Global Assessment of Current Water Resources using Total Runoff Integrating Pathways and Global GIS

Taikan Oki, *Associate Prof., Institute of Industrial Science, Univ. of Tokyo, Tokyo, Japan*

Takao Saruhashi, *Graduate Student, Graduate School of Engineering, Univ. of Tokyo, Tokyo, Japan*

Yasushi Agata, *Postdoctoral Research Associate, Institute of Industrial Science, Univ. of Tokyo, Tokyo, Japan*

Shinjiro Kanae, *Research Associate, Institute of Industrial Science, Univ. of Tokyo, Tokyo, Japan*

Katumi Musiake, *Professor, Institute of Industrial Science, Univ. of Tokyo, Tokyo, Japan*

Abstract:

Anticipated water scarcity in the first half of this century is one of the most concerned international issues. However, even though the issue has an international impact and world wide monitoring is critical, there are limited number of global estimates at present. In this study, annual water availability was derived from annual runoff estimated by land surface models using Total Runoff Integrating Pathways (TRIP) with 0.5 degree by 0.5 degree longitude/latitude resolution globally. Global distribution of water withdrawal for each sector in the same horizontal spatial resolution was estimated based on country-base statistics of municipal water use, industrial water use, and agricultural intake, using global geographical information system with global distributions of population and irrigated crop land area. The total population under water stress estimated for 1995 corresponded very well with former estimates, however, the number is highly depend on how to assume the ratio how much water from outside of the region can be used for water resources within the region. It suggests the importance of regional studies evaluating the possibility of water intake as well as the validity of the investment for water resources withdrawal facilities.

1 Introduction

It is anticipated that the world's water will be under more pressure in the first half of this century than at any time during the recorded history. The estimation of current water stress situation is important for reliable projection of water crisis in the future. However, most of the previous global analysis on water scarcity have been country basis or river basin basis except for Takahashi et al. (2000) and Vörösmarty et al. (2000), that presented water scarcity in each 0.5 degree by 0.5 degree longitude and latitude grid box. Considering the importance of global water scarcity, future projections should be preferably evaluated by multiple procedure/model/method at multiple organizations in order to eliminate the uncertainty, as the future projection of the global warming under IPCC (Intergovernmental Panel on Climate Change) has been done.

For the global estimation of water supply, observed runoff or simulated runoff are generally used. Shiklomanov(2000a; 2000b) estimated water availability for 26 regions of the world based on observed river discharge at 2,500 stations. Takahashi et al. (2000) estimated monthly water balance at 0.5 degree by 0.5 degree longitude/latitude grid boxes using bucket model(Manabe, 1969) with potential evapotranspiration given from Penman method for current and future climate (temperature, wind speed, and precipitation) simulated by GCMs (General Circulation Models) at Canadian Climate Centre, Max Planc Institute, and Center for Climate System Research (CCSR) at University of Tokyo. Vörösmarty et al. (2000) adopted the similar approach but their water supply estimates are adjusted to observation where discharge information is available. In this study, water balance estimated by land surface models (LSMs) was used for the global estimates of water availability. Such models are originally developed to be included in numerical atmospheric models for giving the lower boundary condition. The bucket model(Manabe, 1969) is the first generation LSM and relatively simple, however, current LSMs consider detailed energy and water cycles at land surface including hydrological, radiative, and even biogeochemical processes. All the projections of future climate using GCMs are associated with some kind of LSMs, and water resources assessment in the near future will be done directly from the water balance calculated by an LSM included in the GCM used for future climate simulation. Therefore it is worthwhile to assess the current global water balance calculated by LSMs. The methodology and results are presented in section 2.

For the demand side of water resources assessment, practically two distributed information could be used globally in 0.5 degree by 0.5 degree longitude/latitude grid boxes; these are population and irrigated land area. The other country-base statistics, such as municipal water supply or agricultural intake, were assumed to be proportional to either of them. Global geographical information system (G-GIS) was developed to convert country-base statistics into grid base global distribution, and the divergent year of the statistics were adjusted to 1995 during the data processing described in section 3.

From these estimates of global annual water supply and demand, the global distribution of water stress was estimated in 0.5 degree by 0.5 degree longitude/latitude grid boxes. The result is compared with previous estimates by country, river basin, and grid basis in section 4. Even though there was some attempts to consider the difference of water intake facilities and investment level for water resources management, that will be introduced in another report.

2 Water Availability Estimated by TRIP

Simulated runoffs from offline simulations by LSMs are used for estimating water availability in this study. Under the Global Soil Wetness Project (GSWP; IGPO (1995)), global water balance was estimated by 10 LSMs with forcing data from ISLSCP (International Satellite Land Surface Climatology Project)(Meeson et al., 1995). Due to the limitation of submitted data to Data Center of the GSWP, average of the surface runoff simulated by CCSR-Bucket(Numaguti et al., 1997) and JMA-SiB(Sato et al., 1989) and the mean total runoff by all 10 LSMs were utilized. The target period of the GSWP was from 1987 through 1988, and the surface and total runoff were produced approximately every 10 days in 1 degree by 1 degree grid boxes.

To estimate the river discharge, the gridded surface and total runoff data was divided into 0.5 degree longitude/latitude resolution and TRIP (Total Runoff Integrating Pathways)(Oki and Sud, 1998) corresponding to the horizontal resolution was used to determine the flow direction globally. Flow routing was improved from simple linear scheme(Oki et al., 1999) and similar to Arora et al. (1999). The governing equations are the continuity equation of water mass in the grid box and Manning's equation.

Firstly, ground water process is considered and represented by a simple linear reservoir.

$$\frac{dS_g}{dt} = D_{LSMg} - D_{OUTg} \tag{1}$$

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

$$D_{OUTg} = \frac{1}{\tau} S_g \tag{2}$$

where τ is the time constant. Globally τ =30 [days] was assumed in this study.

The continuity equation of water in the river channel is

$$\frac{dS_{rc}}{dt} = D_{IN} + D_{OUTg} + D_{LSMs} - D_{OUT} \tag{3}$$

where S_{rc}, D_{IN}, D_{LSMs}, 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 width and depth of the river channel to be w and h, outflow is $D_{OUT} = hwv$ where v is the flow velocity. For 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 the Manning's coefficient and I is the slope. In this study n is assumed to be 0.045 globally.

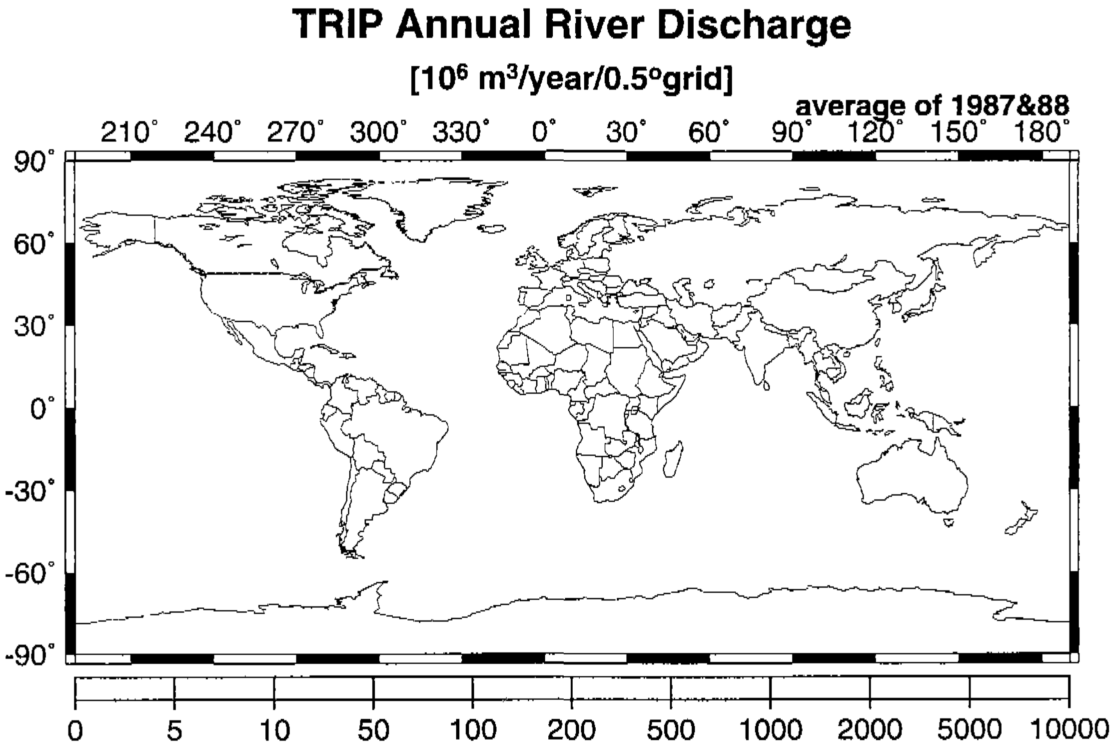

Figure 1: Estimated annual total river discharge in each 0.5x0.5 lon./lat. degree grid box.

Volume of the water in the river channel is

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

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 and 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) and river width w (m) (Leopold, 1996),

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

was empirically obtained. The tentative annual mean discharge Q_M was calculated with effective velocity v_e=0.5 [m/s] globally, and river width w at each grid box was determined by Eq.(6) with setting the minimum w to be 10 [m]. From these estimates, the maximum river width estimated was nearly 3km and should be reasonable. The slope I was determined from digital elevation model (DEM) with setting minimum slope to be 10^{-5}. Even though not a few assumptions are involved in the calculation, the routing scheme will not cause significant error for the annual water balance utilized in this study.

Figure 1 illustrates the annual total river discharge in each 0.5 by 0.5 degree longitude/latitude grid box. The distribution is basically corresponding to annual precipitation and runoff, however, due to the

Table 1: Continental Runoff (km^3/year)

Region	This study	Shiklomanov (2000a)	Vörösmarty (2000)
AFRICA	5,815	4,050	4,520
ASIA	13,014	13,510	13,700
EUROPE	6,286	2,900	2,770
OCEANIA	1,912	2,404	714
NORTH AMERICA	5,345	7,890	5,890
SOUTH AMERICA	14,906	12,030	11,700
Total	47,278	42,784	39,394

effect of accumulation through the river channel network, higher discharge is observed at the down stream of large rivers.

For the examination of the reliability of the result, annual runoff, before calculate the flow down through the river routing scheme, was compared with other estimates in Table 1. Detailed comparison with observed discharge can be found in previous study(Oki et al., 1999) and it clearly revealed that the accuracy basically depends on the accuracy of forcing data, which can be inferred from the density of raingauges. From Table 1, estimates are close each other with slight positive bias of current result globally.

From the runoff R estimated by LSM and river discharge D after routing scheme, water availability W at each grid box can be calculated as:

$$W = R + \alpha \Sigma D_{up} \tag{7}$$

where D_{up} is river discharge from upstream and ΣD_{up} indicates the sum of them. α is the ratio how much water from outside of the region (grid box) can be used as water resources within the grid box. The same concept can be applied for the water availability estimation in countries. In this case, ΣD_{up} corresponds to the transboundary water through natural river systems. The values in Table 1 corresponds to the cases of $\alpha = 0.0$, and discharge in Figure 1 at each grid box corresponds to $\alpha = 1.0$. The effect of α on water stress assessment will be examined in section 4.

Table 2: Country statistics used for estimating annual water withdrawal (from WRI CD-ROM).

Data	unit	Year	Source
Total withdrawal	km^3	1970-1995	various
Sectoral withdrawal	%	1970-1995 or 1987	UN
Desalinzed water	10^6m^3	1990	FAO
Population	10^3	1950-2050	UN
Irrigated Area	10^3ha	1961-1994	FAO
GDP per capita	US$ in 1995	1970• 1995• •	WB

3 Water Demand Estimated using G-GIS

Statistics related to water withdrawal (demand side) were given in each country and obtained from the CD-ROM of World Resources Institute(WRI et al., 1998). These are summarized in Table 2.

As can be seen, the year of the statistics of total/sectoral withdrawal were not unified 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 limitation of necessary information, it was also assumed that the share of water withdrawal did not change during the period.

In order to distribute the annual water withdrawal given by country statistics, global-based geographical information system approach was taken. The basic data summarized in Table 3 were gridded (raster) population from CIESIN (Center for International Earth Science Information Network) and irrigation area from Kassel University(Döll and Siebert, 1999), and vector country boundary from ESRI (Environmental Systems Research Institute).

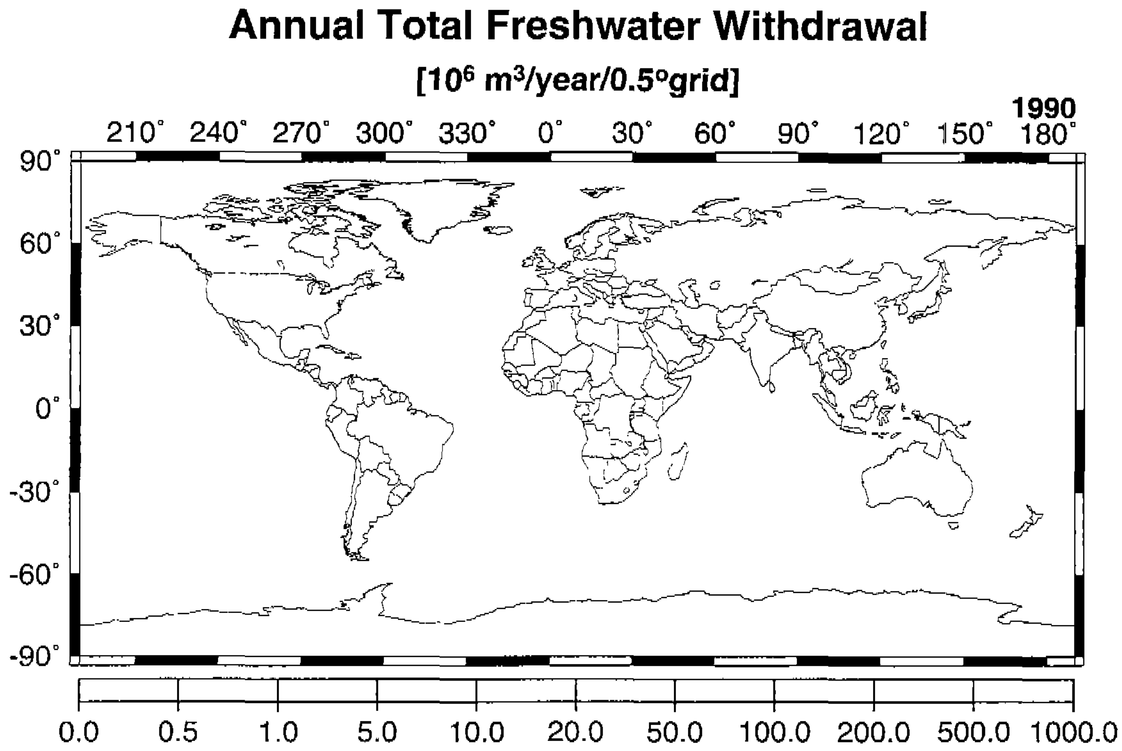

Figure 2: Estimated global distribution of annual water withdrawal

Firstly, template for each country on 0.5 by 0.5 lat./lon. degree grid boxes were generated using a geographical information system, and small modification were applied to fit the situation in 1995. The country area sizes on the 0.5 by 0.5 lat./lon. degree grid were calculated considering the ellipsity of the earth(Oki and Sud, 1998) and compared with national statistics. The error was only 0.5%.

The population distribution given in 2.5 minutes global grid was transferred to 0.5 by 0.5 lat./lon. degree grid, however, it was found that the total population after the conversion was less than reality by nearly 300 million people due to the inconsistency of land/sea mask. This problem was solved by putting the population within sea grid boxes onto the nearest land grid boxes. Consequently the result compared well with national statistics by 1% of error.

Irrigation area data was offered based on the request to the authors of Döll and Siebert (1999). The spatial resolution and the target year correspond to those of current study. Even though the dataset was estimated based on FAO statistics, the accumulated irrigation areas for each country were found to be less than FAO with 12% of bias error. Most of the error was found to be in African countries and further examination will be necessary particularly for the assessment of future water withdrawal estimates.

Based on these global distributions of population and irrigated area, global distributions were estimated from national-level statistics using the unit withdrawal of municipal and industrial water use per capita, and agricultural water withdrawal per irrigated area.

The total annual water withdrawal ($10^6 m^3/y/0.5° x 0.5°$) is illustrated in Fig. 2. The water withdrawal is concentrated in urban areas in industrized countries where population density is high. Irrigated area is also corresponding to the populated area in China and India, and the estimated water withdrawal in these countries are quite high as much as the United States.

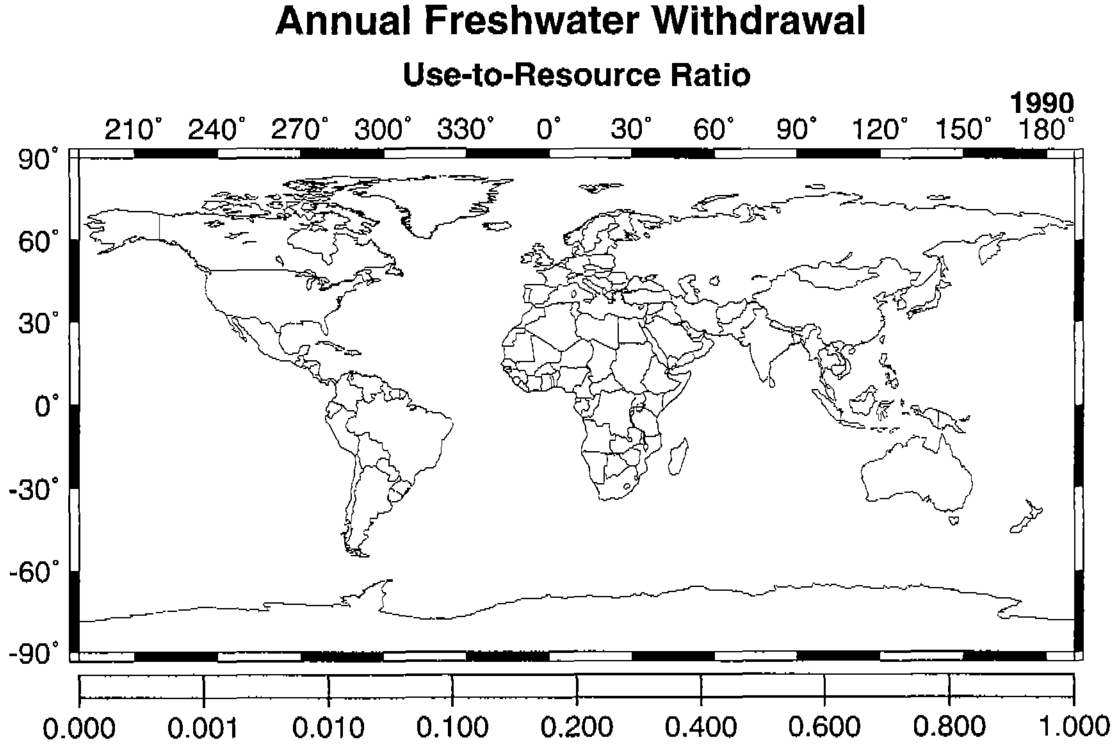

Figure 3: The global distribution of the water scarcity ratio

4 Global Water Resources Assessment

The assessment of the water scarcity in this study adopted the index used by WMO (1997) and Vörösmarty et al. (2000), that is the ratio of the annual water withdrawal W to the available annual water Q. Following to Heap et al. (1998), desalinized water resource S was subtracted from W, and the water scarcity index R_{ws} was derived

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

where Q and W are taken from the result described in sections 2 and 3, and illustrated in Figures 1 and 2, respectively. The global distribution of estimated R_{ws} is shown in Fig. 3. Generally the severity of water scarcity is judged as:

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

Following to this criteria, it is evident from Fig. 3 that water scarcity is severe in the river basins of Yellow, Indus, Ganges, and Amu-Darya, and in the middle west of the United States. In these serious regions, the share of agricultural water withdrawal is generally high.

The estimated water scarcity is compared with those from previous studies in Table 4. The α indicates the ratio how much water from outside of the region (country or grid box) can be used (Eq. 7). The current estimate well corresponded with previous results when α=0.5 is assumed as used in Shiklomanov (2000a) for the comparison by country basis in Table 3. The large number of 29×10^8 people are classified $0.2 \leq R_{ws} < 0.4$ for α=0.0 case by this study (TRIP), and it is mainly because R_{ws} of China is 0.215. It is possible that China, which holds more than 1.2 billion people, will be classified as $R_{ws} < 0.2$ with slight change of source data. Moreover, it is noticeable that the estimate is highly depend on α value as shown

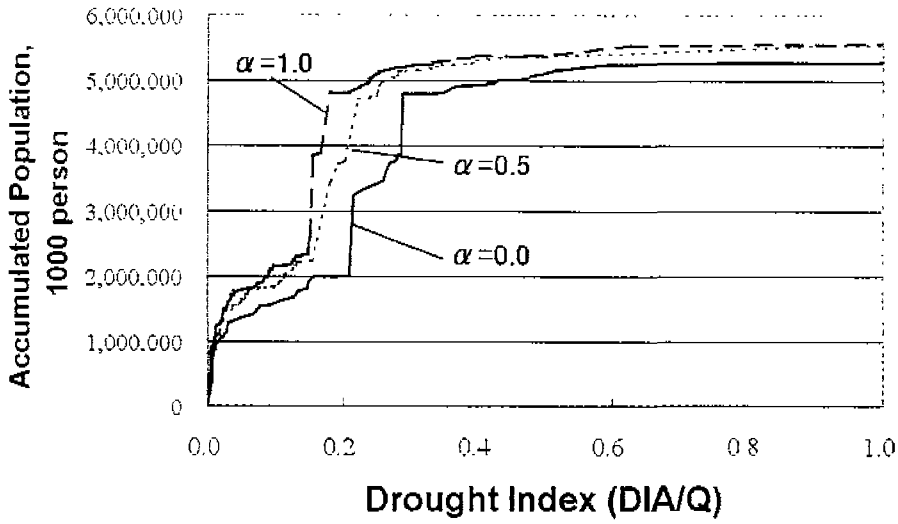

Figure 4: Effect of the α ratio on the water stress assessment by country basis.

Table 3: Comparisons of the population (10^8 capita) under levels of water scarcity by grid, country, and river basin basis.

R_{ws}	Country Base					Grid Base		River Basin Base
	TRIP			UNH	WMO	TRIP	UNH	TRIP
α	0.0	1.0	0.5		(0.5)	1.0		0.0
$R_{ws} < 0.1$	16	21	18	20	17	32	32	18
$0.1 \leq R_{ws} < 0.2$	4	27	19	17	21	6	4	12
$0.2 \leq R_{ws} < 0.4$	29	6	16	15	14	5	4	8
$0.4 \leq R_{ws}$	7	2	3	5	5	13	18	18

WMO : World Meteorological Organization (WMO, 1997)
UNH : University of New Hampshire (Vörösmarty et al., 2000)
TRIP : This Study
R_{ws} : Water scarcity index
α : Availability of water resources originated outside from the region

in Fig. 4. It implicitly suggests the availability of transboundary water has great influence on the global assessment of water scarcity, and more detailed studies should be encouraged on this issue.

As pointed by Vörösmarty et al. (2000), population under high water stress is much higher by the grid base estimates because averaging over a country eliminates the sharp concentration of water withdrawal in limited region in the country, and consequently, R_{ws} is evaluated low. The evaluation of water scarcity in each river basin shows largest population under sever water stress because α is assumed to be zero for this case, and no return flow and reuse of water resources are considered. In reality, the recycling ratios of withdrawn water for agriculture, industry, and municipal use are said to be 25%, 86%, and 60%, respectively. Considering the share of annual water withdrawal for these water use of 69%, 23%, and 8%(WRI et al., 1998), mean recycling ratio is estimated as approximately 42%. Therefore, a new approach to route a part of natural runoff generated in each grid may be required in the future global water resources assessment with the consideration of water withdrawal in the grid box.

Table 4: Summary of Water Resources in Each Continent

Continent	Population 10^3	W km^3	D km^3	I km^3	A km^3	T km^3	R_{ws} %
AFRICA	609332	5815.9	12.9	8.4	123.8	145.1	3
ASIA	3176848	13014.9	127.8	174.0	1539.1	1840.9	14
EUROPE	721378	6286.6	64.4	250.0	130.2	444.7	7
OCEANIA	24343	1912.6	11.5	0.5	6.6	18.6	1
NORTH AMERICA	290427	5345.8	69.0	242.1	209.7	520.7	10
SOUTH AMERICA	429573	14906.9	32.5	29.8	167.9	230.2	1

W: Annual water availability
D: Annual domestic water use
I: Annual industrial water use
A: Annual agricultural water use
T: Total annual water withdrawal ($= D + I + A$)
R_{ws}: Water scarcity index

5 Summary

Water availability and water withdrawal are estimated globally in 0.5 degree by 0.5 degree lon./lat. grid boxes, and water stress distribution are discussed. Summary for each continent is shown in Table 5.

Even though the available water in Asia is huge, population and current water withdrawal, particularly agricultural water demand is extremely high, and the water stress ratio is highest among the continents.

The estimate of water availability is based on the offline simulation by land surface models. Efforts improving the accuracy should be associated with the application of their higher temporal resolution. The seasonal mismatch of the water demand and water availability should be considered in the future water resources assessment even in the global scale.

It is pointed out that the ratio α, how much water from outside of the region (country or grid box) can be used for water resources within the region, has significant influence on the assessment, and the result with $\alpha = 0.5$ corresponded well with previous studies by country basis. It implicitly suggests the availability of transboundary water has great influence on the global assessment of water scarcity. The α=1.0 is the case that all the water generated in the up stream can be used in the down stream, and α=0.0 is the case that only the runoff generated within the region (grid box, country, or river basin) can be used for water withdrawal. Therefore α should be highly depdendent on how much large scale water withdrawal schemes are implemented in the region. Global assessment on α should be necessary for robust estimates of water scarcity, and the influence of the pollution can be included in the α since the polluted water should be excluded from the "available" water resources in the assessments.

Framework employed in this study fits to the global water resources assessment in the future under the influence of global warming and population increase(Saruhashi, 2001). Integrated approach to improve the accuracy of future projections both natural side and social side of the water resources should be promoted for developing action plans to mitigate the water crisis anticipated in the early stage of this 21st century.

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