

Influence of Climate Change on the Seasonal Runoff Pattern in a Headwater Basin, Northern Niigata Prefecture

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Summary

The IPCC has reported that Japan will likely warm 2-3°C by the year 2100, with changes in precipitation dependent on the season. In areas of heavy snowfall like Niigata Prefecture, this will cause the seasonal patterns of river runoff to change, and will greatly influence the availability of water resources for agriculture. Our objective here is to forecast the change in the seasonal and monthly runoff volumes resulting from these future climate change scenarios, especially changes in the spring snowmelt runoff.

Snowmelt Runoff Model (SRM) was applied to the Takiya River basin to simulate daily runoff over the period 2000-2007. Snow accumulation and melt was simulated for each of three elevation zones using air temperature data at high and low elevations to estimate the lapse rate. Key model parameters were determined by analysis of the basin monthly water balance, in addition to model calibration using river discharge and snowpack snow water equivalent.

The Japan Meteorological Agency has published regional scenarios that are based on the IPCC "worst case" Scenario A2. Simulation of the IPCC Scenario A2 for Niigata region showed that runoff would be 2-3 times greater in winter (Dec-Feb), and decrease by half in spring (Apr-May). Changes in monthly runoff volumes are most sensitive to warming in the range +1.0~3.0°C because large shifts occur in the proportions of snow versus rain. In Niigata, and other regions that receive heavy snowfall at temperatures close to 0°C, a small rise in temperature causes large changes in the size of the seasonal snowpack and the seasonal distribution of runoff. Therefore, it is necessary to urgently review disaster prevention and water resources management in such areas.

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Key words : Global warming, snowpack, snowmelt, modeling, water resources

INTRODUCTION

IPCC (Intergovernmental Panel on Climate Change, 2001) have reported that normal temperatures in the world rose by 0.6°C in the 20th century. It has also forecasted that the average temperature of the earth will rise by 1.4~5.8°C between 1990 and 2100. In the high latitudes of the northern hemisphere, the possibility of precipitation increasing by 0.5~1% for every ten years is considerably high in this century. The IPCC report also states that the possibility of winter precipitation increasing is high in the high latitudes of the northern hemisphere by the latter half of the 21st century.

We can assume that temperatures in the Japan region will keep increasing, and precipitation will likely also increase by 2100 (Japan Meteorological Agency, 2005). Therefore, there is a strong possibility that river runoff will change for each season, having a great influence on agricultural water planning and disaster prevention planning. Especially, in Japan's heavy snowfall mountain region, change in the snowmelt season greatly influences agricultural water use for planting rice paddies.

This study aims to forecast the change in the hydrological regime, especially concerning snow and

snowmelt in a heavy snowfall mountain region. Quantitatively, our objective is to forecast the change in the seasonal and monthly runoff volumes resulting from likely future climate change scenarios, especially changes in the spring snowmelt runoff volumes.

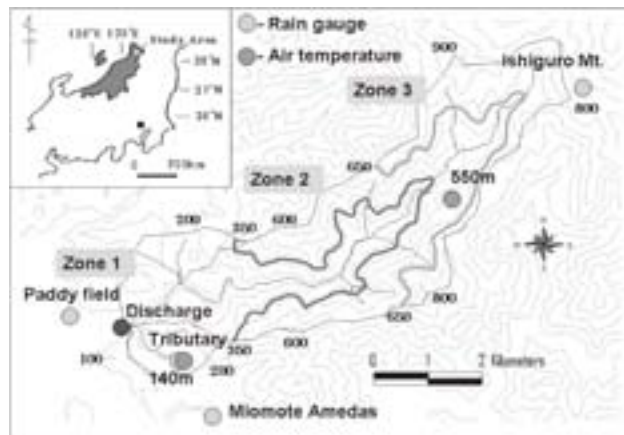


Figure 1. Takiya River basin located in northern Niigata Prefecture, Japan

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STUDY SITE AND METHODS

Study site

Takiya River in northern Niigata Prefecture is a tributary of the Miomote River in the heavy snowfall Japan Sea Region (Figure 1). Basin area is 19.45 km² with an elevation range of 40-950m. The stream channel remains unfrozen even during the winter period, which allows stream gauging year-round. Miomote AMeDAS precipitation gauge has a heater to measure both snowfall and rainfall. The basin is divided into 3 elevation zones, with zones 1, 2 and 3 consisting of about 40%, 40%, and 20% of total area respectively. Air temperature, snowpack and snowmelt are simulated for each elevation zone.

Snowmelt Runoff Model

This study used Snowmelt Runoff Model (Windows SRM version 1.10, Martinec et al., 2005). SRM is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. It can be applied in mountain basins of almost any size and any elevation range. To date the model has been applied by various workers in over 100 basins worldwide. In Japan it has been applied at Okutadami (Mikuni) basin and Sai (Japan Alps) basin. The model structure is as follows:

$$Q = [c_{sn} \cdot a_n (T_n + \Delta T_n) S_n + c_{rn} P_n] \frac{A \cdot 10000}{86400} (1 - k_{n+1}) + Q_n k_{n+1} \quad (1)$$

where Q = average daily discharge (m³/s)

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with c_S referring to snowmelt and c_R to rain.

a = degree-day factor (cm/°C/d) indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days (°C d)

ΔT = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone (°C d)

S = ratio of snow covered area to the total area

P = precipitation contributing to runoff (cm). A threshold temperature, T_{crit} , determines whether this is rain or snow. If precipitation is determined to be snow, it is kept on storage until melting conditions occur

A = area of basin or zone (km²)

k = recession coefficient

n = sequence of days during the discharge computation period. Equation (1) is written for a time lag between the daily temperature cycle and resulting discharge cycle of 18 hours. Various lag-times can be introduced by a subroutine.

$$\frac{10000}{86400} = \text{conversion from cm} \cdot \text{km}^2/\text{d to m}^3/\text{s}$$

T and P are variables to be measured or determined each day for each elevation zone. c_R , c_S , lapse rate ΔT , T_{crit} , k and the lag time are parameters for a given basin or, more generally, for a given climate.

Climate data

Adjustment of input precipitation data is shown in Table 1. Winter precipitation = Miomote AMeDAS $\times \alpha_n$. Precipitation increases with elevation in mountain regions. Therefore, α_n was determined by analysis of basin monthly water balance and by further calibration.

During the warm season (June to October), the temperature lapse rate is 0.6°C /100m. During the snowpack season (November to May), the temperature lapse rate was calculated from measured air temperature data at 140m and 550m elevations:

$$\text{Daily lapse rate} = \{T_{\text{daily}}(140\text{m}) - T_{\text{daily}}(550\text{m})\} / 4.1 \text{ (}^\circ\text{C /100m)} \quad (2)$$

This method was used for years 2000 to 2005, while a mean value of 0.45°C/100m was used for years 2006 and 2007 because temperature at the 550m site has not been measured after 2005.

Model Parameters

Recession coefficient, k

The recession coefficient dictates the decline of discharge (Q) in a period without snowmelt or rainfall by $k = Q_{m+1}/Q_m$, where m and $m+1$ are the sequence of days during a true recession flow period. k is not constant, but increases with decreasing Q according to the equation:

$$k_{n+1} = x \cdot Q_n^{-y} \quad (3)$$

where the constants x and y must be determined for a given basin by solving the equations:

$$k_1 = x \cdot Q_1^{-y}$$

$$k_2 = x \cdot Q_2^{-y}$$

$$\log k_1 = \log x - y \log Q_1 \quad (4)$$

Table 1. Calculation of precipitation for each elevation zone by season

Months	Zone 1 Mean elev. 200m	Zone 2 Mean elev. 509m	Zone 3 Mean elev. 719m
10-11	Average (Tributary + Paddy)	Average (Ishiguro + Zone 1)	Ishiguro Mt.
12-5	Miomote $\times \alpha_1$	Miomote $\times \alpha_2$	Miomote $\times \alpha_3$
6-9	Average (Tributary + Paddy)	Average (Ishiguro + Zone 1)	Ishiguro Mt.

Table 2. Monthly parameter values for SRM in the calibrated model

Month	Lag time	c_s	c_R	x coef.	y coef.	Degree-day factor, α
10	4	0.92	0.75	0.78	0.071	0.475-0.6 ^c
11	4	0.92	0.8	0.78	0.071	0.35-0.475 ^c
12	5	0.92	0.85	0.9 ^b	0.071	0.25-0.35 ^c
1	6	0.92	0.9	0.9 ^b	0.071	0.25 ^c
2	6	0.92	0.85	0.9 ^b	0.071	0.25-0.35 ^c
3	7	0.92	0.8	0.78	0.071	0.35-0.475 ^c
4	5.5-7 ^a	0.92	0.8	0.78	0.071	0.475-0.6 ^c
5	4-5.5 ^a	0.92	0.75	0.78	0.071	0.6
6	4	0.92	0.75	0.78	0.071	0.6
7	4	0.92	0.75	0.78	0.071	0.6
8	4	0.92	0.7	0.78	0.071	0.6
9	4	0.92	0.75	0.78	0.071	0.6

^a During April to May the lag time decreases from 7 hours to 4 hours at a rate of 0.05 hours per day.

^b In winter season (December 15 to February 15) x coefficient was determined to be 0.9 by calibration of the discharge hydrograph

^c Minimum value for the degree-day factor, α , is 0.25 in January. The value of α decreases at a rate of 0.025 per 6 days from October to December, and increases at a rate of 0.025 per 6 days from February to April.

$$\log k_2 = \log x - y \log Q_2 \quad (5)$$

Analyzing the historical discharge data for Takiya River, we determined the constants x and y as:

$$\log 0.8 = \log x - y \log 1$$

$$\log 0.68 = \log x - y \log 10$$

which gives $x = 0.8$ and $y = 0.071$.

Runoff coefficient, c

The runoff coefficients were determined by reference to analysis of the basin water balance (Table 1 in Whitaker et al., 2008). c_s has the same value year-round, but c_R changes by the season (Table 2). c_R is high in winter and lower in summer due to evapotranspiration losses.

Snow covered area, S

SRM was operated in a mode where snowpack snow water equivalent was simulated throughout the year using temperature and precipitation climate data, and snow cover is assumed to be uniform across each elevation zone. Therefore, spring melt-off of snow cover occurs simultaneously within each elevation zone, but melt-off dates vary between zones, becoming later at high elevation.

CALIBRATION AND VALIDATION

Calibration method

Years 2001-2004 were used in the model calibration, while years 2005-2007 were withheld for the model validation (Table 3). The model parameters and the orographic coefficients were determined by a two-step approach. Firstly, model parameters and coefficients affecting snow accumulation and melt are optimized using snow water equivalent (SWE) measurements in the tributary (Figure 1). Next, each orographic coefficient is constrained using measured versus simulated discharge hydrographs. R^2 (a measure of model efficiency) and D_v (percentage difference

Table 3. Calibration and validation results for SRM

Year	R^2	Volume Difference (%)	Precipitation factor α (orographic coefficient)			Critical Temperature T_{crit} (°C)
			Zone 1	Zone 2	Zone 3	
Calibration						
2001	0.7894	-3.63	1.25	1.55	1.75	1
2002	0.7617	5.95	1.13	1.45	1.94	1
2003	0.7202	10.97	1.18	1.5	2.3	1.5
2004	0.6184	7.29	1.28	1.49	2.15	1.5
Validation						
2005	0.5111	8.80	1.06	1.45	2.15	0.5
2006	0.4601	7.26	1.21	1.45	2.3	0.5
2007	0.7174	3.15	1.06	1.43	1.85	1.5

between the total measured and simulated runoff) are used to evaluate the performance of the model.

Step 1: Calibration of snowpack snow water equivalent (SWE) Precipitation factor α

The orographic coefficient α is applied to winter season precipitation (Dec-Apr). Firstly, we assumed values of α from previous work on the water balance of the basin (Table 2 in Whitaker et al., 2008). Secondly, α is adjusted by comparing measured and simulated snow water equivalent through calibration. In mountainous regions α increases with elevation ($\alpha_1 < \alpha_2 < \alpha_3$). In zones 2 and 3, α is determined by comparing the measured and simulated discharge hydrograph (R^2) and the annual water balance or volume difference (D_v). Calibration results are shown in Table 3.

Critical temperature T_{crit}

Critical temperature T_{crit} is the threshold temperature that determines rainfall or snow. In this study, T_{crit} was kept constant through the same year and constant across elevation

zones, but it varied between years in the range 1.0~1.5 during the calibration period (Table 3). It was determined by comparing measured and simulated discharge and snow water equivalent while changing T_{crit} .

Degree-day factor a

Degree-day factor a (cm/°Cd) converts the number of degree-days T (°C d) into daily snowmelt depth M (cm) ($M = a T$). It varies according to the changing snow properties and energy balance during the snowmelt season. The degree-day factor can be computed from daily temperatures and the daily decrease of the snow water equivalent, measured by a snow lysimeter or snow survey. In this study, a was initially set in the range 0.2~0.6 cm/°Cd with minimum values in winter season (Table 2). Then, the minimum value of a was increased by comparing measured and simulated snow water equivalent and discharge.

Step 2: Calibration of discharge hydrograph

After calibration of the simulated snowpack SWE, the simulated and observed discharge hydrographs are compared. The simulated and observed hydrographs are close, but in winter season the simulated discharge is lower than the measured discharge, mainly due to the inability of the model to simulate slow melting due to ground-heat exchange. There are many runoff peaks in the hydrographs throughout the year. The calibrated model's discharge peaks

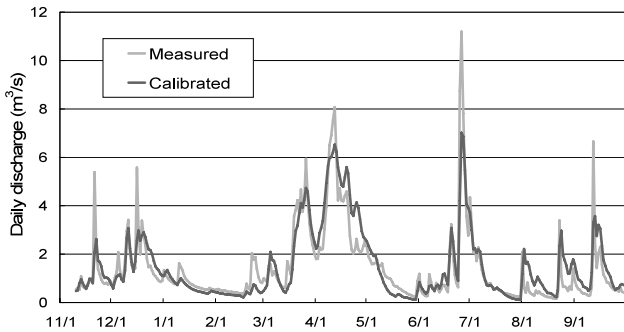


Figure 2. Calibration result showing measured versus simulated discharge for year 2001

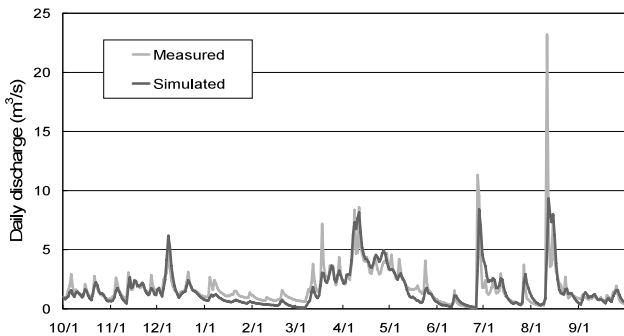


Figure 3. Validation result showing measured versus simulated discharge for year 2005

are generally lower than the measured discharge peaks. This is partly due to problems in the precipitation data (e.g. localized heavy rain not measured by the rain gauges) and also due to difficulties in calibrating the model. Some calibration of the recession coefficients was necessary to improve the simulation of winter low flows (in mid-winter season, the recession coefficient x was increased).

Calibration result

Calibration results are shown in Table 3, and an example hydrograph is shown in Figure 2. Overall the hydrographs for the calibrated model and measured discharge are close, but runoff peaks are not so well simulated. This is because of error in the discrimination between rainfall and snowfall in winter season (T_{crit}), and localized heavy rainfall in summer. R^2 is over 0.70 in 2001 to 2003, but in 2004 it is low partly because there was a large summer flood on July 17.

Validation results

The years 2005 to 2007 were withheld for the validation (Table 3). Model parameters were the same for both the calibration period and the validation period, with the exception of the precipitation factor α and the critical temperature T_{crit} that are different for each year.

Model performance, R^2 , is over 0.70 in 2007, but in 2005 and 2006 it is low partly due to the occurrence of large summer floods (Table 3). The simulated and observed hydrographs are close, but in winter season the simulated discharge is lower than the measured discharge (Figure 3). Simulated SWE was higher than the measured snow survey data in 2007, but lower than the measured data in 2005 and 2006. The poor simulation of winter season low flows is partly the result of ground melt not being simulated by the model, and partly due to problems in the precipitation data and variability in critical temperature T_{crit} during the winter season.

SIMULATION OF CLIMATE SCENARIOS

IPCC SRES Scenarios

IPCC has published the Special Report of Emissions Scenarios (IPCC, 2000). There are over 35 SRES scenarios.

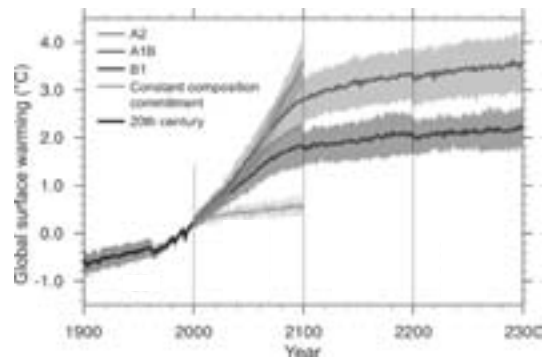


Figure 4. IPCC SRES scenarios

Table 4. IPCC A2 regional scenarios for eastern and northern Japan Sea region 2081-2100 in relation to 1981-2000 values

Month	Scenario 1(S1)		Scenario 2(S2)	
	$\Delta T(^{\circ}\text{C})$	Precip(%)	$\Delta T(^{\circ}\text{C})$	Precip(%)
10	3.00	+10	3.00	+10
11	2.80	-5	2.90	0
12	3.10	-15	3.40	-20
1	2.55	-10	3.05	+20
2	2.60	-15	3.10	0
3	2.75	-15	3.10	0
4	2.90	-15	3.10	0
5	2.80	-5	2.90	+5
6	2.20	+20	2.25	+20
7	1.80	+30	2.25	+20
8	1.30	+40	2.00	+20
9	2.25	+20	2.40	+10

These scenarios are divided into 4 scenario groups (A1, A2, B1, and B2). The year 2100 is expected to be 0.6~3.6°C warmer than the year 1990 (Figure 4).

IPCC Scenario A2 for Eastern and Northern Japan Sea Region

The Japan Meteorological Agency has published regional scenarios that are based on IPCC Scenario A2 as shown in Table 4 (Japan Meteorological Agency, 2005). The study site is on the boundary of Eastern Japan Sea region (EJJ, Scenario 1) and Northern Japan Sea region (NJJ, Scenario 2). Comparing these two regional scenarios, we can see there is greater warming in Scenario 2, while Scenario 1 shows greater variability in precipitation changes.

RESULTS

Changes in the seasonal runoff pattern were similar in each year of simulation. We show the example of year 2001 (Figure 5). The vertical lines mark the start and end of the winter season or snowmelt season. In both scenario simulations, winter season runoff increases greatly as snowfall events become rainfall events producing many runoff peaks well above the current condition. On the other hand, during the snowmelt season the discharge amounts for S1 and S2 are lower than the current condition. In winter season the discharge for each scenario varies with the different weather conditions, but in snowmelt season they are more similar, showing large reductions in runoff during April and May.

Figure 6 shows the monthly runoff volume difference averaged over the 7 years of simulation. In winter season (January-February), runoff volume increases by over 100% in S1 and by over 200% in S2. In contrast, the snowmelt season (April) shows runoff volume decreases of more than 50% in both scenarios. In S1 January and February precipitation decreases (Table 4) but runoff increases because warming changes snowfall to rainfall that rapidly becomes runoff. In S2 April and May precipitation doesn't decrease (Table 4) but

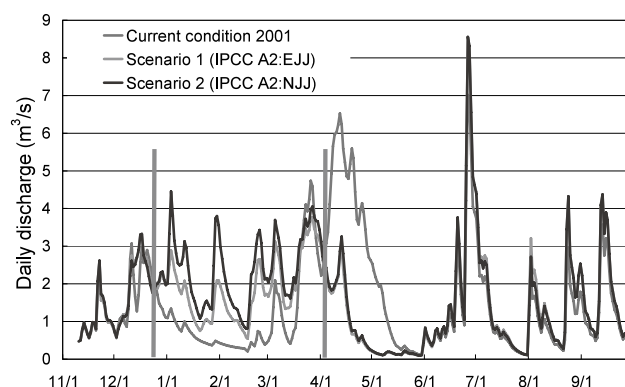


Figure 5. Hydrographs for IPCC A2 scenarios for Japan Sea region (2081-2100)

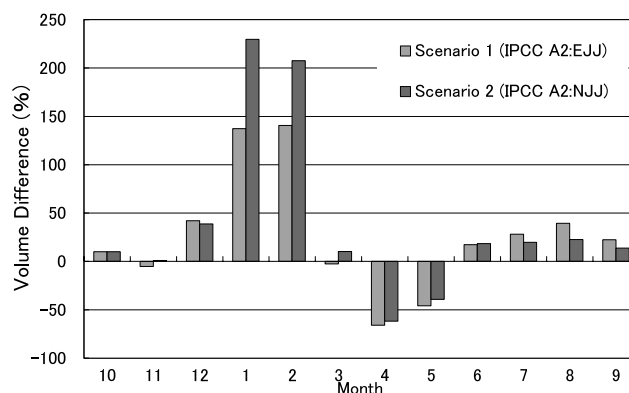


Figure 6. Change in monthly runoff volume for IPCC A2 regional scenarios

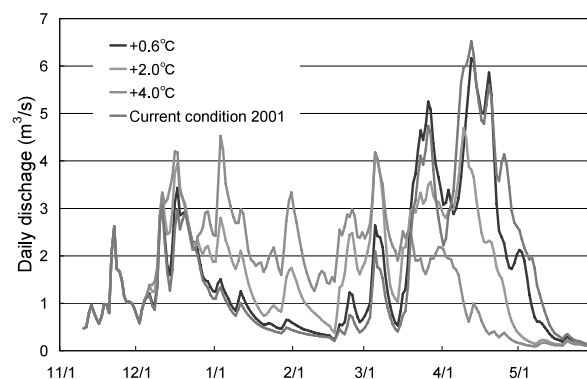


Figure 7. Change in discharge hydrograph with warming scenarios for winter to spring (precipitation unchanged)

runoff decreases because warming reduces snowpack size and the amount of snowmelt in spring. Therefore, it was found that temperature change has a greater influence on runoff than precipitation change.

Global Warming Scenarios

Global warming is expected to be in the range 0.6~3.6°C by the year 2100 in relation to 1990 (IPCC, 2000). This study

simulated warming of mean daily temperature in the range +0.6~4.0°C. In the simulation hydrograph for 2001, the discharge for warming of 0.6°C is close to the current condition (Figure 7). But simulated discharge for warming of +2.0°C changes greatly from the current condition. For a warming of +4.0°C the change is even more dramatic. Changes in runoff for warming in the range +1.0~3.0°C are greatest because large shifts occur in the proportions of snow versus rain. A rise in temperature of just 2.0°C is enough to advance and shorten the snowmelt season so that it no longer extends as far as May (Figure 7).

DISCUSSION AND CONCLUSIONS

Model Performance

Considering the performance of the model, the R^2 coefficient is high in the years 2001, 2002, 2003, and 2007 (over 0.70) but is low in the years 2004, 2005, and 2006 (under 0.70). The main causes of low performance simulation are:

1. Problems with the precipitation data. Localized heavy rainfall and winter precipitation are not measured by the rain gauge. Especially difficulty in determining orographic coefficient α for the upper elevation zones.
2. Problems with the temperature data. Difficulty in estimating areal average air temperature using point measured data and a lapse rate. This will cause errors in the snowpack simulation.
3. Errors in measured flood discharge data caused by extrapolation of the stage-discharge rating curve.
4. The SRM model does not simulate ground melt. This will cause winter season low flow to be too low. In this study, time constraints did not allow changes to be made to the model structure, and so some calibration of the recession coefficients was undertaken to improve the simulation of winter low flows.
5. Critical temperature T_{crit} is constant during each year in this study. However, the threshold temperature that determines rainfall or snowfall may be changing with the weather conditions.

The performance of the model could be improved by further careful consideration of these points together with better data measurement techniques.

Global Warming Scenarios

Simulation of the IPCC Scenario A2 using the SRM snowmelt model showed that runoff would be 2-3 times greater in winter, and decrease by half in spring. Losses of spring snowmelt runoff are especially significant as the spring season currently provides the most water resources and the timing corresponds to the planting and cultivation of rice paddies. Change in runoff is particularly large with warming of up to 3.0°C, and snowmelt no longer extends into May with warming of over 2.0°C.

For a small rise in temperature, there will likely be large changes in the seasonal distribution of runoff. Higher runoff peaks during winter season will influence disaster prevention

planning and snowmelt season low flows will severely constrain agricultural water use (e.g. for rice paddies). Change in the seasonal pattern of river runoff may also influence the ecology of the river and riverbank environments. Therefore, it is necessary to review disaster prevention, water supply planning, and management of river habitats to ease these global warming impacts.

Future Research

In this study, the study basin is divided into 3 elevation zones, but if it is divided into more elevation zones the performance of the model may be improved. There are 2 points for measuring air temperature and 4 points with rain gauges. If there are more of these data measuring points, the basin could be further divided. There are 2 types of scenario simulations in this study. One concerns the worst-case scenario of IPCC A2 regional scenario, and the other concerns warming scenarios in the range +0.6~4.0°C. In these scenario simulations, input daily average temperature was determined to be current condition +0.6~4.0°C, but warming is unlikely to be constant each day. Another method would be to simulate random different degrees of warming on each day, with the average warming value matching that of the regional scenario.

Information forecasting concrete changes in the amount of runoff due to climate change is necessary for the planning of water resources utilization and the planning of concrete targets for global warming measures.

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新潟県下越地域における気候変動による流出パターンへの影響

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要 約

IPCC (気候変動に関する政府間パネル) によると、日本地域は2100年ごろまでに平均気温が2～3℃上昇し、降水量にも変化がおこる可能性が高いとされています。新潟県のような積雪量の多い地域では、季節ごとの河川の流出量に大きな影響を与え、農業用水資源の利用にも影響があるでしょう。この研究では、将来の気候変動シナリオ (特に春の融雪流出の変化) から、季節ごと、月ごとの流出量の変化を予測しています。

Snowmelt Runoff Modelを2000年から2007年の滝矢川 (新潟県村上市旧朝日村) の流量データに適用させ、毎日の流出量を予測できるモデルを確立します。積雪量と融雪量は、標高ごとに分けた3つの流域エリアで、気温データによる割増係数を用いて決定しました。モデルの主要な係数は、河川の流量と積雪水量の実測値を用いた、月ごとの水収支の分析で決定しました。

気象庁は気温の上昇が「最悪の場合」の IPCC A2シナリオに基づいて、それぞれの地域の気温上昇シナリオを発表しています。このシナリオを用いて Snowmelt Runoff Model による予測をすると、新潟地域の滝矢川では、河川の流出量が冬期間 (12月-2月) に2～3倍、春 (4月-5月) に半減するという結果を示します。毎月の流出量は、雪と雨の割合で流出時期にずれが生じるため、気温の上昇が+1.0-3.0℃の範囲で最も敏感に変化します。新潟及び周辺の地域では気温0℃付近で大量の積雪があるため、気温の僅かな上昇が、積雪量と流出量に大きな影響を与えます。このような地域では防災と水資源管理の早急な見直しが必要です。

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キーワード：地球温暖化、積雪、雪解け、シュミレーション、水資源

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