

Global water resources assessment under climatic change in 2050 using TRIP

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Abstract Annual water availability was derived from annual runoff estimated by land surface models using Total Runoff Integrating Pathways (TRIP) with $0.5^\circ \times 0.5^\circ$ 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. Based on this framework, future projections of the global water resources considering population growth, climatic change, and the increase of water consumption *per capita* were carried out. Change in annual runoff was estimated based on the climatic simulation by a general circulation model coupled with TRIP. With the increase of population only, the future population under strong water scarcity, (water scarcity index is larger than 0.4), will increase by 90% in 2050 compared to the situation in 1995. Consideration of the climatic change due to global warming will relax this situation, and only 74% will be under strong water scarcity according to the future projection used in this study.

Key words downscaling GCM simulation; global warming; global water balance; Total Runoff Integrating Pathways, TRIP; water scarcity; water withdrawal

INTRODUCTION

The water resources situation is seriously under pressure, even at present in some regions on the Earth, and it is anticipated that the situation will be worse during the first half of the 21st century (Cosgrove & Rijsberman, 2000). The estimation of the current level of water stress is important for reliable projections of the severity of the water crisis in the future. However, most of the previous global analyses on water scarcity have been carried out on a country basis or a river basin basis with the exceptions of Takahashi *et al.* (2000), Vörösmarty *et al.* (2000), and Oki *et al.* (2001), who each presented water scarcities on a $0.5^\circ \times 0.5^\circ$ longitude and latitude grid for the globe. Considering the importance of global water scarcity, future projections should be evaluated by multiple procedures, models, and methods at multiple organizations, since the reliability of the estimates will be supported if similar results are obtained from different scientific approaches, information, and data processing. As the future projection of global warming has been done under IPCC (Intergovernmental Panel on Climate Change), such an approach to evaluate the future prediction by multiple models/procedures is expected to reduce the uncertainty naturally embodied in the projections.

In this study, water balances estimated by land surface models (LSMs) were used for the global estimates of water availability. Country-based statistics, such as municipal water supply and industrial water use, were assumed to be proportional to the population distribution, and agricultural intake was assumed to be proportional to the irrigated land area. Detailed procedures are described in Oki *et al.* (2001), and future projections of world water resources assessment were carried out using this framework, considering the change in water withdrawals due to population growth and the increase of water usage *per capita* and in water availability associated with the change of climatic conditions estimated by a general circulation model (GCM).

From these estimates of global annual water supply and demand in 2050, the global distribution of water stress was estimated for every $0.5^\circ \times 0.5^\circ$ longitude/latitude grid box globally, except for grid boxes which are more than half covered by ice or water. The result was examined in terms of increase or decrease of water stress levels compared to the situation current in 1995, and the dominant factors on the increase were evaluated among population growth, climate change, and the increase of water usage *per capita*.

WATER AVAILABILITY IN 2050

There are several methods to adopt to estimate the water availability in the future. Firstly, the water cycles projected by climate models may be directly used for water resources assessment. This is straightforward; however, model outputs often suffer bias errors, particularly river runoff estimates, and correcting the errors is generally required for quantitative estimation of available water resources in the future. The coarse spatial resolution of the ordinary climate model is repeatedly claimed for the insufficiency of utilizing model outputs, but the spatial resolution is becoming rapidly higher. Regional climate models may be nested in the global projection of the future climate in order to obtain the future projection with higher spatial resolution. However, the model bias should be removed.

There are ways to downscale the frequency of weather pattern to the climate on regional scales. It assumes the current relationship between weather pattern and climatic variables, such as pressure distribution and precipitation at each point, persists in the future. There is no guarantee to assume the persistence and another uncertainty of the relationship used to convert weather pattern to climatic variables is involved in the future projection, in addition to the uncertainty originated from the climate models.

Another way to estimate the future situation under global warming is to use historic climatic data when it was warmer, as a proxy of the future situation. This procedure is also claimed to be ambiguous since, for example, there is no guarantee that the hydrological cycles are similar for the past warm period and future climate under global warming. In practice it is difficult to apply this proxy method for global water resources assessment because it is not easy to obtain global information on water availability in the past.

In this study, the current global distribution of available water resources was estimated, adjusted using GCM simulation on the future climate, and used for global water resources assessment.

For the estimation of the current runoff distribution on a global scale, offline runs by 11 different LSMs were used. Under the Global Soil Wetness Project (GSWP; IGPO, 1995), the global water balance was estimated by the LSMs using forcing data, such as precipitation, downward shortwave and longwave radiation, wind speed, temperature, humidity, and surface pressure, from the International Satellite Land Surface Climatology Project (ISLSCP) (Meeson *et al.*, 1995). The Total Runoff Integrating Pathways (TRIP; Oki & Sud, 1998) was used for the river routing calculations to convert runoff from LSMs into river discharge. Details are described in Oki *et al.* (2001), but basically the estimated annual discharge corresponded fairly well with observation where forcing data to run LSMs were made with enough real observations, such as rainfall (Oki *et al.*, 1999). As seen in Oki *et al.* (2001), the river discharge used here is smaller compared to the previous estimates by approximately 20%, and this shortcoming is one of the critical points of the current study for further improvement.

Two methods are applied here to adjust the current river runoff into future river runoff. One method is to use the difference in GCM simulation for current and future climatic conditions, and the other one is to use the ratio. Both methods may suffer technical problems when adjusting current river runoff to the future. The difference method estimates future river runoff r_{fd} by modifying current river runoff r_n with the difference of current R_n and future R_f runoff simulations by GCM:

$$r_{fd} = r_n + (R_f - R_n) \quad (1)$$

As equation (1) can be written as:

$$r_{fd} = R_f - (R_n - r_n) = R_f - \Delta R \quad (2)$$

with the model bias $\Delta R = R_n - r_n$, it implicitly assumes the water balance estimated by the GCM may have a bias error but that it is constant through the future. The technical problem is that the negative runoff can be estimated when the model bias is larger than GCM estimates of future river runoff $\Delta R > R_f$. In practice, negative runoff should be filled with zero runoff.

The ratio method estimates future runoff r_{fr} by:

$$r_{fr} = r_n \times \frac{R_f}{R_n} \quad (3)$$

and it assumes the systematic error by GCM simulation keeps the ratio constantly. A tremendously big value for r_{fr} may be estimated if the current GCM runoff (R_n) is close to zero, but some future runoff (R_f) is predicted (R_f/R_n is huge), and real runoff (r_n) is not zero. Such a situation occurs mainly in desert regions where the availability of water resources can be neglected; therefore such an unrealistic estimate may be neglected for use in water resources assessment. In this study, both r_{fd} and r_{fr} are estimated and used for future water resources assessments.

An atmospheric general circulation model (AGCM) of the Centre for Climate System Research, University of Tokyo and the National Institute of Environmental Studies, Japan (Numaguti *et al.*, 1997) was run with boundary conditions of sea surface temperature in both 1990 and 2060, that are obtained from coupled ocean-atmospheric general circulation model (AOGCM) run for increasing carbon dioxide conditions.

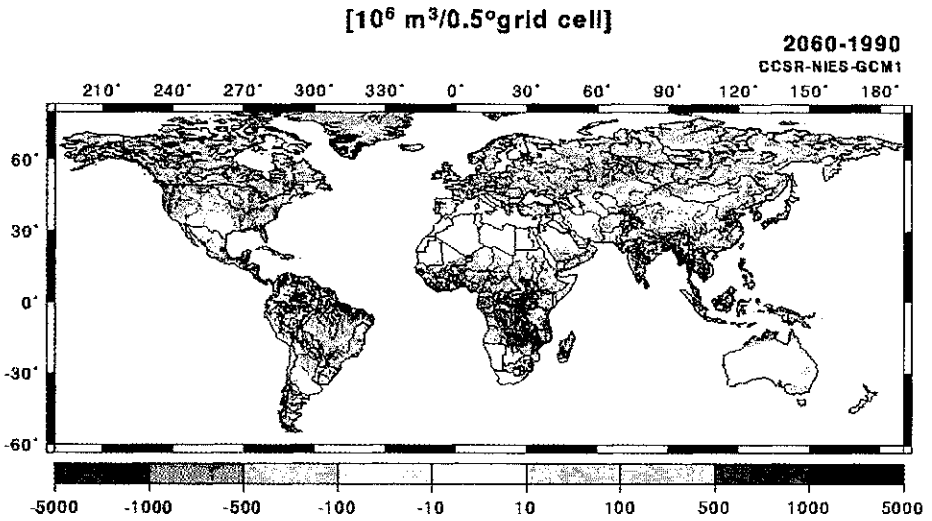


Fig. 1 The difference of the simulated river discharge for 1990 (R_f) and 2060 (R_n).

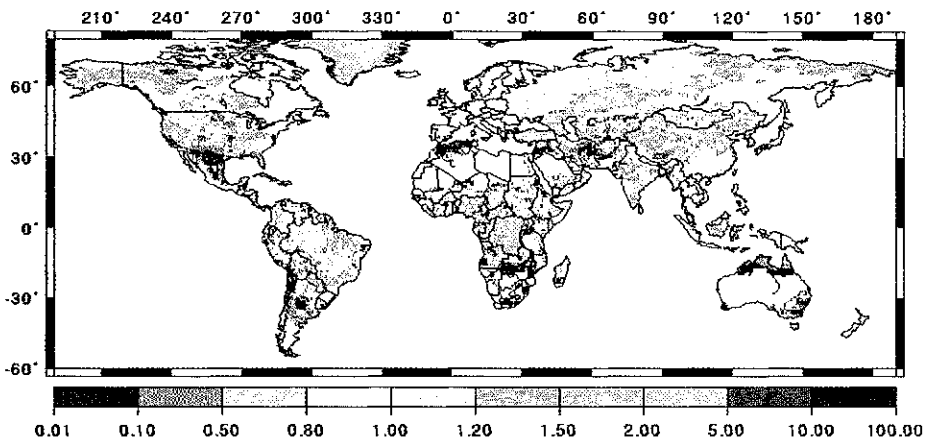


Fig. 2 The ratio of the simulated river discharge for 2060 (R_f) to that of in 1990 (R_n).

The horizontal resolution of the model simulation was carried out with T106, which corresponds to approximately 100-km grid boxes globally. Daily runoff estimates from AGCM outputs were taken and routed using TRIP. The annual mean discharges in 1990 and 2060 were regarded as current (R_n) and future (R_f) river discharge. The difference $R_f - R_n$ and ratio R_f/R_n are shown in Figs 1 and 2.

From this particular simulation, the Asian monsoon is enhanced due to the enhancement of the temperature difference between the Indian Ocean and the Eurasian continent. River discharge is expected to increase in the Indian sub-continent through the western part of the Indo-China Peninsula. Northern China, where water is relatively scarce at present, is also expected to increase its potentially available water resources, and a decrease is projected in between. Most of Europe is projected to decrease its annual river discharge. In contrast, the simulation projects an increase in Central to West Africa.

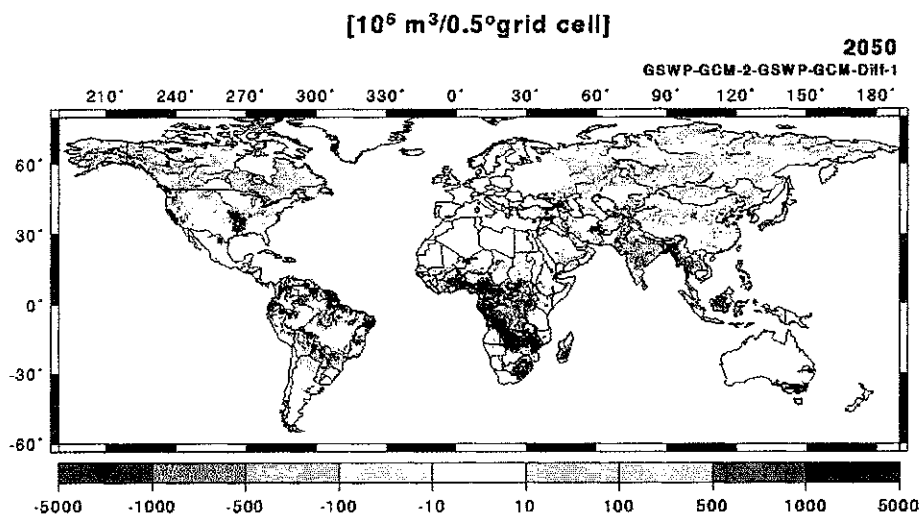


Fig. 3 The difference of river discharge in 2050 estimated by difference method r_{fd} and ratio method r_{fr} .

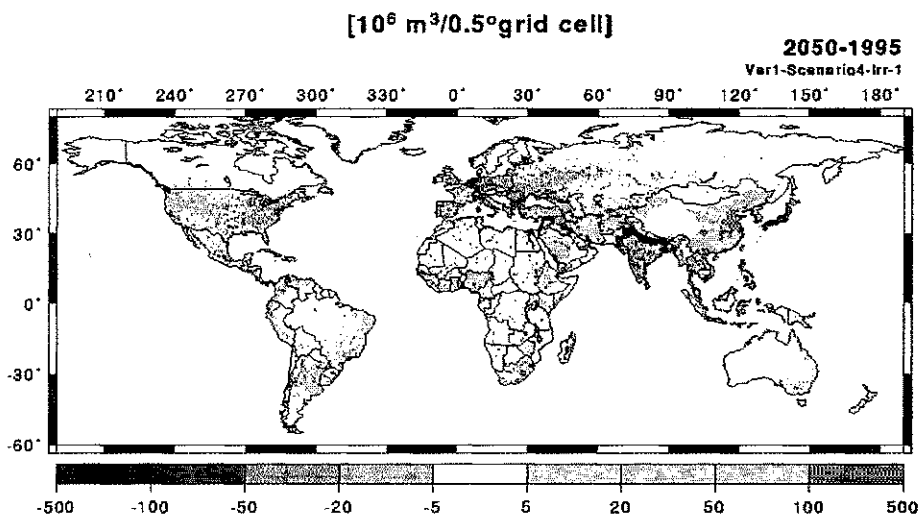


Fig. 4 The change in the total water withdrawal per year under case 3 in 2050.

The ratio R_f/R_n is sometimes extremely large near and along the edge of the dry region in Fig. 2, and the small increase of river runoff is exaggerated, as expected. The future river runoff estimated using difference r_{fd} is negative in some parts of the western USA (not shown). The difference of these two kinds of future estimates ($r_{fr} - r_{fd}$) is shown in Fig. 3. Since the area of 0.5° grid cell is approximately 2500 km^2 in tropical regions, $5000 \times 10^6 \text{ m}^3$ per 0.5 grid cell corresponds to a difference of $2000 \text{ mm year}^{-1}$. Therefore, for some regions future projection is highly dependant on the assumption employed for bias error correction of GCM.

Both estimates of r_{fr} and r_{fd} were used to assess the water resources in 2050, together with the future projection of water withdrawals described in the next section.

FUTURE WATER WITHDRAWAL

The current water withdrawal estimated in Oki *et al.* (2001) was used as the baseline for the future prediction of water withdrawal in the world. Three cases were assessed in this study. The first case assumes that only the population will increase according to the medium prediction of the United Nations. The river discharge will change due to the climatic variation in the second case, in addition to the increase of population. The future river discharges of r_{fd} and r_{fr} presented in the previous section were used. The unit withdrawal of municipal and industrial water will increase or decrease because of the economic growth and technological development in the third case, in addition to the population growth and climatic change.

The municipal water withdrawal increases, even in cases 1 and 2, according to the population growth. In case 3, the unit municipal water withdrawal will change with the ratio projected by Takahashi *et al.* (2000). Water-use efficiency will increase in North America where unit withdrawal will decrease by approximately 20%. Water-use efficiency will be neutral for OECD and western Europe, but gradually increase in developing countries.

The industrial water withdrawal will change only under case 3 with the ratio by Takahashi *et al.* (2000). In case 3, it was also assumed that the unit water withdrawal would increase in proportion to the growth of GDP predicted by Raskin *et al.* (1995) in each region.

The future projection of irrigation withdrawal in this study is not sophisticated and will need further refinements. From the past 40 years of records it was found that the increase in irrigation area in the world is approximately proportional to the increase in the world population, and it was assumed the situation would continue for the next 50 years. Since the unit irrigation withdrawal was assumed to be constant in each country, as a result, the increase in irrigation withdrawal is proportional to the population growth here.

Figure 4 illustrates the change in the predicted total water withdrawal per year under case 3. Basically it reflects the change in population and therefore decreases in developed countries and increases in developing countries.

GLOBAL WATER RESOURCES ASSESSMENT IN THE FUTURE

The assessment of the water scarcity in this study adopted the index based on the ratio of the annual water withdrawal W to the available annual water Q , as used by UN *et al.* (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} by Falkenmark *et al.* (1989) was derived as:

$$R_{ws} = \frac{W - S}{Q} \quad (4)$$

The global distribution of estimated R_{ws} is shown in Fig. 5 for case 3 using r_{fd} . Generally the severity of water scarcity is judged as:

$$R_{ws} \leq 0.1 \quad \text{no water stress}$$

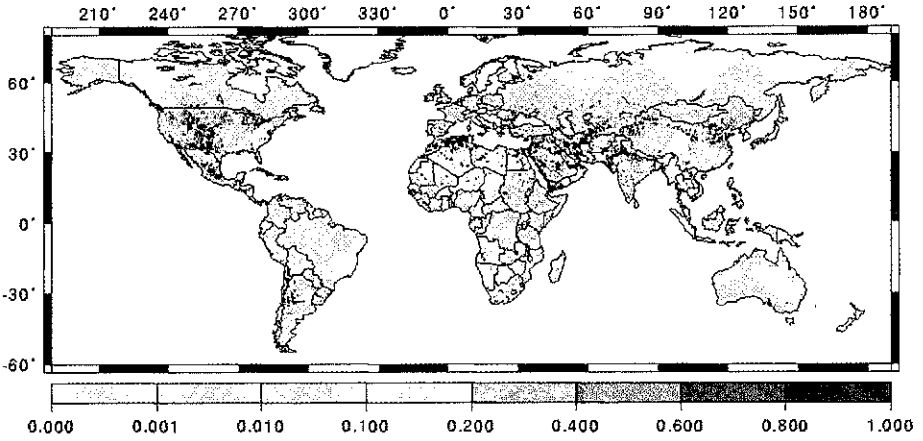


Fig. 5 The future projection of the water withdrawal to availability ratio in 2050.

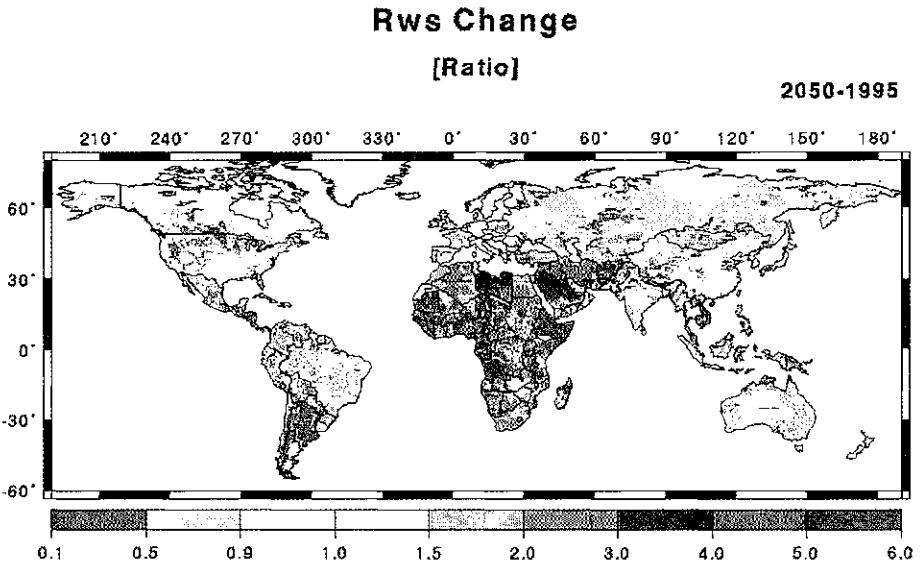


Fig. 6 The change in the ratio of water withdrawal to availability in 2050 compared to that of 1995.

- | | |
|-------------------------|-----------------------|
| $0.1 < R_{ws} \leq 0.2$ | low water stress |
| $0.2 < R_{ws} \leq 0.4$ | moderate water stress |
| $0.4 \leq R_{ws}$ | high water stress |

Following these criteria, it is evident from Fig. 5 that water scarcity is severe in the river basins of the Yellow, Indus, Ganges, and Amu-Darya rivers, and in the mid-west of the USA. These distributions are generally similar to the current situation. However, looking at the change in ratio of R_{ws} in the future to the current R_{ws} (Fig. 6), it is apparent that a drastic change is anticipated in Africa. In that continent, current water

Table 1 World Population (billion people) under each water stress level projected in 2050. Future river discharge under climatic condition was estimated in two ways r_{fd} using the difference and r_{fr} using the ratio of current and future GCM simulations.

Stress level	Current (1995)	Population growth only	+ Climate change:		+ Unit demand increase:	
			r_{fd}	r_{fr}	r_{fd}	r_{fr}
High	1.67	2.66	2.43	2.57	2.51	2.65
Moderate	0.58	0.91	0.93	0.93	0.97	0.95
Low	0.62	0.94	0.96	0.94	1.00	0.96
No	2.78	4.31	4.45	4.28	4.28	4.15

withdrawal is comparatively little, however, rapid increase of water withdrawal is projected according to the population growth. The situation should be more serious than those regions where R_{ws} will be as high as these African regions but R_{ws} is already high, because social infrastructure to secure water resources and better water resources management system should already be in place in such regions. However, a sudden increase in R_{ws} should demand the development of such an infrastructure and better management systems. The situation will become serious if this cannot be achieved.

Impacts of climatic change and economic growth associated with technology development are assessed in Table 1 for r_{fd} and r_{fr} . The estimated values for the current situation are also presented in Table 1 for comparison. Basically, the population growth has the largest impact on the increase of people under high water stress level from 1.7 billion now to 2.5, through 2.7 billion in 2050. Since global river runoff increases in the GCM simulation used in this study, the water stress level is somewhat relaxed by the climate change effect. This is the opposite result to that of Vörösmarty *et al.* (2000) in which the population under high water stress level increases if the impact of climate change is considered. However, the impact of the climate change effect is not as dominant as population growth in their estimates either. Of course, in developed countries, population will decrease and the water stress level will be reduced. Therefore the precise prediction of the impact of climate changes should have more relevance in developed countries.

Even though the difference of r_{fd} and r_{fr} are large in some regions, the difference shown in Table 1 is comparatively small. The impact of unit demand increase is also small. These results may suggest that such a presentation showing population under each water stress level is useful to know the relative impact of the factors changing the water supply and demand. However, further indexing and detailed presentation are also necessary to assess the change in water resources situation in the future.

SUMMARY AND FUTURE RESEARCH NEEDS

A framework to assess the future water resources condition on a grid base was shown globally and preliminary results are presented. However, each component of the future projection should be more sophisticated, particularly with respect to the irrigation withdrawal. It should be coupled with the changes of land use and climate, such as temperature and precipitation. Urbanization was not explicitly considered in this research; however, it may have a big impact, particularly in developing countries, and may need to be considered separately.

The impact of climatic change may be evaluated more if seasonal change of potential water resources is used for assessment, since global warming will change the snow accumulation and the timing of snowmelt. At such time scales, river runoff routing calculations should be incorporated with anthropogenic activities on hydrological cycles, such as reservoir operations and water withdrawals. As a result of the increase of human impacts on nature, "natural" hydrological cycles excluding anthropogenic activities are different from "real" hydrological cycles now. It is important for water resources assessment to deal with "real" hydrological cycles.

Much more effort should be made to investigate the robust information we can extract from GCM simulations. The ultimate goal should be to utilize the realistic and unbiased simulation of hydrological cycles by GCM directly for water resources assessment. However, this may not be achieved for several years and we need some proxy method for practical needs, at least for a while.

As for the evaluation of water stress level, it may be necessary to consider the virtual water trade (Oki et al., 2002), how much water resources are saved by importing agricultural and cattle products. Including such aspects, an integrated approach to improve the accuracy of future projections on both the natural and social aspects of water resources should be promoted for developing action plans to mitigate the water crisis anticipated in the early stages of the 21st century.

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