Taking into Account Environmental Water Requirements in Global-scale Water Resources Assessments

Vladimir Smakhtin, Carmen Revenga and Petra Döll

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Vladimir Smakhtin
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and Petra Döll

With contributions from
Rebecca Tharme
Janet Nackoney
and Yumiko Kura

Comprehensive Assessment of Water Management in Agriculture

The authors: Vladimir Smakhtin is Principal Scientist in Eco-hydrology and Water Resources at the International Water Management Institute (IWMI) Colombo, Sri Lanka. Carmen Revenga is a Senior Associate in the Information Program of the World Resources Institute (WRI) Washington D.C., USA. Petra Döll is a Professor of Hydrology at the Institute of Physical Geography, University of Frankfurt, Germany (Former address: Center for Environmental System Research, University of Kassel, Germany). Contributors to map design and analysis: Rebecca Tharme is a researcher in aquatic ecology at IWMI, Colombo, Sri Lanka. Janet Nackoney and Yumiko Kura are GIS specialists at WRI, Washington D.C., USA.

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/ water availability / water stress / water use / water scarcity / water requirements / ecosystems / water resource management / hydrology / water allocation / natural resources / food security / environmental effects /

Please direct inquiries and comments to: comp.assessment@cgiar.org

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Summary

Assessment of water availability, water use and water stress at the global scale has been the subject of increasingly intensive research over the course of the past 10 years. However, the requirements of aquatic ecosystems for water have not been considered explicitly in such assessments. It is, however, critically important that in global studies a certain volume of water is planned for the maintenance of freshwater ecosystem functions and the services they provide to humans. This report summarizes the results of the first pilot global assessment of the total volumes of water required for such purposes in world river basins. These volumes are referred to in this report as Environmental Water Requirements (EWR). The total EWR are assumed to consist of ecologically relevant low-flow and high-flow components. Both components are related to river flow variability, and estimated by conceptual rules from the discharge time series simulated by the global hydrology model. The concept of environmental water scarcity is then introduced and analyzed using a water stress indicator, which shows what proportion of the utilisable water in world river basins is currently withdrawn for direct human use and where this use is in conflict with EWR. The results are presented on global maps. EWR required to maintain a fair condition of freshwater ecosystems range globally from 20 to 50 percent of the mean annual river flow in a basin. It is shown that even at estimated modest levels of EWR, parts of the world are already or soon will be classified as environmentally water scarce or environmentally water stressed. The total population living in basins where modest EWR levels are already in conflict with current water use, is over 1.4 billion, and this number is growing. The necessity of further research in this field is advocated and the directions for such research are discussed.

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Introduction

Emerging freshwater scarcity has been recognized as a global issue of the utmost importance. There is a growing awareness that increased water use by humans does not only reduce the amount of water available for future industrial and agricultural development but also has a profound effect on aquatic ecosystems and their dependent species. Balancing the needs of the aquatic environment and other uses is becoming critical in many of the worlds' river basins as population and associated water demands increase (Postel et al. 1996; Vörösmarty et al. 2000; Naiman et al. 2002). In this context, what is often lacking is the understanding that planning environmental water allocation means striking the right balance between allocating water for direct human use (e.g. for agriculture, power generation, domestic purposes and industry) and indirect human use (maintenance of ecosystem goods and services, e.g. Acreman 1998).

The services that freshwater ecosystems provide to humans such as fisheries, flood protection, recreation and wildlife are estimated to be worth trillions of US dollars annually (Constanza et al. 1997; Postel and Carperter 1997). A recent global assessment of the status of freshwater ecosystems (Revenga et al. 2000) showed that their capacity to provide the full range of such goods and services appears to be drastically degraded. Many freshwater species are facing rapid population decline or extinction, and yields from many wild fisheries have dwindled as a result of flow regulation, habitat degradation and pollution.

Every inland or coastal, fresh or brackish water ecosystem has specific water requirements for the maintenance of the ecosystem structure, functioning and the dependent species. For river dependent aquatic ecosystems, these are normally referred to as environmental flow requirements, or environmental flows. There is no universally agreed definition of environmental flows. On the one hand, they may be defined in rather general terms as an allocation of water for conservation purposes. On the other hand, the definition may be very specific as a suite of flow discharges of certain magnitude, timing, frequency and duration, all of which jointly ensure a holistic flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes (Knights 2002).

In order to sustain the ability of freshwater dependent ecosystems to support food production and biodiversity, environmental flows must be established scientifically, made legitimate and maintained. This poses a number of challenges. The physical processes and interactions between freshwater ecosystem components are extremely complex, and their

understanding and quantification in most of the world remains poor. The impacts of changing hydrological regimes on ecosystems are not properly understood. A satisfactory level of confidence in environmental flow estimates may be achieved by the application of time-consuming methods, which involve multidisciplinary expert judgment and site-specific information. This information and the expertise required to apply such methods are limited. As a result, in most of the world, environmental flows have never been estimated. The allocation of water for environmental purposes is still assigned a low priority in water resources management, and the condition of freshwater ecosystems worldwide continues to deteriorate (Revenga et al. 2000; Rosenberg et al. 2000). The current situation therefore points to the need for an intensive, large-scale research program on environmental flow assessment.

At the same time, there are areas of water research and planning, where at least crude, pilot estimates of environmental water needs are urgently required at the global scale. In recent years, a number of global assessments of water resources, current and future water use, water and food security projections and water poverty analyses have been completed (Alcamo et al. 2000; FAO 2000; IWMI 2000; Shiklomanov 2000; Sullivan et al. 2003; Vörösmarty et al. 2000; UNESCO 2003). Global approaches help identify the areas of present and future water scarcity, the areas of potential water related conflicts, and also set priorities for international financing of water projects. However, as a rule, global studies undertaken to date were limited to assessing whether the human water needs (domestic, industrial and agricultural) can be satisfied by the total renewable water resources in a country, a river basin or a grid cell. These studies did not explicitly consider the water requirements of ecosystems and the needs of people, who depend upon them. It is therefore critically important to assess environmental water

requirements in the context of global water resources assessment and to respond to the need for incorporating these requirements in water-food-environment projection models (Comprehensive Assessment of Water Management for Agriculture 2002: http://www.cgiar.org/iwmi/Assessment/Index.htm).

This report presents the first attempt to include environmental flow requirements in a global water resources assessment. Due to the lack of river basin specific ecological information and also the scale of this assessment, we attempt to estimate only the mean total annual volume of water that should be allocated for environmental purposes. This total annual volume is hereafter referred to as Environmental Water Requirements (EWR), and is computed for all world river basins. No attempt was made in this study to determine environmental flow regimes which would include seasonal low flows, peak flows, their timing, frequency and duration. The computed EWR values are based on the time series of monthly river flows that are modeled by a state-of-the-art global hydrological model.

We then use the EWR values to calculate a new basin-specific water scarcity index that takes into account environmental requirements. This index combines three components: total available water resources, total actual water use and EWR.

In the following sections, we first describe the global hydrology and the water use models, followed by the description of the conceptual rules for the estimation of EWR. We then present global maps of the estimated EWR and of the new water scarcity index that takes into account environmental requirements, identifying areas where current water use is in conflict with EWR. After a discussion of the results, the current trends, problems and initiatives in the global environmental water management are explored and steps for future research in this field, in a global scale, are suggested.

Data and Methodology

Global Hydrology and Water Use Modeling

Basin-specific information on river discharges and water use used in this study were simulated by the global water model WaterGAP 2 (Alcamo et al. 2003; Döll et al. 2003), which has a spatial resolution of 0.5 by 0.5 (approximately 67,000 grid cells worldwide). The model consists of two main parts; the Global Water Use Model and the Global Hydrology Model.

The physically based global hydrology model computes the 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 routes river discharge through each river basin according to a global drainage direction map. Computations are based on the time series of monthly climate variables for the period 1961-1990. The model is calibrated against the 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 long-term mean annual runoff (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 global water use model includes sub-models for irrigation, livestock, households, thermal power plants and manufacturing industry. Irrigation water requirements (withdrawals) are simulated as a function of a 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.

Conceptual Rules for a Pilot Global Assessment of EWR

Existing methods for the estimation of EWR differ in input information requirements, types of ecosystems they are designed for, time which is needed for their application, and the level of confidence in the final estimates. They range from purely hydrological methods, which derive environmentally acceptable flows from flow data and use limited ecological information or eco-hydrological hypotheses (e.g. Richter et al. 1997; Hughes and Münster 2000), to multidisciplinary, comprehensive methods, which involve expert panel discussions and collection of significant amounts of geo-morphological and ecological data (e.g. Arthington et al. 1998; King and Louw 1998). Reviews of these methods may be found in multiple sources, including Tharme 1996, Arthington et al. 1998 and Dunbar et al. 1998. The necessary quantitative information on the ecological functioning of aquatic ecosystems and their dependent species in many parts of the world is currently lacking and in many regions,

even basic inventories for freshwater species are non-existent. Therefore, for this first global-scale assessment of EWR, it was not feasible to rely on data intensive methods, and hence, it was considered logical to use and/or develop hydrology-based conceptual rules.

It is now an accepted concept in aquatic ecology that the conservation of aquatic ecosystems should be considered in the context of the natural variability of flow regime (Poff et al. 1997; Richter et al. 1997; Hughes and Münster 2000). The two primary genetic components of any flow regime are baseflow and quickflow. Baseflow represents that part of the river flow, which originates from an aquifer hydraulically connected with the river or from other delayed sources such as perched subsurface storage or lakes. In perennial rivers, throughout 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 composed of both baseflow and quickflow, but is dominated by the latter. Baseflow and quickflow components may be separated from each other by digital filtering applied to observed or simulated flow time series (Smakhtin 2001). Both components can be expressed as a proportion of the long-term MAR in a river.

A hydrology-based approximation of EWR should therefore endeavor to incorporate portions of both baseflow and quickflow that would contribute to maintaining freshwater ecosystem productivity and dynamics. To be consistent with the emerging terminology, we further refer to these components as the environmental low-flow requirement (LFR) and the environmental high-flow requirement (HFR). LFR is believed to approximate the minimum requirement of water of the fish and other aquatic species throughout the year. HFR is important for river channel maintenance, as a stimulus for processes such as migration and spawning, for wetland flooding and recruitment of riparian vegetation. The sum of LFR and HFR forms the total EWR.

The principles, which were used in developing the conceptual rules for this pilot global assessment, were similar to those which underpin the method for the preliminary estimation of the water quantity component of ecological reserve for rivers currently in use in South Africa. This method is described in detail by Hughes and Münster (2000) and Hughes and Hannart (2003). It was developed through the analysis of quantitative results from a number of specialist workshops on the estimation of environmental flows held in South Africa in the late 1990s. Each such workshop focused on specific rivers and produced estimates of environmental flows for each month of the year and for several components of the river flow regime (high and low flows required for years of normal wetness, and high and low-flows required for dry years). Hughes and Münster (2000) related these environmental recommendations to a combined non-dimensional hydrological variability index. The latter accommodated a measure of long-term flow variability (a coefficient of variation of seasonal flow) and a measure of flow 'stability' (base flow index, defined in hydrology as a proportion of subsurface flow in the total river flow (e.g. Smakhtin 2001)). Hughes and Hannart (2003) further suggested that in basins with highly variable flow regimes, a larger proportion of the total annual flow occurs as "short periods of high flow interspersed with low or no flow". The assumption was then made that "the biota will be adjusted to a relative scarcity of water and therefore requires a lower proportion of the long-term mean". For less variable flow regimes it was assumed that "the biota is more sensitive to reductions in flow and that a larger proportion of the long-term mean will be required to achieve the ecological objectives."

The concepts suggested by Hughes and Münster (2000) and Hughes and Hannart (2003) may be reinterpreted in the global context as follows. In basins with highly variable flow regimes, a larger proportion of the total annual flow occurs during the wet period, which (in such basins) usually lasts for one to three months. During a dry period of the year, such rivers may either go completely dry, or have very low discharges. Estimates of the total EWR for such basins or regions will most likely be dominated by the estimates of the environmental HFR component. The annual total flow in basins with stable flow regimes is made of a significant LFR, which continues through most of the year and of relatively small flow increases during the wetter period. Estimates of the total EWR for such basins will most likely be dominated by the estimates of the environmental LFR component.

To illustrate the differences in flow regimes, we used several observed data sets available from the Internet at http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml - a joint web site of Russian State Hydrological Institute and International Hydrological Programme of UNESCO. The Krishna River in India is a typical example of a monsoon-driven flow regime, where most of the annual flow (up to 80% of MAR) occurs in the 3-4 wettest months of the year (figure 1). During the rest of the year, the river carries a relatively low proportion of the total flow. Small and medium-sized rivers in arid and semi-arid regions, and even some large rivers like the Limpopo in southern Africa, on the other hand, may go completely dry for several months during the dry season. These are referred to as intermittent rivers. The extreme case is the ephemeral rivers, which flow only after infrequent rainfall events. On the opposite end of the spectrum are rivers with very stable flow regimes (figure 1). These normally have stable groundwater inflow and/ or are naturally regulated by lakes in the catchment. The types of flow regimes in the world are numerous, and consequently, the proportion of environmental LFR and HFR components in total EWR vary. The quantitative, hydrology-based rules, which approximate these two components, are described below.

FIGURE 1.
Examples of two contrasting seasonal flow distributions.
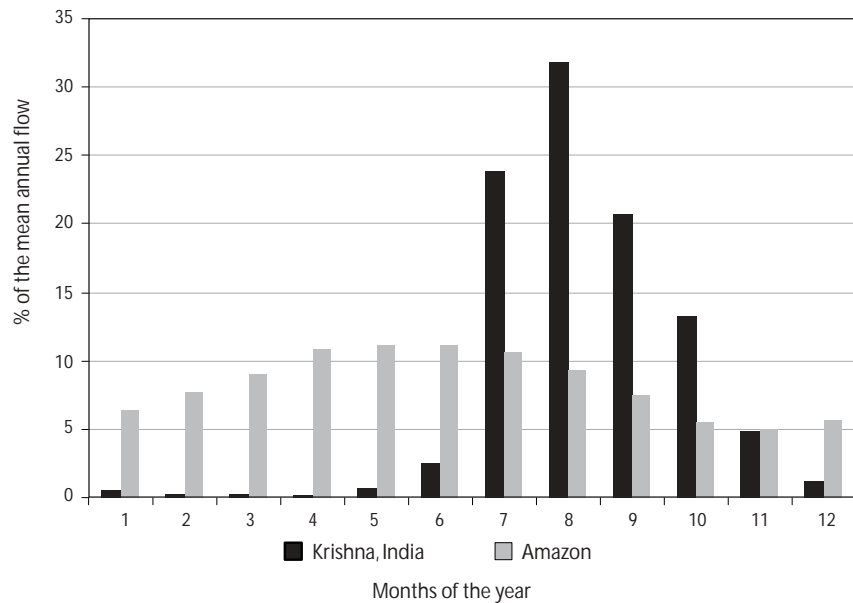
Environmental LFR was assumed to be equal to the monthly flow, which is exceeded 90 percent of the time on average throughout a year (Q90). This flow may be interpreted simply as the discharge that is exceeded 9 out of 10 months. It represents one of the low-flow characteristics widely used in hydrology and water resources assessments (e.g. Smakhtin 2001) and is normally estimated from a flow duration curve (FDC). FDC is a cumulative distribution of flows recorded at a site in a river basin over a certain period of observations. Alternatively, a FDC may be constructed from a simulated flow record (e.g., such as simulated by WaterGAP 2 model). A FDC is constructed by ranking all the flows in a record from the highest to the lowest and assigning the probability (% time of exceedence) to each flow in a ranked series.

The area under the curve represents MAR. The area under the threshold of the median flow (Q50) may approximate the total annual baseflow. A "steep" FDC is a reflection of a very variable flow regime, and a FDC with a small slope is the indication of a stable flow regime. For rivers with highly variable flow regimes (like the Krishna or the Limpopo in figure 2), Q90 may be equal to zero, or be very small. For basins with a stable flow regime, it may constitute a larger proportion of MAR. Many studies on low-flow hydrology, reviewed by Smakhtin (2001) suggest that Q90 varies primarily in the range of 0 to 50 percent of MAR. Q90 accounts only for a smaller part of the total annual baseflow (Smakhtin 2001). By using Q90 as a measure of LFR, we implicitly suggest that only part of the river baseflow could be allocated to the environment.

Some existing experience with setting HFR (e.g. Hughes and Hannart 2003) suggests that HFR may vary in the approximate range of 5 to 20 percent of MAR, depending on the type of flow regime and the objective of the environmental flow management. Following the principles of highly variable and stable flow regimes described above, it was decided to

FIGURE 2.
Examples of non-dimensional flow duration curves for rivers with different flow regimes.
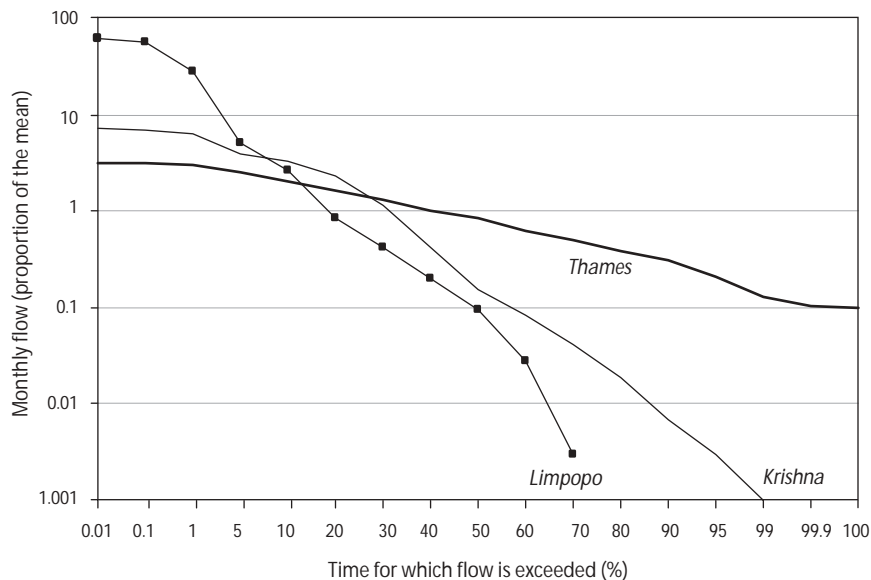
TABLE 1.

A conceptual rule for the estimation of environmental high-flow requirement.

Low Flow Requirement (Q90)	High Flow Requirement (HFR)	Comment
If Q90 < 10% MAR	Then HFR = 20%MAR	Basins with very variable flow regimes. Most of the flow occurs as flood events during the short wet season.
If 10%MAR ≤ Q90 < 20%MAR	Then HFR = 15%MAR	
If 20%MAR ≤ Q90 < 30%MAR	Then HFR = 7%MAR	
If Q90 ≥ 30%MAR	Then HFR = 0	Very stable flow regimes (e.g. groundwater dominated rivers). Flow is consistent throughout the year. Low-flow requirement is the primary component.

Note: MAR= Mean annual runoff.

approximate HFR by a set of thresholds linked to the different LFR levels (table 1). For basins with highly variable flow, where Q90 < 10 percent of MAR, HFR was set at 20 percent of MAR. For rivers with stable flow, where Q90 is higher than 30 percent of MAR, HFR was considered to be equal to zero. Finally, for rivers with Q90 ranging from 10 to 20 percent and from 20 to 30 percent of MAR, HFR levels were set at 15 percent and 7 percent of MAR, respectively. These "rules of thumb" effectively represent a stepwise substitute for the method suggested by Hughes and Münster (2000) and Hughes and Hannart (2003) as the two components of EWR –LFR (Q90) and HFR –complement each other. In reliably flowing rivers with high baseflow contribution (and consequently high LFR), HFR is low. In highly variable rivers, baseflow contributions are normally low (and consequently LFR is low), and the total environmental requirement is dominated by high HFR.

The total annual EWR was calculated as a sum of two estimates: LFR and HFR. As both components varied between river basins, the total EWR reflected the differences in flow regimes globally. The main restriction of the developed rule in its present form was that it did not explicitly specify a desired conservation status or environmental management class in which an ecosystem needed to be maintained. Therefore the estimation rules effectively produced one possible "scenario" of EWR,

which is interpreted in one of the following sections.

Environmental Water Scarcity Indices and Mapping

Every river may be characterized by its total resource capacity. The measure of this capacity is MAR, which is the average of total annual volumes of water, recorded or calculated at a particular point in a river over a long period. The concept of long-term average water resource is equally applicable at the scale of a specific aquatic ecosystem, a country, a geographical region or the entire world. For example, the sum of all the world rivers' long-term average annual flow at their outlets would represent MAR of the world. The difference between total resource and EWR represents utilizable capacity of the resource. Ideally, it is only the surplus water, in excess of these requirements, that should be made available for human use (Molden and Sakthivadivel 1998; Smakhtin 2002).

By comparing estimates of total resource capacity with estimates of EWR and actual total water use, it is possible to identify the regions where the human water use and the maintenance of functional ecosystems are in conflict. Cases where the total actual water use exceeds the difference between the total water available and EWR may be referred to as cases

of 'environmental water scarcity'. Depending on the spatial resolution used in such calculations, the regions, countries, watersheds or parts thereof may be declared as environmentally water scarce.

The concept of environmental water scarcity is illustrated graphically in figure 3. The entire box in these pictures represents the average total volume of water available in a basin (e.g. MAR). The bottom portion of the box represents the ecological water needs; that is the amount of water needed to sustain a functioning ecosystem. The rest of the box represents the amount of water that can potentially be put to other uses: agriculture, industry etc. – utilizable water. The actual water use can be represented either by the consumptive water use or by the total water withdrawals. The consumptive water use is the complete removal of water for use from the system. Withdrawal is the water that is taken out of the system, b•But part of this water, may return to the system after use. Withdrawal is a better indication of impacts on available water resource and ecosystems,

FIGURE 3.
A schematic representation of the relationships between total water resources, total present water withdrawals and EWR in (a) environmentally safe, (b) environmentally water scarce, and (c) environmentally water stressed river basins.
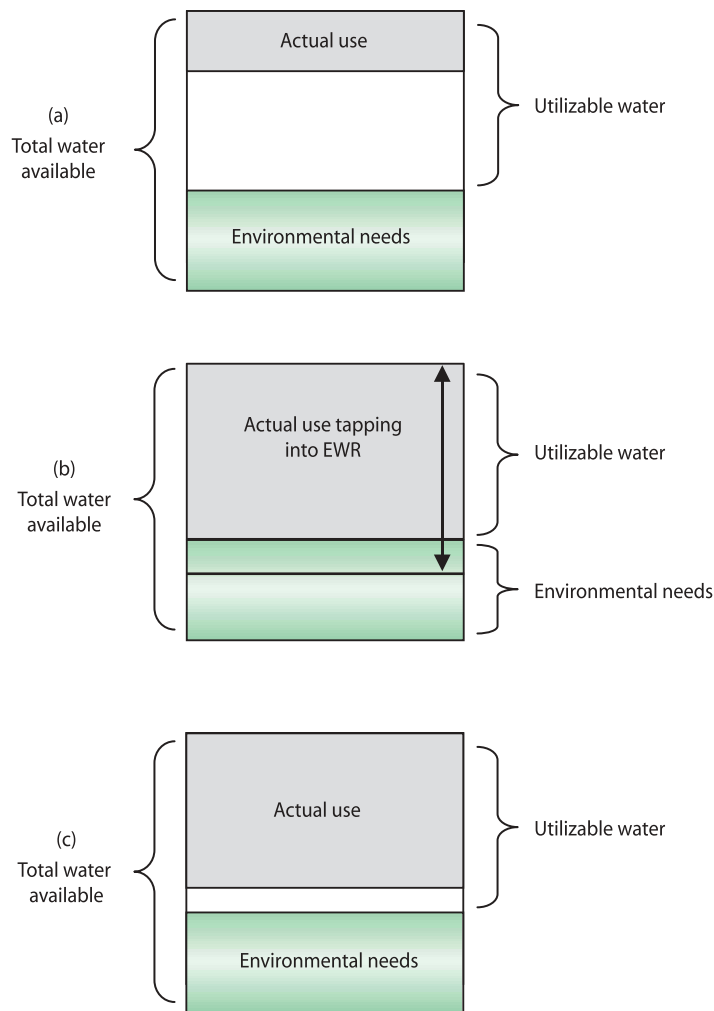
because it is normally not clear how much water returns to the system, in what condition or where in the basin. The present actual water use (withdrawals) is represented in figure 3 by light gray shading.

Basins where the use is not tapping into or not even close to the water reserved for the environment were considered to be ecologically "safe" (at least in the present water use terms, and irrespective of possible degradation due to pollution, figure 3a). Basins where the use is tapping into EWR were "environmentally water scarce" (figure 3b). In basins like this, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the basin is less than estimated EWR. Basins in which the total water use is such that the remaining amount of water is close to the estimated EWR, are at risk of becoming "environmentally water scarce" i.e. highly likely to be degraded and threatened (figure 3c). The latter may also be referred to as "environmentally water stressed". It should be recognized that many of the basins that appear to be on the "safer side" in our approach may, however, already be environmentally stressed from other causes (pollution, siltation, introduced species etc). Water withdrawals at that point can cause ecological damage to them much quicker.

There are several possible ways of numerically categorizing environmental water scarcity. The option we selected for this pilot assessment focuses exclusively on that portion of water, which is available in a basin on top of the estimated EWR, that is the utilizable water section in figure 3. We then define a water stress indicator (WSI), which reflects the scarcity of water for human use by taking into account EWR.

$$\text{WSI} = \frac{\text{Withdrawals}}{\text{MAR-EWR}} \qquad (1)$$

This index may not be negative, as EWR is always less than total water available (MAR). WSI calculated by this method implicitly

assumed that water had been reserved for ecological purposes and estimated a ratio (or a percentage) of total withdrawals to utilizable water. If the index exceeded 1, the basin was classified as water scarce (table 2). Smaller index values indicated progressively lower water resources exploitation, and consequently, lower risk of environmental water scarcity. Water stress indicators of a similar form are commonly used in human water stress assessments (Alcamo et al. 2002; Oki et al. 2001). However, EWR have not been considered in human water stress assessments before, and only the ratio of total use to total water available was calculated. The previous expression for WSI was therefore:

$$\text{WSI} = \frac{\text{Withdrawals}}{\text{MAR}} \qquad (2)$$

The severity of water scarcity in these publications was ranked as follows: WSI < 0.1 no water stress; $0.1 \leq$ WSI < 0.2 low water stress; $0.2 \leq$ WSI < 0.4 moderate water stress; WSI $\geq$ 0.4 high water stress and WSI >0.8 very high water stress.

These categories, as well as the categories suggested in table 2, were rather arbitrary. However, the following should be taken into account while interpreting WSI values. Water problems usually aggravate during the dry season of the year or in drought years. The methods at present do not suggest means of addressing this seasonal issue as average annual values are used throughout the study. It is however very likely that in basins with a high WSI, EWR are tapped into during dry periods and during dry years. This is why the basins with WSI values of 0.6 may be classified as water stressed. In the context of figure 3, the total water (entire box size) available during a drought year is much smaller than the average MAR. The actual water use in a dry year does not change much. Even if EWR are smaller during a drought, the buffer between the water use and the water available gets smaller or

disappears completely. Therefore, basins with higher WSI values have a higher risk of being "environmentally water scarce" during droughts. It has to be understood however that a threshold of 0.6 is rather arbitrary. Without explicitly introducing the concepts of frequency and assurance into the assessment of environmental flows, it is impossible to predict whether the estimated EWR will or will not be satisfied in any particular year.

TABLE 2.
Categorization of environmental water scarcity.

WSI (proportion)	Degrees of Environmental Water Scarcity of River Basins
WSI > 1	Overexploited (current water use is tapping into EWR)— environmentally water scarce basins.
$0.6 \leq$ WSI < 1	Heavily exploited (0 to 40% of the utilizable water is still available in a basin before EWR are in conflict with other uses) – environmentally water stressed basins.
$0.3 \leq$ WSI < 0.6	Moderately exploited (40% to 70% of the utilizable water is still available in a basin before EWR are in conflict with other uses).
WSI < 0.3	Slightly exploited.

Notes: WSI= Water stress indicator; EWR= Environmental water requirements.

Discussion

## Global Mapping of Environmental Water Requirements and Water Scarcity

The estimates of the long-term total annual water resources (MAR) calculated by WaterGAP 2 model are presented in figure 4. The detailed analysis of this map and other model outputs are presented in Döll et al. (2003) and are not repeated here. It may be noted that the model is likely to underestimate the water availability in those snow-dominated basins where no discharge measurements are available for calibration, due to the fact that snow precipitation is strongly underestimated by precipitation gauges. In some semi-arid and arid basins, water availability is likely to be overestimated, as the model in its present form does not capture some of the complex processes in these areas, like transmission losses. Similar problems are encountered in other global water modeling studies (e.g. Fekete et al. 1999). In general, the map in figure 4 reproduces well the known pattern of water availability distribution over the globe.

The estimates of EWR based on the simulated monthly time series, range from 20 to 50 percent of MAR (figure 5). At the lower end of EWR (20%), there are river basins with extremely variable flow regimes, where EWR are dominated exclusively by HFR (table 1). At the top end of EWR (50%) there are river basins with stable flow regimes where EWR are dominated exclusively by LFR (represented by Q90). While the calculated values of Q90 range globally mostly from 0 to 50 percent of MAR, in North America, a number of river basins were found to have unrealistically high Q90 values (up to 83 % of MAR). It is unlikely that such estimates can be correct in basins with a pronounced annual snowmelt-generated rise in flow, which should increase flow variability, ensure a large slope in the shape of FDCs and consequently result in smaller low-flow proportion

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FIGURE 4.
A map of long-term average annual water resources (MAR) by the basin, calculated by the WaterGAP 2 model.
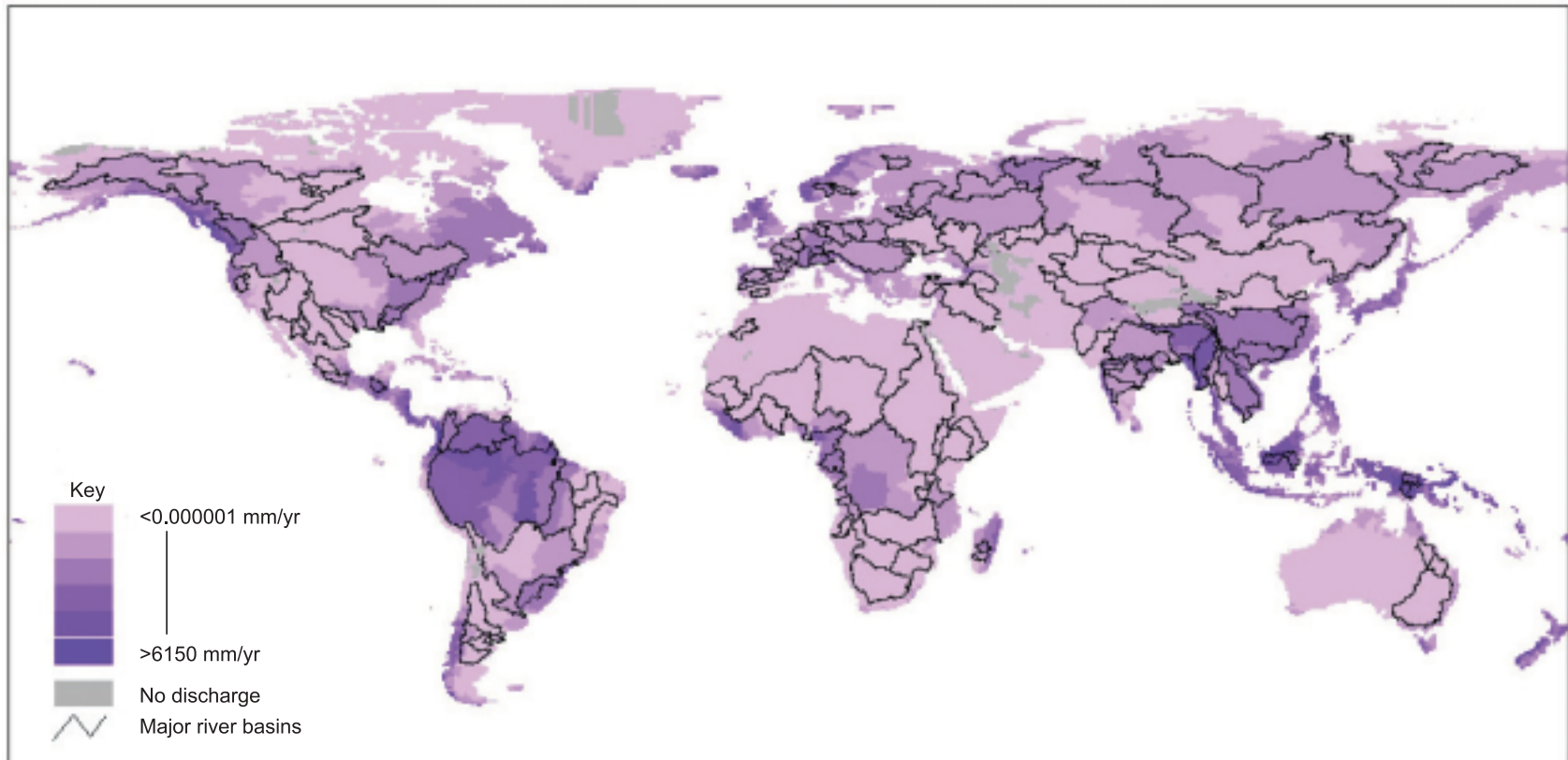
in total annual runoff. The maximum value of 50 percent of MAR has been assigned in this study to LFR for all those basins, where Q90 exceeded the threshold of 50 percent of MAR. This rule of thumb, albeit arbitrary, ensured that the total EWR in such basins were coherent with the range of Q90 values normally referred to in the literature (Smakhtin 2001). One possible reason for the calculated high Q90 values in North America was that the hydrological model was calibrated against observed flow records affected by regulation for hydropower. Such impacts are typical in Canada, for example. They may decrease flow variability and escalate Q90 (and subsequently LFR and total EWR). This issue needs to be examined more closely in the future in a broader context of simulating natural flow sequences throughout the world.

As the map in figure 5 shows, EWR are the highest (normally over 40% of 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 5). In highly variable monsoon-driven rivers (e.g. in India), the rivers of the arid areas that flow after infrequent rains (e.g. Limpopo basin, North Africa), and also in most of the East Siberian rivers with high snowmelt flows, the estimates of EWR are lower (20-30% of MAR).

EWR estimates obtained by any method may not be considered without a reference to some negotiated or prescribed ecosystem conservation status (Petts 1996; Durban et al. 1998; DWAF 1997). The higher this status, the higher the required EWR will be. Some earlier studies (Tennant 1976) suggested that 10 percent of

MAR is the lowest feasible limit for EWR as it corresponds to a severe degradation of an ecosystem, while 60 to 100 percent of MAR represents an "optimal range". Other sources suggest that "the probability of having a healthy river falls from high to moderate when the hydrological regime is less than two-thirds of the natural" (Jones 2002). In this context, the estimates in figure 5 appear to be on the low side of the plausible EWR. In Tennant's (1976) terminology, they may be interpreted as EWR, which are required to ensure a "fair" condition of ecosystems (in terms of water volume only and without taking into account water pollution). On the other hand, most estimates of the total annual EWR obtained by comprehensive expert-panel methods for rivers in South Africa and range between approximately 15 to 55 percent of MAR, correspond to ecosystems that are "moderately modified" from the natural state (Hughes and Hannart 2003). This is the third conservation status (environmental management class) in the South African category system (DWAF 1997), after "largely natural" and "slightly modified" ecosystems. "Moderately modified" ecosystems are interpreted as those where "sensitive biota is reduced in numbers and extent". This category is followed only by "highly modified" ecosystems with a very high degree of degradation. EWR estimates obtained in our global scenario vary from 20 to 50 percent of MAR, and therefore are in the "moderately modified" ecosystem range at least in terms of the South African system, which we have effectively used at this stage. The discussion above may suggest that, to avoid further degradation of freshwater dependent ecosystems, attempts should be made to achieve a compromise between the allocation of water for environment and other uses (e.g. agriculture), at least in the calculated range (20 to 50% of MAR should be allocated for environmental purposes). It does not however imply that more detailed ecosystem-specific studies may not indicate higher or lower EWR.

FIGURE 5.
A global distribution of estimated total EWR expressed as a percentage of long-term mean annual river runoff.

Key

20 - 25%

25 - 30%

30 - 35%

35 - 40%

40 - 45%

45 - 50%

No discharge
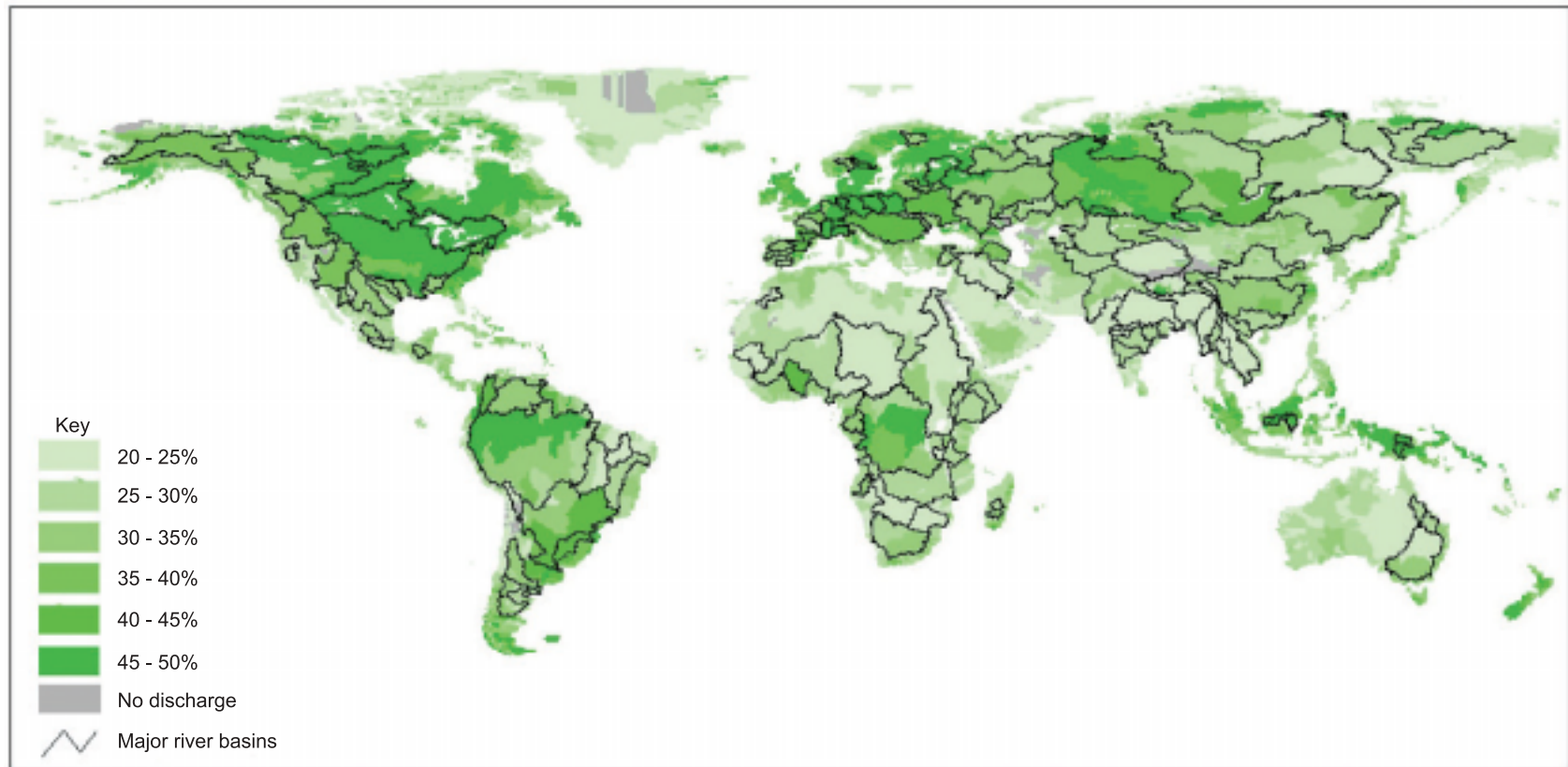
Major river basins

The higher EWR could be established for ecosystems with high conservation importance and / or sensitivity. The lower EWR may be negotiated in river basins with already oversubscribed water resources.

The distribution of WSI values over the globe (water withdrawal as a proportion of water available for human use) is presented on the map in figure 6. This map was developed based on the estimated EWR illustrated by figure 5. It highlights basins where there is insufficient water to meet EWR and therefore it may be interpreted as a first global picture of environmental water scarcity by the basin. In contrast to figure 6, figure 7 reflects the traditional way in which water scarcity is assessed (as expressed by (2) above). It compares water withdrawals with the water availability, without taking into account EWR. This is the approach used in most of the current water resources models and scenarios (Alcamo et al. 2002; Oki et al. 2001). The comparison of maps in figures 6 and 7 illustrates that when the ecosystem's water requirements are taken into account, more basins show a higher degree of water stress. This is not surprising as, if water is reserved for the environmental purposes, its availability for other human uses naturally decreases. This seemly straightforward fact is hardly taken into account in most current water scarcity assessments and projections. And, given that many livelihoods, especially those of the poor, depend on productive freshwater-dependent ecosystems, these assessments currently overestimate the amount of water directly available for people.

In this context, the basins in the yellow and red bands are those, where humans are at a higher water stress if water allocations are made for the maintenance of freshwater dependent ecosystems in moderately modified conditions. On the other hand, if environmental water allocations are not maintained at the estimated EWR levels over a long term, the ecosystems of the basins in the yellow and red bands may not be preserved even in moderately modified state and are likely to deteriorate further, consequently affecting local livelihoods. The circled basins in figure 6 are a few example basins where over-abstraction of water is causing problems to the ecosystems and to the people that depend on their environmental services. These and some other basins "move" into the higher water stress category, if EWR are "reserved".

The Murray–Darling Basin in Australia, with a water stress indicator greater than 1 (figure 7), is an example of an environmentally water scarce basin. This basin, the largest in Australia, has a total area of just over 1 million km^2 with highly uneven distribution of flow (both spatially and in time). Throughout Australia's history, the rivers in the basin have been severely modified and regulated. The main economic activity, which uses 95 percent of the total water withdrawal in the basin, is irrigated agriculture. This sustained over-abstraction of water has negatively impacted agricultural production and has caused severe environmental problems in the system. These impacts include high salinity levels that affect soil productivity, massive algae booms, nutrient pollution, and the consequent loss of native species, floodplain areas and wetlands. Maintaining EWR at even a modest level of 30 percent of the total flow to ensure a fair condition of the river (as estimated and shown in figure 5) is a big challenge, as water consumption above the mouth of Murray has reduced the mean flow by nearly 80 percent.

The Orange River in southern Africa is another example of a river with a high water stress indicator (0.8-0.9). The basin, with an area of just over 1 million km^2 and a total flow of 12 km^3 , crosses the boundaries of four southern African countries and carries approximately 25 percent of the total surface water resources of semi-arid South Africa. The upstream reaches of the basin have been so severely modified and regulated that the combined reservoir storage in the basin has already exceeded the total annual flow. This degree of modification will increase

FIGURE 6.
A map of a water stress indicator which takes into account EWR. Areas shown in red are those where EWR presented in fig. 5 may not be satisfied under current water use. Most of the areas with variable flow regimes (and consequently the modest EWR of 20-30% of MAR) fall into the areas of environmental water scarcity. The circles include example river basins which can move into a higher category of human water scarcity, if EWR are to be satisfied. The risk of not meeting EWR will remain high in these basins, particularly as water withdrawals grow.

Key
Low WSI <0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
High WSI >=1
No discharge
Major river basins

Huang-Ho (Yellow) Basin, China
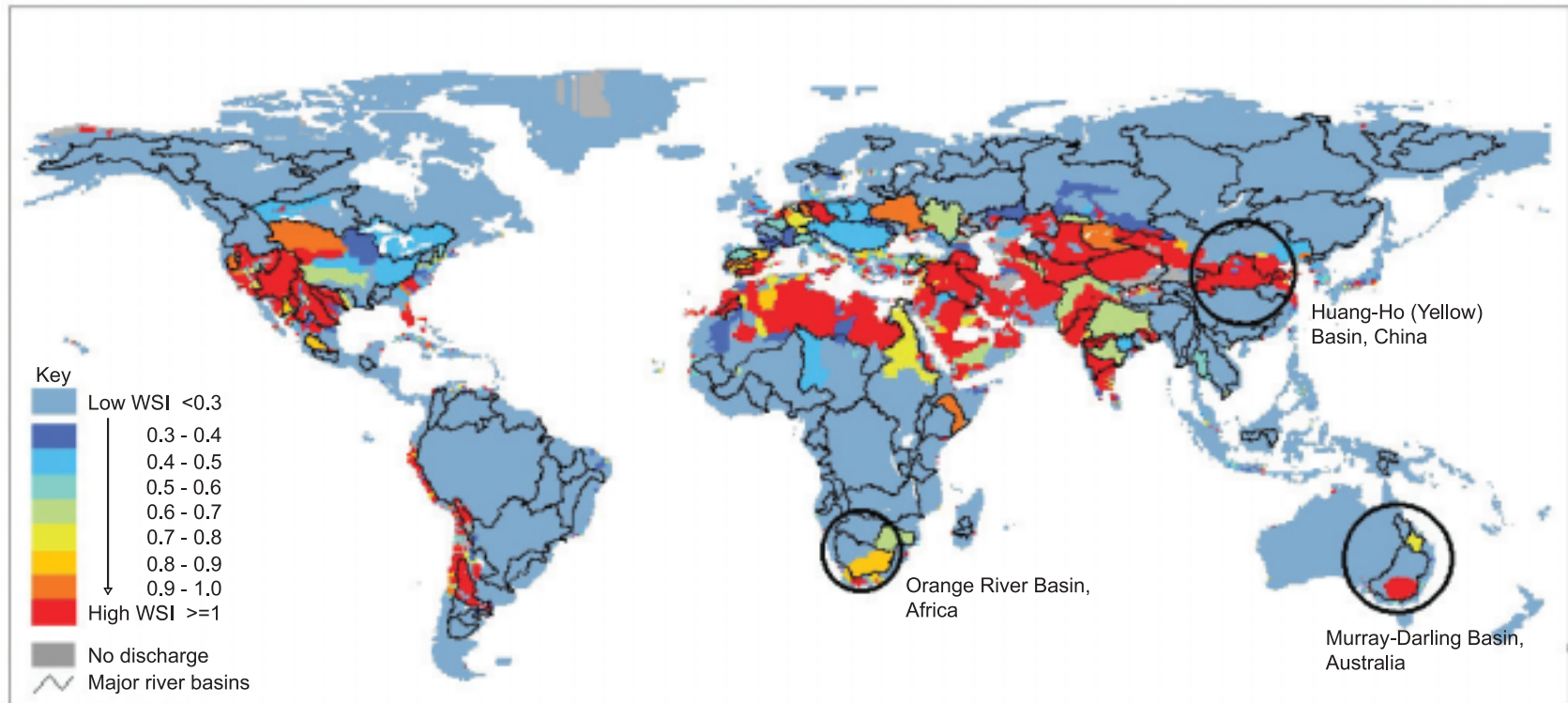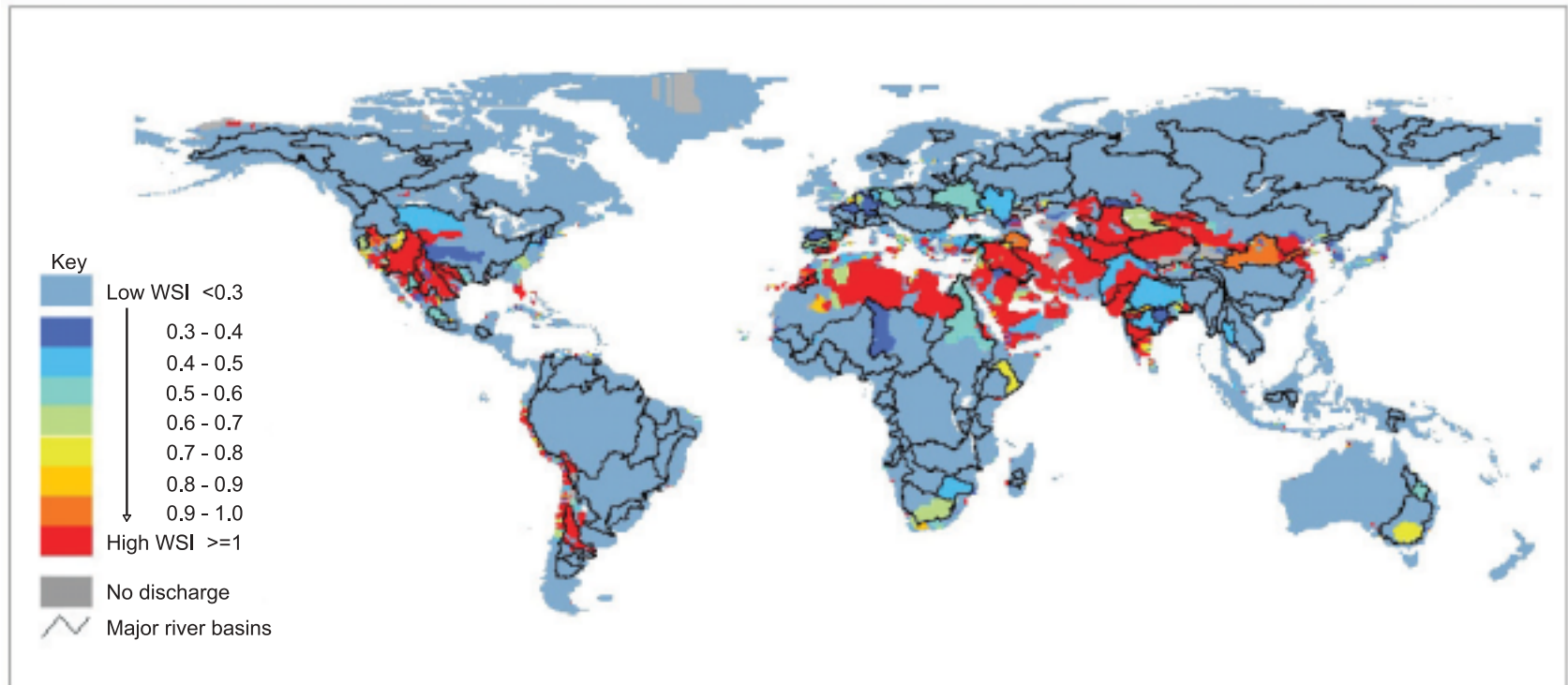
Orange River Basin, Africa

Murray-Darling Basin, Australia

FIGURE 7.
A map of the "traditional" water stress indicator (water withdrawals as a proportion of the mean annual river runoff).

Key

Low WSI <0.3

0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
High WSI >=1

No discharge

Major river basins

even more with the development of Lesotho Highland Water Scheme. In addition to the impacts of dams and canals on migratory and other native freshwater species, other environmental problems in the basin include deteriorating water quality, the occurrence of black fly pest populations, and the proliferation of reed beds in river channels that affect native species.

The Huang-Ho River (Yellow River) Basin in China is one of the major river basins of the country, with an area of almost 800,000 km^2, a population of over 100 million, and an annual flow of 70 km^3. The river has nearly reached the level of complete water resources exploitation and can be defined as an area in crisis both for people and nature. The water utilization rate in the Huang-Ho River is about 90 percent of the available water. The duration of low flow periods in the river has increased from forty days in early 1990s to two hundred days in 1997. As reflected in figures 6 and 7, reserving even a bare minimum of 25 percent of the total flow for the environment brings the basin to the level of absolute water scarcity with a water stress indicator exceeding 1.

We have overlaid the country boundaries (with country population figures at the 1995 level) on the major river basin boundaries to quantify the extent of environmental water scarcity. Basins where the current water use is already in conflict with 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 the "environmentally safe" to the "environmentally stressed" and further into the "environmentally scarce" categories. It is highly unlikely that any transition in the reverse order is possible if food production is not intensified in the agricultural sector (which currently accounts for approximately 70 percent of the total water withdrawals in the world), and if environmental water allocation is not made a common practice

and an integral part of every river basin management plan.

Improving Methodology and Data Collection Efforts

This first attempt to consider ecosystem water requirements as a factor in the assessment of global water resources used an estimate of these requirements based exclusively on hydrological data and simple conceptual rules. No ecological information is currently explicitly present in the approach.

It is clearly recognized that such quick methods to establish EWR will not provide information with the level of confidence needed to guide day to day water management decisions in individual river basins. These methods are also unlikely to provide anything more than estimates of total environmental water volumes, as opposed to the full environmental flow regime, which could be established using more detailed assessment approaches. However, such estimates are vital to raise the awareness of the need to conduct more detailed assessment on environmental flows taking into consideration ecological variables. Global estimates, even crude, may also positively influence water allocation policies worldwide, by highlighting the limitations of current water scarcity assessments that do not consider aquatic ecosystems as legitimate users of water. Increased awareness of the need to establish environmental allocations, and the need for more detailed data and understanding of the relationships between a productive and healthy aquatic ecosystem and the flows required to sustain its functioning, should direct funding and effort into these research areas. This will be a step forward in achieving sustainable use of water resources for both people and ecosystems. The preliminary EWR estimates presented here may and should be further refined through the testing of methods

with local data and dialogues with stakeholders on the ground. Such refinement would effectively constitute the "groundtruthing" of any desktop assessment and would provide the feedback, which is necessary to improve it.

The future development of the work reported here should focus on the development of a more ecologically relevant method for the assessment of EWR. The latter would require that locally and/or regionally available information on freshwater biodiversity and also on the sensitivity and conservation importance of aquatic ecosystems is collated and analyzed in the context of hydrological variability. This would allow a better understanding and quantification of hydrology and aquatic ecology links to be achieved, and the realistic environmental water management targets to be formulated for different aquatic ecosystems, basins and regions. Some useful indices of biodiversity (fish family richness) and stress on water resources (wilderness measure, water resources vulnerability) have been suggested and calculated for major river basins by various development and conservation organizations such as WRI, WWF-US, and UNEP-WCMC (Revenga et al. 1998; 2000; Abell et al. 2000; Groombridge and Jenkins 1998). These indices, however, are not related to the productivity of freshwater dependent ecosystems, which is a more important parameter for considering the links between environmental flows and livelihoods. The relevant indices of productivity should be suggested/developed and used to improve the existing crude estimates.

As was already mentioned, estimates of EWR for an individual aquatic ecosystem depend upon and should be related to the environmental management target set for this system. The study in its present form does not explicitly consider such targets. It is possible that the environmental management class or the desired future state of a basin may be (at least at the preliminary level of global assessment) determined using these or similar indices, where

highly diverse and/or highly stressed river systems have the highest conservation priority and basins with low diversity and/or low stress have the lowest priority. Information on freshwater biodiversity and its condition, however, is sparse worldwide, even in those developed nations that have considerable financial and technical resources. With a few exceptions, such as Australia and the United States, most countries have a large information gap regarding freshwater species, especially at lower taxonomic orders. This makes the establishment of EWR an even greater challenge. Fortunately there are currently a few ongoing freshwater assessments and initiatives around the world that focus on inland water species, their status and conservation. As part of IUCN's large-scale Water and Nature Initiative (WANI), the IUCN's Species Survival Commission (SSC) and the Ramsar Bureau are engaged in synthesizing data on the status of freshwater biodiversity. In addition, the IUCN/SSC has a broader Freshwater Initiative, which intends to identify a set of species groups to serve as indicators of freshwater biodiversity and ecosystem integrity. Also, the IUCN/SSC is compiling baseline species data including species distribution maps, population trends, species' ecological requirements (e.g., habitat preferences, altitude ranges), the degree and types of threat, conservation actions (taken and proposed) and key information on the use of each particular species. These programs aim to address the gaps and the lack of global coverage in current information on freshwater ecosystems. It is envisaged that information generated through these initiatives will enable the development of a more ecologically sound method for EWR at the global scale. At the same time, while it is logical to build on these initiatives, it must be noted that biodiversity as defined in terms of species diversity is only a partial indicator of the ecosystem importance for humans. It can omit many of the natural resources that are important for supporting food

security and livelihoods. Other goods and services of freshwater dependent ecosystems should also be quantified in different hydrological settings and used to obtain more robust and ecologically sound desktop methods for the assessment of EWR.

The study at present deals exclusively with the river flow (discharge). Changes in flow may impact ecosystem processes indirectly through water temperature, flow velocity, water depth, etc. The sensitivity of river ecosystems to water abstractions may be determined by channel geometry (M.Acreman, CEH, pers.comm). For example, wide shallow rivers may have a tendency to be sensitive to water abstractions, as any reduction in flow reduces available habitat (e.g. represented by wetted perimeter), while narrow deep rivers tend to be less sensitive to water abstraction. Rivers in upland areas with wide and shallow channels may thus be sensitive to flow reduction, and have higher EWR, while still having flashy, variable hydrological regimes. Similarly, narrow deep rivers in lowland areas may appear to be less sensitive to flow reduction and thus have lower EWR, while still having invariant hydrological regimes. These considerations may also need to be taken into account in the future in refining the EWR desktop assessment methods.

Another issue that may need addressing when discussing the establishment of EWR, is whether the water left in the system is of sufficient quality to sustain ecosystems and their dependent species. Unfortunately, as in many other aspects of freshwater resources, the information and data on the quality of rivers, lakes, streams and groundwater resources are lacking in most countries. Information about water quality at the global level is difficult to obtain for a number of reasons. Water quality problems are often local, and natural water quality is highly variable depending on the location and season. There have been few sustained programs for the global monitoring of the quality of water, and the information received is highly localized and far from complete. One of the global attempts at water quality monitoring has been the UNEP GEMS/WATER program that examined data from 82 major river basins worldwide over a period of a decade and a half. This program gathered data on a variety of water quality issues, including nutrients, oxygen balance, suspended sediments, salinization, microbial pollution, and acidification. Yet, the number of monitored watersheds was too small and the frequency and type of measurements were too inconsistent to paint a comprehensive picture of the global water quality trends. Further studies of this kind need more comprehensive and systematic data collection, and monitoring should be carried out indefinitely so that long-term trends can be analyzed. Data needs are especially critical for developing countries, which often do not have strong national monitoring programs, yet, face serious water quality problems.

The hydrological data will remain an important integral part of EWR assessments at the global scale. Therefore, subsequent research should also focus on improved estimates of the flow time series and water use characteristics. As has already been mentioned above, flow simulations in several basins in North America have produced unrealistically high values of Q90. In some other areas (e.g. upstream Nile basin, where most of the Nile water is generated and low flows maintained partially due to lake regulation), Q90 values were found to be close to zero. Such problem areas will need to be revisited and model simulations, adjusted. It may also be useful and necessary to compare the performance of other global hydrology models (Fekete et al. 1999; Oki et al. 2001) in this regard.

Taking into Account the Spatial and Temporal Dimensions

Our study at present does not explicitly consider the differences in the availability of water between the different seasons of the year. Nor did we attempt to analyze the conditions which occur during droughts. However, it is clear that a number of the water-related problems, including the provision of water for ecosystems, occur during the dry season of the year and during prolonged multi-annual droughts. The monthly temporal resolution of simulated hydrological data, however, allows these analyses to be carried out in the future. A combination of the improved estimates of EWR and water resources availability during droughts and dry seasons should allow deeper insights into water scarcity.

One of the possible spin-offs of the global assessment of EWR could be the development of more detailed, regionally or basin level focused methods and guidelines. While a few countries already have expertise and a good track record of developing and applying different environmental water assessment methodologies, many developing countries have neither of these. For countries, where experience and relevant legislation already exist (e.g. South Africa, Australia, New Zealand, UK), the estimates of EWR, which emerge from this pilot global assessment are too coarse. However, for those countries that do not have such experience, legislation and expertise, the global estimates may represent a starting point to help set priorities for action, or at least develop awareness of the possible consequences of not accounting for environmental water allocations. Global estimates may be "downscaled" to the level of a particular country, basin, or a geographical region and interpreted/developed further, using more detailed, region/basin-specific information. While every attempt should be made to make use of ecological information,

there is still an urgent need to improve the hydrologically 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 and/or ecological characteristics. More specifically, it could include baseflow filtering from the available flow records, or the incorporation of river classification studies (e.g. such as Haines et al. 1988). As global study progresses, it could be possible to design "environmentally acceptable modified flow regimes" and eventually convert them into operational rules.

This study deals with the "current" water use (withdrawals) at the 1995 reference level. By using various projections of water use for the future, it would be possible to determine which basins may become environmentally water scarce in the future and when. It could also be possible to identify the risks of further ecological degradation if an ecosystem's EWR are not met. Many environmental NGOs, conservation organizations and funding agencies may be able to use such projections to aid in their priority setting exercises.

The current study does not distinguish between different types of water uses. By comparing the estimates of water use in a specific sector (e.g. agriculture) with EWR, it could be possible to establish where environmental degradation is caused by a specific sector, and identify policies and management changes that will help improve the situation.

Finally, because many rivers cross international boundaries, political conflicts and national priorities need to be considered. The necessity and commitment to satisfy EWR in one country, for example, may cause or aggravate a water scarcity problem in another. The lack of commitment in one of the neighboring countries to satisfy environmental water demand may cause similar problems within the basin. Global assessments, such as

the one presented here, may therefore point to the regions where conflicts may occur due to environmental water scarcity. This may be of particular interest to many development agencies that find it difficult to decide as to how to allocate aid. A global assessment highlighting problem areas and potential future conflicts among water users and countries can be used by these agencies as a tool in their resource allocation process.

Policy Considerations and Institutional Challenges

This pilot study attempts to highlight the urgent need to set and implement EWR for river basins globally, and suggests some directions for future research. It has been largely technical. There is however a number of non-technical issues which pertain to EWR, scarcity and security. It is no longer proper to manage water in a fragmented and sectoral manner, as has hitherto prevailed in the world. To achieve sustainable development, future water management will require an ecosystem approach, that recognizes the importance of the functioning and integrity of the ecosystem for an adequate water supply and the attainment of development objectives (Poff et al. 1997; Naiman et al. 2002).

One of the major challenges in adopting and implementing an ecosystem approach to water resources management is overcoming institutional barriers. A first step in this regard would be the establishment of basin-level dialogues among different users to negotiate and agree on the allocation of water resources. These dialogues, in combination with improved data on water availability, use and quality, as well as improved information on ecosystem requirements, can lead to a range of measures that would prevent future water scarcity while meeting development needs and maintaining functional ecosystems.

The incorporation of EWR in the picture of global water resources assessment may change the existing estimates of water availability in different regions and lead to re-evaluation of the concepts of water scarcity. The results of improved global water analyses would show where populations and ecosystems are more at risk of water scarcity and help formulate environmentally relevant policy options and water resource management strategies for selected countries, basins and other levels of spatial resolution.

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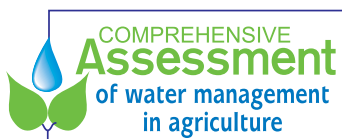
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COMPREHENSIVE
Assessment
of water management
in agriculture