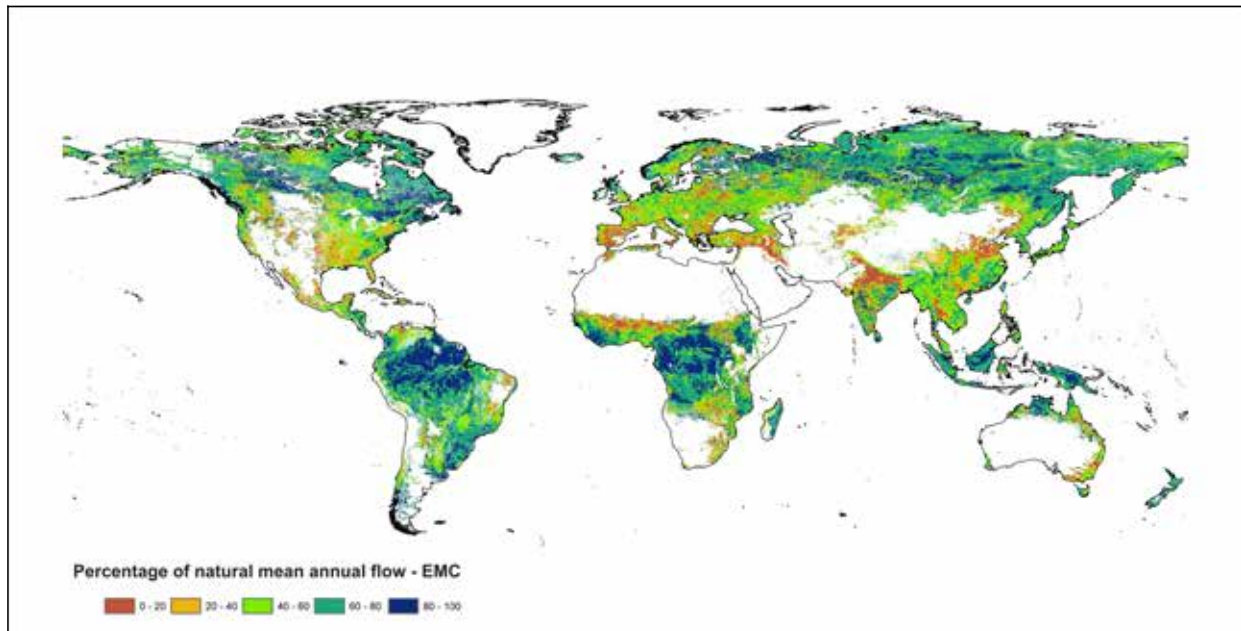


FIGURE 13. Sustainable annual groundwater abstraction that can ensure that EF for present-day EMCs will be met ($10^{-3} \text{ Mm}^3 \text{ a}^{-1}$).

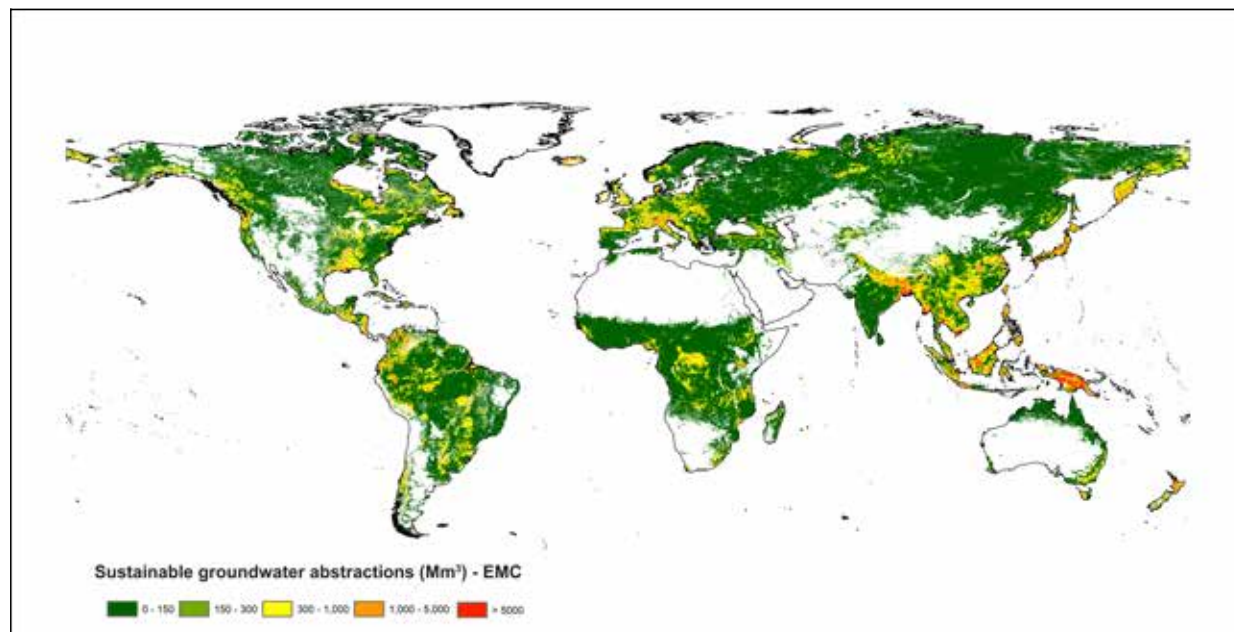


Table 6 presents the continent-wide cumulative annual flow and sustainable groundwater abstraction to maintain the present-day EMCs. Globally, 63% of natural flow needs to be maintained. This represents an EMC between B and C. South America and Africa are required to maintain more than 70% of the natural flow (EMC between A and B). In comparison, Australia and Oceania, where rivers are more degraded, need to maintain 48.4 (EMC between B and C)

and 35.1% (EMC lower than D), respectively. Annual sustainable groundwater abstraction for the present-day EMC at global scale is 203.3 km^3 , with more than half (110.3 km^3) from Asia. Globally, about 1.6% of groundwater recharge ($12,666 \text{ km}^3 \text{ a}^{-1}$) can be sustainably abstracted at present-day EMC. Not all the groundwater recharge stays as groundwater. As discussed above, a large portion of groundwater recharge reaches the streamflow as baseflow.

TABLE 6. Continent-level distribution of EF and sustainable groundwater abstraction for the present-day EMCs.

Region	Annual flow (km^3) percentage of natural flow [%]	Sustainable groundwater abstraction ($\text{km}^3 \text{ a}^{-1}$) (percentage of natural recharge [%])*
Asia	10,178.2 (57.0)	110.3 (3.4)
North America	3,656.3 (55.2)	30.3 (1.9)
Europe	1,489.7 (52.8)	20.0 (1.7)
Africa	5,032.1 (70.2)	14.3 (0.7)
South America	11,242.9 (73.4)	24.0 (0.6)
Oceania	240.4 (35.1)	2.6 (1.0)
Australia	251.0 (48.4)	1.9 (1.3)
Global	32,090.6 (63.0)	203.3 (1.6)

Source: * Natural groundwater recharge as calculated by Döll and Fiedler 2008.

User Interface and Example for Estimating Environmental Flows

The outputs shown above provide an annual global snapshot of environmental water needs for possible use in the context of the SDGs. For more detailed assessments (at country and sub-national levels), this information should be easily accessible online to water resource managers and policymakers. EF and sustainable groundwater abstraction data for the various EMCs have been uploaded onto the International Water Management Institute (IWMI) Global Environmental Flow Information System (<http://gef.iwmi.org> - accessed on February 8, 2017) as separate geographic information system (GIS) layers. These are further overlaid with global river basin and country boundary GIS layers. This provides users with an opportunity to interactively select areas either at a country or river basin level (or any other area of choice). Once the area is selected, users can select the EMC for the rivers in the area. The online tool then provides the corresponding EF, BF contribution, and sustainable surface water and groundwater abstraction for the selected EMC. Either a single EMC (i.e., A to D) can be selected for all the objects at once or the current EMC layer can be selected. This can then be compared either directly with the information on water withdrawal in the selected area or can be fed into the SDG target equations (indicators in Equation [1])

to define targets of water abstractions for the selected areas/regions. Figure 14 provides details of the steps that have to be followed when using IWMI's Global Environmental Flow Information System.

Step 1: Either a predefined country or river basin boundary is selected. The user can also define an area of interest more specifically, e.g., at sub-national administrative level. In Figure 14, India is selected.

Step 2: Based on the area selected in step 1, the tool will calculate EF as an average percentage of natural river flow for the selected area for the 'current probable' EMC. It will also provide an estimate of additional sustainable surface water and groundwater that can be abstracted (in cubic meters) for the current EMC.

Step 3: Select any EMC to obtain information on the sustainable surface water and groundwater that can be abstracted.

Step 4: Click on the 'Summarize Area' button. This will open a pop-up window with the aggregated numbers for EF shown in a table format. The 'Download' button in the pop-up window allows the user to download grid-level data.

This information can then be used in the SDG indicators to calculate indicator values, if current water abstraction data exist.

FIGURE 14. Steps that have to be followed when using IWMI's Global Environmental Flow Information System to estimate sustainable surface water and groundwater abstractions for a selected area.

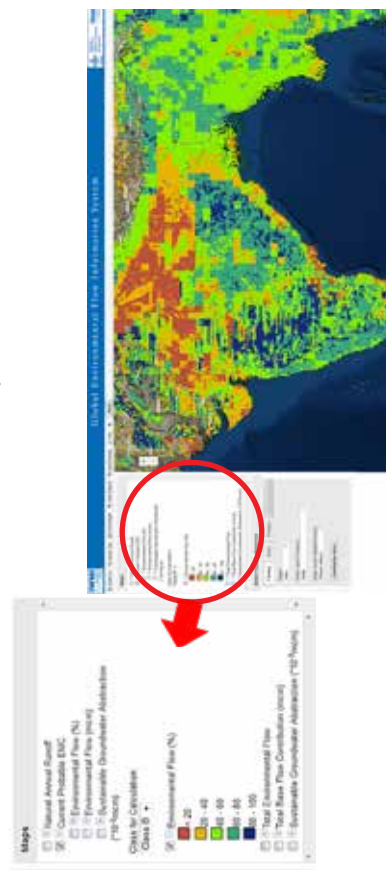
Step 1



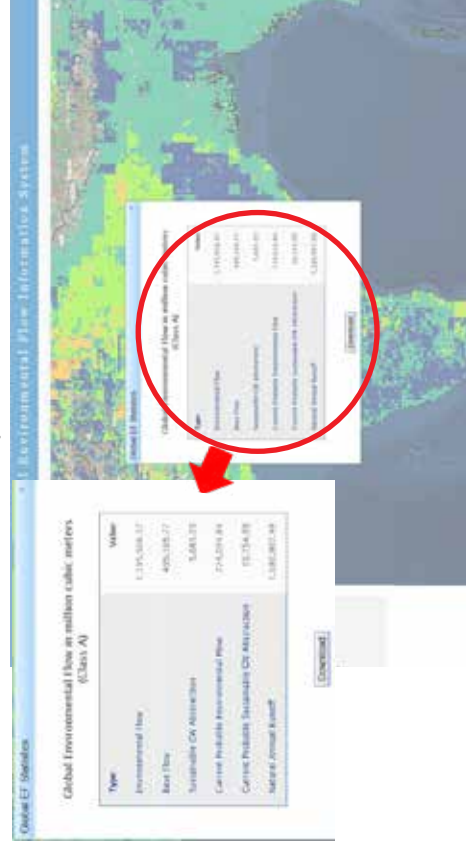
Step 2



Step 3



Step 4



Tables 7 and 8 show outputs from the tool (IWMI's Global Environmental Flow Information System) for the Ganges River Basin and India in South Asia, and the Tana River Basin and Kenya in sub-Saharan Africa. The total annual natural discharge of the Ganges River Basin and India are approximately 530 km³ and 1,589 km³, respectively. Amarasinghe et al. (2004) calculated the total renewable water resources in the Ganges River Basin and India as 525 km³ and 1,887 km³, respectively. The *Little Green Data Book 2016* of the World Bank (<http://data.worldbank.org/products/data-books/little-green-data-book> – accessed in January 2017) provides a value of 1,445.6 km³ for internal freshwater resources in India. The runoff used in this study is reasonably close to the river discharge, as provided in the above-mentioned studies. Based on these values, the EF requirements are calculated for different EMCs. For the Ganges River Basin, the EF requirements are 77.0%, 50.1%, 32.5% and 21.5% for EMCs A, B, C and D, respectively. For India, EF requirements are 75.2%, 57.9%, 46.1% and 37.9% for EMCs A, B, C and D, respectively. In terms of groundwater abstraction, for EMC A,

approximately 5.0 km³ of groundwater can be abstracted sustainably from the Ganges River Basin, and this figure goes up to 10.8 km³ for EMC D. For India, these values for EMCs A and D are 5.7 km³ and 12.1 km³, respectively. The estimated sustainable groundwater abstraction for the Ganges River Basin may be overestimated, because this river is significantly affected by snowmelt, a process not considered in this study. This leads to high dry season flows, while groundwater-derived BFs are low, erroneously generating 'excess' BFs.

The total annual natural discharge of the Tana River Basin and Kenya are approximately 10.6 km³ and 137.4 km³, respectively. These values are higher than that stated in the literature. According to the *Little Green Data Book 2016* of the World Bank, internal freshwater resources for Kenya are 20.73 km³. The Kenya National Water Master Plan (<http://www.wrma.or.ke/index.php/projects/nwmp-2030.html> – accessed in January 2017) estimates the total annual runoff for Kenya as 20.64 km³ and total annual renewable water resources to be between 42.1 km³ and 76.6 km³, depending on how evapotranspiration is

TABLE 7. EF, contribution of groundwater to EF and sustainable groundwater abstraction for the Ganges River Basin and India.

Region	River flow (km ³ a ⁻¹)				
	Natural	EMC A	EMC B	EMC C	EMC D
Ganges River Basin	530.1	408.2	266.0	172.3	114.1
India	1,589.2	1,194.6	920.6	731.8	601.5
	BF contribution (km ³ a ⁻¹)				
Ganges River Basin	191.9	133.8	85.5	56.0	38.8
India	650.3	498.0	398.3	327.4	277.5
	Surface water contribution (km ³ a ⁻¹)				
Ganges River Basin	338.2	274.4	180.6	116.4	75.3
India	938.9	696.6	522.3	404.5	324.0
	Sustainable groundwater abstraction (km ³ a ⁻¹)				
Ganges River Basin		5.0	8.2	9.9	10.8
India		5.7	9.2	11.1	12.1
	Sustainable surface water abstraction (km ³ a ⁻¹)				
Ganges River Basin		63.8	157.6	221.9	262.9
India		242.3	416.6	534.4	614.9

TABLE 8. EF, contribution of groundwater to EF and sustainable groundwater abstraction for the Tana River Basin and Kenya.

Region	River flow (km ³ a ⁻¹)				
	Natural	EMC A	EMC B	EMC C	EMC D
Tana River Basin	10.6	7.9	6.0	4.6	3.5
Kenya	137.4	109.5	89.8	75.2	63.9
BF contribution (km ³ a ⁻¹)					
Tana River Basin	3.9	2.8	2.0	1.4	1.0
Kenya	49.0	52.7	43.8	37.4	32.8
Surface water contribution (km ³ a ⁻¹)					
Tana River Basin	6.7	5.0	4.0	3.2	2.5
Kenya	88.3	56.8	46.1	37.9	31.1
Sustainable groundwater abstraction (km ³ a ⁻¹)					
Tana River Basin		0.1	0.1	0.2	0.2
Kenya		0.4	0.6	0.8	0.9
Sustainable surface water abstraction (km ³ a ⁻¹)					
Tana River Basin		1.7	2.7	3.5	4.2
Kenya		31.6	42.3	50.5	57.2

estimated. This indicates that a lot of water is lost during routing in Kenya. Another report, Baker et al. 2015, showed much higher annual flow (5.02 km³) at Garissa in the Tana River Basin than at the coast (approximately 250 km downstream) where it is only 3.12 km³, indicating a loss of water during routing. In Kenya, there is significant inter-annual variation in terms of rainfall, leading to a wide variation in runoff generated in the country. For example, the in-house hydrological modeling simulations (done using climate data from the Climate Forecast System Reanalysis [CSFR] dataset [https://climatedataguide.ucar.edu/climate-forecast-system-reanalysis-cfsr - accessed in January 2017]) for the Tana River Basin shows annual rainfall in the range of 400 mm to 1,200 mm, and consequently water yield ranging from 2.8 km³ to 20.4 km³ for the period from 1983 to 2011. Based on the natural flow calculated by the PCRGLOB-WB model, the EF requirements are calculated for different EMCs. For the Tana River Basin, the EF requirements are 74.2%,

56.4%, 43.5% and 33.4% for EMCs A, B, C and D, respectively. For Kenya, the EF requirements are 79.7%, 65.4%, 54.8% and 46.5% for EMCs A, B, C and D, respectively. In terms of groundwater abstraction, for an EMC A, approximately 0.1 km³ of groundwater can be abstracted sustainably from the Tana River Basin. For an EMC D, this figure increases to 0.2 km³. These values for Kenya are 0.4 km³ and 0.9 km³ for EMCs A and D, respectively. The Kenya National Water Master Plan estimates annual “sustainable yield of groundwater” from the Tana River to be between 0.68 km³ and 1.92 km³ at country level.

In general, both the case studies (Ganges River Basin/India and Tana River Basin/Kenya) show that this tool gives a very conservative value for sustainable groundwater abstraction. As mentioned above, this tool calculates the permissible change in storage of a shallow aquifer rather than the actual groundwater withdrawn. First, some of the groundwater abstracted may be compensated with the groundwater recharge and is hence not included

in this analysis. Second, it is assumed that the proportion of the BF component of EF at an annual level is the same as the natural EF. This too leads to a conservative estimate of sustainable groundwater abstraction. Finally, the analysis can only consider the shallow aquifer

that is hydrologically connected to a river system. Due to the lack of global datasets on depths of shallow and deep aquifers, the shallow aquifers deeper than the riverbed or deep aquifers are not covered in this study – these may also contribute to sustainable groundwater abstraction.

Conclusions

Goal 6 of the SDGs is focused explicitly on water. Target 6.4 of the SDGs requires that an estimate of the environmental water component of both surface water and groundwater is known to ensure that abstractions of water are sustainable. However, in most countries, there is a lack of awareness of EF at multiple stakeholder levels, and a lack of consistent, easy-to-use, readily available EF data to feed into the SDG process.

This research study focused on making data on EF, and sustainable surface water (SR) and groundwater (BF) abstractions available at a global, regional and subregional level. Using 0.1 degree spatial resolution data on SR and BF for natural flow conditions, annual EF values were quantified with the help of the Global Environmental Flow Calculator, developed by IWMI, and based on the outputs of the PCR-GLOBWB model. EF were defined for four EMCs. The contribution of groundwater to EF was also calculated, by filtering baseflow from total flow and converting BFs into utilizable (available for abstraction) groundwater storage volumes. Finally, sustainable groundwater and surface water withdrawals relative to pristine conditions were estimated for the four EMCs considered in this study.

The analysis was carried out for each grid cell independently. This enables aggregation of EF requirements for any country, or at sub-national scale, which will be required by the SDG process. The outputs derived in this study provide initial, hydrology-based information to assist countries in assessing the SDG 6 indicators

– at least as baselines, and especially for those countries which have not yet made their own EF assessments.

Being based exclusively on the natural flow variability of rivers, the tools presented do not take into account water quality issues and no local ecological data were used. Also, the approach does not differentiate between the contribution of groundwater and snowmelt to the ‘slow flow’, which may lead to an overestimation of the BF and by implication groundwater availability, in those regions where the contribution of snowmelt to the river flows in warmer months is significant. Only the shallow aquifers that are hydrologically connected to the streams are considered. Determination of relative surface water and groundwater availability hinges on the separation of BF from total streamflow. This was partly constrained by using modelled streamflow components and the BF separation method. Ultimately, the decision on the optimal share of abstraction between groundwater and surface water must depend on local assessments.

The above are limitations of the approach presented. Naturally, a number of assumptions had to be made while working at a global level with such a complex issue as environmentally sustainable water management of rivers and aquifers. It is important to stress that the data and tools described in this report are developed exclusively for the purpose of filling data gaps for some SDG 6 indicators, particularly those related to SDG target 6.4.2, where EF are used explicitly. These data, and the process and tools suggested,

may be useful in defining initial values of relevant SDG indicators, for certain areas/countries where other data alternatives are not yet available. Therefore, this report also aims to stimulate further work in this direction, and try and ensure that EF are not ignored completely and “left to

be dealt with in the future.” The data for EF to be used as input to SDG 6 are available, and the existing science and practice of EF assessment, globally, can step into the SDG process to help improve such estimates and monitor the EF-related targets over the lifetime of the SDGs.

References

- Acreman, M.C.; Dunbar, M.J. 2004. Defining environmental river flow requirements – A review. *Hydrology and Earth System Sciences* 8(5): 861-876.
- Amarasinghe, U.A.; Sharma, B.R.; Aloysius, N.; Scott, C.; Smakhtin, V.; de Fraiture, C. 2004. *Spatial variation in water supply and demand across river basins of India*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 42p. (IWMI Research Report 083).
- Baker, T.; Kiptala, J.; Olaka, L.; Oates, N.; Hussain, A.; McCartney, M. 2015. *Baseline review and ecosystem services assessment of the Tana River Basin, Kenya*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 107p. (IWMI Working Paper 165).
- Beck, H.E.; van Dijk, A.I.J.M.; Miralles, D.G.; de Jeu, R.A.M.; Bruijnzeel, L.A.; McVicar, T.R.; Schellekens, J. 2013. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. *Water Resources Research* 49(12): 7843-7863.
- Chapman, T.G. 1991. Comment on “Evaluation of automated techniques for base flow and recession analyses” by R. J. Nathan and T.A. McMahon. *Water Resources Research* 27(7): 1783-1784.
- Döll, P.; Kaspar, F.; Lehner, B. 2003. A global hydrological model for deriving water availability indicators: Model tuning and validation. *Journal of Hydrology* 270(1-2): 105-134.
- Döll, P.; Fiedler, K. 2008. Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences* 12: 863-885.
- Döll, P.; Fiedler, K.; Zhang, J. 2009. Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrology and Earth System Sciences* 13: 2413-2432.
- Döll, P.; Müller Schmied, H.; Schuh, C.; Portmann, F.T.; Eicker, A. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research* 50(7): 5698-5720.
- Ebrahim, G.Y.; Villholth, K.G. 2016. Estimating shallow groundwater availability in small catchments using streamflow recession and instream flow requirements of rivers in South Africa. *Journal of Hydrology* 541(Part B): 754-765.
- Famiglietti, J.S. 2014. The global groundwater crisis. *Nature Climate Change* 4: 945-948.
- FAO. 2003. Digital soil map of the world. Version 3.6. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). Available at <http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/> (accessed on February 8, 2017)
- Giordano, M. 2009. Global groundwater? Issues and solutions. *Annual Review of Environment and Resources* 34: 153-178.
- Gleeson, T.; Wada, Y.; Bierkens, M.F.P.; van Beek, L.P.H. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature* 488: 197-200.

- Hagemann, S.; Gates, L.D. 2003. Improving a subgrid runoff parameterization scheme for climate models by the use of high resolution data derived from satellite observations. *Climate Dynamics* 21(3): 349-359.
- Hanasaki, N.; Kanae, S.; Oki, T.; Masuda, K.; Motoya, K.; Shirakawa, N.; Shen, Y.; Tanaka, K. 2008. An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing. *Hydrology and Earth System Sciences* 12: 1007-1025.
- Hoekstra, A.Y.; Mekonnen, M.M. 2011. *Global water scarcity: The monthly blue water footprint compared to blue water availability for the world's major river basins*. Value of Water Research Report Series No. 53. Delft, the Netherlands: UNESCO-IHE Institute for Water Education. No. 53.
- Hughes, D.A.; Smakhtin, V. 1996. Daily flow time series patching or extension: A spatial interpolation approach based on flow duration curves. *Hydrological Sciences Journal* 41(6): 851-871.
- Hughes, D.A.; Hannart, P.; Watkins, D. 2003. Continuous baseflow separation from time series of daily and monthly streamflow data. *Water SA* 29(1): 43-48.
- Kleynhans, C.J.; Louw, M.D. 2008. *River EcoClassification: Manual for ecoStatus determination (version 2) Module A: EcoClassification and EcoStatus Determination*. Report No. TT 329/08. South Africa: Water Research Commission.
- Kraijenhoff van de Leur, D.A. 1958. A study of non-steady groundwater flow with special reference to the reservoir-coefficient. *De Ingenieur* 70(19): 87-94.
- Nathan, R.J.; McMahon, T.A. 1990. Evaluation of automated techniques for base flow and recession analyses. *Water Resources Research* 26(7): 1465-1473.
- Nijssen, B.; O'Donnell, G.M.; Lettenmaier, D.P.; Lohmann, D.; Wood, E.F. 2001. Predicting the discharge of global rivers. *American Meteorological Society* 14: 3307-3323.
- Oki, T.; Kanae, S. 2006. Global hydrological cycles and world water resources. *Science* 313(5790): 1068-1072.
- Pastor, A.V.; Ludwig, F.; Biemans, H.; Hoff, H.; Kabat, P. 2014. Accounting for environmental flow requirements in global water assessments. *Hydrology and Earth System Sciences* 18: 5041-5059.
- Poff, N.L.; Matthews, J.H. 2013. Environmental flows in the Anthropocene: Past progress and future prospects. *Current Opinion in Environmental Sustainability* 5: 667-675
- Richter, B.D.; Davis, M.M.; Apse, C.; Konrad, C. 2012. A presumptive standard for environmental flow protection. *River Research and Applications* 28(8): 1312-1321.
- Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *Water International* 25(1): 11-32.
- Smakhtin, V.U. 2001. Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. *Water SA* 27(2): 213-218.
- Smakhtin, V.; Revenga, C.; Döll, P. 2004a. A pilot global assessment of environmental water requirements and scarcity. *Water International* 29(3): 307-317.
- Smakhtin, V.U.; Revenga, C.; Döll, P. 2004b. *Taking into account environmental water requirements in global-scale water resources assessments*. Colombo, Sri Lanka: International Water Management Institute (IWMI), Comprehensive Assessment Secretariat. 29p. (Comprehensive Assessment of Water Management in Agriculture Research Report 002).
- Smakhtin, V.; Anputhas, M. 2006. An assessment of environmental flow requirements of Indian river basins. Colombo, Sri Lanka: International Water Management Institute (IWMI). 42p. (IWMI Research Report 107).
- Smakhtin, V.U.; Eriyagama, N. 2008. Developing a software package for global desktop assessment of environmental flows. *Environmental Modelling and Software* 23: 1396-1406.
- Sood, A.; Smakhtin, V. 2015. Global hydrological models: A review. *Hydrological Sciences Journal* 60(4): 549-565.

- Sutanudjaja, E.H.; van Beek, L.P.H.; Villholth, K.G.; Ebrahim, G.Y.; Sood, A.; Zhu, T. Forthcoming. Progress and challenges in modelling global groundwater depletion - experience with PCR-GLOBWB. *Hydrology and Earth System Sciences*. In prep.
- Todini, E. 1996. The ARNO rainfall-runoff model. *Journal of Hydrology* 175(1-4): 339-382.
- United Nations. 2015. *Transforming our world: The 2030 agenda for sustainable development*. Seventieth session, Agenda Items 15 and 116, United Nations General Assembly, September 18, 2015, New York, USA.
- van Beek, L.P.H.; Wada, Y.; Bierkens, M.F.P. 2011. Global monthly water stress: 1. Water balance and water availability. *Water Resources Research* 47(7).
- Vörösmarty, C.J.; Fekete, B.M.; Meybeck, M.; Lammers, R.B. 2000. Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles* 14(2): 599-621.
- Vörösmarty, C.; Lettenmaier, D.; Leveque, C.; Meybeck, M.; Pahl-Wostl, C.; Alcamo, J.; Cosgrove, W.; Grassl, H.; Hoff, H.; Kabat, P.; Lansigan, F.; Lawford, R.; Naiman, R. 2004. Humans transforming the global water system. *Earth and Space Science News* 85(48): 509-514.
- Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Reidy Liermann, C.; Davies, P.M. 2010. Global threats to human water security and river biodiversity. *Nature* 467(7315): 555-561.
- Wada, Y.; van Beek, L.P.H.; van Kempen, C.M.; Reckman, J.W.T.M.; Vasak, S.; Bierkens, M.F.P. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37(20).
- Wada, Y.; van Beek, L.P.H.; Viviroli, D.; Dürr, H.H.; Weingartner, R.; Bierkens, M.F.P. 2011. Global monthly water stress: 2. Water demand and severity of water stress. *Water Resources Research* 47(7).
- Wada, Y.; van Beek, L.P.H.; Bierkens, M.F.P. 2012. Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research* 48(6).
- Wada, Y.; Wisser, D.; Bierkens, M.F.P. 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics* 5: 15-40.
- Wada, Y.; de Graaf, I.E.M.; van Beek, L.P.H. 2016. High-resolution modeling of human and climate impacts on global water resources. *Journal of Advances in Modelling Earth Systems* 8(2): 735-763.

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P O Box 2075
Colombo
Sri Lanka

Location

127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone

+94-11-2880000

Fax

+94-11-2786854

E-mail

iwmi@cgiar.org

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