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A GLOBAL RIVER DISCHARGE SIMULATION TAKING INTO ACCOUNT WATER WITHDRAWAL AND RESERVOIR OPERATIONS

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SYNOPSIS

A global river discharge simulation was conducted taking anthropogenic water withdrawal and artificial reservoir operations into account in order to investigate the balance of seasonally varying water resources and water demand globally. The simulation used a newly developed global river model. It has a digital global river channel map with 1°×1° spatial resolution and routes global gridded runoff data along the river channel. In the simulation, monthly water demands were withdrawn from the river channel. Also, the world's largest 452 reservoirs were geo-referenced to the channel and operated individually according to the estimated operating rules. The simulation results show that only 30% of the observed water withdrawal can be withdrawn from the river channel globally, because the river discharge and water withdrawal is very seasonal and their timing does not usually coincide. By taking water withdrawal into account, the water stressed area was extended to the lower stream compared to the non-water-withdrawal simulation. The contribution of major reservoir operation was limited in this study. The results indicate, to balance water resources and water demand at less than annual interval, water resources other than river water, and water storage facilities should be incorporated in global water resources modeling and assessment.

INTRODUCTION

Water is one of the most fundamental resources for human beings. The sustainability of the world's water resources has drawn increasing public attention, because of the future explosion of water demand caused by the rapidly growing world population and economy, and the projected risks of future water resources caused by global warming.

A number of global water resources assessments have been reported to project the geographical distribution of water scarce area (1,10, 11, 13). Their fairly common approach is to calculate the withdrawal to water resources ratio ($R_{WWR} = W_a / Q_a$) using the annual river discharge data (Q_a) and the reported annual total water withdrawal data (W_a). Shiklomanov (11) calculates the ratio for 26 regions in the world based on statistical data. Vörösmarty et al. (13), Oki et al. (10), Alcamo et al. (1) calculate the ratio globally with 0.5°×0.5° longitude-latitude spatial resolution using a global water resources model. They showed the distribution of water and areas where water is scarce as well as the number of people living in those areas.

There are two limitations of their study. First, they used annual river discharge and water withdrawal data, although both of them have large seasonality. They did not focus on a fundamental question whether water is available when it is needed. Averaging or accumulating seasonally varying water withdrawal and resources may underestimate the water scarcity in the low river discharge season. Second, the water withdrawal in the upper stream decreases the river discharge in the lower stream, although they (except Alcamo et al.) did not explicitly express this process.

In this study, a new global water resources assessment was conducted to examine the above issues based on an earlier study of Oki et al. (10). They used global annual water withdrawal data (irrigation, domestic, industrial water) provided by World Resources Institute (WRI; 14). They converted the WRI's country-based data into gridded data. In this study, we focused on the seasonality of irrigation water withdrawal which occupies 70% of the total water withdrawal (11). We estimated the monthly irrigation water demands using a crop calendar model and a crop water demand model. Oki et al. (10) obtained the global gridded river discharge data by routing global gridded runoff data with a global river routing model, namely Total Runoff Integrating Pathways model (TRIP; 8). We added a water withdrawal module to TRIP, so that the water which was withdrawn was removed from the river channel. We also added a reservoir operation module (6) to examine the contribution of major reservoir operations in the world. In this study, we mainly examined whether the monthly water demand could be withdrawn from the river. The results showed that, in areas where water is scarce, the simulated water withdrawal from the river was far below the reported water withdrawal for several months. To balance monthly water resources and water demand, three matters should be examined that were neglected in the earlier studies: water resources other than river water, such as ground water, aquifer or inter-basin water transfer; water storage facilities such as irrigation ponds and small reservoirs; and demand-side adaptation, such as shifting and dispersing cropping period. Introduction of these processes are critical for further improvement of global water resources modeling and assessment.

Finally, we define some technical terms that are frequently appears in this manuscript. We define "reported water withdrawal" as the volume of water that is withdrawn from river or ground water reported by researchers based on various statistics. Then we define "water demand" as the volume of water that has tried to withdraw from river in our simulation. Next we define "simulated water withdrawal" as we obtained with our simulation.

MODEL AND DATA

Three models (Crop calendar model, Crop water demand model and Global river model) were developed and used in this study (Fig. 1). Every model produces outputs with 1°×1° spatial resolution, monthly temporal resolution.

Crop Calendar Model

The crop calendar model estimates the best time for cropping for each calculating grid cell. The monthly air temperature and precipitation data are the input and the monthly crop calendar is the output. It is based on the algorithm of Döll and Siebert (4). Their approach is to assign a score to the suitability for cropping from hydrometeorological conditions, and to find the maximum accumulated score, that is, the best cropping times for a calculating grid. The cropping period is assumed to be five months for every crop. If conditions are suitable, double cropping is possible.

Crop Water Demand Model

The crop water demand model calculates the amount of irrigation water demand that is needed for the optimum crop growth. The crop calendar, meteorological data and irrigated area information are the input and the monthly irrigation water demand is the output. The model is based on the CROPWAT model (12) and a study of Döll and Siebert (4). The crop water demand W_{CWD} [kg s^{-1}] is calculated:

$$W_{CWD} = k_{eff}\left(k_c \cdot ET_{pot} - P_{eff}\right) \times k_{intensity} A \qquad (1)$$

where k_{eff} is the irrigation efficiency [0-1], k_c is the crop coefficient [0-1] to reflect the growing stage of crop, ET_{pot} is the potential evaporation [kg m^{-2} s^{-1}], P_{eff} is the effective precipitation [kg m^{-2} s^{-1}], $k_{intensity}$ is the crop intensity [0-1] to indicate the ratio of the actually cropped area to the total irrigated area and A is the irrigated area [m^2]. The irrigation efficiency was set at globally constant 0.5 by simplifying the estimation of Döll and Siebert (4). In this simulation, two types of crop are considered; rice and non-rice following to Döll and Siebert (4). The crop coefficient was prepared for each crop (4). It is assumed that the rice is cropped in the rainy season in eastern India, Southeast Asia and East Asia including southern China, Korean peninsula and Japan. The non-rice is cropped in the remaining area. The potential evaporation was calculated by FAO Penman-Monteith equation (12). The effective precipitation was calculated by means of the Soil Conservation Service Method given by the USDA (12). The crop intensity was set at 1.0 for first crop and at 0.3 for second crop for double cropping area by simplifying the estimation of Döll and Siebert (4). The irrigated area was provided by Döll and Siebert (3).

Global River Model

We used the TRIP model (8, 9), a global river model that routes global gridded runoff data along the digital global river map. This model has a digital river map with 1°×1° spatial resolution that delineates the rivers in the world. The flow velocity was fixed globally constant to 0.5 m s^{-1}as done by Oki et al. (9).

Two modules, the water withdrawal module and reservoir operation module, were incorporated in the global river model. The water withdrawal module withdraws water demand from the river channel. In this study, we set no upper limitation of withdrawal, therefore, water is withdrawn until the water demand is fulfilled or the river water is used up. The reservoir operation module estimates operating rules for world's largest 452 reservoirs (larger than 1.0×10^9 m^3 storage capacity; their total storage capacity is 4140 km^3). The reservoirs were geo-referenced to the TRIP digital river map and store and release water according to the allocated operating rules. The module can generate two types of operating rules: Irrigation operation for reservoirs whose primary purpose is to supply irrigation water, and non-irrigation operation for others. Irrigation operation releases stored water proportional to the monthly irrigation water demand in the lower reach of reservoirs.

Non-irrigation operation releases stored water to stabilize the seasonal fluctuation of river discharge. The model is described in detail in Hanasaki et al. (6).

Input Data

To run the crop calendar model and the crop water demand model, a global meteorological dataset, namely, International Satellite Land Surface Climatology Project initiative I (ISLSCP I; 7) data was used. It covers 2 years from 1987 to 1988 with 6 hourly temporal resolutions, 1°×1° spatial resolution.

To run the global river model, gridded runoff data produced by the Global Soil Wetness Project (GSWP; 2) was used. GSWP is an international modeling research activity whose aim is to produce the state of the art global datasets of land surface fluxes and state variables. GSWP provides the offline simulation outputs for 11 land surface models (LSMs). ISLSCP I meteorological data was input to each LSM and land surface flux and land state variables were calculated. To exclude the bias inherent in individual models, we used the average of the total runoff of 11 LSMs. Guo et al. (5) showed that this so called "multi-model ensemble approach" perform significantly better than a single model system. Oki et al. (9) reported a limitation of the global river discharge simulation using GSWP runoff. They noted that while the GSWP runoff dataset reproduced seasonal patterns of river discharge well, but it underestimated annual total river discharge. The simulated global annual total river discharge for the average of the 11 GSWP-participating LSMs was 28845 km^3 yr^{-1} (average of 1987-1988), while earlier studies estimate around 40000 km^3 yr^{-1}. The underestimation of runoff is not a negligible problem, but the timing of the water resources and water demand is the main focus of this study. For this reason, we concluded that the runoff dataset was appropriate for this study.

For the domestic and industrial water demand data, WRI (14) dataset was used. The dataset is one of the few global comprehensive datasets on reported water withdrawal. We used the gridded data that Oki et al. (10) converted from the WRI's original country based data assuming that the distribution of water withdrawal is proportional to that of population. In this study, we assumed that the domestic and industrial water demand does not have any seasonal fluctuations and that the monthly water demand is annually constant.

SIMULATION AND ANALYSIS

The schematic diagram of the simulation is shown in Fig. 1. First, a global gridded monthly crop calendar was estimated using the monthly meteorological data (average of 1987 and 1988). Secondly, a global gridded monthly crop water demand was estimated using the crop calendar, irrigated area and monthly meteorological data of each year (1987 and 1988). The monthly total water demand is the summation of simulated irrigation water demand (varies monthly) and WRI's domestic and industrial water demand (annually constant, identical to reported water withdrawal). Thirdly, three types of global river discharge simulation runs were conducted as listed in Table. 1.

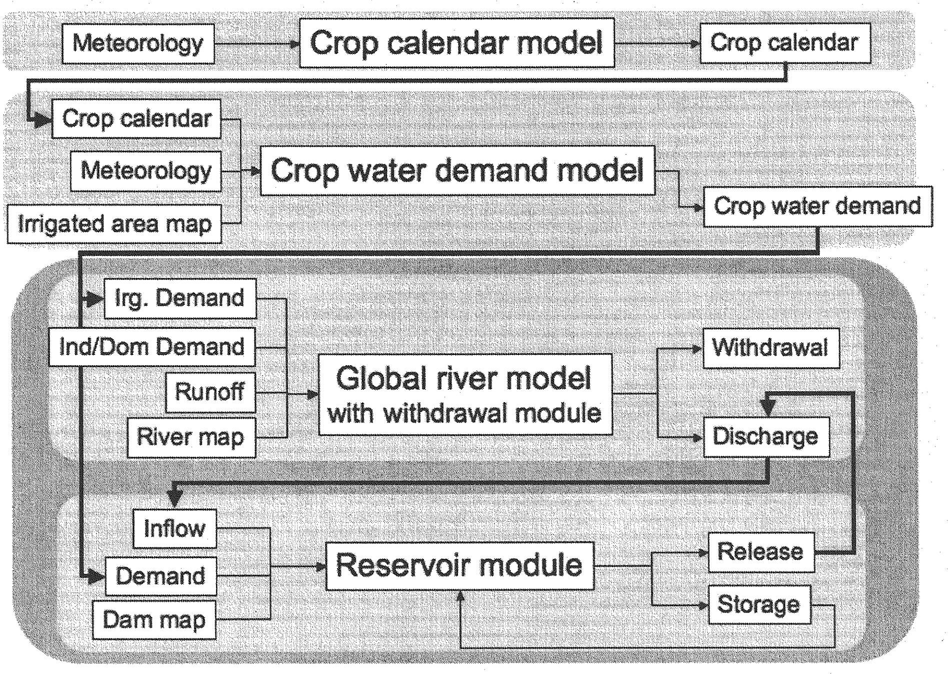

Fig. 1. Schematic diagram of simulation

Table. 1 Three types of simulation run. Checked (×) modules were enabled.

Runs \ Module	River	Withdrawal	Reservoir
CTRL	×		
INT	×	×	
INT-RSVR	×	×	×

The water availability was examined using a new index, the cumulative withdrawal to demand ratio (R_{CWD}).

$$R_{CWD} = \sum_{m=1}^{12} W_m \Big/ \sum_{m=1}^{12} D_m \tag{2}$$

where W_m is the water withdrawal of the m th month, D_m is the total water demand of the m th month. W_m was calculated from INT and INT-RSVR simulation. Note that simulated water withdrawal is always less or equal to water resources ($W_m \le D_m$), therefore, the amount of monthly river discharge that exceeds the monthly water demand is not included as water resources. We also calculated the withdrawal to water resources ratio (R_{WWR}):

$$R_{WWR} = \sum_{m=1}^{12} D_m \Big/ \sum_{m=1}^{12} Q_m \tag{3}$$

where Q_m is the river discharge of m th month. Q_m was calculated from CTRL simulation.

RESULTS AND DISCUSSION

Validation of Irrigation Water Demand Simulation

Table. 2 shows WRI's reported annual irrigation water withdrawal that was used in Oki et al. (10) and the simulated one in this study. The simulated irrigation water demand agrees well with that of WRI. Fig. 2 shows the geographical distribution of difference between two data. For Asia's case, the underestimation of the irrigation water demand mainly in China is canceled out by the overestimation around the Indus River basin. Similarly, for Europe's case, the overestimation in the Volga River basin is canceled out by the underestimation in southern Europe. The discrepancy shows the limitation of our method. To fit the simulated distribution to that of Oki et al. (10), we needed to tune model parameters of Eq. 1 regionally. Because the primary purpose of this research is to discuss the difference of monthly and annual water withdrawal, and as Table. 2 shows the simulated results agrees well with WRI for each continent, we used the simulated irrigation water demand and kept on the study.

Table. 2 Global irrigation water demand (withdrawal) estimation (km^3/year)

	Asia	Europe	Africa	North America	South America	Oceania	Global
WRI, 1998	1691	140	136	316	101	6	2390
This study	1610	145	168	333	65	21	2342

Global Assessment

Table. 3 shows the annual global water balance components for 1987. The annual total water demand (3448 $km^3\ yr^{-1}$) is 12% of the annual total global river discharge (29295 $km^3\ yr^{-1}$), however, the simulated withdrawal (972 $km^3\ yr^{-1}$ for no reservoir operation, 1041 $km^3\ yr^{-1}$ for with major reservoir operations) was less than 30% of the demand. Even 452 major reservoirs that have altogether 4140 km^3 of storage capacity were incorporated, the availability increased by only 7%. Fig. 3 shows the global distribution of two indices, R_{CWD} (the cumulative withdrawal to demand ratio) and R_{WWR} (the withdrawal to water resources ratio). Notice that R_{CWD}'s color bar was set so that the distribution looks similar to that of R_{WWR}. Two figures indicate that the area with R_{WWR} larger than 0.4 (earlier studies categorized as high water stress) roughly corresponds to the area with R_{CWD} less than 0.4, or the available water from the river is less than 40% of the annual total water demand. In other words, in the high water stressed area, the monthly available water from the river was far below the monthly water demand for several months. These areas are located mainly in the arid to semi-arid areas such as western US, the Indus River basin, northern China, central Asia, the Middle East.

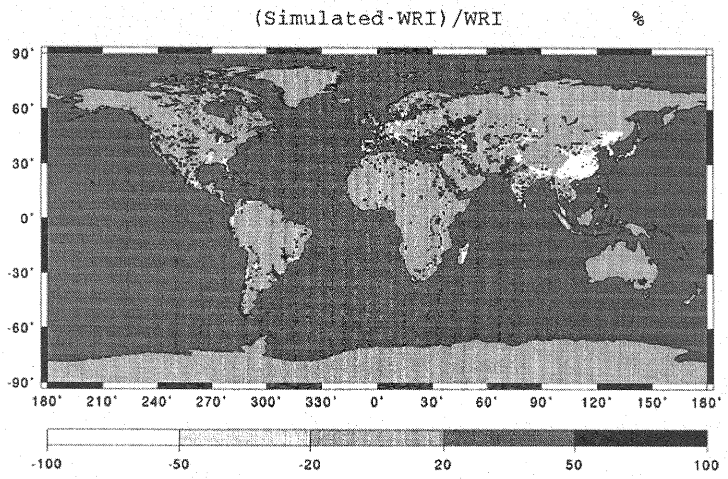

Fig. 2. The difference between simulated and WRI reported annual irrigation water demand.

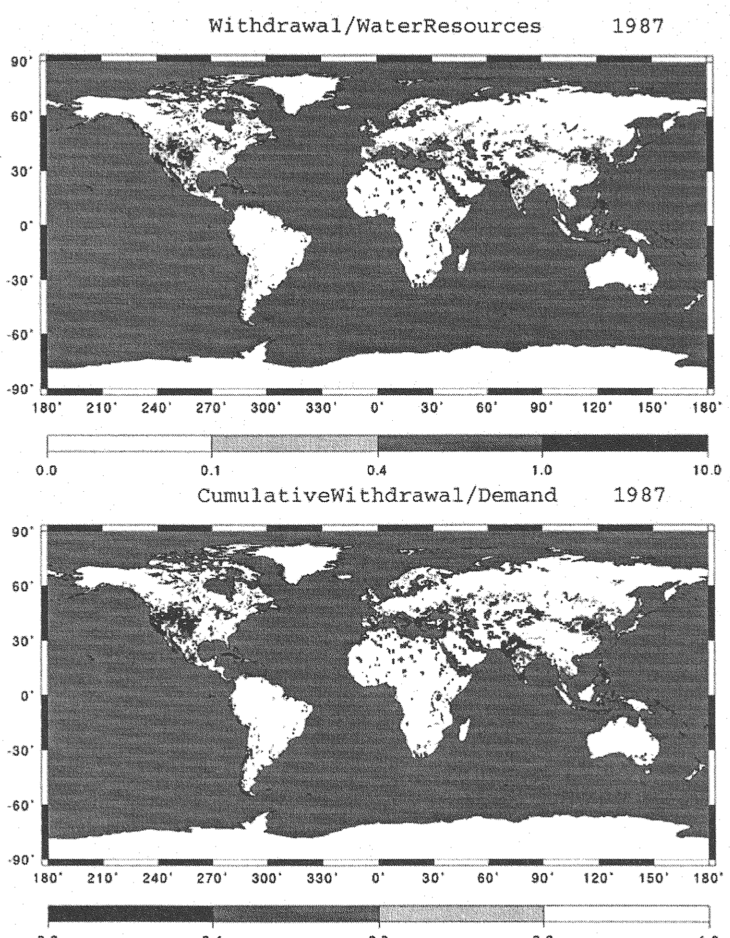

Fig. 3. The global distribution of the withdrawal to water resources ratio and the cumulative withdrawal to demand ratio.

Table. 3 Global water balance ($km^3\ yr^{-1}$, for 1987)

	CTRL	RSVR	INT	INT-RSVR
Runoff	29295	29295	29295	29295
Discharge	29295	29307	28346	28370
Demand			3448	3448
Intake			972	1041
Change of river storage	0	-1	-23	-19
Change of reservoir storage		-11		-97

Assessment at Nine River Basins

Next, nine river basins in the world (The Yellow, Nile, Amu Darya, Syr Darya, Colorado, Chao Phraya, Ganges, Indus and Euphrates Rivers) became the focus of further examination, because earlier studies reported that they suffered from high water stress.

Fig. 4 shows the geographical distribution of R_{WWR} and R_{CWD} for each basin. The former is derived from the result of CTRL simulation and the annual total water demand data, no water is withdrawn from the channel. The latter is derived from the results of the INT-RSVR simulation, so the withdrawn water was not returned to the channel. The water withdrawal in the upper reach affects the water availability in the lower reach. For example, in the Indus River and the Ganges River, the low R_{CWD} area expands to the lower reach. In the Chao Phraya River, the Amu Darya River and the Yellow River, the low R_{CWD} area appears in the lowermost reach where R_{WWR} showed as low stress area.

Fig. 5 shows the monthly time series of available water resources and demand of each basin from 1987. The figure shows that the water stress is low in the Yellow River and the Nile River throughout a year, but this is attributable to the overestimation of runoff. We excluded these two rivers from our analysis. The water stress is high in the Ganges River and the Indus River throughout a year. In the Colorado River, the Syr Darya River and the Amu Darya River, the water demand is concentrated in few months in a year. The Chao Phraya River and the Euphrates River show clear seasonality of the monthly balance of water resources and demand. In the Chao Phraya River, water is sufficient in the late rainy season (from August to November), insufficient in the dry season (from February to May) in the Asian monsoon climate. In the Euphrates River, water is sufficient in the snow melting season (from February to April), insufficient in other months.

The simulation results indicate that the reservoir operation increases the water withdrawal. For example, the reservoir operation doubled water withdrawal in some months in the Euphrates River and the Colorado River. The water storage facilities are important in these basins, which make it possible to convert water resources in the rainy season for use in the dry season. In this study, the world's largest 452 reservoirs were taken into account, however, their contribution was limited. Irrigation ponds and small reservoirs should be also incorporated in the global model. The shallow ground water has a similar function, which is to maintain precipitation in the rainy season in the soil. To balance water resources and water demand monthly, it is also important to incorporate water resources other than river water, such as deep ground water, aquifer or inter-basin water transfer, and because the water demand is concentrated in few months in many basins, demand-side adaptation, such as shifting and dispersing cropping period. However, as of today most of global water resources models neglects these processes.

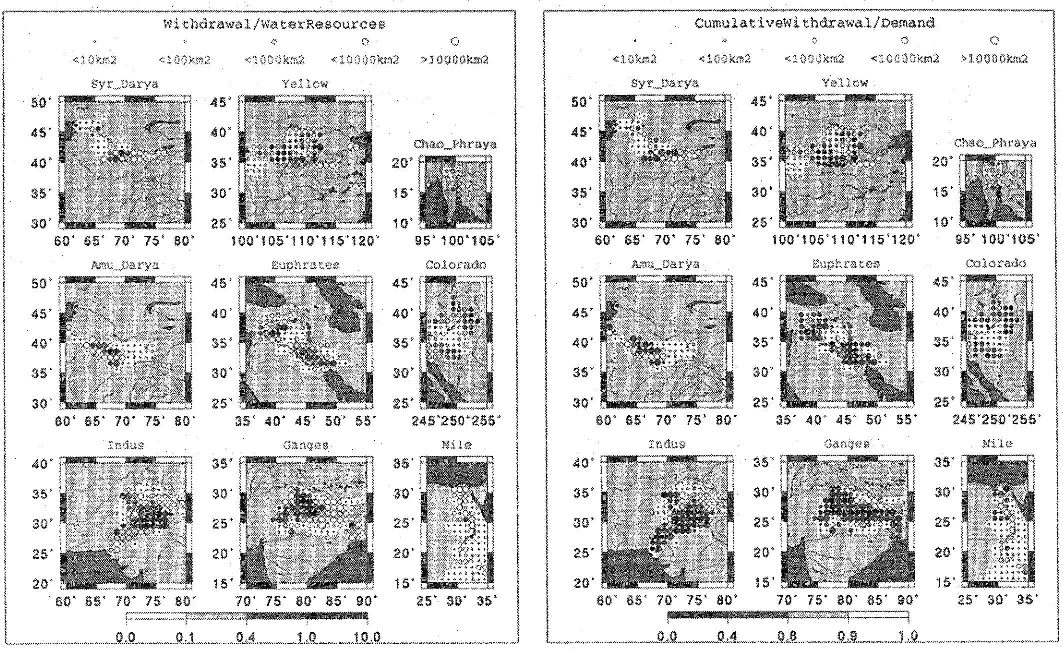

Fig. 4. Left: The withdrawal to water resources ratio from CTRL simulation. Right: The cumulative withdrawal to demand ratio from INT-RSVR simulation. The size of symbols shows the irrigated area of the grid. + indicates less than $10km^2$ or no irrigated area. The darker color indicates the high water stress area.

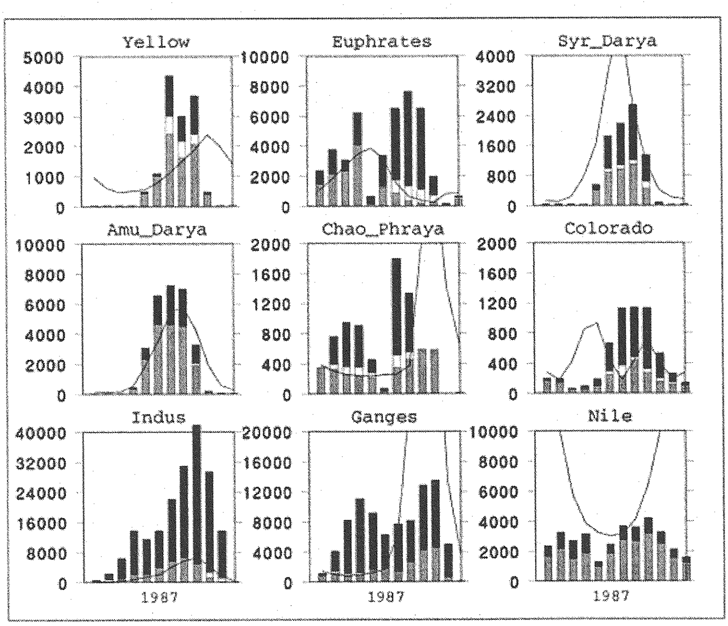

Fig. 5. Monthly total water demand and simulated water withdrawal for nine river basins in 1987. Black: monthly total water demand, White: monthly total available water (INT-RSVR simulation), Gray: monthly total available water (INT simulation). Note that these three bars are overlaid. The black part shows the shortage of water, the white part shows that it can be available for INT-RSVR simulation, not for INT simulation. Solid line shows CTRL river discharge at river mouths.

CONCLUSION

A global river discharge simulation was conducted taking water withdrawal and reservoir operation into account in order to investigate the balance of seasonally varying water resources and water demand globally. In a large part of high water stress area (by conservative water stress indicator $R_{WWR} \leq 0.4$), the annual simulated water withdrawal from the river is less than 40% of the total annual water demand. To balance the water resources and water withdrawal in global water resources modeling studies, the following three matters should be examined. The first matter is the incorporation of water resources other than river water. In fact, deep aquifers, natural lakes and melting water of glacier are important water resources, especially for dry regions in the world. The second matter is the incorporation of water storage facilities or functions to convert the rainy season's water resources for use in the dry season, such as reservoirs and irrigation ponds. In this study, the world largest 452 reservoirs were considered, although, their contribution was limited in global scale. The third matter is the incorporation of demand-side adaptation, such as shifting and dispersing cropping period.

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REFERENCES

1. Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch and S. Siebert : Development and testing of the WaterGAP 2 global model of water use and availability, Hydrological Sciences Journal, Vol.48, No.3, pp.317-337, 2003
2. Dirmeyer, P. A., A.J. Dolman and N. Sato : The pilot phase of the global soil wetness project, Bulletin of American Meteorological Society, Vol.80, pp.851-878, 1999.
3. Döll, P. and S. Siebert : A Digital Global Map of Irrigated Areas, Journal of International Commission on Irrigation and Drainage, VOl.49, pp.55-66, 2000
4. Döll, P. and S. Siebert : Global modeling of irrigation water requirements, Water Resources Research, Vol.38, No.4, pp. 2002.
5. Guo, Z., P.A. Dirmeyer , X. Gao and M. Zhao : Improving the quality of simulated soil moisture with a multi-model ensemble approach, Center for Ocean-Land-Atmosphere Studies Technical Report, 2005
6. Hanasaki, N., S. Kanae and T. Oki : A reservoir operation scheme for global river routing models, Journal of Hydrology, Vol.327, pp.22-41, 2006
7. 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 : ISLSCP Initiative I - Global datasets for land-atmosphere models 1987-1988, NASA, 1995
8. Oki, T. and Y.C. Sud : Design of Total runoff integrating pathways (TRIP) –A global river channel network, Earth Interactions, Vol.2, 1998
9. Oki, T. and T. Nishimura and P. Dirmeyer : Assessment of land surface models by runoff in major river basins of the globe using Total Runoff Integrating Pathways (TRIP), Journal of Meteorological Society of Japan, Vol.77, pp.235-255, 1999

10. Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D. Yang and K. Musiake : Global assessment of current water resources using total runoff integrating pathways, Hydrological Sciences Journal, Vol.46, No.6, pp.983–995, 2001
11. Shiklomanov, I.A. : Appraisal and assessment of world water resources, Water International, Vol.25, No.1, pp.11-32, 2000
12. Smith, M. : CROPWAT -A computer program for irrigation planning and management, FAO Irrigation and Drainage Paper, Vol.46, 1992
13. Vörösmarty, C. J., P. Green, J. Salisbury and R.B. Lammers : Global water resources: Vulnerability from climate change and population growth, Science, Vol.289, pp.284–288, 2000
14. WRI (World Resources Institute) : 1998-99 World Resources. Report of UNEP, UNDP & World Bank, Oxford University Press, Oxford, UK, 1998

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