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ASSESSMENT OF WATER RESOURCE PROBLEMS UNDER CLIMATE CHANGE

-CONSIDERING INTER-ANNUAL VARIABILITY OF CLIMATE DERIVED FROM GCM CALCULATIONS-

Kiyoshi Takahashi[1]
Yuzuru Matsuoka[2]
Yoko Shimada[3]
Hideo Harasawa[4]

Abstract

Due to various reasons such as increasing population, industrial development, and expanding irrigation, which are expected to continue in the future, water resource shortages have become more severe in many parts of the world. In order to assess the balance between water supply and demand in the future under conditions of climate change, surface runoff and water demand in each river basin were estimated from 2050 through 2059. It was found that the estimated spatial patterns of runoff change in the 2050s differ considerably according to the GCM used, especially in Central Africa and the northern part of South America. In developed countries, industrial water demand will increase, while agricultural water demand will slightly decrease. In developing countries, water demand will increase in all sectors, with the share of industrial water demand showing a particularly significant increase. In some river basins, the degree of inter-annual fluctuation of runoff in 2050 might be more critical factor of water scarcity than the mean change of climatology or the change of water demand.

KEYWORDS: *water resources, climate change impact, water shortage*

1. Introduction

The shortage of water resources and various resultant environmental problems have come to the forefront accompanying population growth, industrial development, expansion of irrigated agriculture, and other factors. Based on the premise of development type scenarios in which population growth continues and industrialization rapidly progresses for some time in the developing countries, there are concerns that further serious water shortages may occur over wide areas due to the growth in demand

1 Researcher, Social and Environmental Systems Division, National Institute for Environmental Studies, Tsukuba, JAPAN.
2 Dr.Eng, Prof., Graduate School of Engineering, Kyoto University, Kyoto, JAPAN.
3 Dr.Eng, Laboratory of Environmental Chemistory, Kobe Institute of Health, Kobe, JAPAN.
4 Dr.Eng, Social and Environmental Systems Division, National Institute for Environmental Studies, Tsukuba, JAPAN.

for water, and that these may become a factor constraining future economic development. Since climate change alters spatial and temporal patterns of precipitation and evaporation, water resources may increase or decrease depending on the region. Whichever the case may be, it is unlikely that the current distribution of water resources can be maintained in the future.

Many studies have been conducted and considerable efforts have been expended to promote the sustainable use of water resources, in response to increasing water demand resulting from economic development and other factors, at both the regional and global levels. However, due in part to the uncertainty of climate change itself, when assessing such future water resources there are still many cases in which alterations in water resource distribution patterns due to climate change are not taken into consideration (Siklomanov, 1997, Raskin, 1997). Alcamo et al. (1999) developed a global water assessment model (WaterGAP) which considered not only socio-economic factors but also climate change projected by General Circulation Model (GCM). Although the study provided the projection of future water resource altered under climate change, it did not take into account the inter-annual fluctuation of climate which could be a significant determinant of stability of water resource as well as the change of mean climatology. The aim of our study is to forecast water demand and the volume of water resources available at the global level over the medium to long term taking climate change into consideration. It is also the first trial to evaluate significance of the inter-annual fluctuation of climate in global water-resource assessment.

This paper describes our study targeting the ten years from 2050 to 2059 in which we estimated water demand and the volume of water resources available for use, and according to the changes in the ratios from the present conditions, investigated qualitative changes in the likelihood of water shortages occurring compared with the present. We also argued ways of improving the method used in this study in the future so as to enable concrete strategies for water shortage measures to be proposed.

2. Estimation method

Figure 1 shows the estimation scheme of this study. In the surface runoff module, runoff volume is estimated based on grid climate information and surface information and the volume of water potentially available for use within river basins is estimated. In the water demand module, future water demand in each river basin is estimated from the current estimated volume of water demand, population distribution estimation, and economic development scenarios. Moreover, with the changes in the ratio of water available for use to water demand, changes in the balance between water supply and demand in the future are qualitatively grasped. Assessment of the balance between supply and demand was carried out for each river basin. For the river basin divisions, TRIP (Oki *et al.*, 1998) with a $1^{\circ} \times 1^{\circ}$ resolution estimated from altitude data was used.

2.1 Water demand estimation

Water demand was estimated for the household, industrial, and agricultural sectors, respectively (Fig. 2). For each sector, first, based on population changes and the growth in scale of economic activities as well as scenarios concerning the improvement of future water use efficiency, water demand was estimated for each country (top part of Fig. 2). Next, based on an estimate of population

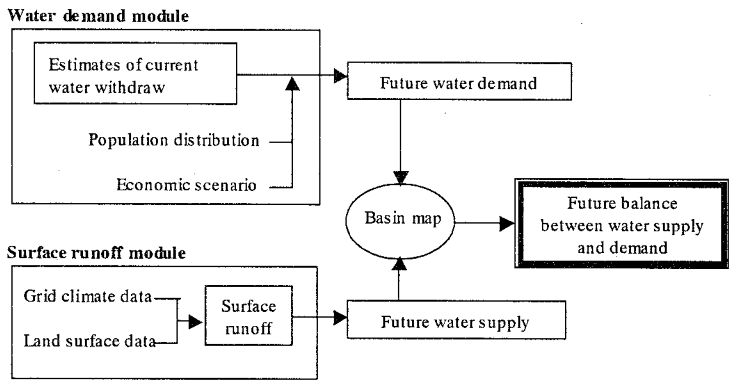

Fig. 1 Estimation scheme of the study

spatial distribution and land use distribution (cropland density), the spatial distribution of the water demand was estimated (middle part of Fig.2). Finally, the estimated spatial values were totaled for each river basin to provide a value for water demand (bottom part of Fig. 2).

As the basis for the estimates for each country, the withdrawal data compiled by the World Bank (1998) were used in each sector as of 1990. For countries with missing data in the World Bank's database, sector-wise withdrawal data are collected from Gleick (2000). For the estimates for each country in the future (2050), different methods were used for each sector. It was assumed that water demand in each country in the household sector will change in proportion to midrange population estimates made by the World Bank (1993). The estimated values were then multiplied by the value of the per capita change in water use established for each region. For the scenario of change in per capita water use, the study by the Stockholm Environment Institute (Raskin, 1997) was used, since it covered whole the world and suitable for this study. When more detailed information on future plan of municipal water supply comes to be available, this scenario should be replaced. In the case of the

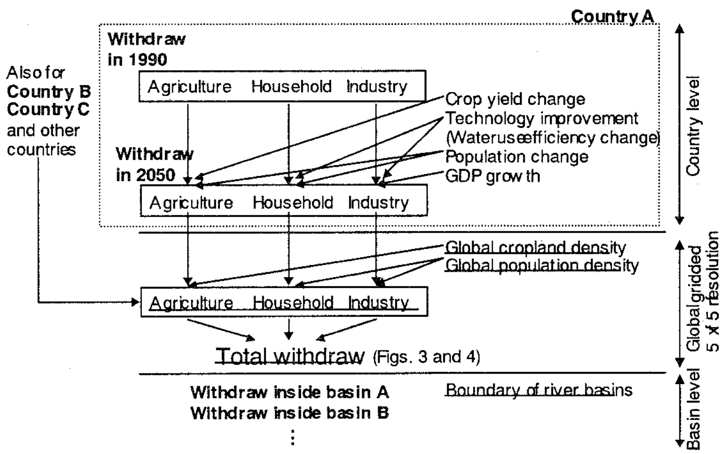

Fig. 2 Outline of the water demand estimation

industrial sector, it was assumed that water demand will be in proportion to the GDP growth rate of each country and also that reductions will be realized according to the water use efficiency improvement scenario. Share of industrial sector in GDP is assumed to be constant in future. The assumption may cause underestimation of industrial withdraw in developing countries where industrial sector has a potential to increase its share in GDP. Table 1 shows the water use efficiency improvement coefficients, with 1990 as the base year, that were used for demand estimation for 2050. For the same reason with household sector, Raskin (1997) is referred to. In the case of the agricultural sector, demand was estimated according to the following equation. The last term ($Y_{i,1990}/Y_{i,2050}$), the inverse of the change of crop yield, corresponds to the improvement of water use efficiency. As crop yield increases, the water required for producing one unit of crop will decrease.

$$ADEM_{i,2050} = ADEM_{i,1990} \times \frac{POP_{i,2050}}{POP_{i,1990}} \times \frac{Y_{i,1990}}{Y_{i,2050}}$$

$ADEM_{i,y}$: Agricultural water withdraw in the year y at the nation i

$POP_{i,y}$: Population in y at i

$Y_{i,y}$: Averaged crop yield in y at i

The increase in yield per unit area was based on the assumption of an annual rate of increase of 1% until 2010 and 0.5% thereafter in the industrialized countries; 1.4% until 2010 and 0.7% thereafter in the developing countries (Alexandratos, 1995); and 1.015% until 2000, 1.007% until 2005, 1.004% until 2010, and 0.5% thereafter in China (Research Institute for Development Assistance of the Overseas Economic Corporation Fund, 1995).

The spatial distributions of water demand in 1990 and 2050 were estimated for the household sector by spatially weighting the estimated water demand for each country by GPW population distribution estimation (CIESIN *et al.*, 2000). Although this method cannot differentiate wateruse per capita in city area from that in rural area, we adopted the method because of limitation of spatial data on population distribution. Since the gap of wateruse per capita between city and rural area will decrease in 2050, this method seems appropriate for future. In the case of the industrial sector, following the method of Klepper *et al.* (1998), it was assumed that for countries with population density grids of 75 persons/km^2 or more, domestic industrial water demand is distributed in the grids in proportion to the population density. For other countries, it was assumed that domestic industrial water demand is similarly distributed in population density grids of 20 persons/km^2 or more. This reflects the fact that industries are concentrated in urban (high population density) areas. In the case of the agricultural sector, the distribution was estimated based on the assumption that it is in proportion to the grid agricultural land area percentage data estimated by linking remote sensing data and agricultural land area data by statistical data (Ramankutty *et*

Table 1 Water use efficiency improvement coefficients in 2050 (with 1990 as the base year)

Region	Household	Industry
N. America	0.798	0.613
W. Europe	1	0.886
OECD Pacific	1.01	0.487
Former Soviet	1.233	0.696
E. Europe	1.385	0.709
Africa	1.5	0.921
Latin America	1.64	0.701
Middle East	1.951	0.938
Central Planning Asia	1.667	0.699
S. and S.E. Asia	2.278	0.763

al., 1998). Agricultural land area percentage data may be replaced with irrigate land area percentage, if reliable irrigated area map is available in future.

2.2 Surface runoff estimation

For the estimation of surface runoff in each grid, one of the bucket-type models (Vorosmarty *et al.*, 1989) was used with the inputs of monthly mean climate data and surface data having a 0.5°× 0.5° spatial resolution. Taking snow coverage during periods of low temperature into consideration, within effective precipitation (Precipitation - Evapotranspiration), the amount exceeding the maximum water content able to be retained in the soil was calculated as the surface runoff. Evapotranspiration was calculated as a function of monthly mean potential evapotranspiration (PET) using the method of Penman (FAO, 1992) and the degree of saturation of the soil. The basic equations applied to each grid are as follows. For details, refer to AIM (1996).

(A) Runoff

$$RO_m = \max(SM_{m-1} + P_m + RS_m - PS_m - ET_m, 0)$$

(B) Soil moisture accumulation

$$SM_m = SM_{m-1} + P_m + RS_m - PS_m - ET_m - RO_m$$

(C) Snow pack accumulation

$$SP_m = SP_{m-1} - RS_m + PS_m$$

(D) Evapotranspiration depending on the degree of soil moisture saturation

$$\text{if} \quad SM_{m-1} + P_m + RS_m - PS_m \geqq PET_m$$

$$ET_m = PET_m$$

$$\text{if} \quad SM_{m-1} + P_m + RS_m - PS_m < PET_m \quad \text{and} \quad SM_{m-1} \geqq FC/2$$

$$ET_m = P_m + RS_m - PS_m + (PET_m - P_m - RS_m + PS_m) \times (2 \times SM_{m-1}/FC - 1)$$

$$\text{if} \quad SM_{m-1} + P_m + RS_m - PS_m < PET_m \quad \text{and} \quad SM_{m-1} < FC/2$$

$$ET_m = 0$$

Here, RO_m is surface runoff in month m (mm), ET_m is evapotranspiration (mm), PET_m is potential evapotranspiration (mm) estimated by Penman method, SM_m is soil moisture (mm), P_m is precipitation (mm), SP_m is snow pack (mm), RS_m is melted snow (mm), PS_m is snowfall (mm), FC is field capacity (mm).

The monthly 24-hour-mean temperature, diurnal temperature range, cloud coverage, wind velocity, ratio of day to night wind velocities, surface albedo, and latitude were used as the input data for PET estimation by the Penman method. For current climatic conditions, the monthly-mean values from 1980 to 1989 of the CRU Global Climate Dataset developed by LINK project (New *et al.*, 1998) were used for the 24-hour-mean temperature, diurnal temperature range, cloud coverage, wind velocity, and precipitation. The CRU Global Climate Dataset consists of 0.5 ° latitude by 0.5 ° longitude resolution monthly time series of climatology for global land areas, excluding Antarctica for the period 1901-1995. The ratio of day to night wind velocities was determined based on the wind velocity in 1987 and 1988 reported by ISLSCP (Meason *et al.*, 1995). The data sets of ISLSCP are mapped to a common spatial resolution (1°x1 °). Temporal resolution of ISLSCP data for wind velocity is 6-hourly, which was appropriate for creating the ratio of day to night wind velocity. For the surface albedo, monthly data were prepared by time-interpolating Matthews' seasonal albedo data (Matthews, 1983).

2.3 Development of future climate scenario

Future climate data for 24-hour-mean temperature, diurnal temperature range, cloud coverage, wind velocity, and precipitation were prepared as follows. The differences between the 30-year normal monthly-mean values (calculated values) from 1961 to 1990 obtained by General Circulation Model (GCM) experiments for a gradual increase of 1% in greenhouse gas concentrations and the monthly-mean values (calculated values) for the year 205x obtained in these experiments were added to the current 30-year (1961-1990) normal monthly observed values obtained by LINK as mentioned above (the values for cloud coverage, wind velocity, and precipitation were multiplied by the rate of change). Due to the limited availability of data, we assumed no change in the ratio of day and night wind velocities and in albedo from the current conditions. As an example, the method of obtaining the daily mean temperature in August 2055 ($T_{2055,8}$) is as follows.

$$T_{2055,8} = \frac{\sum_{y=1961}^{1990} TL_{y,8}}{30} + \left(TG_{2055,8} - \frac{\sum_{y=1961}^{1990} TG_{y,8}}{30} \right)$$

$T_{y,m}$: Scenario of monthly mean temperature for the year y and the month m

$TL_{y,m}$: Monthly mean temperature for the year y and the month m by LINK

$TG_{y,m}$: Monthly mean temperature for the year y and the month m by GCM

In order to avoid bias due to the use of a single GCM, among the seven CO_2 transient experiments provided by the IPCC Data Distribution Centre, three experiments, the Canadian Climate Centre (CCC), the Max Planck Institute (ECHAM4), and the Tokyo University Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES), were selected for development of the climate scenario. These were selected among the experiments evaluated because they exhibited comparatively good reproducibility in a study on reproducibility of the current climate (Takahashi *et al.*, 1999), and provided all of the necessary climate parameters for the trial calculations in the present study. Since the spatial resolution of the output of the transient experiments is very rough at 2 ° to 5°, when developing the scenario it was interpolated to 0.5 ° by means of splines with tension. This scenario development method enabled a climate scenario to be obtained for each year from 2050 to 2059, and allowed impact assessments reflecting the range of inter-annual fluctuations of the future climate to be forecast by GCM.

3. Estimation results

Figures 3 and 4 show the spatial distributions of water demand density (mm/year, total of three sectors) with a 5' x 5' resolution in 1990 and 2050, respectively, estimated in this study. White-colored grids show the area where water demand density is very low. Areas with extremely high density of water demand exist in various regions including eastern China, Southeast Asia, India, Japan, eastern U.S.A., and Europe. Among these, eastern China and India will have extremely high demand resulting from the trend toward a rapid increase in demand in the first half of the 21st century. When the trend of change from the current situation is roughly examined, in the industrialized countries where population is on a stable trend, water demand will increase only in the industrial sector. It will not change significantly in the household sector, and will show a decreasing tendency in the agricultural sector (Fig. 5). In contrast, reflecting the trends of both population growth and

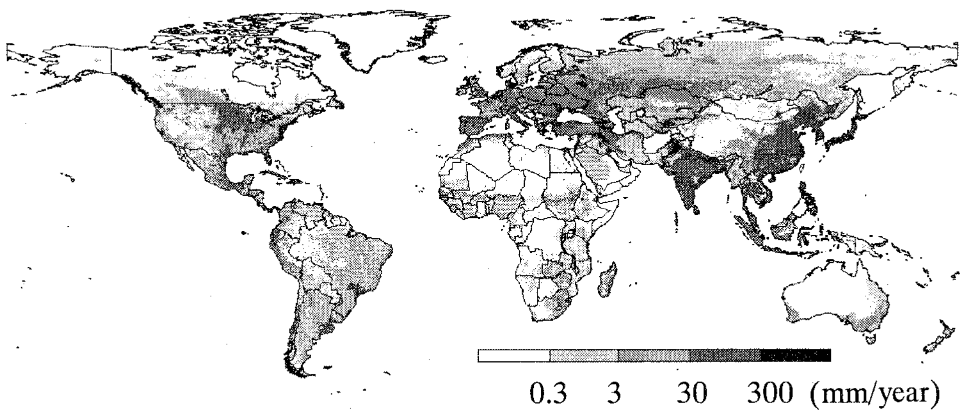

Fig. 3 Water demand density in 1990 (mm/year)

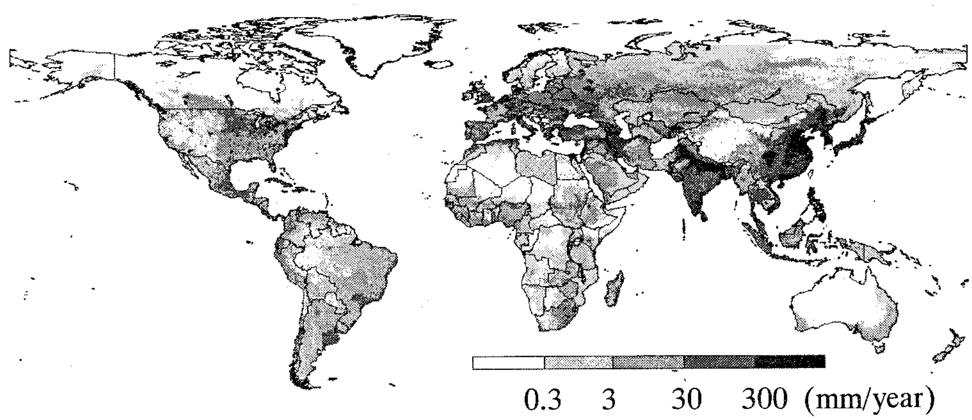

Fig. 4 Water demand density in 2050 (mm/year)

economic development in the developing countries, increases will simultaneously occur there in the industrial sector and the agricultural/household sectors. In terms of the share of each sector, the increase in the industrial sector will be large. Figure 6 shows the difference of water demand density between 1990 and 2050. White- colored grids show the area where water demand density is very low both in 1990 and in 2050. There will be a very high increase in China, India, East and Central Europe. In the developed countries such as U.S.A and Western European countries, water demand density will decrease slightly.

Figures 7, 8, and 9 show changes in runoff calculated based on the results of the transient experiments of the CCC, ECHAM4, and CCSR/NIES climate models, respectively (Mean runoff for 10 years from 2050 to 2059 - Mean runoff for 10 years from 1980 to 1989). White-colored grids show the area where no runoff is estimated both in 1990 and in 2050. From those figures, it can be seen that some increase in runoff will occur throughout the whole of Siberia. Large increases in runoff in southern China and the Indian subcontinent are also common features of the two figures.

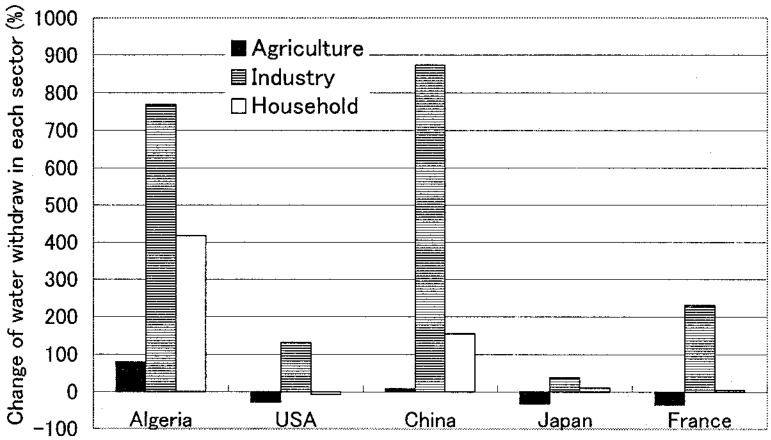

Fig. 5 Percentage change of sector-wise water demand between 1990 and 2050 in some countries (%)

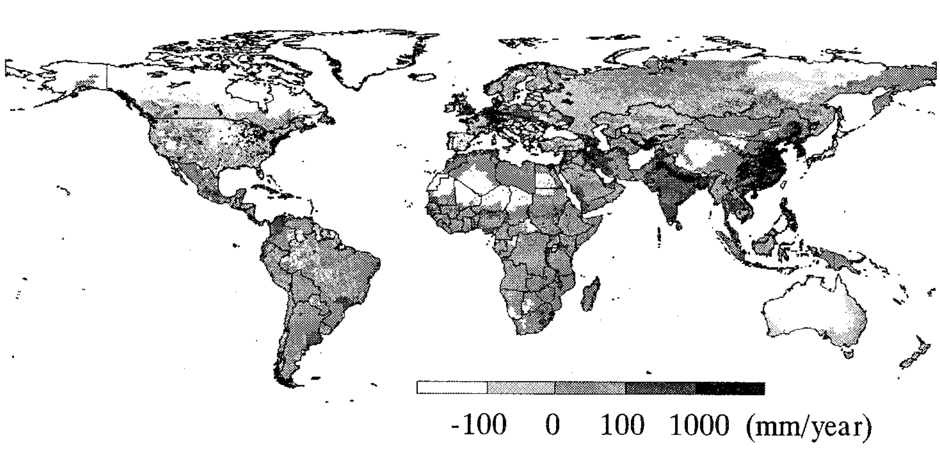

Fig. 6 Change of water demand density between 1990 and 2050 (mm/year)

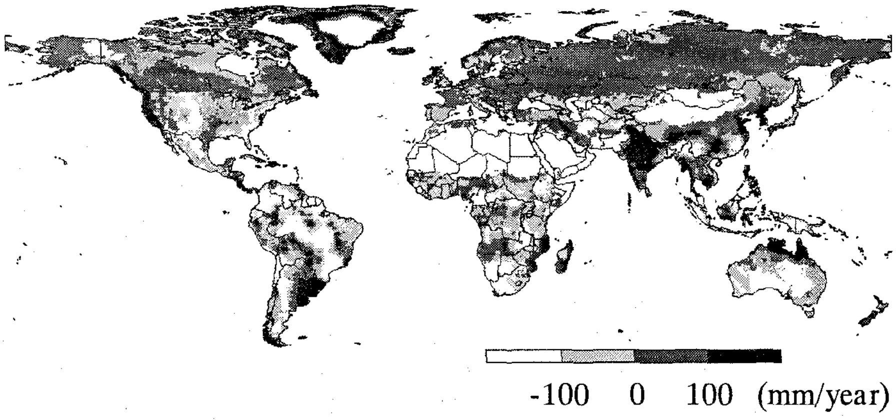

Fig. 7 Change of 10-year mean surface runoff between 1980s and 2050s (mm/year, CCCma model)

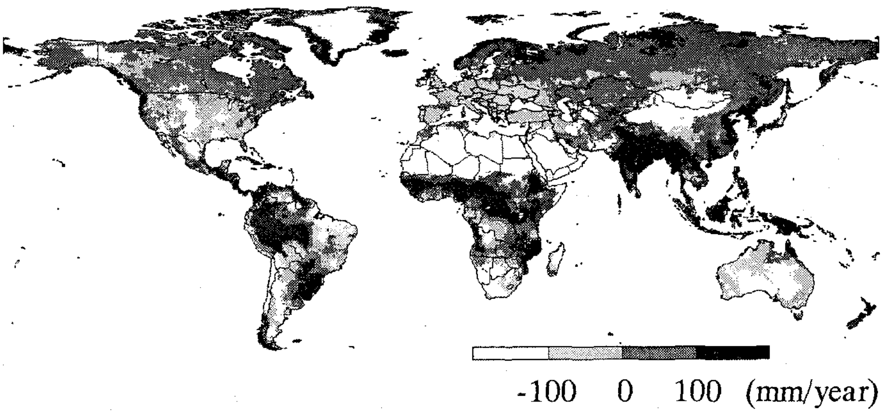

Fig. 8 Change of 10-year mean surface runoff between 1980s and 2050s (mm/year, ECHAM4 model)

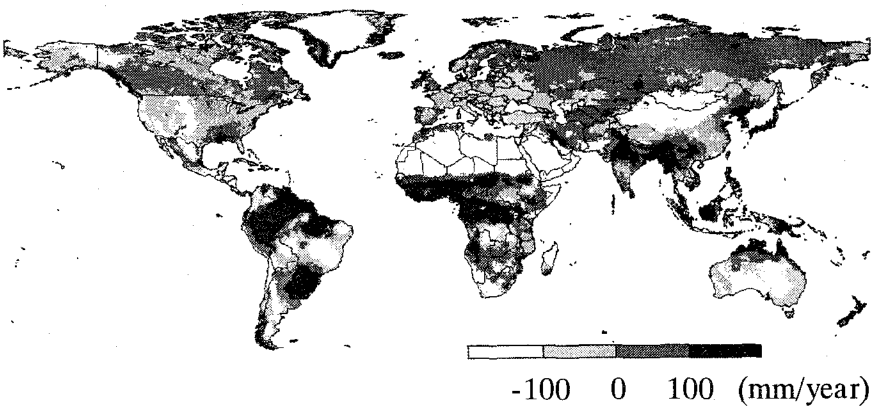

Fig. 9 Change of 10-year mean surface runoff between 1980s and 2050s (mm/year, CCSR/NIES model)

On the other hand, completely opposite change patterns are shown by each of the climate models for central Africa and northern South America. This reveals that the spatial distribution of change in runoff significantly varies depending on the type of climate model.

In order to examine qualitative changes in the water shortage trend compared with the current situation due to changes in runoff caused by future climate change and to changes in demand caused by changes in social factors, the supply and demand ratio (Volume of water demand / Volume of runoff) was calculated for each river basin. There is a study reporting that a supply and demand ratio of 0.2 marks the boundary of an area with almost no water shortages and an area where water shortages occasionally occur (Alcamo *et al.*, 2000), although the criteria is very primitive and rough one and further detailed studies are required in the future. Figures 10-a to 10-l show the inter-annual changes in the supply and demand ratio from 2050 to 2059 for the Amazon (S. America), La Plata (S. America), Mississippi (N. America), Nile (Africa), Ob (W. Siberia), Volga (E. Europe), Danube (C. Europe), Amur (N.E. China), Changjiang (S. China), Ganges (S. Asia), Brahmputra (S. Asia), and Mekong (S.E. Asia) river basins, respectively.

At the Amazon river basin, the surface runoff in the 2050s will increase under the CCSR/NIES and ECHAM4 scenarios, while it will decrease only under CCCma scenario. Other rivers in the northern part of S. America such as the Orinoco river have the same tendency. Since the runoff in this region is plenty enough, the supply and demand ratio is low even under the increasing water demand in 2050. At the La Plata river basin, although the surface runoff can be found to increase under the all three climate model scenarios according to Figs. 7, 8, and 9, the supply and demand ratio in the 2050s is higher than the current value. It is because the increase in water demand will exceed the increase in runoff here. At the Mississippi river basin, inter-annual fluctuation of runoff is projected to be more than now. At the Nile river basin, surface runoff is governed by the amount of precipitation in the upper stream of the river (Central Africa). As you can also find from Figs. 7, 8, and 9, runoff is estimated to be less only under CCCma sceanrio, and it causes the high supply and demand ratio in Fig. 10-d. Except for ECHAM4 scenario, the inter-annual fluctuation of runoff is project to be more in the 2050s in this region. For the rivers in Siberia and East Europe, reflecting the increase in runoff, supply and demand ratio is lower in the 2050s than now (Fig. 10-e and 10-f). In the Danube river basin, the supply and demand ratio of around 0.55 shows that water resources are not fully sufficient with respect to demand even in the current situation, and in 2050 the stress of further water shortages is predicted to increase. This trend is particularly conspicuous in the estimate using the CCSR/NIES model. In the Amur and Changjiang river at China, supply and demand ratio is relatively high even in the current condition. Supply and demand ratio will become higher with increase in water demand according to the significant population increase and rapid industrialization. In Ganges river basin, supply and demand ratio will not change so much, since the increase in runoff is expected to cancel out the increase in water demand due to population growth and economic development. The CCSR/NIES model shows different behavior for the Ganges river basin compared with the other two models. In the Mekong and Brahmputra river basins at Southeast Asia, supply and demand ratio will increase according to the increasing water demand, however, the ratio will be still not so high.

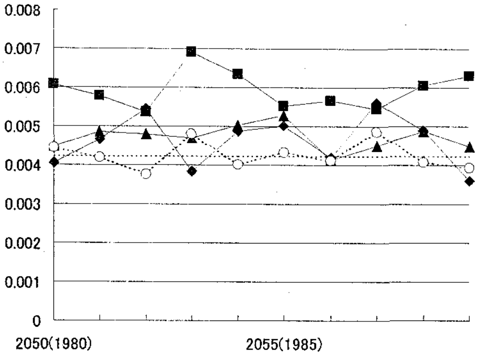

Fig. 10a Amazon

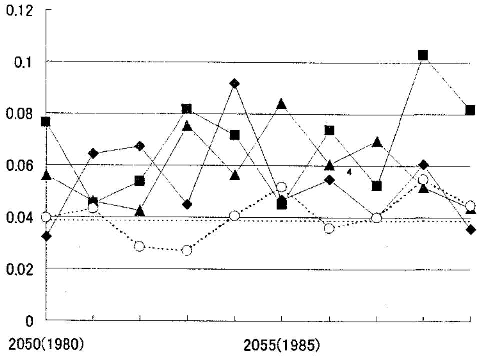

Fig. 10b La Plata

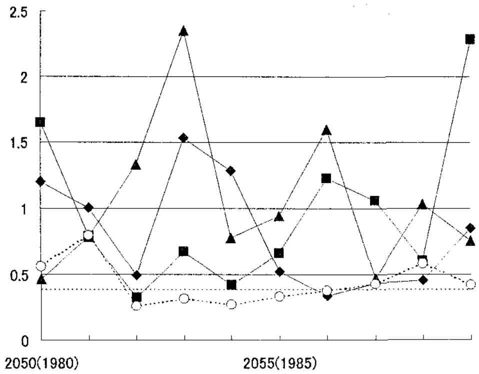

Fig. 10c Mississippi

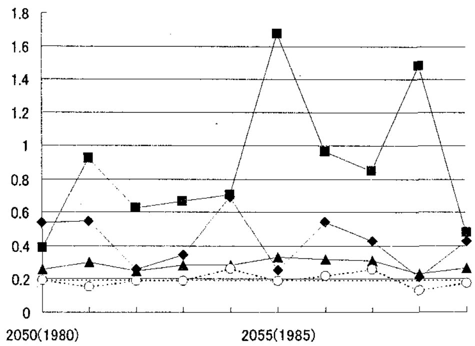

Fig. 10d Nile

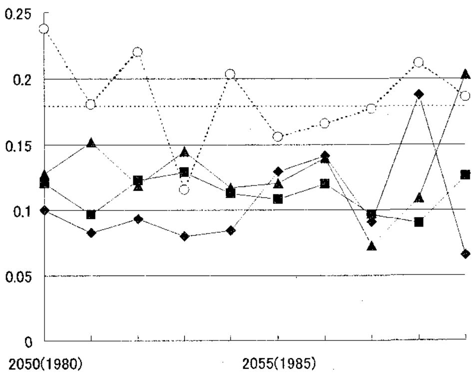

Fig. 10e Ob

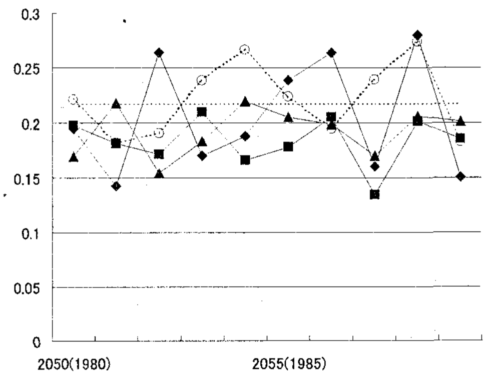

Fig. 10f Volga

CCC LINK (1980-89)
ECHAM4 Ten-year average (1980-89)
CCSR/NIES

Figs.10a – 10f Inter-annual fluctuation of supply and demand ratios in 1980s and 2050s (X-axis: year, Y-axis: supply and demand ratio)

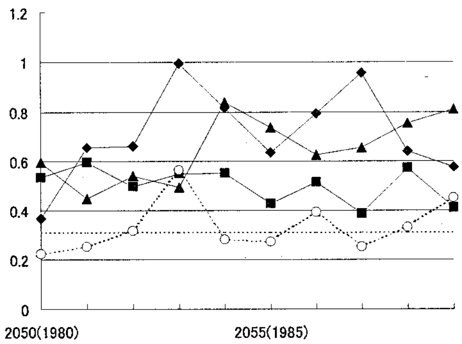

Fig. 10g Danube

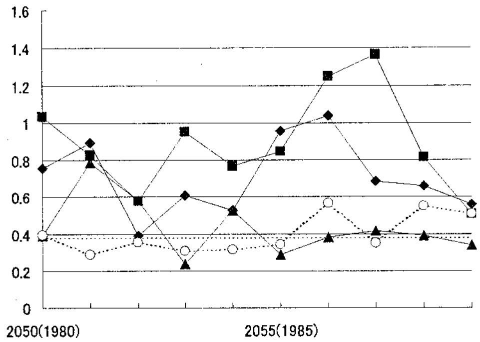

Fig. 10h Amur

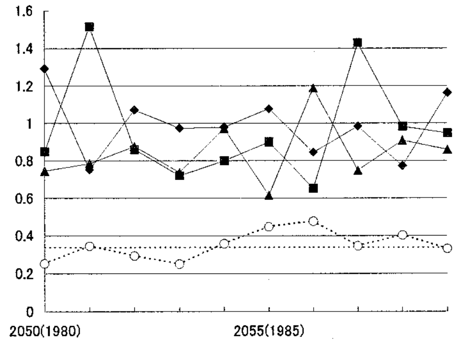

Fig. 10i Changjiang

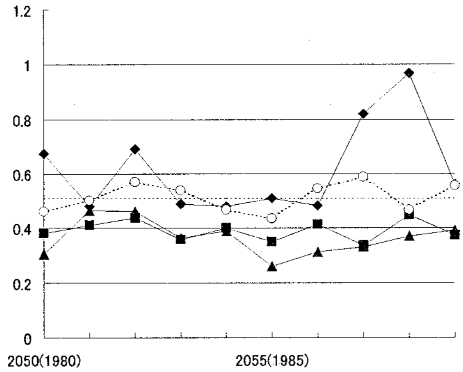

Fig. 10j Ganges

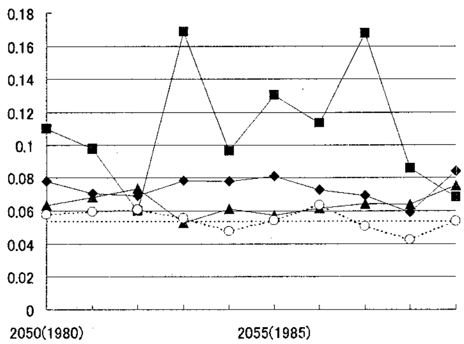

Fig. 10k Brahmputra

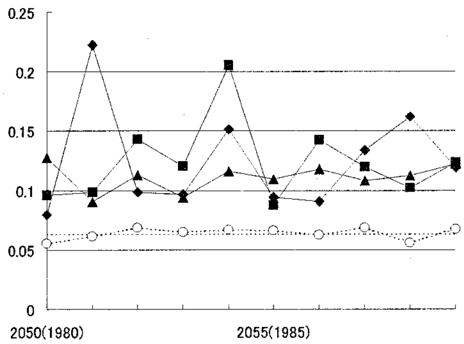

Fig. 10l Mekong

CCC
ECHAM4
CCSR/NIES
LINK (1980-89)
Ten-year average (1980-89)

Figs.10g – 10l Inter-annual fluctuation of supply and demand ratios in 1980s and 2050s (X-axis: year, Y-axis: supply and demand ratio)

4. Future tasks

This report has described a method for roughly estimating the supply and demand for water on a global scale based on the estimation of future socioeconomic factors and future climate change by climate models, and a trial calculation of the changes in the water supply and demand balance for all areas of the world in the 2050s. From the results of the trial calculation, it is possible to qualitatively grasp how the susceptibility to water shortages will change compared with the present condition in each area. However, the estimation method presented here has not reached the point at which concrete measures can be proposed to avoid such water shortages, and the accuracy of estimation also has room for improvement. The future tasks can be summarized as follows.

For the estimation of runoff in this report, the water balance between precipitation, evaporation, and runoff was calculated for each month. However, it was not possible to express runoff reflecting concentrated precipitation, so that evaporation tends to be calculated at a slightly higher value and runoff at a slightly lower value than the amounts that occur in reality. Upgrading of climate data and the development of future climate scenarios for simulating daily water balances are therefore necessary. Moreover, the runoff model does not consider the amount of underground water and sub-surface water flow. It prohibited us from predicting the water balance in the river basins where underground water use is significantly important such as the Huanghe river basin (N. China). It is urgent task to improve the model by considering infiltration process. Since it is now becoming possible to obtain river flow rate data for the entire world from various international institutions, adjustment of the parameters used in the runoff model has room for improvement. As concrete measures for water shortages from the supply side, flow rate adjustment in water reservoirs, etc. can be considered. However, this is not expressed by the current module. It is necessary to improve the model taking the effect of flow rate adjustment into account using dam statistics.

With regard to demand calculation, future demand estimation is greatly influenced by the scenarios with regard to such socioeconomic factors as population and industrialization as well as assumptions concerning the improvement of future water use efficiency. This study used the extent of efficiency improvement as a given scenario. However, from the standpoint of proposing measures, it is necessary to prepare a detailed database of the cost-effectiveness of concrete technical options for improving water use efficiency and to specifically identify water-saving technical options that should be introduced.

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