Climate Change Impacts on the Seasonal Distribution of Runoff in a Snowy Headwater Basin, Niigata

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Abstract:

In snowy regions, the seasonal runoff pattern is greatly influenced by winter season temperature and precipitation. Our objective is to forecast the change in seasonal and monthly runoff volumes resulting from regional climate change scenarios, especially concerning spring snowmelt runoff. Snowmelt Runoff Model (SRM) was applied to Takiya River (19.45 km²) 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 snowpack snow water equivalent and river discharge. Simulation of the IPCC Scenario A2 (high impact) for Niigata region showed that runoff would be 2–3 times greater in winter (Dec–Feb), and decrease by half in spring (Apr–May). Even with warming restricted to +2.0°C, major changes in monthly runoff volumes occur because of large shifts 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.

KEYWORDS Global warming; snowpack; snowmelt runoff; modeling; water resources

INTRODUCTION

IPCC (Intergovernmental Panel on Climate Change, 2007) reports that global average surface temperatures will most likely rise by 1.8–4.0°C during the 21st century, depending on global development and levels of greenhouse gases in the atmosphere. Assuming the relatively high-impact A2 scenario for global development (IPCC, 2000), the likely range in warming is given as 2.0–5.4°C. At the regional scale, warming is projected to be greatest at high northern latitudes, where precipitation is also very likely to increase. We can therefore assume that temperatures in the Japan region will keep increasing, and precipitation will likely also increase by 2100 (Japan Meteorological Agency, 2005).

Concerns over the impacts of climate change on water resources in snowy mountain regions has led to several studies on important river basins internationally (e.g. Hamlet and Lettenmaier, 1999; Ozdogan 2011), and regionally in

Japan (e.g. Fujihara *et al.*, 2006; Tachikawa *et al.*, 2009; Ma *et al.*, 2010). In snowy regions such as Niigata, the seasonal runoff pattern is greatly influenced by winter season temperature and precipitation. Even with increases in winter precipitation, the likely range of warming suggests there will be a dramatic shift from snowfall to rainfall and much-reduced seasonal snowpack in Japan's maritime climate (Hara *et al.*, 2008). Indeed it has already been reported that snowfall amounts have fallen sharply along the Sea of Japan coastal region (Japan Meteorological Agency, 2002). Any change in seasonal river runoff will greatly influence agricultural and industrial water use, and natural hazards planning. In particular, the Niigata Plain is one of the most important rice-producing areas in Japan.

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, particularly changes in the spring snowmelt runoff volumes. In the current climate, snowmelt water is released from mountain snowpack primarily during April and May, supplying the vast quantities of water needed for transplanting rice seedlings to irrigated paddy fields. Snowmelt continues to be a vital water resource up until the arrival of the rainy season in late June, especially as April to late-June is a period of relatively little precipitation in Niigata. Predictions of likely future changes in the availability of water through this critical season are of the utmost importance for regions such as Niigata.

STUDY SITE

Takiya River in northern Niigata Prefecture is a tributary of the Miomote River in the heavy snowfall Japan Sea Region (Figure 1). Long-term hydrological monitoring has been undertaken here since 2000, giving a valuable database on snow processes and the natural hydrological regime in a relatively undisturbed basin (Whitaker *et al.*, 2008). Basin area is 19.45 km² with an elevation range of 40–950 m. The stream channel remains unfrozen even during the winter period, allowing stream gauging all year-round. Miomote AMeDAS (Automatic Meteorological Data Acquisition System) precipitation gauge operated by the Japan Meteorological Agency is equipped with a heater, allowing measurement of both snowfall and rainfall. A snow lysimeter experiment has been in operation since 2002 giving detailed information on snowmelt rates at three forested locations

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(Whitaker and Sugiyama, 2005), and snow survey has been undertaken at locations from 40–650 m in elevation.

METHODS

Snowmelt runoff model

Snowmelt Runoff Model (WinSRM Version 1.11; Martinec *et al.*, 2008) takes an empirical approach based on daily air temperature to simulate and forecast daily streamflow in mountain basins where snowmelt is a major contributor to annual runoff. The model has been applied by various workers in over 100 basins worldwide, not only for forecasting under the current climate, but also to evaluate changes in runoff due to future global warming (e.g. Seidel *et al.*, 1998). In Japan, it has been applied at Okutadami basin (Ishihara *et al.*, 1985) and the Sai basin (Kawata *et al.*, 1988). For a full list of applications, the reader is referred to Table I in Martinec *et al.* (2008). The model structure is as follows:

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

where Q = average daily discharge (m^3/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 ($\text{cm}/^\circ\text{C}/\text{d}$) indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days ($^\circ\text{C}$)

ΔT = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone ($^\circ\text{C}/\text{d}$)

S = ratio of snow covered area to the total area

P = precipitation contributing to runoff (cm). A critical temperature, T_{crit} , determines whether precipitation 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 (km^2)

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 , a , lapse rate ΔT , T_{crit} , k and the lag time are parameters for a given basin or, more generally, for a given climate.

Due to the empirical nature of the model, there may be concerns regarding the suitability of certain parameter values under a warmer future climate. For example, the runoff coefficients related to evapotranspiration under the current climate may not be of the same value under a warmer climate. We acknowledge this limitation in our approach. However,

Figure 1. Takiya River basin showing elevation zones and locations of hydrological monitoring stations

Table I. Calculation of precipitation for each elevation zone (mean zonal elevation given in parenthesis)

Season	Zone 1 (200 m)	Zone 2 (509 m)	Zone 3 (719 m)
Dec–May	Miomote x α_1	Miomote x α_2	Miomote x α_3
Jun–Nov	(Tributary + Paddy)/2	(Zone 1 + Zone 3)/2	Ishiguro Mt.

we anticipate that changes in the form of precipitation between rain and snow will be far more dominant in affecting seasonal patterns of runoff. If so, evaluation of the T_{crit} parameter is of the utmost importance for both empirical and energy balance approaches.

Climate data

The basin was divided into 3 elevation zones, consisting of about 40%, 40%, and 20% of total area respectively (Figure 1). Air temperature, precipitation, snow water equivalent (SWE) and snowmelt vary for each elevation zone, and a precipitation factor α was applied to simulate the increase in precipitation with elevation (Table I, Supplement Table S2). Precipitation gauges without heaters (Paddy, Tributary, and Ishiguro Mt.) do not operate during the winter months. Otherwise, there are no significant periods of missing data.

The under-catch of snowfall by precipitation gauges (e.g. Sevruk *et al.*, 2009), especially in windy locations such as Niigata, is a serious problem in the accurate simulation of the basin snowpack, water balance and runoff. However, detailed hydrological measurements and analysis at the Takiya River basin provide some insight into the issue. Twice-monthly snow survey measurements of SWE were used to constrain the simulations of snowpack within the model, at least for the lowest elevation zone (infrequent snow surveys available for high elevations bordering Zones 2 and 3). The value of the precipitation factor for Zone 1 (Table II) is largely accounting for the under-catch of snowfall by the Miomote AMeDAS gauge, which does not have a wind-shield. In addition, Whitaker *et al.* (2008) analyzed the monthly water balance of the basin by using estimated evapotranspiration to derive values for the

Table II. Calibration and validation results for SRM

Year	R ²	D _v (%)	Precipitation factor, α			T _{crit} (°C)
			Zone 1	Zone 2	Zone 3	
Calibration						
2001	0.79	3.6	1.25	1.55	1.75	1.0
2002	0.76	−6.0	1.13	1.45	1.94	1.0
2003	0.72	−11.0	1.18	1.5	2.3	1.5
2004	0.62	−7.3	1.28	1.49	2.15	1.5
Validation						
2005	0.51	−8.8	1.06	1.45	2.15	0.5
2006	0.46	−7.3	1.21	1.45	2.3	0.5
2007	0.72	−3.2	1.06	1.43	1.85	1.5

orographic increase in precipitation over the same three elevation zones.

We calculated mean zonal temperatures separately and they became climate input to the model. During the warm season (June to October), the temperature lapse rate used was 0.6°C/100 m. During the snowpack season (November to May), the temperature lapse rate was calculated from measured air temperature data at 140 m and 550 m elevations:

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

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

Model parameters

The recession coefficient, k , 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:

$$\begin{aligned} k_1 &= x \cdot Q_1^{-y} \\ k_2 &= x \cdot Q_2^{-y} \end{aligned} \quad (4)$$

$$\begin{aligned} \log k_1 &= \log x - y \log Q_1 \\ \log k_2 &= \log x - y \log Q_2 \end{aligned} \quad (5)$$

Analyzing true recession flow periods (i.e. excluding rainfall days and periods with snowpack) for Takiya River, we determined the constants x and y as:

$$\begin{aligned} \log 0.8 &= \log x - y \log 1 \\ \log 0.68 &= \log x - y \log 10 \end{aligned}$$

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

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 of 0.92 year-round, but c_R changes by the season (range 0.7–0.9, Supplement Table S1). c_R is high in winter and lower in summer due to evapotranspiration losses.

In the absence of remotely sensed snow cover data at adequate spatial and temporal resolution, SRM was operated

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

CALIBRATION AND VALIDATION

Years 2001–2004 were used in the model calibration, while years 2005–2007 were withheld for the model validation (Table II). The model parameters and the precipitation factors were determined by a two-step approach. Firstly, model parameters and coefficients affecting snow accumulation and melt are optimized using SWE measurements in the tributary (Figure 1). Next, each precipitation factor is constrained using measured versus simulated discharge hydrographs. R^2 (coefficient of determination) and D_v (percentage difference between the total measured and simulated runoff) are used to evaluate the performance of the model (Martinec *et al.*, 2008).

Step 1: Calibration of snowpack SWE

The precipitation factor α is applied to winter season precipitation (Table I). 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_1 is adjusted by comparing measured and simulated SWE at the 140 m snow course location. In mountainous regions, α increases with elevation ($\alpha_3 > \alpha_2 > \alpha_1$). 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).

Critical temperature T_{crit} determines whether precipitation is rain or snow. In this study, T_{crit} was constant through one winter season and constant across elevation zones, but it varied between years in the range 1.0–1.5 during the calibration period (Table II). The T_{crit} was calibrated at the final step by comparing measured and simulated discharge and SWE.

Degree-day factor a (cm/°Cd) converts the number of degree-days T (°Cd) into daily snowmelt depth M (cm) ($M = aT$). 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 release of SWE, 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 (Supplement Table S1). Then, the minimum value of a was increased by comparing measured and simulated SWE and discharge.

Step 2: Calibration of discharge hydrograph

After calibration of the simulated snowpack SWE, the simulated and observed discharge hydrographs are compared (Supplement Figure S1). 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 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 coefficient was necessary to improve the simulation of winter low flows (in mid-winter season, the constant x in Equation (3) was increased).

Calibration result

Calibration results are shown in Table II, and an example hydrograph is shown in Supplement Figure S1. 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. Model performance, R^2 , is over 0.70 in 2001 to 2003, but in 2004 it is low partly because there was a large summer flood that was not fully captured by the rain gauge network. The mass balance error, D_v , is generally negative meaning that the simulated discharge volume is too low.

The precipitation factors for each elevation zone and the critical temperature for rain/snow will vary from year to year depending on the particular weather patterns in a given year. Therefore, these values were not constant for all years (Table II), as previously demonstrated by Whitaker *et al.* (2008) for the precipitation factor. All other model parameters were evaluated during the calibration period only and fixed, while snow survey data was used to constrain the value of the critical temperature for rain/snow.

Validation results

The years 2005 to 2007 were withheld for the validation (Table II). 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} which 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 II). By excluding the summer rainy season which occurs after snowmelt season has finished, the R^2 term increased dramatically to 0.83 for 2005. The simulated and observed hydrographs are close, but in winter season the simulated discharge is often lower than the measured discharge (see Jan–Feb in Supplement Figure S2). Simulated SWE for Zone 1 was higher than the measured snow survey data in 2007, but lower than the measured data in 2005 and 2006 (Supplement Table S2). 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 T_{crit} during the winter season.

SIMULATION OF CLIMATE SCENARIOS

IPCC published the Special Report on Emissions Scenarios (IPCC, 2000), which contains over 35 scenarios divided into 4 groups (A1, A2, B1, and B2). The Japan

Table III. Summary of IPCC A2 regional scenarios for Eastern and Northern Japan Sea regions showing change from 1981–2000 values to 2081–2100 values by season

Season	Eastern Japan Sea		Northern Japan Sea	
	ΔT (°C)	Precip. (%)	ΔT (°C)	Precip. (%)
Dec–May	2.8	–13	3.1	1
Jun–Nov	2.2	+19	2.5	+13

Meteorological Agency subsequently published regional scenarios that are based on IPCC Scenario A2 (high-impact), containing mean monthly changes in temperature and precipitation (Japan Meteorological Agency, 2005). Table III summarizes these scenarios by cold season and warm season for the Eastern and Northern Japan Sea regions. The study site is located just within the boundary of the Eastern Japan Sea region and close to the Northern Japan Sea region. Comparing these two regional scenarios, we can see that there is slightly greater warming in the Northern Japan Sea (NJS) regional scenario, while the Eastern Japan Sea (EJS) regional scenario is notable in that winter season precipitation is projected to decrease (Table III). Due to the proximity of the study site to the boundary of these two regions, both regional scenarios were evaluated.

The future climate data was developed by taking the measured climate data (2000–2007) and changing the daily values based on the projected changes for each month given by the Japan Meteorological Agency (2005) for the A2 scenario as summarized in Table III. As such our approach is based on future climate projections of a single climate model. Within each month, the same degree of warming was added to each day, and the precipitation values were multiplied by the same ratio. In addition, simpler temperature scenarios were evaluated which contained the same degree of warming in each month (+0.6–4.0°C), without any changes made to precipitation. The precipitation factors and T_{crit} remained unchanged in the future climate.

RESULTS

Temperature scenarios

Figure 2 shows temperature scenarios evaluated for the winter season of 2001. We can see that the daily discharge for a warming of 0.6°C is close to the original seasonal runoff pattern. But simulated discharge for a warming of +2.0°C changes greatly from the original baseline condition. Flows are increased throughout the winter season, snowmelt season peaks are reduced, and the snowmelt season ends at least two weeks earlier by late-April. For a warming of +4.0°C the change is even more dramatic, because large shifts occur in the proportions of rain versus snow and the seasonal snowpack is becoming much less dominant in the hydrological regime.

Regional scenarios

Changes in the seasonal runoff pattern were similar in each year of simulation during 2000–2007 (figure not shown). In both regional scenario simulations (EJS and NJS), winter season runoff increases greatly as snowfall events

become rainfall events producing many new runoff peaks. On the other hand, during the snowmelt season the discharge amounts for the regional scenarios are lower than the original condition. In winter season the discharge for each scenario varies with the different weather conditions, but in snowmelt season they are very similar, showing large reductions in runoff during April and May.

Figure 3 shows the monthly runoff volumes averaged over the 7 years of simulation for the baseline condition and the EJS regional scenario. In winter season, runoff volume increases by 100% or more even while precipitation amounts decrease (Table III). This can be explained by the significant shift from snowfall to rainfall, which almost immediately becomes runoff. In contrast, the snowmelt season shows runoff volume decreases of up to 70%, due to the earlier melting of a much-reduced snowpack. April dominates the seasonal runoff with about 11 million m^3 in the baseline condition, but under the EJS regional scenario this volume is cut to only 4 million m^3 and a much reduced snowmelt peak occurs a month earlier in March. The hydrological

Figure 2. Change in discharge hydrograph during winter and spring for various warming scenarios (precipitation unchanged)

Figure 3. Change in monthly runoff pattern between simulated baseline and IPCC A2 scenario for Eastern Japan Sea region

regime changes from dominant April snowmelt runoff to a pattern with similar-sized peaks in both early winter and summer rainy season (Figure 3). Overall, it can be seen that temperature change has a greater influence on the seasonal distribution of runoff than changes in precipitation amounts, due to the shift from snowfall to rainfall.

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:

- Limitations with the precipitation data. The precipitation gauge network does not measure localized heavy rainfall and winter precipitation adequately. Especially, there is difficulty in determining the precipitation factor α for the upper elevation zones.
- Limitations 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.
- Errors in measured peak discharge data caused by extrapolation of the stage-discharge rating curve.
- SRM does not simulate ground melt. This will cause winter season low flows to be too low. We attempted to address this problem by further calibration of the recession coefficient to improve the simulation of winter low flows.
- Critical temperature T_{crit} is constant during each year in this study. However, the critical temperature that determines rainfall or snowfall is likely changing with the weather conditions on a storm-by-storm basis.

The performance of the model could be improved by further careful consideration of these points.

Regional and temperature scenarios

Simulation of IPCC Scenario A2 for a relatively small basin in the Niigata region showed that runoff would be 2–3 times greater in winter, and decrease by 40–70% 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. Instead of naturally abundant water resources in spring and early summer, the results of our simulations demonstrate a relatively minor spring snowmelt peak towards the end of this century, and the emergence of peak seasonal runoff in the July rainy season and secondarily in the early winter of December to January.

For even a small rise in temperature ($+2^\circ\text{C}$), there will likely be large changes in the seasonal distribution of runoff. Higher runoff peaks during winter season, and especially summer rainy season, will greatly influence flood-risk hazards and disaster mitigation planning. Conversely, the risk of low flows during spring and early summer 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 urgently review

water resources planning and the management of river habitats in preparation for these global warming impacts. Quantitative information on likely changes in the seasonal distribution of runoff due to climate change is necessary for the planning of water resources utilization and the planning of measures to mitigate the impacts of global warming.

Future research

Because the model is operated in a mode where snowpack is assumed uniform across each elevation zone, dividing the basin into more elevation zones may improve the performance of the model. A greater number of measuring points for air temperature and precipitation would allow the basin to be further divided more effectively. However, incorporating remotely sensed snow cover data, when available, promises a greater level of improvement in simulating snow cover distribution. Another area of concern is the method by which the future climate data are developed. In this study, the same increment of warming was added to all measured daily temperatures (2000–2007), but warming is unlikely to be constant each day. An alternative method would be to simulate variable degrees of warming on each day. Similarly the precipitation was adjusted by the same ratio each day, whereas in reality there would be a more complex change in precipitation patterns. In fact, downscaling and bias-correction of future climate data for use in hydrological simulation is a current topic of much debate (e.g. Wood *et al.*, 2004; Tachikawa *et al.*, 2009). The exact combination of changes to both temperature and precipitation will be crucial in the accurate prediction of changes to seasonal snowpack and river runoff in regions such as Niigata.

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SUPPLEMENTS

Supplement 1. This includes:

Table S1. Monthly parameter values for SRM in the calibrated model.

Table S2. Example of mass balance, temperature, and snowpack SWE characteristics for water year 2005 (basin mean precipitation 3510 mm, simulated runoff 2678 mm, simulated evapotranspiration 832 mm).

Figure S1. Calibration result showing measured versus simulated discharge hydrographs for the water-year 2001.

Figure S2. Validation result showing measured versus simulated discharge hydrographs for the water-year 2005.

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