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Global Water Resources Assessment under Climatic Change in 2050 using TRIP

Short title: GLOBAL WATER RESOURCES IN 2050

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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 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. Based on the framework, future projections of the global water resources considering population growth, climatic change, and the increase of water consumption per capita were carried out. Population growth scenario follows the UN projection in each country. Change in annual runoff was estimated based on the climatic simulation by a general circulation model by the Center of Climate System Study, U of Tokyo, and the National Institute for Environmental Studies, coupled with TRIP. The increase in unit consumption of water was related to the predicted growth of GDP. With the increase of population only, future population under strong water scarcity, with water scarcity index is larger than 0.4, will increase by 90% in 2050 compared to the current situation in 1995. Consideration of the climatic change due to the global warming will relax this situation, and only 74% will be under the strong water scarcity according to the future projection used in this study.

1. Introduction

The water resources situation is seriously under pressure even at present in some regions of the earth, and it is anticipated that the situation will be worse during the first half of this century (Cosgrove and 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 analysis 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 presented water scarcities on a each 0.5 degree by 0.5 degree 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 the similar results are obtained from different scientific approaches, information, and data processing. As the future projection of the global warming has been done under IPCC (Intergovernmental Panel on Climate Change), such a 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 are assumed to be proportional to the population distribution, and agricultural intake is assumed to be proportional to the irrigated land area. Detailed procedures are described in Oki et al. (2001), and future projection of world water resources assessment was carried out using the frame work, considering the change in 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 degree by 0.5 degree longitude/latitude grid boxes globally, except for grid boxes more than half of that are covered by ice or water. The result is examined with water stress levels in terms of increase or decrease compared to current situation in 1995, and the dominant factors on the increase was evaluated among population growth, climate change, and the increase of water usage per capita.

2. Water Availability in 2050

There are several methods to be adopted to estimate the water availability in the future.

Firstly, the projected water cycles by climate model may be directly used for the 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 as for the insufficiency of utilizing model outputs, but the spatial resolution is becoming higher rapidly in these days. Regional climate model 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 anyway even in the case.

There are ways to down-scale 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 also another uncertainty of the relationship 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 the historical climatic data when it was warmer as a proxy of future situation. This procedure is also claimed to be ambiguous since there is no guarantee that the hydrologic cycles are similar for past warm period and future climate under global warming, for example. It is practically 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 global scale, offline runs by 10 different LSMs are used. Under the Global Soil Wetness Project (GSWP; IGPO (1995)), the global water balance was estimated by 11 LSMs using forcing data, such as precipitation, downward short wave and long wave radiation, wind speed, temperature, humidity, and surface pressure, from ISLSCP (International Satellite Land Surface Climatology Project) (Meeson et al., 1995). TRIP (Total Runoff Integrating Pathways) (Oki and 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 seem in Oki et al. (2001), the river discharge here is smaller compared to the previous estimates by approximately 20%, and this shortcomings is one of the critical points of 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 problem 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:

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

As Eq. 1 can be written as

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

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 is constant through future. The technical problem is the negative runoff can be estimated in the case the model bias is larger than GCM estimates of future river runoff $\Delta R > R_f$. Practically negative runoff should be filled with zero runoff.

The ratio method estimates future runoff r_{fr} by

$$r_{fr} = r_n \times \frac{R_f}{R_n} \tag{3}$$

and it assumes the systematic error by GCM simulation keeps the ratio constantly. r_{fr} may be estimated tremendously big if current GCM runoff (R_n) is close to zero, but some future runoff (R_f) is predicted ($\frac{R_f}{R_n}$ is huge), and real runoff (r_n) is not zero. Such a situation occurs mainly in desert region 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 Center for Climate System Study, University of Tokyo and the National Institute of Environmental Studies (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. The horizontal resolution of the model simulation was carried out with T106, which corresponds to approximately 100km 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 Figures 1 and 2.

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

The ratio R_f/R_n is sometimes extremely large near the dry region in Figure 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 part in the western US (not shown). The difference of these two kinds of future estimates ($r_{fr} - r_{fd}$) is shown in Figure 3. Since the area of 0.5 degree grid cell is approximately 2,500 km^2 in tropical region, $5{,}000 \times 10^6 m^3$/0.5 grid cell corresponds 2,000mm/y of difference. Therefore some region, the future projection is highly depend on the assumption employed for bias error correction of GCM.

The 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.

3. Future Water Withdrawal

The current water withdrawal estimated in Oki et al. (2001) was used for the baseline for the future prediction of the water withdrawal in the world. Three scenarios were assessed in this study. The first scenario assumes 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 scenario, 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 technology development in the third scenario, in addition to the population growth and climatic change.

The municipal water withdrawal increases even in the scenarios 1 and 2 according to the population growth. In the scenario 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 and unit withdrawal will decrease by approximately 20% there, neutral for OECD and Western Europe, but gradually increase in developing countries.

The industrial water withdrawal will change only under the scenario 3 with the ratio by Takahashi et al. (2000), as well. In the scenario 3, it was also assumed that the unit water withdrawal will increase proportional 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 should need further refinements. From the past 40 years of record, 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 will continue in another 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 the scenario 3. Basically it reflects the change in population, therefore decreases in developed countries and increases in developing countries.

4. 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, and 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} Falkenmark et al. (1989) was derived

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

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

$$
\begin{array}{rl}
R_{ws} < 0.1 & \text{no water stress} \\
0.1 \leq R_{ws} < 0.2 & \text{low water stress} \\
0.2 \leq R_{ws} < 0.4 & \text{moderate water stress} \\
0.4 \leq R_{ws} & \text{high water stress}
\end{array}
$$

Following this criteria, it is evident from Fig. 5 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. 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} (Figure 6), it is apparent that the drastic change is anticipated in Africa. In the continent, current water 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 now, because social infrastructure to secure water resources and better water resources management system should have already be ready in such regions, at least somehow. However, sudden increase in R_{ws} should demand the development of such an infrastructure and better management system, and the situation will be serious if that cannot be achieved.

Impacts of the climatic change and economic growth associated with the technology development are assessed in Table 1 for r_{fd} and r_{fr}. The estimated values for current situation is also presented in Table 1 for comparison. Basically, the population growth have the large 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 climate change effect. This is opposite to the result by 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 climate change effect is not as dominant as population growth in their estimates, as well. 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 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.

5. Summary and Future Research Needs

A framework to assess the future water resources condition by grid base globally was shown and preliminary results were presented. However, each component of the future projection should be sophisticated, particularly about 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 the global warming will change the snow accumulation and the timing of snow melt. In such time scales, river runoff routing calculations should be incorporated with anthropogenic activities on hydrologic cycles, such as reservoir operations and water withdrawals. According to the increase of human impact on nature, "natural" hydrologic cycles excluding anthropogenic activities is different from "real" hydrologic cycles now. It is important for water resources assessment to deal "real" one.

Much more efforts should be paid to investigate what is the robust information we can extract from GCM simulations. Ultimate goal should be to utilize the realistic and unbiased simulation of hydrologic cycles by GCM directly for water resources assessment, however, it may not be achieved within 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 required to consider the virtual water trade, how much water resources is 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 sides 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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References:

Cosgrove, W. J. and F. R. Rijsberman, 2000: *World Water Vision.* Earthscan Publications Ltd, London.

Falkenmark, M., J. Lundqvist and C. Widstrand, 1989: Macro-scale water scarcity requires micro-scale approaches; Aspects of vulnerability in semi-arid development. *Natural Resources Forum*, **14**, 258–267.

Heap, C., E. Kemp-Benedict and P. Raskin, 1998: *Conventional Worlds: Techinical Description of Bending the Curve Scenarios.* Polestar Series Report.

IGPO, , 1995: Global Soil Wetness Project. Technical report, International GEWEX Project Office, Silver Spring, MD 20910.

Meeson, B. W., F. E. Corprew, J. M. P. McManus, D. M. Myers, J. W. Closs, K.-J. Sun, D. J. Sunday and P. J. Sellers, 1995: ISLSCP Initiative I — Global Data Sets for Land-Atmosphere Models, 1987-1988., Published on CD-ROM by NASA (USA_NASA_GDAAC_ISLSCP_001 - USA_NASA_GDAAC_ISLSCP_005).

Numaguti, A., S.Sugata, M. Takahashi, T. Nakajima and A. Sumi, 1997: Study on the climate system and mass transport by a climate model. *CGER's Supercomputer Monograph Report*, **3**, National Institute for Environmental Studies, Environment Agency of Japan (Eds.).

Oki, T. and Y. C. Sud, 1998: Design of Total Runoff Integrating Pathways (TRIP) – A global river channel network. *Earth Interactions*, **2**, [Available on-line at http://EarthInteractions.org/].

Oki, T., T. Nishimura and P. Dirmeyer, 1999: Assessment of annual runoff from land surface models using Total Runoff Integrating Pathways (TRIP). *J. Meteor. Soc. Japan*, **77**, 235–255.

Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D. Yang and K. Musiake, 2001: Global Assessment of Current Water Resources using the Total Runoff Integrating Pathways. *Hydrol. Sci. J.*, **46**, 1159–1171.

Raskin, P., E. Hansen and R. Mongolis, 1995: *Water and Sustainability: Global Outlook*. No. 4 in POLESTAR Series Report, Stockholm Envirnment Institute.

Saruhashi, T., 2001: Global Water Resource Assessment using Total Runoff Integrating Pathways. Master's thesis, Graduate School of Engineering, University of Tokyo.

Takahashi, K., Y. Matsuoka, Y. Shimada and R. Shimamura, 2000: Development of the model to assess water resources problems under climate change. *Proc. 8th Symposium on Global Environment*, **8**, 175–180.

UN, , UNDP, UNEP, FAO, UNESCO, WMO, W. Bank, WHO, UNIDO and SEI, 1997: *Comprehensive Assessment of the Freshwater Resources of the World*. World Meteorological Organization, pp.33.

Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers, 2000: Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, **289**, 284–288.

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Table 1. World Population (billion people) under each Water Stress Level projected in 2050. Future river discharge under climatic condition was estimted 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 water stress	1.7	2.66	2.43	2.57	2.51	2.65
Moderate water stress	0.6	0.91	0.93	0.93	0.97	0.95
Low water stress	0.6	0.94	0.96	0.94	1.00	0.96
No water stress	2.8	4.31	4.45	4.28	4.28	4.15

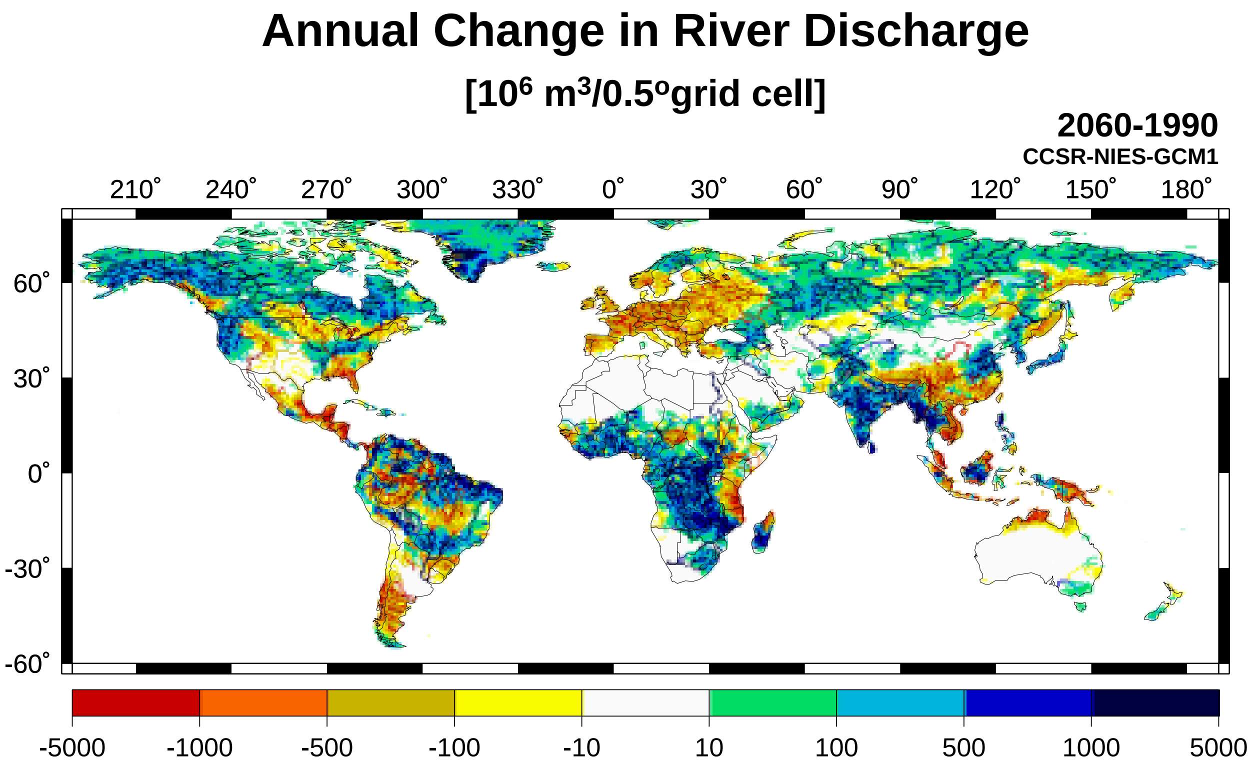


Figure 1. The difference of the simulated river discharge for 1990 (R_n) and 2060 (R_f).

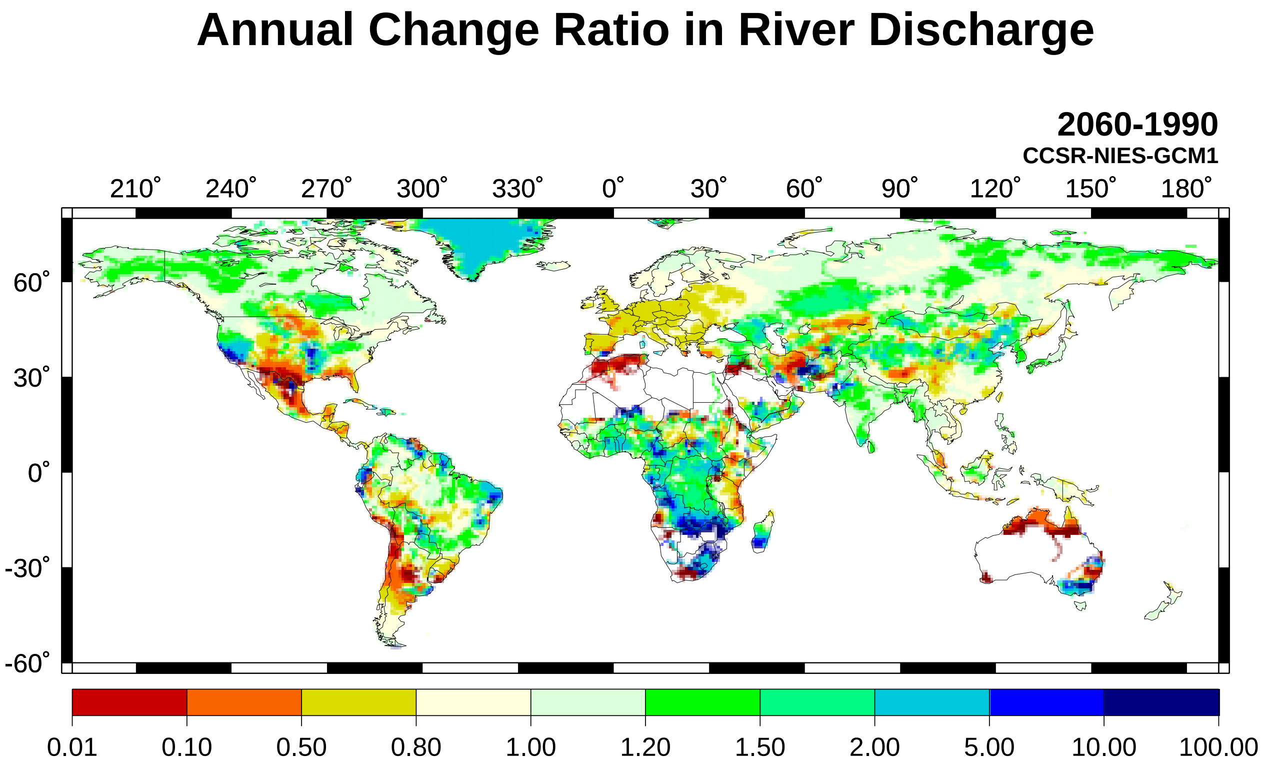
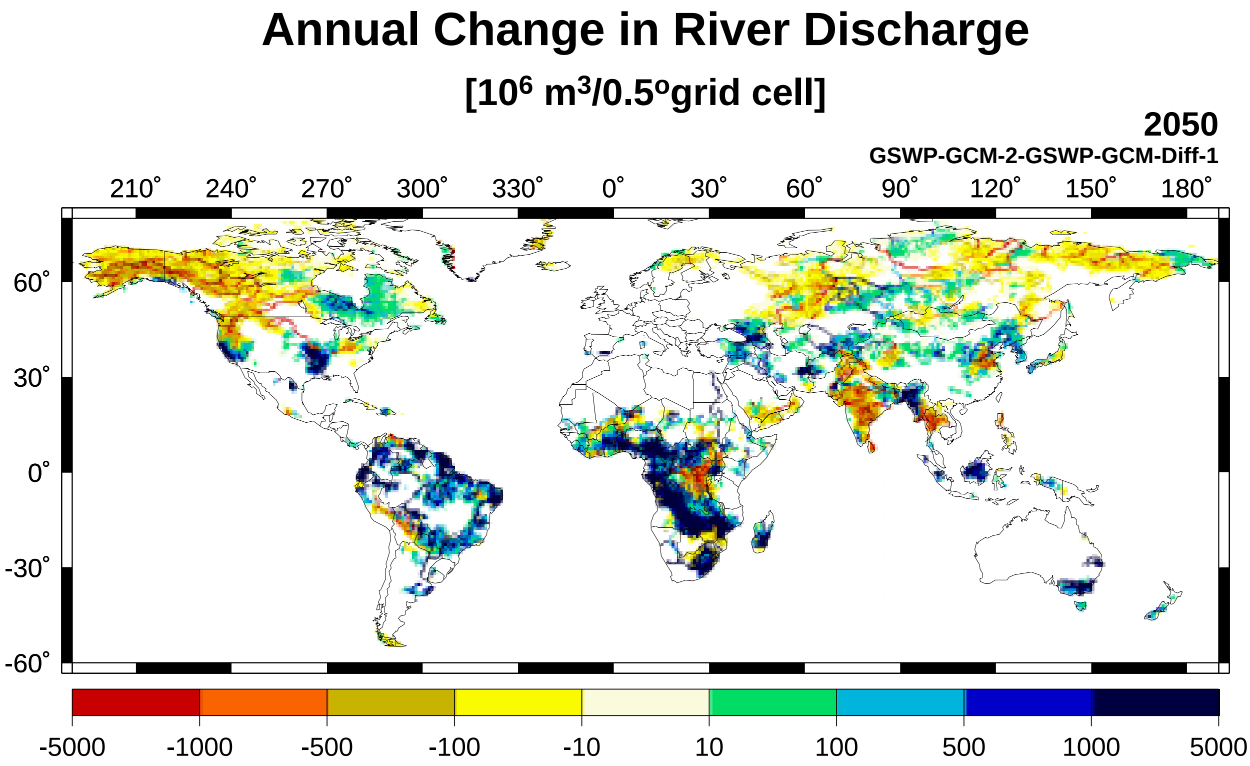


Figure 2. The ratio of the simulated river discharge in 2060 (R_f) to that of in 1990 (R_n).



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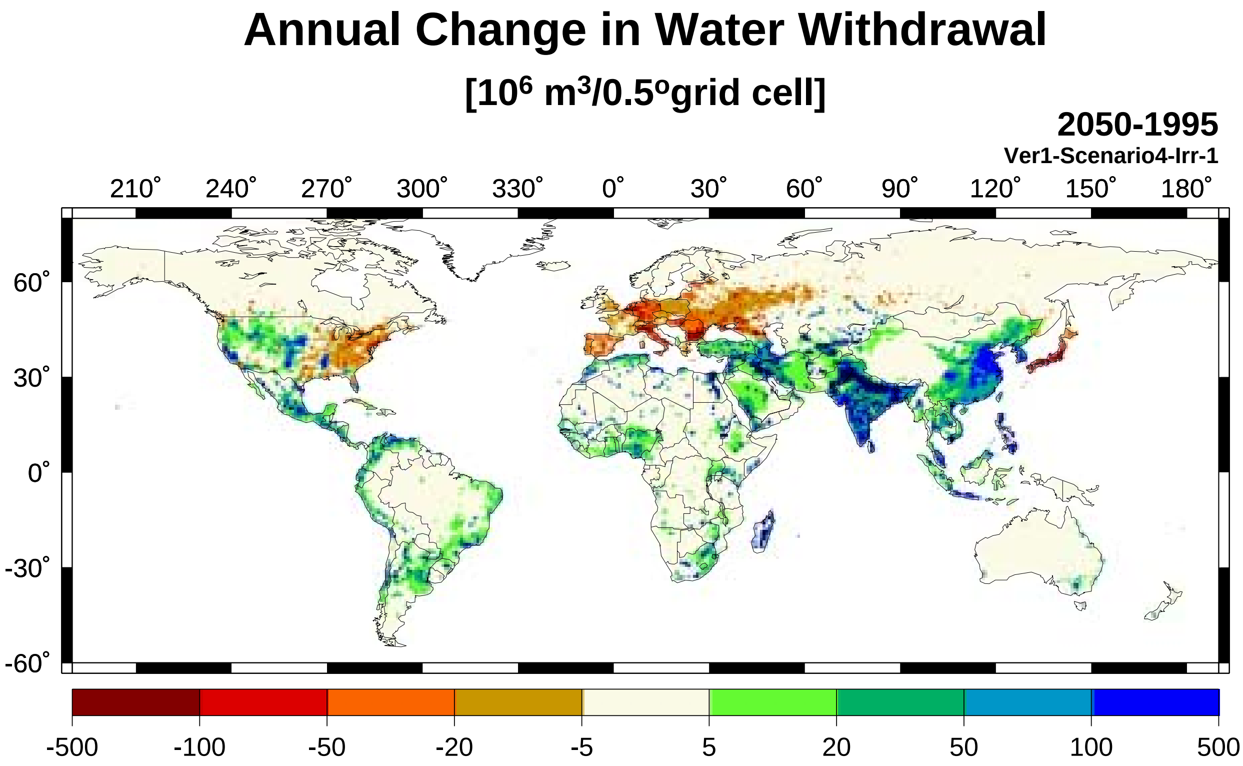

Figure 4. The change in the total water withdrawal per year under the scenario 3 in 2050.

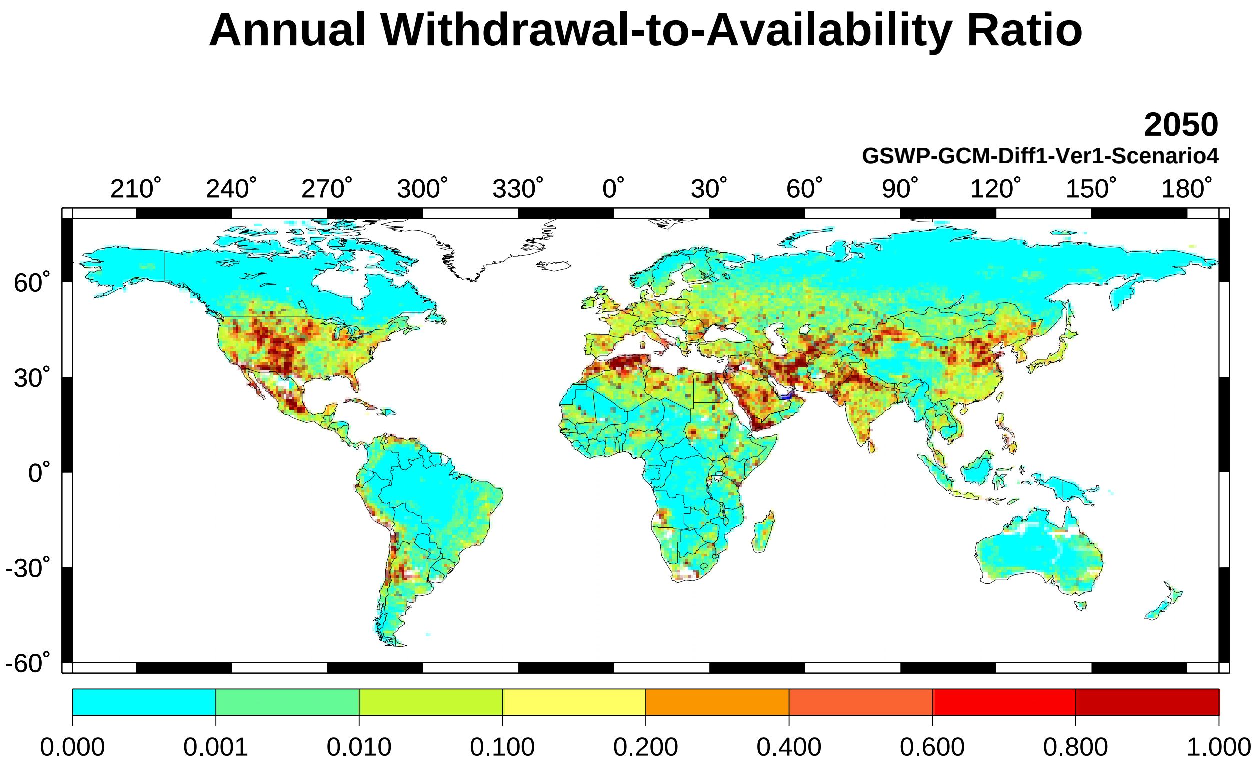

Figure 5. The future projection of the water withdrawal to availability ratio in 2050.

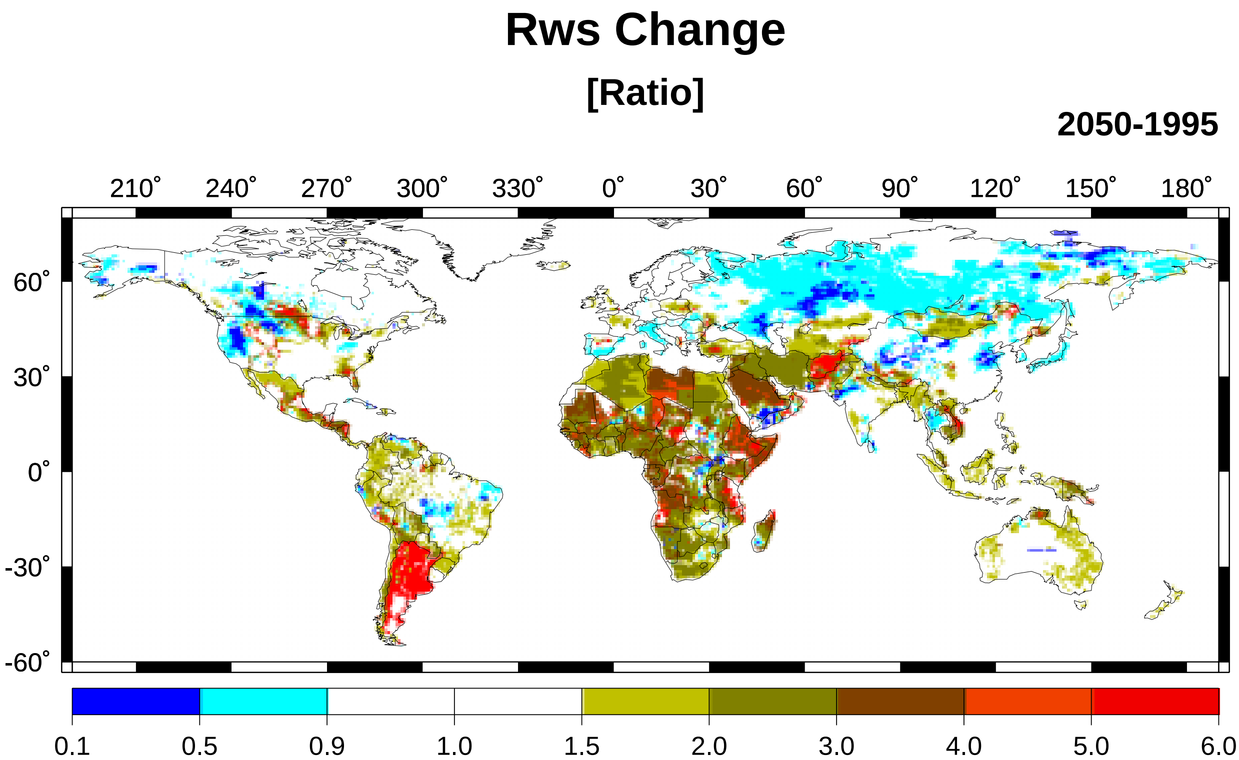

Figure 6. The change in the ratio of water withdrawal to availability in 2050 compared to that of in 1995.