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Global assessment of current water resources using total runoff integrating pathways

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Abstract The anticipated water scarcity in the first half of this century is one of the international issues of most concern, which needs to be adequately addressed. However, even though the issue has an international impact and worldwide monitoring is critical, there are limited global estimates at present. In this study, annual water availability has been derived from annual runoff estimated by land surface models using total runoff integrating pathways (TRIP) with 0.5° by 0.5° longitude/latitude resolution globally. The global distribution of abstraction was estimated for each sector at the same spatial resolution based on country-based statistics of municipal water use, industrial water use, and agricultural intakes, using a global geographical information system with global distribution of population and irrigated crop land area. The total population under water stress estimated for 1995 corresponded very well with earlier estimates. However, the number is highly dependent on how one assumes the volume of water from upstream of a region, which can be considered as "available" water resources within the region. Therefore it is important, even for global scale analysis, to evaluate the regional water quality deterioration and the real consumption of water resources in the upper part of the stream, as well as the accessibility of water. Further studies should be promoted by an integrated approach to improve the accuracy of future projections on both the natural and social aspects of water resources.

Key words water resources assessment; water scarcity; water availability; abstraction; demand for water

Evaluation des ressources en eau à l'échelle mondiale à l'aide des chemins intégrateurs de l'écoulement total

Résumé La pénurie d'eau à laquelle on s'attend au cours de la première moitié de ce siècle est un problème international particulièrement inquiétant qui devrait faire l'objet d'une évaluation adéquate. Il n'y a cependant à l'heure actuelle que peu d'estimations à l'échelle mondiale, en dépit de la dimension internationale du problème et alors que le niveau de l'observation hydrologique est partout critique. Dans cette étude, la disponibilité de l'eau à l'échelle annuelle a été déduite de l'écoulement annuel estimé par des modèles de surface utilisant les chemins intégrateurs de l'écoulement total selon une résolution de 0.5° de longitude par 0.5° de latitude. La répartition des prélèvements, selon la même résolution spatiale, a été estimée sur la base des statistiques par pays des utilisations municipales, industrielles et agricoles de l'eau grâce à l'utilisation d'un système d'information géographique mondial de la répartition de la population et des surfaces irriguées. L'importance de la population souffrant d'un déficit en eau estimée pour 1995 s'accorde très bien aux anciennes estimations mais cette estimation dépend dans une large mesure des hypothèses concernant la fraction de l'eau venant de l'amont qui peut réellement être considérée comme "disponible". Cela souligne l'importance d'études régionales de la détérioration de la qualité des eaux, la consommation réelle et l'accessibilité de l'eau. Ce dernier facteur devrait être mis en rapport avec la façon dont de nombreux grands schémas de prélèvements ont été mis en place régionalement. Il serait nécessaire d'entreprendre des études complémentaires intégrées pour améliorer la précision des projections concernant les aspects hydrologiques et sociaux des ressources en eau.

Open for discussion until 1 June 2002

Mots clefs évaluation des ressources en eau; disponibilité de l'eau; prélèvement; demande en eau

INTRODUCTION

The water resources are seriously under pressure even at present in several regions of the globe, and it is anticipated that the situation will be worse during the first half of this century (Cosgrove & Rijsberman, 2000). The estimation of the current level of water stress is important for reliable projections of the severity of the coming water crisis. However, most of the previous global analyses of water scarcity have been carried out on a country or river basin basis. Among the exceptions are the works by Takahashi *et al.* (2000), Alcamo *et al.* (2000), and Vörösmarty *et al.* (2000), who presented water scarcities on a 0.5° × 0.5° grid for the globe. Considering the importance of global water scarcity, it is postulated that future projections should be evaluated by multiple procedures, models and methods, used by different organizations, since the reliability of the estimates will be supported if similar results are obtained from different scientific approaches, information and data processing.

For the estimation of the global supply of water, observed or simulated runoff data are generally used. Shiklomanov (2000a,b) estimated the water availability for 26 regions of the world based on observed river discharge at 2500 stations. Takahashi *et al.* (2000) estimated the monthly water balance in 0.5° × 0.5° grids using a bucket model (Manabe, 1969), with the potential evapotranspiration derived from the Penman method using current and future climate projections (temperature, wind speed, and precipitation) simulated by general circulation models (GCMs) at the Canadian Climate Centre, the Max Planck Institute, Hamburg, and the Centre for Climate System Research (CCSR) at the University of Tokyo. Vörösmarty *et al.* (2000) used a similar approach, but their water supply estimates are linearly adjusted to observations where discharge information is available, even though Alcamo *et al.* (2000) correlated the calibration factor with (a) the ratio of potential evapotranspiration to the total precipitation, (b) mean temperature, (c) open freshwater area as a ratio of the total catchment area, and (d) the groundwater recharge factor. In this study, water balances estimated by land surface models (LSMs) were used for the global estimates of water availability. Such models were originally developed to be included in numerical atmospheric models to compute the lower boundary condition of the atmospheric circulation. The bucket model (Manabe, 1969) is the first generation LSM and is relatively simple. However, current LSMs consider detailed energy and water balances at land surfaces and include hydrological, radiative, and even biogeochemical processes (e.g. Sellers *et al.*, 1996; Dickinson *et al.*, 1998). All the GCMs that provide future climate projections use some kind of LSM. Since current LSMs can simulate monthly river runoff considerably well, provided that the precipitation and other forcing input data for the LSMs are accurate enough (Oki *et al.*, 1999), it is highly possible that LSMs will be directly used for water resources projections in the future when GCMs will simulate the hydrological cycle with enough accuracy. Therefore it is worthwhile to apply the current global water balances calculated by LSMs for current water resources assessments. The methodology and results are presented in the following sections.

For the demand side of water resources assessments, two distributed data sets can be used globally in 0.5° × 0.5° longitude/latitude grid boxes, namely population and irrigated land area. In this study, country-based statistics, such as municipal water supply and industrial water use, are assumed to be proportional to the population distribution, and the agricultural intake is assumed to be proportional to the irrigated land area. A global geographical information system (G-GIS) was developed to convert country-based statistics into grid-based global distributions. Statistics were given for various "current" years, and all of the statistics were linearly adjusted to 1995. The target year was selected partly in order to compare the results with previous global estimates (WMO, 1997; Vörösmarty *et al.*, 2000), but the most important reason was that the latest information globally available was for 1995.

From these estimates of global annual water supply and demand, the global distribution of water stress was estimated for every 0.5° × 0.5° grid globally, except for those grids more than half of which are covered by ice or water. The result is compared with previous estimates made on a country, river basin, and grid basis in the last section.

WATER AVAILABILITY ESTIMATED BY TRIP

Simulated runoff values from offline runs by 10 different LSMs are used for estimating water availability. Under the Global Soil Wetness Project (GSWP; IGPO, 1995), the global water balance was estimated by 11 LSMs using forcing data, such as precipitation, incoming short-wave and long-wave radiation, wind speed, temperature, humidity and surface pressure, from the International Satellite Land Surface Climatology Project (ISLSCP) (Meeson *et al.*, 1995). The names of the LSMs, references, and the groups handling each LSM for the GSWP are listed in Table 1. Surface runoff values estimated by a bucket model of the Center for Climate System Research, Univ. of Tokyo (CCSR) (Numaguti *et al.*, 1997) and a SiB model of the Japan Meteorological Agency (JMA) (Sato *et al.*, 1989) were sent to the GSWP Data Center. Therefore the average values of these two estimates were used for the surface runoff. As for the total runoff, the average values used were from the estimates of all the 10 LSMs except for BATS. The target period of the GSWP was from 1987 to 1988, and the surface and total runoff were produced approximately every 10 days in 1° × 1° grid boxes.

To estimate the river discharge, the gridded surface and total runoff data were divided into 0.5° longitude/latitude resolution and the total runoff integrating pathways (TRIP) network (Oki & Sud, 1998), corresponding to the horizontal resolution, was used for the river routing calculations. The TRIP network is the global river routing network similar to those developed by Vörösmarty *et al.* (1996) and Renssen & Knoop (2000). The outflow direction from each grid box is given in one of eight neighbouring grid boxes, and the global river channel network is constructed virtually. The flow direction in which the water will be routed was first determined from a digital elevation model, and manually corrected in order to match the actual river channel network. More detailed procedures are described in Okada (2000). The basin boundaries are also delineated from TRIP. Flow routing was improved from a simple linear scheme (Oki *et al.*, 1999) using a system similar to Arora *et al.* (1999). The

Table 1 Land surface models (LSMs) used to estimate the global water balance under the Global Soil Wetness Project (Dirmeyer *et al.*, 1999).

LSM	Affiliation of simulation group	Reference
BATS	University of Arizona, USA	Dickinson *et al.* (1986)
SSiB	Center for Ocean–Land–Atmosphere Studies, USA	Sellers *et al.* (1986)
SiB2	Colorado State University, USA	Sellers *et al.* (1996)
CAPS	National Center for Environmental Prediction, USA	Chen *et al.* (1997)
SSiB	GSFC* Climate & Radiation Branch, USA	Sud & Mocko (1999)
PLACE	GSFC Mesoscale Modeling Branch, USA	Wetzel & Boone (1995)
Mosaic	GSFC Hydrology Branch, USA	Koster & Suarez (1992)
JMA-SiB	CCSR†, University of Tokyo, Japan	Sato *et al.* (1989)
Bucket	CCSR, University of Tokyo, Japan	Manabe (1969)
ISBA	Météo France, France	Noilhan & Mahfouf (1996)
BASE	Macquarie University, Canada	Desborough & Pitman (1998)

* GSFC: Goddard Space Flight Center, National Aeronautics and Space Administration.
† CCSR: Center for Climate System Research.

governing equations are the continuity equation of water mass in the grid box and Manning's equation.

Firstly, groundwater is represented by a simple linear reservoir:

$$\frac{\mathrm{d}S_g}{\mathrm{d}t} = D_{\mathrm{LSM}g} - D_{\mathrm{OUT}g} \tag{1}$$

where S_g, D_{LSMg}, and D_{OUTg} are groundwater storage, inflow from LSM substituted for the amount of surface runoff, and the outflow from the groundwater reservoir, respectively. The outflow is parameterized as:

$$D_{\mathrm{OUT}g} = \frac{1}{\tau} S_g \tag{2}$$

where t is the time constant. Globally t = 30 (days) was assumed in this study.

The continuity equation for water in the river channel is:

$$\frac{\mathrm{d}S_{rc}}{\mathrm{d}t} = D_{\mathrm{IN}} + D_{\mathrm{OUT}g} + D_{\mathrm{LSM}s} - D_{\mathrm{OUT}} \tag{3}$$

where S_{rc}, D_{IN}, $D_{\mathrm{LSM}s}$, and D_{OUT} are water in the river channel, total inflow from surrounding grid boxes, surface runoff calculated by LSM, and outflow from the grid box, respectively. Assuming the river channel is of width *w* (and depth *d*) outflow is $D_{\mathrm{OUT}} = hwv$, where *v* is the flow velocity. For a large river channel, Manning's equation can be written as:

$$v = \frac{1}{n} h^{\frac{2}{3}} I^{\frac{1}{2}} \tag{4}$$

where *n* is Manning's coefficient and *I* is the slope. In this study, *n* is assumed to be 0.045 globally, which is within the range of the values for meandering river channels.

The volume of the water in the river channel is:

$$S_{rc} = w \cdot h \cdot l \cdot r_M \tag{5}$$

where l is the straight length of the river channel within the grid box calculated geometrically and r_M (= 1.4 globally) is the meandering ratio (Oki & Sud, 1998) adjusting the river length to be realistic. To obtain h, information on w should be given. Applying an empirical function to the relationship between the annual mean discharge, Q_M ($m^3\ s^{-1}$) and river width, w (m) (Leopold, 1996):

$$w = (100.9 \cdot Q_M)^{0.4856} \tag{6}$$

was obtained empirically. The tentative annual mean discharge, Q_M was calculated with effective velocity, v_e = 0.5 ($m\ s^{-1}$) globally, and w at each grid box was determined by equation (6), setting the minimum value of w at 10 m. From these calculations, the maximum river width estimated was nearly 3 km. The slope, I was determined from a digital elevation model by setting the minimum slope to 10^{-5}.

Figure 1 illustrates the annual total river discharge in each 0.5° × 0.5° grid. The distribution generally corresponds to annual precipitation and runoff patterns. However, due to the effect of accumulation of water as it moves through the river channel network, higher discharge values occur in the downstream reaches of large rivers.

To examine the reliability of the results, the annual runoff, before being routed through the river network, was compared with other estimates (see Table 2). Detailed comparisons with observed discharge can be found in a previous study (Oki *et al*., 1999) which shows that the accuracy of the discharge estimates depends on the accuracy of forcing data, which can be inferred from the density of raingauges. Oki *et al*. (1999) also point out that most of the LSMs tend to underestimate the runoff in higher latitudes. According to Table 2, estimates tend to be smaller compared to the previous estimates by approximately 20%. Some part of this result should have come from the insufficiency of the forcing data and shortcomings of the physics considered in LSMs. However, as Oki *et al*. (1995) demonstrated, regions where runoff data are available have higher annual runoff than those areas without discharge observation, and the global runoff estimated by extrapolating from river discharge observations may overestimate reality. Therefore, the uncorrected estimates of runoff are used in this study, and the assessment results may have a severe bias due to the underestimated error of the runoff.

From the runoff, R, estimated by the LSMs, and river discharge, D, from the routing scheme, the water availability, Q for each grid can be calculated as:

$$Q = R + \alpha \sum D_{\mathrm{up}} \tag{7}$$

where D_{up} is river discharge from grid boxes upstream.

Table 2 Continental runoff ($km^3\ year^{-1}$).

Region	WMO (1997)	Vörösmarty *et al.* (2000)	This study
Africa	4 050	4 520	3 616
Asia	13 510	13 700	9 385
Europe	2 900	2 770	2 191
Oceania	2 404	714	1 680
North America	7 890	5 890	3 824
South America	12 030	11 700	8 789
Total	**42 784**	**39 394**	**29 485**

The term α is the ratio of water from outside of the region (grid box) that contributes to water resources within the grid box. When $\alpha = 1.0$, all the water generated upstream can be used in the downstream reach, and when $\alpha = 0.0$, only the runoff generated within the region (grid box, country, or river basin) can be abstracted. The value of α should be influenced by at least three factors: the water quality deterioration upstream, the real consumption of water resources in the upstream reach, and the accessibility of water. The last factor is closely related to how many large-scale water schemes are implemented in the region.

The same concept can be applied for the water availability estimation for countries. In this case, ΣD_{up} corresponds to the transboundary water moving through the natural river systems. Transboundary water from other river basins is not considered here.

The values in Table 2 correspond to the cases when $\alpha = 0.0$, and discharge in Fig. 1 at each grid box corresponds to $\alpha = 1.0$. The sensitivity of how a affects water stress assessments is examined in the last section below.

WATER DEMAND ESTIMATED USING G-GIS

Statistics on water abstractions (demand side) for each country were obtained from the CD-ROM of the World Resources Institute (WRI , 1998). The data set is a synthesis of global data sets from various data sources as can be seen in Table 3. The most serious issue in the data is that only the statistics of water abstracted from rivers and aquifers are available globally, and no information on the actual consumption of water is available.

As can be seen, the years of the statistics of total/sectoral abstraction were not the same and some adjustment was required to standardize the year. In this study, linear trends between 1970 and 1995 are assumed for each continent and estimated from Shiklomanov (2000b). Due to the limitations of the available information, it was also assumed that the share of abstraction water did not change during the period. The interannual variability of abstractions, including the high value in 1995 when the climate anomaly was large, was eliminated by fitting a linear trend.

In order to distribute the annual total of abstractions by country statistics, a global GIS-based approach was taken. The gridded (raster) data are summarized in Table 4. Population data were taken from the Center for International Earth Science

Table 3 Country statistics used for estimating annual water abstractions (from WRI, 1998).

Data	Unit	Year	Source*
Total abstractions	km^3	1970–1995	Various
Sectoral abstraction	%	1970–1995 or 1987	WRI
Desalinated water	10^6 m^3	1990	FAO
Population	10^3	1950–1995	UN
Irrigated area	10^3 ha	1961–1994	FAO
GDP per capita	US$ in 1995	1970–1995	WB

* WRI: World Resources Institute;
FAO: Food and Agriculture Organization;
WB: World Bank.

Table 4 Information used to estimate the global distribution of annual abstractions.

Data	Resolution (min)	Year	Source
Country boundary	-	1992	ESRI
Population (persons per grid)	2.5	1990 and 1995	CIESIN
Irrigated area (km^2 per grid)	30	1995	Kassel Univ.

Information Network (CIESIN, Columbia University, USA), the irrigated area from Kassel University, Germany (Döll & Siebert, 1999), and the vector country boundary from the Environmental Systems Research Institute (ESRI, USA). Cropland distribution was taken from data of the Center for Sustainability and Global Environment (SAGE, University of Wisconsin-Madison, USA) for use instead of the distribution of irrigated land; however, it was judged that cropland distribution is not a good alternative for the spatial distribution pattern for irrigation, since it includes rainwater harvested areas.

First, templates for each country were generated for 0.5° × 0.5° grid boxes using a GIS, and small modifications were applied to fit the situation in 1995, since some national boundaries had changed since the issuing of the data by ESRI. The country area sizes were calculated on the 0.5° × 0.5°grid considering the ellipsoid nature of the Earth (Oki & Sud, 1998) and compared with national statistics. The mean of the error was 5% and the standard deviation (SD) was 32%. This error is mainly influenced by the large error for small countries, such as Sao Tome and Principe (960 km^2) and Bahrain (690 km^2), as they are each represented by a single grid box, which is approximately 2500 km^2. The error statistics for countries represented by more than one grid box are 1.5% (mean) and 8.3% (SD).

The population distribution given on a 2.5′ global grid was transferred to a 0.5° × 0.5° grid. However, it was found that the total population after the conversion was less than reality by nearly 300 million people. This happened because each 0.5° × 0.5° grid box was considered to be ocean if more than half of the grid box was ocean. However there were some 2.5′ × 2.5′ grid boxes with inhabitants. This problem was solved by counting the population in "sea" grid boxes in the nearest "land" grid boxes. Consequently the result compared well with national statistics with a 1% mean error and 14% SD.

Irrigated area data were provided by Döll & Siebert (1999). The spatial resolution and the target year correspond to those of the current study. Even though the data set was estimated based on Food and Agriculture Organization (FAO) statistics, the accumulated irrigated areas for each country were found to be less than those of FAO with a mean bias error of 12%. Most of the error occurs in African countries. Further examination of these data will be necessary, particularly for the assessment of future abstractions.

Based on these global distributions of population and irrigated area, national-level statistics on municipal and industrial water use per capita, and agricultural water use per irrigated area were used to estimate global distributions of abstractions.

The total annual abstraction (10^6 m^3 $year^{-1}$ per 0.5° × 0.5°) is illustrated in Fig. 2. It is concentrated in urban areas in industrialized countries where the population density is high. The principal irrigated area corresponds to the densely populated areas in China and India, and the estimated abstractions in those countries are as large as those in the United States and European countries.

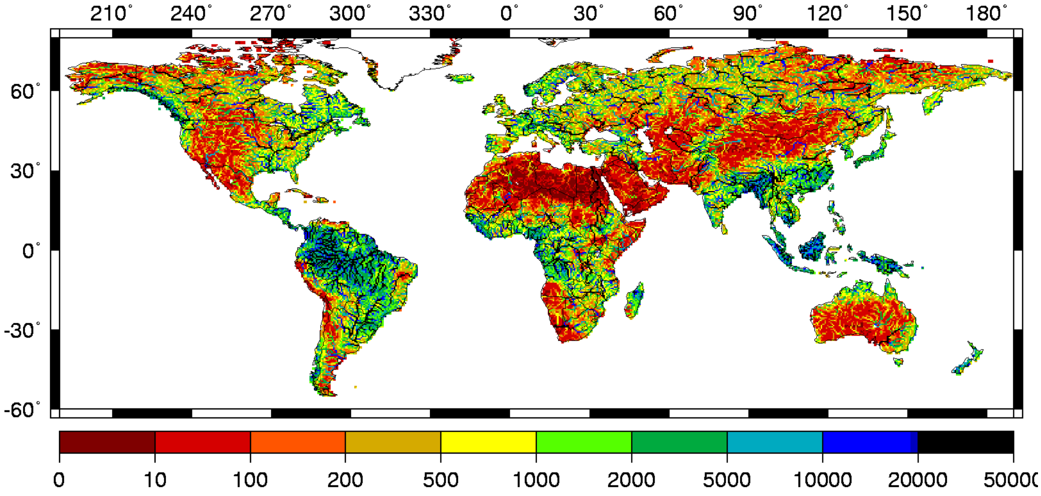

Fig. 1 TRIP estimated annual total river discharge (10^6 m^3 year^{-1}) in each 0.5° × 0.5° grid. The average of estimates for 1987 and 1988 are presented and considered as the available water resources for 1995.

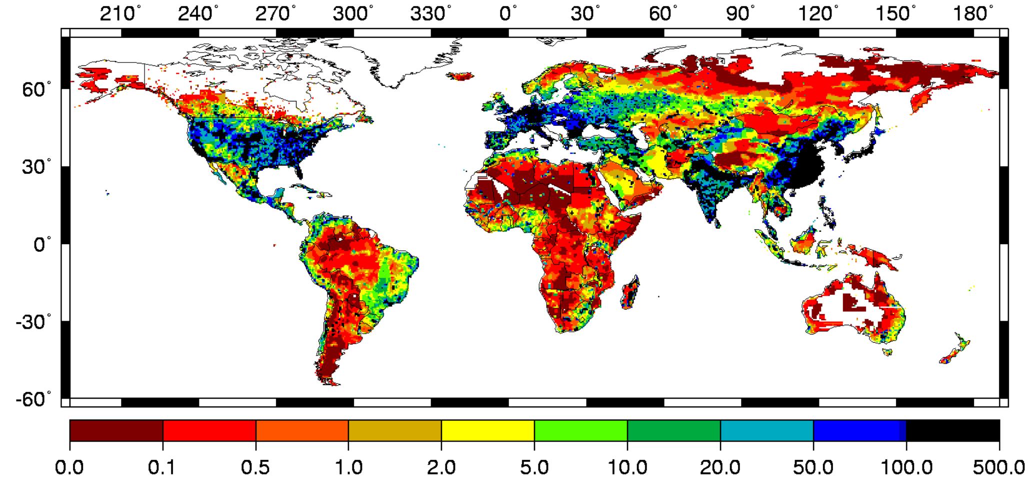

Fig. 2 G-GIS estimated global distribution of annual abstraction in 1995.

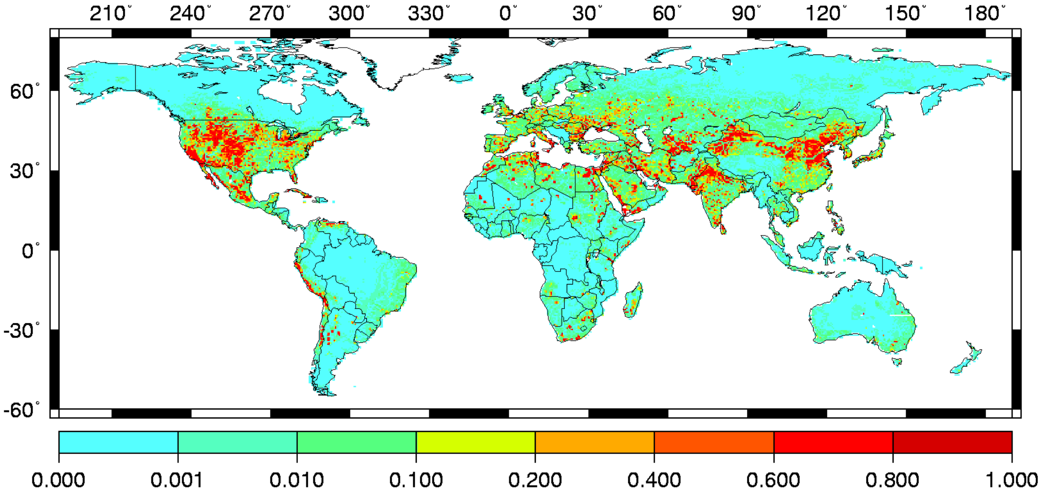

Fig. 3 The global distribution of the ratio of abstraction to availability, $(W - S)/Q$, in 1995.

GLOBAL WATER RESOURCES ASSESMENT

For the assessment of water scarcity, an index was adopted based on the ratio of the annual abstraction, W, to the annual available water, Q, and used in the studies of WMO (1997) and Vörösmarty *et al.* (2000). Following Heap *et al.* (1998), the desalinated water resource, S, was subtracted from W, and the water scarcity index, R_{ws} (Falkenmark *et al.*, 1989) was derived:

$$R_{\mathrm{ws}} = \frac{W - S}{Q} \tag{8}$$

where Q and W are taken from the result described in the sections above, and illustrated in Figs 1 and 2, respectively. Desalinated water, S, is a minor resource on the global scale, but it is important in some regions. For example, $S = 385 \times 10^6$ m^3 year^{-1} in the United Arab Emirates, where the annual abstraction is 2.11 km^3 year^{-1} and S represents 18% (WRI, 1998). The global distribution of estimated R_{ws} is shown in Fig. 3. The severity of water scarcity is ranked as:

$R_{\mathrm{ws}} < 0.1$	no water stress
$0.1 = R_{\mathrm{ws}} < 0.2$	low water stress
$0.2 = R_{\mathrm{ws}} < 0.4$	moderate water stress
$0.4 = R_{\mathrm{ws}}$	high water stress

Following these criteria, it is evident from Fig. 3 that water scarcity is severe in the Yellow River, Indus, Ganges, and Amu-Darya basins, and in the mid-west of the USA. In these high stress regions, the share of agricultural water is generally high.

The estimated water scarcity was compared with those from previous studies (WMO, 1997; Vörösmarty *et al.*, 2000) (Table 5). Even though the annual runoff estimated by LSMs was lower than in previous studies (see Table 2), the current assessment corresponds well with previous results (Vörösmarty *et al.*, 2000) for grid-based results shown in Table 5. For country-based assessments, previous studies shown in Table 5 assumed that all the runoff generated in the upstream can be used in the down stream and these estimates should be compared with the case where $\alpha = 1.0$ derived by TRIP. The discrepancy seems large; however, as the withdrawal to availability ratio R_{ws} for China is 0.26, it was classified in this study in the category of $0.2 = R_{\mathrm{ws}} < 0.4$. China has a population of more than 1.2 billion, and the estimates in this study are not robust enough for both the supply side and demand side. Therefore, China could be classified as $R_{\mathrm{ws}} < 0.2$ with a slight change in the source of the dataset and the way of extrapolation of national statistics. In that case ($\alpha = 1.0$* in Table 5), the estimated results correspond fairly well with previous estimates with a slight overestimate of the stressed population due to the underestimate of the annual runoff. This suggests the need for further refinements of the assessments, while, at the same time, the country-based assessments with discrete classification of water stress could lead to quite different results. It should be noted again that the grid-based assessment results are similar to those by UNH (Vörösmarty *et al.*, 2000) and TRIP (current study).

Moreover, it is noticeable that the estimate is highly dependent on the a value, as shown in Fig. 4, assessed by the grid-based method: the number of people affected by water stress below the water withdrawal to availability ratio R_{ws} clearly depends on the

Table 5 Comparisons of the population (10^8 capita) under levels of water scarcity on a grid, country, and river basin basis.

R_{ws}	Country based:						Grid based:		River basin based:
	TRIP				UNH	UN	TRIP	UNH	TRIP
α	0.0	0.5	1.0	1.0*	1.0	1.0	1.0	1.0	0.0
$R_{ws} < 0.1$	15	17	18	18	20	17	28	32	12
$0.1 = R_{ws} < 0.2$	2	3	3	15	17	21	6	4	5
$0.2 = R_{ws} < 0.4$	17	27	27	15	15	14	6	4	12
$0.4 = R_{ws}$	22	9	8	8	5	5	17	18	27

UN: UN system organizations (WMO, 1997);
UNH: University of New Hampshire (Vörösmarty *et al.*, 2000);
TRIP: this study.
R_{ws}: water scarcity index; a: availability of water resources from outside of the region.
α = 1.0* (TRIP): in this case China ($R_{ws} = 0.26$) has been classified as $0.1 = R_{ws} < 0.2$.

availability of water from outside of the region. The maximum R_{ws} was more than 20; however, the range of the Figure is only $0 = R_{ws} = 2.0$. As suggested in the previous section, the value of a is decreased by pollution and the actual consumption of water resources upstream. In contrast, development of the infrastructure may increase the value of α; for example, the construction of a large reservoir may increase the available water if the reservoir can hold the flood water which would otherwise be lost to the ocean. Figure 4 implies that the availability of transboundary water has a great influence on the global assessment of water scarcity, and more detailed studies should be encouraged on this issue.

As pointed out by Vörösmarty *et al.* (2000), estimates of the population under high water stress, and also the population under no water stress, are much higher using a

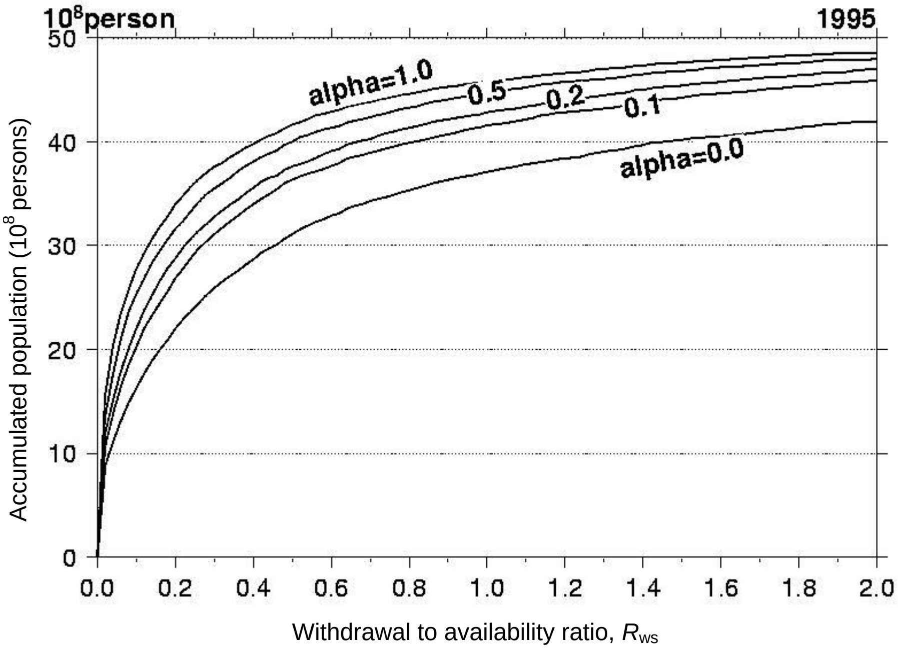

Fig. 4 Effect of α on the grid-based water stress assessment.

0.5° grid, because averaging on a country basis eliminates the differences in abstractions and supply which exist spatially. Consequently R_{ws} will be underestimated. The evaluation of water scarcity in each river basin shows the largest population under severe water stress because α is assumed to be zero in this case, and no water from upstream is considered to be available in the downstream area.

For a more realistic estimate of the assessment, abstractions, as well as the return flow and the recycling of water, should be considered in the simulation. The recycling ratios of water for agriculture, industry and municipal use are said to be 25, 86 and 60%, respectively. Considering the share of annual abstractions for these uses, which are 69, 23 and 8%, respectively (WRI, 1998), the mean recycling ratio could be estimated as 42% for the first order approximation. In order to assess future global water resources more realistically, a new approach should be attempted to route the natural runoff generated in each grid with estimates of abstractions and return flows.

SUMMARY AND FUTURE RESEARCH NEEDS

Water availability and abstractions are estimated globally in 0.5° × 0.5° grids using an LSM, and the global distribution of those areas under water stress are discussed. A summary for each continent is shown in Table 6. The delineation of the continents follows that of Baumgartner & Reichel (1975).

Although the amount of available water in Asia is large, the population and the use of water, particularly agricultural water demand, are very high, and therefore the water stress ratio is highest among the continents. The estimate of water availability is based on the offline simulation by land surface models, and seems to be underestimated by approximately 20% compared to previous estimates (Table 2). Therefore the assessment could exaggerate water scarcity compared to reality. Efforts to improve accuracy should be carried out, including analyses carried out at a higher resolution.

It should be noted that the available global-scale information, particularly data on water demand, is limited, and it is still possible that the results presented here may have significant errors, especially if examined in detail at the local scale. Therefore, the interpretation of the estimates presented requires care because of the representativeness of some of the input data and the assumptions made.

In order to improve the reliability of these estimates, critical examination of global information on water demand is needed, correlated with crop calendars, real consump-

Table 6 Summary of water resources in each continent (estimated for 1995).

Continent	Population (10^3)	Q (km^3)	D (km^3)	I (km^3)	A (km^3)	W (km^3)	R_{ws} (%)
Africa	690 550	3616.5	13.9	9.1	136.1	159.1	4.4
Asia	3 469 180	9384.9	142.4	203.8	1697.4	2043.7	21.8
Europe	688 143	2190.9	59.7	233.4	139.2	432.3	19.7
Oceania	28 164	1679.6	8.9	0.4	6.0	15.4	0.9
North America	454 926	3824.4	80.5	263.7	315.8	660.0	17.3
South America	319 214	8789.3	22.2	13.1	102.1	137.4	1.6

Q: annual water availability; D: annual domestic abstraction; I: annual industrial abstraction; A: annual agricultural abstraction; W: total annual abstraction ($= D + I + A$); R_{ws}: ratio of abstraction to availability.

tion of water resources (particularly for agriculture), and reservoir operation. Model development is also needed to improve the information handling in the calculation of water availability. The seasonal mismatch of water demand and water availability should be considered in future water resources assessments, even on the global scale.

It is pointed out that the ratio α has significant influence on the assessment. It is suggested that the availability of transboundary water has a great influence on the global assessment of water scarcity. Global assessments using a are necessary for robust estimates of water scarcity, and the influence of pollution can be included in a, since polluted water should be excluded from "available" water resources in the assessments. For international rivers, where a legal agreement or a treaty between the riparian upstream, downstream or neighbouring countries may be in place to regulate abstractions, legally available water may differ from physically available water, and the available water amount, Q, may not simply be expressed in the form of equation (7). Further studies focusing on the question "What are the available water resources?" should be encouraged in this context.

The framework employed in this study complements other global water resources assessments and those which may be undertaken under the influence of global warming and population increase (Saruhashi, 2001). An integrated approach to improve the accuracy of future projections, in terms of both the natural and social aspects of the water resources, should be promoted in support of developing action plans to mitigate the water crisis anticipated in the early stages of the 21st century.

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