No. B-11.2 Assessment of the Global Warming Effects on Hydrologic Cycles and Water Resources in Snowy and Cold Regions

Contact Person Hiroyasu Kyoshi, Section Chief
Environmental Engineering Sec., Civil Engineering Research Institute
Hokkaido Development Agency
Hiragishi 1-3, Toyohiraku, Sapporo, Hokkaido, 062 Japan
Tel +81-11-841-1111 (Ext. 290) Fax +81-11-824-1226
e-mail: hiro@ceri.go.jp

Total Budget for FY1993-FY1995 8,978,000 Yen (FY1994; 2,743,000 Yen)

Abstract

In this research, we estimated the existing amount of precipitation, snow accumulation, and evapotranspiration constituting the hydrologic cycle process of catchment areas in snowy cold regions. We also calculated the changes in these estimates from the scenario of global warming. We investigated the Ishikari River catchment area, whose area is 14,330 km^2.

First, we estimated the existing amounts of precipitation, snow accumulation, and evapotranspiration constituting the hydrologic cycle process of catchment areas in snowy cold regions. The precipitation and evapotranspiration were estimated from meteorological data of the catchment area. The amount of water equivalent to the snow cover was estimated by finding snowlines from satellite LANDSAT, MOS-1, NOAA images and aerial photographs, and applying the degree day method to the snowlines. The estimates of the effective precipitation values calculated by the above methods were compared with the volume of runoff from the river to examine the process of the hydrologic cycle from the water balance.

Next, we examined the changes in these estimates from a scenario of global warming in which the current carbon dioxide emissions are doubled. We obtained the scenario from data computed from the mesoscale model based on the General Circulation Model. Using this data, we projected how the hydrologic cycle of catchment areas in snowy cold regions would change. As a result, a smaller amount of snowfall and snow accumulation, and an earlier arrival of the snow melt period, would be conspicuous.

Key Words Global warming, Hydrologic cycle of large catchment areas, Water balance, Catchment areas in snowy cold regions, Satelite images

1. Introduction

Global warming affects the pattern of the hydrologic cycle, changing the conditions of runoff into rivers and the amount of the water resources. It is of our concern that this would greatly influence the planning and management of rivers and dams. To take appropriate measures, techniques are necessary to evaluate the changes in the condition of precipitation, snow accumulation, snowmelt, evapotranspiration and runoff due to global warming. Especially in snowy cold regions, it is essential to evaluate the transitions in the conditions of snow accumulation and snowmelt since they have major impacts on the hydrologic cycle. In this research, we estimated the amounts of precipitation, water equivalent to the snow cover, and evapotranspiration as valid indicators of the water balance through the application of remote sensing technologies. We also examined the deviation of these estimates from the existing values from the scenario of global warming.

2. Research Objective

From the hydrologic environment of the catchment areas of snowy cold regions, we need to understand the changes in the water environment caused by the global environmental changes and to consider the future planning and management of rivers and dams accordingly.

In this study, we estimated hydrologic quantities, such as rainfall, snow accumulation, and evapotranspiration, by inspecting the water balance within the catchment areas. Furthermore, using the scenario of global warming with the current carbon dioxide emissions doubled, we made a tentative prediction of the changes in the existing states of rainfall, snow accumulation, and evapotranspiration. Using these techniques, we attempted to evaluate the influence of environmental change on the hydrology and water resources in snowy cold regions.

3. Research Method

From a long term perspective, the water balance of a catchment area can be expressed as;

$$Q = R - E \pm \Delta S \tag{1}$$

where Q is the runoff from a catchment area, R is the amount of precipitation, E is the amount of evapotranspiration, and ΔS is the change in the amount of water storage of the catchment area. The following are the techniques used in this study to estimate the amounts of precipitation, evapotranspiration, and snow accumulation in a large catchment area. Also, we describe the method to establish a weather change scenario due to global warming to make a tentative prediction on the change in these variables.

(1)Estimating the amount of precipitation

In general, the precipitation in a large area is estimated by multiplying the precipitation data obtained at observation points with their areas. We obtained AMeDAS data and data from local meteorological offices in the whole catchment area and estimated the areal rainfall amount by the Thiessen method. We used a method of calibration in which the estimated rainfall for higher altitudes is calibrated by a greater weight multiplied by the total amount of rainfall.

(2)Estimating the amounts of water equivalent to the snow cover and snowmelt

In snowy cold regions, we need to understand accurately the amount of water equivalent to the snow cover and the runoff of snowmelt to maintain water resources and to prevent the natural disaster of floods caused by snowmelt. To obtain the amount of water equivalent to the snow cover, we generally make a field investigation in the basin by a snow survey. Since there is a danger of disasters, the place and the time at which the data can be obtained is limited. Also, since the investigation can only yield the amount of water equivalent to the snow cover on a line, an error when the results of the investigation is extended to the whole catchment area is possible. To cope with this error, various remote sensing applications have been designed. Following are the techniques we used to estimate the amount of water equivalent to the snow cover using remote sensing.

(i) Extracting the snow covered areas; remote sensing information used in this study came from aerial photographs taken from airplanes and satellite (LANDSAT, MOS-1, NOAA) images. The procedure started with 1)geometric calibration, 2)producing false color images, 3)extracting snow covered areas to end up with a snow cover distribution map.

(ii) Extracting the snowlines; since we were using the degree day method to calculate the amount of snowmelt, snowlines, which are at the border between a snow-covered area and a non-snow area, were extracted from the snow cover distribution map.

(iii) Determining the model parameters: we determined the following parameters, 1)the starting date of snowmelt, 2)the last date of snowmelt, and 3)the degree-day factor. The starting date of snowmelt is defined as the day on which the mean daily temperature is greater than 0℃ at each observation site, the last date of snowmelt is defined from the discharge as the day on which the runoff from the snowmelt is considered to end data, and the degree-day factor is determined from experience by trial and error according to the replicability of the results.

(iv) Determining the estimation sites on the snowline and calculating the amount of water equivalent to the snow cover at the sites; the estimation sites on the extracted snowline were chosen to estimate the amount of water equivalent to the snow cover. Using the degree-day method, the amount of snowmelt in a unit area, that is the amount of water equivalent to the snow cover, was calculated for each estimation site.

(v) Calculating the amount of water equivalent to the snow cover for the whole catchment area; the values of the amount of water equivalent to the snow cover obtained by the procedure in (iv) were interpolated to estimate the amount of water equivalent to the snow cover for the whole catchment area.

(3)Estimating the evapotranspiration

In this study, we calculated the amount of evapotranspiration by using the Thornthwaite, Hamon, and Penman methods. However, these methods yield the amount of potential evapotranspiration.

(4)Setting the scenario of global warming

We obtained a scenario of global warming in which the current carbon dioxide emissions were doubled ($2 \times CO_2$). This data was computed from the mesoscale model built by the Public Works Research Institute and University of California at Davis, based on the Meteorological Research Institute General Circulation Model (MRIGCM). The model produces at a rate of every 12 hours the potential temperature, the mixture ratio, the wind velocity and the precipitation as the output of the first layer ($\sigma = 0.995$). The following example shows how we obtained each of the values when we assumed the current carbon dioxide emissions were doubled.

(i)Setting the temperature

Temperature T_2 in the case of $2 \times CO_2$ can be given as follows:

$$T_2 = T_1 + \Delta T = T_1 + \tilde{\theta}_2(P_0/\tilde{P}_2)^{-R/C_P} - \tilde{\theta}_1(P_0/\tilde{P}_1)^{-R/C_P} \qquad (2)$$

where T, θ, P are the ground temperature, the potential temperature ($\sigma = 0.995$) and the barometric pressure, respectively. The notations, $\tilde{}$, 1 and 2 are the output of the model, the current value, and the value when we assumed the existing carbon dioxide emissions were doubled ($2 \times CO_2$), respectively. Also, P_0, R and C_P are the standard barometric pressure (1,000hPa), the gas constant of air, and specific heat under constant pressure.

(ii)Setting the precipitation, the wind velocity and the relative humidity

If the current carbon dioxide emissions were doubled, the precipitation amount R_2, the wind velocity v_2 and the relative humidity rh_2 can be given as follows;

$$R_2 = \tilde{\alpha_R} R_1, \qquad v_2 = \tilde{\alpha_v} v_1, \qquad rh_2 = \tilde{\alpha_{rh}} rh_1 \qquad (3)$$

where R, v and rh are the precipitation, the wind velocity and the relative humidity, respectively. Each of $\tilde{\alpha_R}$, $\tilde{\alpha_v}$ and $\tilde{\alpha_{rh}}$ is the ratio of the precipitation, the ratio of the wind velocity, and the ratio of the relative humidity under $2 \times CO_2$ compared to under $1 \times CO_2$, respectively. To discriminate the amount of rainfall from the amount of snowfall within the amount of precipitation, we defined the precipitation at temperatures above 0℃ as rainfall at temperatures below 0℃ as snowfall.

We tentatively calculated the annual precipitation (the annual amount of rainfall and snowfall), the annual maximum of water equivalent to the snow cover, and the annual evapotranspiration under $2 \times CO_2$. The difference between the annual precipitation and the annual rainfall was considered to be the annual maximum of water equivalent to the snow cover. The annual maximum of water equivalent to the snow cover under $2 \times CO_2$ was estimated by multiplying the existing annual maximum of water equivalent to the snow cover by the ratio of the annual snowfall under $2 \times CO_2$ compared to under $1 \times CO_2$.

4. Results and Discussion

In this section we report our estimations of the annual precipitation, the annual maximum of water equivalent to the snow cover, and the annual evapotranspiration obtained by the methods described in the previous section, and evaluated the estimations by comparing the water balance calculated from the estimations with the runoff of the river (the total annual runoff). We will show how these quantities change under the scenario of global warming. The catchment area and the years studied were the Ishikari River basin in 1987, 1989 and 1992. The main stream of the river is 268km long. The river is one of the major rivers in Japan and has a catchment area of 14,330km^2 (the catchment area at the Ishikari Ohashi Bridge site, 12,696.7km^2). Figure 1 shows the locations of these catchment area.

(1)Results of estimating the annual precipitation

We estimated the average precipitation and the amount of rainfall by using precipitation data from the nearest observatories (the AMeDAS or the local meteorological offices). With the rainfall factor calibrated linearly by temperature and altitude, we defined precipitation at temperatures above 0℃ as rainfall. As an example of the results of the estimation, Figure 2 shows the distribution of the annual precipitation in 1989.

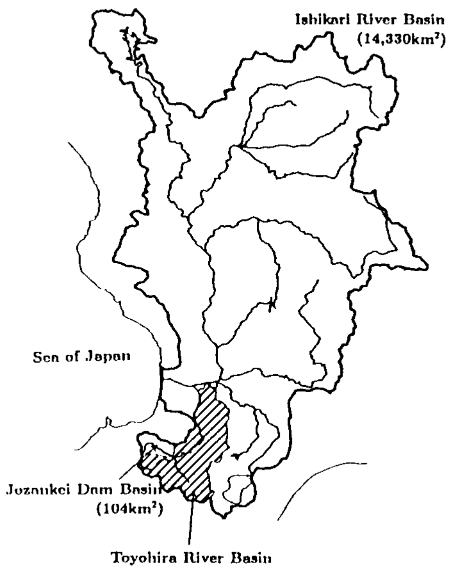

Fig.1 A schematic view of the Ishikari River catchment area

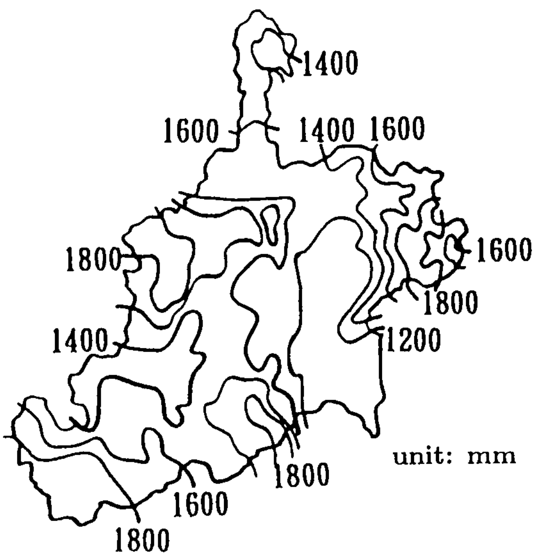

Fig.2 Estimated precipitation (1989)

(2)Results of estimating the annual maximum of water equivalent to the snow cover

We used the NOAA AVHRR satellite data to calculate the annual maximum of water equivalent to the snow cover in the Ishikari River catchment area. The degree-day factor used in this estimation was determined by comparing two estimates of snowline: the snowline reproduced by snowmelt assumed by the degree-day method and the snowline read on the NOAA images. As a result we adopted the value of 0.58g/cm^2/℃/day. We defined the starting date of snowmelt as the day on which the estimated temperature exceeded 0℃; the estimated temperatures were from a simple linear regression of the daily average temperature data obtained by 27 AMeDAS observatories within the catchment area. Figure 3 shows the distribution of the annual maximum of water equivalent to the snow cover in 1989.

(3)Results of estimating of the annual evapotranspiration

The evapotranspiration was calculated as the potential evapotranspiration using the Thornthwaite, Hamon and Penman methods. The meteorological data was from 27 observatories. As in the case of calculating the precipitation, the data used for this estimation were from the nearest local meteorological observatory to each site of the study. As an example of the estimation, Figure 4 shows the distribution of the annual evapotranspiration in 1989 using the

Thornthwaite method.

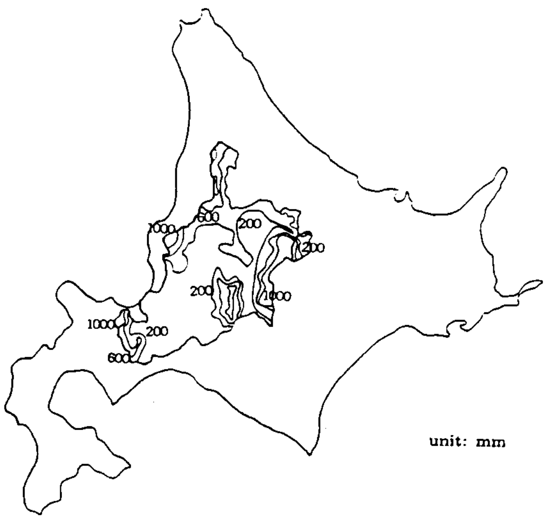

Fig.3 Estimated water equivalent to the snow cover (1989)

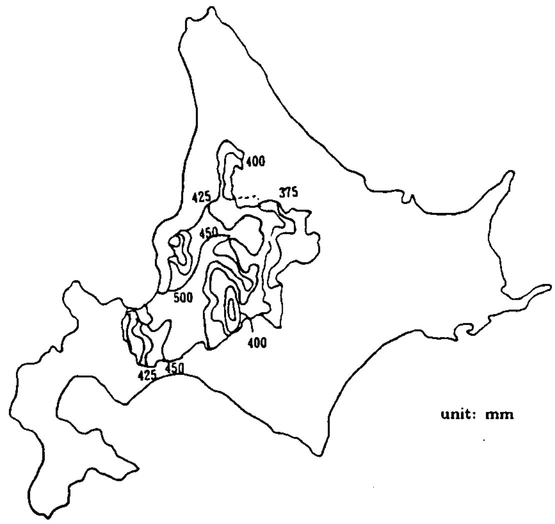

Fig.4 Estimated evapotranspiration (1989)

(4)Evaluation of the water balance

Following the equation that represents a long-term water balance (Eq.1), we investigated the annual water balance of the Ishikari River catchment area. However, since ΔS, the change in the water storage of the catchment area, remained unknown, we assumed a steady state to evaluate it as follows: the effective precipitation amount (rainfall+snow accumulation-evapotranspiration)=runoff. We used the observed discharge at the Ishikari Ohashi Bridge site as the runoff. Table 1 shows the results of the investigation.

From the results, the estimated values in the Ishikari River catchment area seem to underestimate the real runoff height by 20% at its maximum. We need to increase the precision of each item (water equivalent to the snow cover, the amount of rainfall, the evapotranspiration, the observed discharge) to improve the accuracy of the estimated values. In particular, a future task would be to find solutions to the problems of estimating the evapotranspiration and water storage of the catchment area.

(5)Changes in the hydrologic foctors due to global warming

Figure 5 shows the increase in temperature from the existing temperature assuming that the current carbon dioxide emissions were doubled. The figure does not show much change in the summer temperatures. However, the rise in the winter (November to March) temperatures is conspicuous. Table 2 shows the comparison between the annual precipitation in 1987, 1989, and 1992 and the estimated annual precipitation for these years when the levels of carbon dioxide emissions were doubled. The table shows a 6% to 15% increase in the precipitation when the current carbon dioxide emissions were doubled. In particular, it shows an increase of 29 to 42% of the rainfall through conversion of snow into rain due to the rise in temperatures.

The annual maximum of water equivalent to the snow cover was obtained by multiplying the existing amount of water equivalent to the snow cover with the ratio of the snowfall computed for $1 \times CO_2$ to that of $2 \times CO_2$. The ratios calculated were 0.54 for 1987, 0.41 for 1989, and 0.38 for 1992, showing that in each of the years the annual amount of water equivalent to the snow cover declined as much as a half to 40% of the existing value. Table 2 shows the annual maximum of water equivalent to the snow cover obtained by this method.

Table 1 Annual water balance (the Ishikari Ohashi Bridge site)

Year	1987	1989	1992
Rainfall(mm)	779	1,015	1,101
Snowpack(mm)	554	588	379
Evapo.*(mm)	439	492	396
Estimated Runoff(mm)	894	1,111	1,084
Observed Runoff(mm)	1,128	1,143	1,296
(Est./Obs. × 100)%	79	97	84

* estimated by the Thornthwaite method.

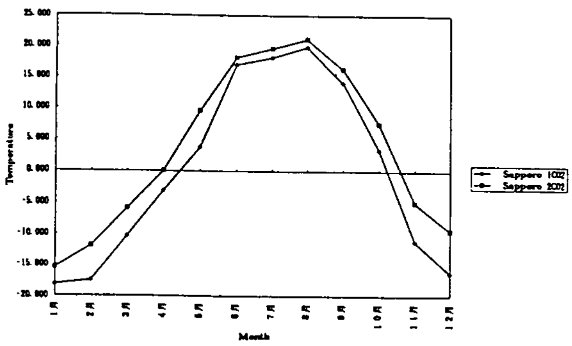

Fig.5 Temperatures under 1 × CO_2 and those under 2 × CO_2

Next, we calculated the starting date of snowmelt under 2 × CO_2 at each of the AMeDAS observation sites in the basin using temperature change. The last date of snowmelt was defined as the day on which the water equivalent to the snow cover was exceeded by the snowmelt calculated by the degree-day method. Table 2 shows these estimates under 2 × CO_2, under 1 × CO_2 and their comparisons. Our estimation indicates that the starting date of snowmelt is about two months earlier, and the last date of snowmelt is about two to three months earlier under 2 × CO_2.

In Table 2, we compare the amounts of evapotranspiration calculated for the existing levels of carbon dioxide emissions and that for 2 × CO_2 using the Thornthwaite method for 1987, 1989 and 1992. Due to rising temperatures, an increase in the annual evapotranspiration under 2 × CO_2 is as much as 13% to 33% in comparison to that under 1 × CO_2.

Table 2 Changes in hydrologic values as a result of global warming

Year	1987			1989			1992		
	1*CO_2	2*CO_2	Change(%)	1*CO_2	2*CO_2	Change(%)	1*CO_2	2*CO_2	Change(%)
Precip.(mm)	1,274	1,374	7.8	1,352	1,558	15.2	1,484	1,569	5.7
Rainfall(mm)	779	1,109	42.4	1,015	1,419	39.8	1,101	1,425	29.4
Snowpack(mm)	554	325	-41.3	588	257	-56.3	379	168	-55.7
Start of melt	3.13-4.6	1.13-2.21	–	3.1-3.19	1.1-1.29	–	3.8-4.4	1.4-2.8	–
End of melt	4.24-5.24	2.4-3.6	–	4.19-5.8	1.20-3.2	–	4.21-5.18	1.16-3.2	–
Evapo.(mm)	439	526	19.8	492	554	12.6	396	527	33.1
Runoff(mm)	894	908	1.6	1,111	1,122	1.0	1,084	1,066	-1.7

Table 2 shows estimates of the annual total runoff (= the annual rainfall+the annual maximum of water equivalent to the snow cover - the annual evapotranspiration) in the Ishikari River catchment area. Due to the change in the distribution of rain and snow within the annual precipitation, the seasonal change in the runoff pattern is expected to change dramatically under global warming.

5. Summary

(1) We estimated the amount of rainfall in the Ishikari River catchment area for 1987, 1989 and 1992, that ranged from 780mm to 1,100mm. We estimated the amount of rainfall from AMeDAS data and data from local meteorological offices using a calibration according to the altitude.

(2) Using image information of NOAA, the amounts of water equivalent to the snow cover in the Ishikari River catchment area for the years 1987, 1989 and 1992 were estimated to range from 380mm to 590mm.

(3) The evapotranspiration in the Ishikari River catchment area for the years 1987, 1989 and 1992 were estimated to be within the range of 400 to 560mm. In estimating these values, we used the Thornthwaite, Hamon, and Penman methods.

(4) We compared the water balance using the above results with the observed runoff in the Ishikari River at the Ishikari Ohashi Bridge site. The ratios of the runoff height to the quantities of the rainfall plus the water equivalent to the snow cover minus the evapotranspiration using the Thornthwaite method were 79%, 97% and 84% for 1987, 1989 and 1992, respectively.

(5) We computed the results from the mesoscale model built by the Public Works Research Institute and University of California at Davis, based on the Meteorological Research Institute General Circulation Model (MRIGCM). We showed changes in temperature, the precipitation, wind velocity and relative humidity under $2 \times CO_2$ compared with under $1 \times CO_2$.

(6) When comparing the precipitation under $1 \times CO_2$ with that under $2 \times CO_2$ for the years 1987, 1989 and 1992, the precipitation under $2 \times CO_2$ was greater than under $1 \times CO_2$ by 6% to 15%. However, the rainfall increased by 29% to 42% due to the conversion of snowfall into rainfall produced by the rising temperature.

(7) Comparing the evapotranspiration under $1 \times CO_2$ with that under $2 \times CO_2$ for the years 1987, 1989 and 1992, the evapotranspiration under $2 \times CO_2$ was greater than under $1 \times CO_2$ by 13% to 33%. This increase was accompanied by a rise in temperatures.

(8) Comparing the amount of water equivalent to the snow cover under $1 \times CO_2$ and that under $2 \times CO_2$ for the years 1987, 1989 and 1992, the amount of water equivalent to the snow cover under $2 \times CO_2$ (170 to 330mm) was less than under $1 \times CO_2$ (380 to 590mm) by about 41% to 56%. This was due to the conversion of snowfall into rainfall.

(9) Comparing the pattern of snowmelt under $1 \times CO_2$ with that under $2 \times CO_2$ for the years 1987, 1989 and 1992, the starting date of snowmelt occurred about two months earlier and the last date of snowmelt occurred about two to three months earlier under $2 \times CO_2$

7. References

1) Nakatsugawa, M., M. Yamaguchi, M. Setojima and N. Mushiake, 1995: Investigation of Water Balance in the Ishikari River Catchment Area, Proc. 1995 Annual Conference Japan Society of Hydrology and Water Resourcese, 240-241, (in Japanese).

2) Nakatsugawa, M., 1995: Hydrologic Processes in Hokkaido, Lecture Notes of the 31st Summer Seminar on Hydraulic Engineering, 1995, Course A, A-1-1-A-1-17, (in Japanese).

3) Nakatsugawa, M., 1995: A Study on Effects of Climate Change on Hydrologic Processes in Cold and Snowy Regions, Report of the Civil Engineering Research Institute, **106**, 5-22, (in Japanese).

4) Hibino, T., 1995: Study on Rainfall Characteristics in Mountainous Basins, Chuo University Doctoral Dissertation, 21-44, (in Japanese).

5) Takeda, K. and Y. Takahashi, 1981: Estimation of Basin-wide Snow Water Equivalentusing LANDSAT-derived Snow Line and Degree-day Method, Proc. JSCE, **311**, 81-92, (in Japanese).

6) Kazama, S. and M. Sawamoto, 1994: On Water Balance in a Basin with Heavy Snow Area, Procs. Hydraulic Engineering, JSCE, **38**, 113-118, (in Japanese).

7) Nakatsugawa, M. and T. Koike, 1993: Snow Hydrology: Journal of Hydroscience and Hydraulic Engineering, **SI-3**, Hydrology, 101-111.