International Water Resources Association
Water International, Volume 29, Number 3, Pages 307–317, September 2004

A Pilot Global Assessment of Environmental Water Requirements and Scarcity

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***Abstract**: This paper presents a first attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale. This total environmental water requirement consists of ecologically relevant low-flow and high-flow components and depends upon the objective of environmental water management. Both components are related to river flow variability and estimated by conceptual rules from discharge time series simulated by the global hydrology model. A water stress indicator is further defined, which shows what proportion of the utilizable water in world river basins is currently withdrawn for direct human use and where this use is in conflict with environmental water requirements. The paper presents an estimate of environmental water requirements for 128 major river basins and drainage regions of the world. It is shown that approximately 20 to 50 percent of the mean annual river flow in different basins needs to be allocated to freshwater-dependent ecosystems to maintain them in fair conditions. This is unlikely to be possible in many developing countries in Asia and North Africa, in parts of Australia, North America, and Europe, where current total direct water withdrawals (primarily for irrigation) already tap into the estimated environmental water requirements. Over 1.4 billion people currently live in river basins with high environmental water stress. This number will increase as water withdrawals grow and if environmental water allocations remain beyond the common practice in river basin management. This paper suggests that estimates of environmental water requirements should be the integral part of global water assessments and projections of global food production.*

***Keywords**: environmental water requirements, global hydrology and water use model, flow variability, water scarcity*

Introduction

In recent years water availability has become an issue of global concern. A number of global water availability assessments have been carried out and many projections and scenarios of the future water supply and demand have been developed and analyzed (Gleick, 1993; Seckler et al., 1998; Rijsberman, 2000; Shiklomanov, 2000). Global water studies help identify areas of present and future water scarcity and areas of potential water related conflicts, as well as help set priorities for international financing of water projects. However, almost all such studies undertaken to date were limited to assessing if human water needs (domestic, industrial, and agricultural) can be satisfied by the total renewable water resources in a country or a river basin. These studies did not consider the water requirements of freshwater-dependent ecosystems and, consequently, the needs of people who directly depend upon them.

Freshwater ecosystems provide a range of goods and services for humans, including fisheries, flood protection, wildlife, etc. (Revenga et al., 2000; Acreman, 2001). These services are worth trillions of US dollars annually (Postel and Carperter, 1997). To maintain them, water needs to be allocated to ecosystems, as it is allocated to other users like agriculture, power generation, domestic use, and industry. Balancing the requirements of the aquatic environment and other uses is becoming critical in many of the world's river basins as population and associated water demands increase (Postel et al., 1996; Vörösmarty et al., 2000). On the other hand, the assessment of the requirements of freshwater-dependent ecosystems also represents a major challenge due to the complexity of physical processes and interactions between freshwater ecosystem components.

For day-to-day management of particular rivers, environmental water requirements are defined in a form of a suite of flow discharges of certain magnitude, timing, frequency, and duration. These flows jointly ensure a holistic flow regime capable of sustaining complex set of aquatic habitats and ecosystem processes and are referred to as “environmental flows” (Knights, 2002; Dyson et al., 2003). The sum of estimated environmental flows over a year represents a total annual water volume, which could be allocated for environmental purposes. The process of detailed environmental flow assessment normally includes comprehensive analysis of different ecosystem components and their responses to flow changes. This analysis is accomplished by a multidisciplinary panel of experts and involves collection and processing of large amounts of eco-hydrological data.

At the same time, it is critically important to explicitly include estimates of environmental water requirements (EWRs) in the context of global water resources assessments and to respond to a need to incorporate these requirements into water-food-environment projection models (Comprehensive Assessment of Water Management for Agriculture 2002: http://www.cgiar.org/iwmi/Assessment/Index.htm). The scale and the resolution of this type of models suggest that the estimates of total annual environmental water volume may initially be sufficient for this purpose (e.g. Rosegrant and Cai, 2002). This paper presents the first attempt to estimate the total volume of water, which may need to be allocated for environmental needs in world river basins. It further illustrates how these estimates could be used in the context of the assessment of global water availability and scarcity.

Hydrological Background

It is now internationally accepted that conservation of freshwater ecosystems and estimation of their environmental requirements should be viewed in the context of natural variability of flow regime (Poff et al., 1997). To a large degree, flow variability determines the composition, the diversity, the productivity, and resilience of a freshwater-dependent ecosystem. The two primary genetic components of any flow regime are baseflow and quickflow. Baseflow represents that part of the river flow that comes from an aquifer hydraulically connected with the river or from other delayed sources such as perched subsurface storage or lakes. In perennial rivers through most of the dry season of the year, the discharge is composed entirely of baseflow. In intermittent and ephemeral rivers, baseflow during the dry season is zero. Quickflow represents the immediate response of a catchment to rainfall or snowmelt events and is composed primarily of overland flow or interflow in the topsoil. During the wet season, discharge in most of the rivers is made of both baseflow and quickflow, but is dominated by the latter. Both baseflow and quickflow components can be expressed as a proportion of the long-term mean annual runoff (MAR) in a river.

A number of “hydrology-based” indices and methods for the estimation of EWR have been suggested in the past decades (the most recent review of environmental flow assessment techniques may be found in Tharme [2003]). The most advanced hydrology-based methods (e.g. Hughes and Hannart, 2003) effectively focus on estimating the ecologically acceptable proportions of baseflow and quickflow, which could be allocated for freshwater ecosystem maintenance. To be consistent with the emerging terminology, these components will be further referred to here as environmental low-flow requirement (LFR) and environmental high-flow requirement (HFR). The LFR indicates the minimum requirement of fish and other aquatic species for water throughout the year. The HFR is important for river channel maintenance, wetland flooding, and riparian vegetation. Both LFR and HFR change with flow variability (e.g. Hughes and Hannart, 2003).

Environmental Flow Objectives

EWRs vary depending on the objective of environmental water management. Such an objective would aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition or status also referred to as “desired future state,” “environmental management class,” etc. (DWAF, 1997; Durban et al., 1998, Hughes and Hannart, 2003). As a general rule, the higher this status, the more water will need to be allocated for ecosystem maintenance or conservation and, therefore, the higher EWR will be. In the context of the global study, it is not possible to be specific about the objectives of environmental water management in individual river basins. It is, however, possible to specify several broad categories of aquatic ecosystem statuses.

The set of ecosystem management objectives (statuses) used in this study (Table 1) was effectively the same as the one described in DWAF (1997). It starts with the natural condition, where no modification is present (or will be allowed, from the management perspective). Aquatic ecosystems in good conditions may be slightly or moderately modified, but the modifications are such that they generally did not (or will not, from the management perspective) affect the ecosystem integrity. Fair condition of an ecosystem would correspond to moderate or considerable modification from the natural state where the sensitive biota is reduced in numbers and extent. All three conditions may be considered acceptable from the management perspective. Ecosystems in poor condition are those that are critically modified and where most of the ecosystems functions and services are lost. Natural ecosystems in fair and poor conditions would normally be present in densely populated areas with multiple man-induced impacts. Poor ecosystem condition shall not be considered acceptable from the management perspective. Apart from these four categories, there are also systems that have been modified beyond rehabilitation to anything approaching a natural condition. Such systems are not considered here.

Table 1. Categorization and description of objectives of environmental water management adopted in this study

Conservation status or management objective	*Ecological description*	*Management perspective*	*Corresponding low-flow characteristic as a measure of LFR*
Natural (unmodified)	Pristine condition or negligible modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No water projects (dams, diversions etc.) allowed.	Q50
Good (slightly or moderately modified)	Largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Minor water supply schemes or irrigation development present and / or allowed.	Q75
Fair (moderately or considerably modified)	The dynamics of the biota have been disturbed. Some sensitive species are lost and/or reduced in extent. Alien species may occur.	Multiple disturbances associated with the need for socio-economic development, e.g. dams, diversions and transfers, habitat modification and water quality degradation.	Q90
Poor (critically modified and degraded)	Habitat diversity and availability have declined. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Management intervention is needed to restore flow pattern, river habitats etc. This status is not acceptable from the management perspective.	N/A

Linking Hydrology and Environmental Management Objectives

Each acceptable conservation status (natural, good, and fair) now needs to be associated with two hydrological indices, representing LFR and HFR. LFR for each conservation status may be approximated by low-flow indices, extracted from a flow duration curve. A flow duration curve (FDC) is a cumulative probability distribution of flows recorded or simulated at a site in a river basin over a long period. The area under the curve represents the MAR. The area under the threshold of the median flow (Q50) may approximate the total annual baseflow, which occurs in natural conditions (Smakhtin, 2001). It is therefore logical to use Q50 as a measure of LFR for the top conservation status: natural ecosystems (Table 1). To keep an ecosystem in natural condition, the LFR volume shall not be less than Q50.

To maintain an ecosystem in a "good" condition, a smaller proportion of the total baseflow will be required. Their LFR is represented by the flow, which is exceeded 75 percent of the time (Q75). This characteristic may be interpreted simply as the discharge that is exceeded 9 out of 12 months. Smakhtin and Toulouse (1998) have shown that for a variety of perennial flow regimes, Q75 constitutes approximately 65 to 80 percent of the total annual baseflow. Therefore, setting a LFR at the level of Q75 implies that a significant proportion of annual baseflow will be allocated to ecosystems.

To maintain ecosystems in "fair" condition, LFR is approximated by the discharge, which is exceeded 90 percent of the time on average throughout a year (Q90). This characteristic may be interpreted simply as the discharge that is exceeded nine months out of each ten. This index was widely used to set "minimum flow requirements" in rivers (Tharme, 2003) and therefore was considered as the low limit for the LFR that is necessary to ensure "fair" ecosystem conditions. Smakhtin and Watkins (1997) have shown that the variety of perennial rivers, a ratio of Q90/Q50 varies primarily in the range of 1 to 45 percent. This may serve as a rough indication of the proportion of baseflow, which will be available for ecosystems in "fair" conditions.

In rivers with highly variable flow regimes, like Krishna in India or Limpopo in southern Africa (Figure 1), up to 80

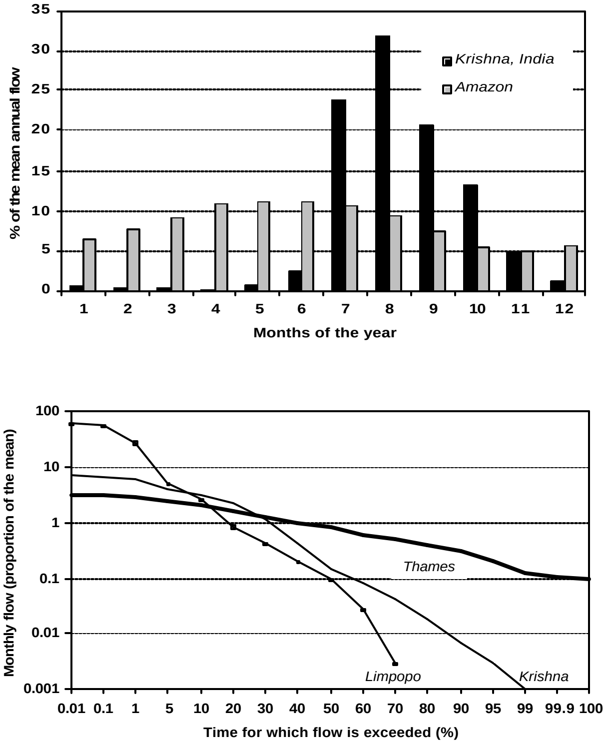

Figure 1. Examples of contrasting monthly flow distributions (a) and flow duration curves (b).

percent of the annual flow may come during three wet months. During a dry period, such rivers may go dry or have very low discharges. Consequently, these regimes are characterized by the steep FDCs and low proportions of Q75 and Q90 in total annual flow volume. Stable hydrological regimes (Amazon, Thames) are dominated by baseflow through the year with relatively small flow increases during the wetter period. They have gradually sloping curves and higher Q75 and Q90 values.

The flow volumes, which would make up the HFRs, may not be read directly from the FDC, and therefore, a different estimation approach is necessary. Some existing experience with setting HFR (Hughes and Hannart, 2003) suggests that they may vary in the approximate range of 5 to 23 percent of the MAR, depending on the type of flow regime and the objective of the environmental flow management. Considering that this is a relatively narrow range, only one set of HFR estimation rules has been suggested in this study at present (the set applies to all three acceptable conservation statuses listed in Table 1). HFR is set to vary in four thresholds linked to different Q90 levels. For basins with highly variable flow, where Q90 is less than 10 percent of the MAR, the HFR is set to 20 percent of the MAR. For rivers with stable flow, where Q90 is higher than 30 percent of the MAR, the HFR is set to zero. For rivers where Q90 ranges from 10 to 20 percent and from 20 to 30 percent of the MAR, the HFR levels are set at 15 percent and 7 percent of the MAR respectively. Q90 in this algorithm serves simply as an arbitrary indicator, sensitive to changes between flow regimes globally. The smaller the Q90, the more variable and peaky is the river flow, and therefore, the more flow should be allocated to HFR in order to be consistent with its natural pattern.

The total annual EWR is calculated as a sum of two estimates: a LFR and a HFR. LFR varies between different conservation statuses and both components vary between river basins. The total EWR for a globally-fixed conservation status reflects the global differences in flow regimes. The suggested framework may, in principle, be used to set different conservation objectives to different world river basins. However, given the already existing and increasing pressure on water resources in the world, the study at present considered only one, most feasible scenario of environmental water allocation. The goal of environmental water management in this scenario is to maintain the freshwater-dependent ecosystems in all river basins at least in "fair" condition (Table 1).

Hydrological Modeling

The calculation of EWR components is based on the time series of monthly river flows that are simulated by a state-of-the-art global model: the WaterGAP2 (Alcamo et al., 2003; Döll et al., 2003). The model includes two main sub-models – hydrology and water use – and operates with a spatial resolution of 0.5° by 0.5° (approximately 67,000 grid cells worldwide).

The physically-based global hydrology model computes time series of monthly runoff for each cell (as the sum of surface runoff and groundwater recharge) and river discharge. The calculation of the latter takes into account the storage capacity of aquifers, lakes, wetlands, and rivers, and route river discharge through each river basin according to a global drainage direction map. Computations are based on time series of monthly climate variables for the period of 1961 to 1990. The model is calibrated against measured river discharge at 724 gauging stations worldwide. During the calibration, the simulated values take into account the reduction of river discharge due to total withdrawals (for agriculture, industry etc.). However, for the computation of the MAR and EWR, it is necessary to compute a reference condition – the natural river discharge that would have occurred in the absence of human impacts in river basins. The global hydrology model setup allows a pseudo-natural river discharge to be calculated: the discharge that would occur without withdrawals but with the reservoirs that existed in the world around 1995. The simulated flow data are used to calculate MAR and EWR.

A Global Distribution of Environmental Water Requirements

The estimates of EWR, which correspond to "fair" condition of freshwater-dependent ecosystems worldwide and obtained from simulated hydrological data, range from 20 to 50 percent of the total renewable water resources (Figure 2). Renewable water resources are represented by the MAR. Figure 2 also shows the boundaries of 106 major world river basins, covering a large proportion of the land surface (Revenga et al., 1998).

EWR are the highest (normally over 40 percent of the MAR) for the rivers of the equatorial belt (e.g. parts of Amazon and Congo basins) where there is a stable rainfall input throughout the year and for some lake-regulated rivers (in Canada, Finland, etc). Most of the river flow regimes in northern and central Europe are characterized by the high proportion of groundwater generated baseflow. The plains of the western Siberia are dominated by the vast stretches of swamps, which perform the natural flow regulation function. In such cases the flow variability is relatively low, which leads to higher EWR (Figure 2).

In highly variable monsoon-driven rivers (e.g. in India), rivers of the arid areas that flow after infrequent rains (e.g. Limpopo basin, North Africa) and most of the east Siberian rivers with high snowmelt flows, the estimates of the EWR are lower (20 to 30 percent of the MAR). In general, aside from a few areas that lack suitable quality streamflow gauged data, which could have been used for calibration (e.g. upstream Nile, North Canada), the model satisfactorily simulates the overall global pattern of flow variability which, in turn, is reflected in the EWR estimates.

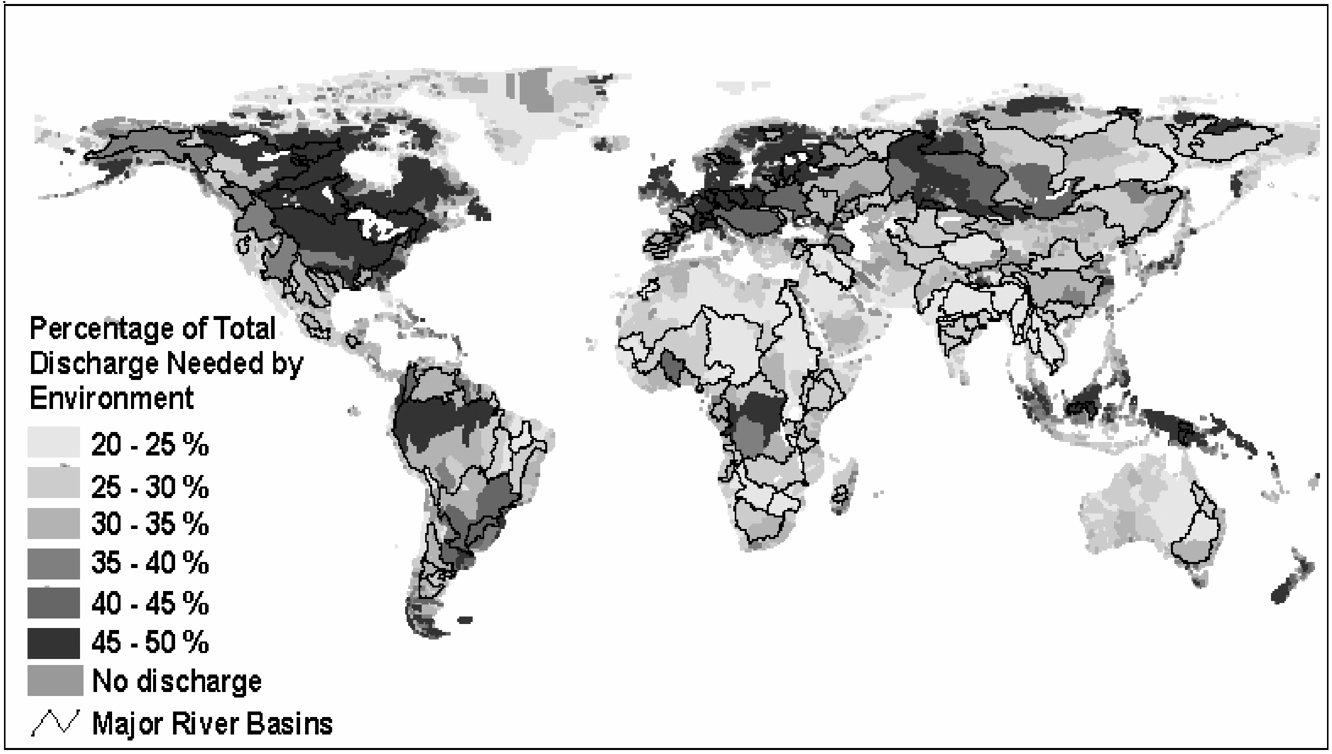

Figure 2. A global distribution of estimated total EWR, which would be required to maintain the freshwater-dependent ecosystems in fair condition

The global picture of EWR (Figure 2) effectively reflects the hydro-ecological assumption formulated by Hughes and Hannart (2003). In highly variable flow regimes, the aquatic life is used to the extended periods of limited or no flow and is, therefore, more resilient to man-induced water scarcity. Consequently, a smaller part of the total flow (compared with a less variable hydrological regime) may be required to achieve the same environmental management objective. Estimates of total EWR for such basins are dominated by the estimates of the HFR component. On the contrary, the aquatic life in basins with stable flow regimes is more sensitive to man-induced water scarcity and is likely to require a larger part of the total annual flow for the same objective. Estimates of total EWR for such basins are dominated by the estimates of the LFR.

As mentioned, the estimates shown in Figure 2 represent just one possible option of bulk water allocation for environmental purposes. The values appear to be on a low side of plausible EWR, but this scenario allocation is likely to ensure a fair condition of freshwater-dependent ecosystems worldwide – the lowest acceptable option from the management perspective. To achieve this, attempts should be made to reach compromises on water allocation between environment and other uses in the calculated range (20 to 50 percent of the MAR). At the same time, detailed basin- and ecosystem-specific studies can result in higher or lower EWR estimates, which correspond to more specific environmental management objectives.

Table 2 lists the estimates of EWR for 128 major river basins and other drainage regions, which cover the entire land surface (their boundaries are shown in Figure 3). These basins and regions have been used by Cai and Rosegrant (2002) and Rosegrant and Cai (2002) for modeling global supply and demand projections by 2025. The estimates have been obtained by averaging the EWR values of all cells within each basin/region and expressed as the percentage of the long-term basin MAR. The EWR values listed in Table 2 may be interpreted as those water volumes, which need to be allocated in the long-term in each river basin or drainage region for the maintenance of freshwater dependent ecosystems in a "fair" condition, which is described in Table 1.

Environmental Water Requirements and Water Scarcity

The EWR may impact the existing assessments of global water availability and scarcity. In Figure 4, the entire box represents the total volume of water available in a basin (MAR). The bottom portion of the box represents the EWR. The rest of the box is the amount of water that can potentially be used by agriculture, industry, etc. as utilizable water. The actual water use is represented by the sum of water withdrawals for different sectors of economy, calculated by the water use sub-model of the WaterGAP 2 (Alcamo et al., 2003). This sub-model includes modules for irrigation, livestock, households, thermal power plants, and manufacturing industry. Irrigation

Table 2. Preliminary estimates of mean Environmental Water Requirements for 128 major basins and drainage regions of the world.

N	*Basins or drainage regions*	*Countries or geographical regions*	*EWR (% of MAR)*
1	Amazon	Brazil, Central South, America, Northern South, America, Peru	31
2	Amudarja	Afghanistan, Tajikistan, Turkmenistan, Uzbekistan	27
3	Amur	China, Russia	28
4	Arabian Peninsula	Iraq, Jordan	21
5	Arkansas	United States	41
6	Baltic	Baltic, Russia	39
7	Black Sea	Caucus, Russia, Turkey, Ukraine	32
8	Borneo	Indonesia, Malaysia	36
9	Brahmaputra	Bangladesh, China, India	27
10	Brahmari	India	24
11	Britain	British Isles	43
12	California	United States	23
13	Canada Arctic Atlantic	Canada	25
14	Caribbean	Caribbean & Central America	30
15	Cauvery	India	25
16	Central African West Coast	SADC North, SADC South, West-Central Africa	29
17	Central America	Caribbean & Central America	28
18	Central Australia	Australia	24
19	Central Canada Slave Basin	Canada	41
20	Chang Jiang	China	30
21	Chile Coast	Chile	23
22	Chotanagpui	India	25
23	Colorado	United States	27
24	Colombia	Canada, United States	33
25	Colombia & Ecuador	Colombia, Northern South America, Peru	32
26	Congo	SADC North, West-Central Africa	31
27	Cuba	Caribbean & Central America	28
28	Danube	Alps, Germany, Ukraine, Baltic, Russia, Ukraine	40
29	Dnieper	Ukraine, Russia	34
30	East African Coast	East Africa, SADC North, Uganda	31
31	Eastern Ghats	India,	26
32	Eastern Australia Tasmania	Australia	29
33	Eastern Mediterranean	Egypt, Gulf, Israel, Jordan, Lebanon, Syria, Turkey	26
34	Elbe	Germany, Scandinavia	45
35	Ganges	Bangladesh, India, Nepal	23
36	Godavari	India	24
37	Great Basin	United States	27
38	Great Lakes	Canada, United States	49
39	Hail He	China	28
40	Horn of Africa	East Africa, Ethiopia, Kenya, Uganda	25
41	Hual He	China	32
42	Huang He	China	31
43	Iberia East Mediterranean	Iberia	37
44	Iberia West Atlantic	Iberia	30
45	India East Coast	India	25
46	Indonesia East	Indonesia	36
47	Indonesia West	Indonesia	30
48	Indus	Afghanistan, India, Pakistan	25
49	Ireland	British Isles	38
50	Italy	Italy	30
51	Japan	Japan	31
52	Kalahari	SADC South, South Africa	23
53	Krishna	India	24
54	Lake Balkhash	Kazakhstan, Kyrgyzstan	37
55	Lake Chad Basin	Nigeria, Sahel, West-Central Africa	24
56	Langcang Jiang	China	26
57	Limpopo	SADC South, South Africa	25
58	Loire Bordeaux	France	34
59	Lower Mongolia	China, Mongolia	29
60	Luni	India	21
61	McKenzie	Canada	35
62	Madagascar	East Africa	29
63	Mahi Tapti	India	23
64	Mekong	Myanmar (Burma), Southeast Asia, Thailand	28

Table 2. (Continued)

N	*Basins or drainage regions*	*Countries or geographical regions*	*EWR (% of MAR)*
65	Middle Mexico	Mexico	27
66	Mississippi	United States	42
67	Missouri	United States	40
68	Murray Australia	Australia	27
69	New Zealand	New Zealand	37
70	Niger	Nigeria, Sahel	28
71	Nile	Egypt, Eritrea, Ethiopia, Libya, Sudan, Uganda	24
72	North African Coast	Algeria, Tunisia	25
73	North European Russia	Russia	31
74	North Korea Peninsula	China, North Korea	27
75	Northeast Brazil	Brazil	25
76	Northeast South America	Brazil	33
77	Northwest African Coast	Morocco, Sahel	23
78	Ob	Kazakhstan, Russia	38
79	Oder	Germany, Poland	47
80	Ohio	United States	45
81	Orange	SADC South, South Africa	27
82	Orinoco	Colombia, Northern South America	32
83	Pacific North America	USA, Canada	30
84	Papua Oceania	Papua New Guinea, Oceania	37
85	Parana	Argentina, Brazil, Central South America	31
86	Peru coast	Peru	23
87	Philippines	Philippines	31
88	Red & Winnipeg	Canada, United States	42
89	Rhine	Alps, Ben-lux, France, Germany, Netherlands	44
90	Rhone	France	40
91	Rio Grande	Mexico, United States	28
92	Rio Colorado	Argentina	29
93	Southeast Asia Coast	China, Thailand, Vietnam	27
94	Sahara	Algeria, Libya, Morocco, Sudan	24
95	Sahyada	India	21
96	Salada Tierra	Argentina	33
97	San Francisco	Brazil	33
98	Scandinavia	Scandinavia	35
99	Seine	Ben-lux, France	37
100	Senegal	Sahel	23
101	Siberia - Other	Russia	25
102	Songhua	China	30
103	South African Coast	SADC South, South Africa	26
104	South Korea Peninsula	South Korea	27
105	Southeast African Coast	SADC North, SADC South	27
106	Southeast USA	United States	35
107	Sri Lanka	Sri Lanka	26
108	Syrdarja	Kazakhstan, Kyrgyzstan, Uzbekistan	27
109	Thai Myan Malay	Malaysia, Singapore, Thailand, Myanmar (Burma)	28
110	Tierra	Argentina, Chile	33
111	Tigris &Euphrates	Iraq, Syria, Turkey	26
112	Toc	Brazil	30
113	USA Northeast	United States	38
114	Upper Mexico	Mexico	22
115	Upper Mongolia	Mongolia, Russia	33
116	Ural	Kazakhstan, Russia	32
117	Uruguay	Argentina, Brazil, Central South America	36
118	Volga	Kazakhstan, Russia,	35
119	Volta	Sahel, West Africa	28
120	West African Coast	Sahel, West Africa, West-Central Africa	24
121	Western Asia, Iran	Afghanistan, Caucuses, Iran, Pakistan, Turkey, Turkmenistan	24
122	Western Australia	Australia	23
123	Western Gulf of Mexico	United States	32
124	Yenisey	Russia	30
125	Yili He	China, Kazakhstan	28
126	Yucatan	Caribbean & Central America, Mexico	28
127	Zambezi	SADC North, SADC South	27
128	Zhu Jiang	China	30

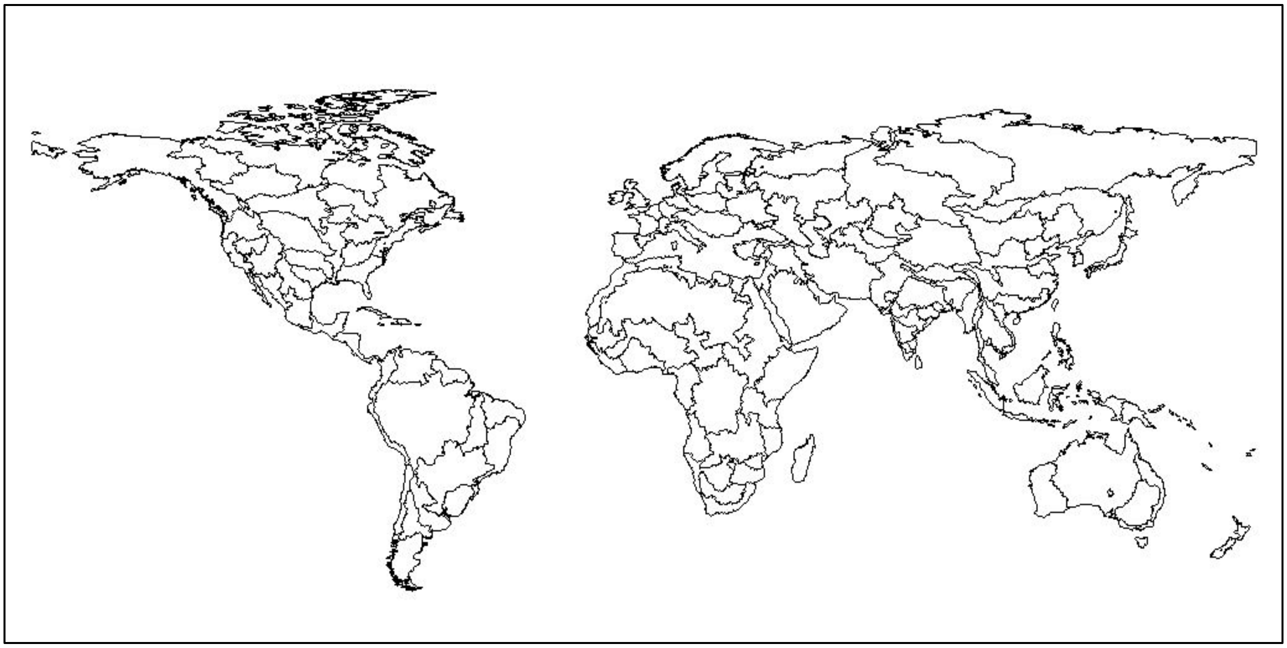

Figure 3. A map of the major river basins and drainage regions of the world adopted for global water demand and supply modeling in Cai and Rosegrant (2002)

water requirements (withdrawals) are simulated as a function of cell-specific irrigated area, crop type, climate variables, and water use efficiency. Livestock water use is calculated by multiplying livestock numbers by livestock-specific water use. Household water use by grid cell is computed by downscaling published country values (Shiklomanov, 1997) based on population density, urban population, and access to safe drinking water. Water use by thermal power plants is derived from the capacity and cooling technology of more than 60,000 power plants worldwide. Manufacturing water withdrawals are estimated using country data (Shiklomanov, 1997) on the main water-using industries and the distribution of the urban population. The total water use is calculated as the sum of water withdrawals for all sectors.

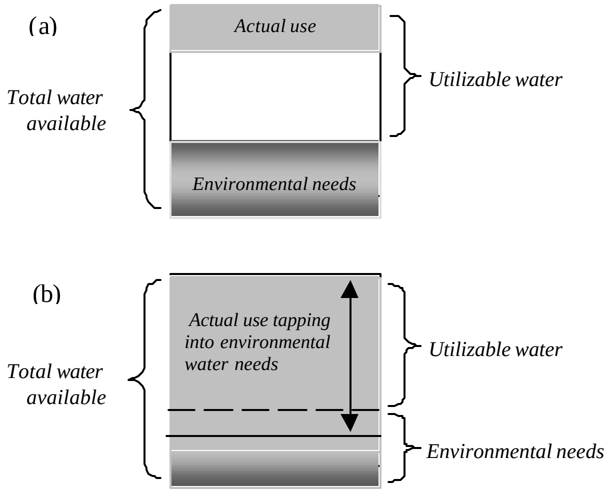

Figure 4. A schematic representation of the relationships between total water resources, total present water withdrawals, and EWR in environmentally safe (a) and environmentally water scarce (b) river basins.

The relationship between water availability, total use and the EWR may be described by the water stress indicator (WSI). WSI of a similar form is commonly used in human water stress assessments (e.g. Rijsberman, 2000), but without EWR term. If WSI exceeds 1, the basin is classified as "environmentally water scarce" (Figure 4). In such a basin, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the basin is less than EWR. Smaller index values indicate progressively lower water resources exploitation and lower risk of "environmental water scarcity." Basins where $0.6 < WSI < 1$ are arbitrarily defined here as heavily exploited or "environmentally water stressed" and basins where $0.3 < WSI < 0.6$ as moderately exploited. In these basins, 0 to 40 percent and 40 to 70 percent of the utilizable water respectively is still available before water withdrawals come in conflict with the EWR. Environmentally "safe" basins are defined as those where $WSI < 0.3$.

The global distribution of WSI is shown in Figure 5, which also displays the boundaries of 106 major river basins, considered by Revenga et al. (1998). The black areas are those where EWR (necessary to ensure a fair ecosystems' condition, see Figure 2) may not be satisfied under current water use. Most of the areas with variable flow regimes (and, consequently, the modest EWR of 20 to 30 percent of the MAR) fall into areas of environmental water scarcity. Some of the major river basins would move into a higher category of human water scarcity, if EWR are to be satisfied. These include Ganges, parts of Murray-Darling, Orange, Limpopo, downstream parts of

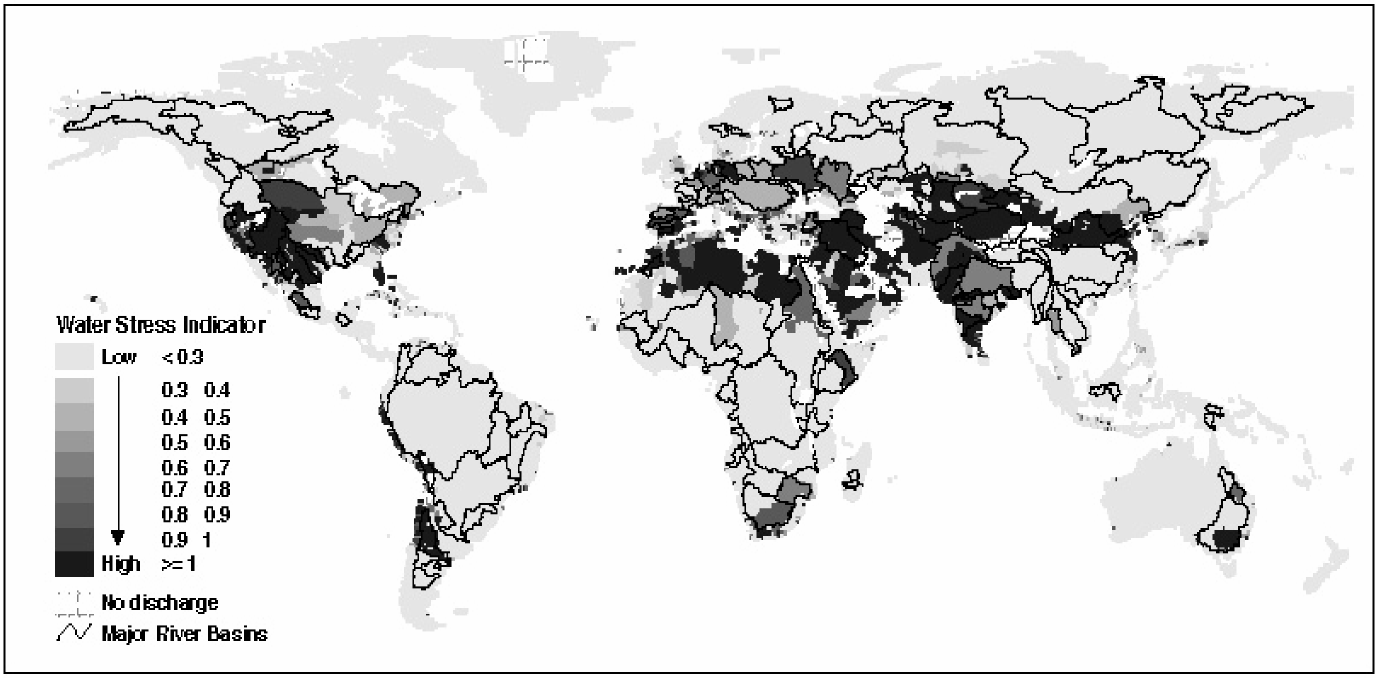

Figure 5. A map of water stress indicator (WSI), which takes into account EWR.

Nile, the upstreams of Missouri, Dneeper and some others. The risk of not meeting EWR will also increase in these and other basins, as water withdrawals grow.

The extent of environmental water scarcity may also be quantified by overlaying the country boundaries (with country population figures at 1995 level) on the major river basin boundaries. This exercise shows that basins where the current water use is already in conflict with the EWR cover over 15 percent of the world land surface and are populated by over 1.4 billion people in total. As water withdrawals increase, more river basins will "move" from "environmentally safe" to "environmentally stressed" and further into "environmentally scarce" categories. It is highly unlikely that any transition in the reverse order will be possible if water productivity is not significantly increased in agricultural sector (which currently accounts for approximately 70 percent of the total water withdrawals in the world) and if the allocation of water for environmental purposes is not made a common practice in river basin management. The increasing levels of environmental water scarcity will have multiple adverse implications for public health, food security, livelihoods, and biodiversity and could result in increasing number of water-related conflicts.

Conclusions

This study presents a set of simple conceptual hydrology-based rules-of-thumb for the assessment of bulk environmental water requirements in world river basins. It was not designed to and did not attempt to determine environmental flow regimes, which would include seasonal low flows, peak flows, their timing, frequency, and duration. These regimes are established by different, more detailed, and site-specific methods.

Such scientifically-justified estimates of total annual environmental water volumes should become an integral part of global water resources modeling initiatives, similar to those described by Cai and Rosegrant (2002). To the best of the authors' knowledge, this study presents the first attempt to estimate environmental water allocations at the global scale for such initiatives.

Being the first of its kind (in scale terms) and having to deal with an extremely complex, controversial, and challenging issue like environmental water allocations, this study relies on a number of assumptions and simplifications. The results reported may therefore be considered only as preliminary. Consequently, the focus for further development is on making the suggested method for assessment of EWR more ecologically relevant. This would require locally and regionally available information on freshwater biodiversity, sensitivity, and conservation importance of aquatic ecosystems to be collated and analyzed in the context of hydrological variability.

While every attempt should be made to make use of ecological information, there is still a need to further improve the hydrology-based methodologies as well. The work in this direction would include a more explicit estimation of high- and low-flow requirements for rivers with different hydrological regimes, improved hydrological simulations, etc.

This study deals at this stage only with water allocations that are directed for ecosystem maintenance. The latter is understood here primarily as preservation of biodiversity and aquatic habitats. Other aspects of in-stream water use (pollution during low-flow periods, navigation, recreation, international water treaties) are also primarily missing from global water studies and will need to be addressed in the future.

Acknowledgements

This study was part of the larger research program on Comprehensive Assessment of Water Management for Agriculture, supported by the Government of Netherlands. The Netherlands Ministry of Foreign Affairs supported the involvement of World Resources Institute (WRI) in this study. We thank Mrs. Janet Nackoney and Mrs. Yumiko Kura (both of the WRI) for the preparation of the original maps and Ms. Rebecca Tharme and Dr. David Molden (both of IWMI) for helpful comments during the course of the study. The map of the 128 river basins and drainage regions of the world (Figure 3) has been provided by the International Food Policy Research Institute (IFPRI).

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Discussions open until March 1, 2005.

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