Year-to-year variation in snowmelt runoff from a small forested watershed in the mountainous region of central Japan

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Abstract:

This study investigates the potential impacts of regional climate change on hydrological cycles using eight years of observations on snowmelt runoff from a small forested watershed (Kurahone watershed) in Nagano Prefecture, Japan. We compared discharge in winter and spring (January–May) in 1991, 1997, 1998, 2003, 2004, 2006, 2012 and 2013. Early years (1991, 1997, 1998 and 2003) were characterized by sporadic-type hydrographs, with concentrated discharge in the beginning of April due to overlaps in snowmelt and rainfall. Later years (2004, 2006, 2012 and 2013) were characterized by sporadic-type hydrographs, with several discharge peaks in midwinter due to rainfall and relatively low ratios of discharge in April to discharge during January to May. Tank-model calculations of discharge rate and snow water equivalent (SWE) over the last 21 years suggest that sporadic-type hydrographs have occurred more frequently in recent years, whereas average air temperature, precipitation amounts and SWE have no increasing or decreasing trends. Discharge in April increased with high maximum SWE and heavy rainfall in April, but decreased with increase of ratios of rainfall to total precipitation in winter. Regional climate change may drive increases in midwinter rainfall and the absence of overlaps in snowmelt and rainfall in recent years.

KEYWORDS climate change; small forested watershed; snowmelt runoff; tank-model; winter rainfall

INTRODUCTION

Understanding variation in snowmelt runoff is key to mitigating the negative impacts of climate change on water resources. Most projections of climate change predict a decrease in snowfall and/or snow cover (McCabe and Wolock, 2010). Studies that link reduced snowmelt to water resources scarcity have been conducted over a wide range of spatiotemporal scales (e.g., Barnett et al., 2005; Brabets and Wolock, 2010). The influence of climate change on hydrological cycles has been examined in several studies in Japan (e.g., Shinozaki et al., 2009; Yamanaka et al., 2012). For example, Yamanaka et al. (2012) investigated long-term changes in discharge of rivers that originate in the Japanese Alps region and found 13 of the 16 rivers showed a forward shift in snowmelt. Climate projections point to decreased snowfall and/or snow cover (Inoue and Yokoyama, 1998; Hara et al., 2008) and springtime discharges (e.g., Whitaker and Yoshimura, 2012; Noto et al., 2011). A scenario whereby climate change reduces snow-associated water resources seems to have become widely accepted.

Several studies suggested trends towards increasing snowfall/snowpack in regions of high elevation (e.g., Shimizu, 2012; Suzuki, 2013). Suzuki (2013) indicated increasing maximum snow depth observed in the meteorological station on Mt. Fuji (a.s.l. 3773 m). Similarly, Shimizu (2012) found increased cumulative snow depth between 1970–2010 in the Sugadaira montane research center of University of Tsukuba (a.s.l. 1320 m). However, Yamanaka et al. (2013) found that the center time (CT, the calculated flow-weighted mean of date) of snowmelt runoff tends to be delayed more for rivers with higher catchment-mean-elevations in the Hokuriku area. Although these contradictions should be examined, limitations on obtaining meteorological and hydrological observation in mountainous regions continue to make this discussion difficult in Japan.

Observations of small watersheds in mountainous regions are particularly valuable to the climate-change dialogue. Headwater streams in these regions are sensitive to environmental change and can therefore act as bellwethers (Campbell et al., 2011). Long-term observations in small watersheds across the globe suggest a seasonal shift of snowmelt over the last several decades (e.g., Campbell et al., 2011; Nayak et al., 2010). In Japan, many studies of snowmelt runoff have been conducted in headwater streams such as the experimental watershed in Moshiri basin in Hokkaido (e.g., Suzuki and Kobayashi, 1987) and Takaragawa basin in Gunma prefecture (e.g., Shimizu and Tsuboyama, 1990). However, long-term trends at high elevation sites rarely appear to be discussed in the context of climate change.

This study presents eight non-consecutive years (1991–2013) of January–May observations to investigate snowmelt runoff in the Kurahone, a small forested watershed in a high elevation area in central Japan. Based on these eight years of observation data, we examine temporal variations in snowmelt runoff. For investigating potential trends related to climate change, we estimate snowmelt runoff and snow water equivalent using a tank model to compensate for the lack of observations.

MATERIALS AND METHODS

Study site

The Kurahone watershed is part of the Kawakami forest of the University of Tsukuba (35°54’90”N, 138°30’20”E), located in Nagano Prefecture, central Japan (Supplement
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Figure S1). The watershed is forested, comprises 38.8 ha and has a high elevation of 1480–1780 m. A 90° V-notch weir was installed at the outlet of the watershed in the 1980’s. The area is underlain by Neogene volcanic rocks and the upper forest soil contains volcanic ash. A natural deciduous forest of oak (Quercus mongolica Fisch) and larch (Larix leptolepis Gordon) plantation covers most of the watershed, and there is bamboo grass (Sasa nipponica) on the slopes.

The region has a humid, temperate climate. Weather data were obtained from the Kawakami weather station operated by the Agricultural and Forestry Research Center, University of Tsukuba. Annual mean air temperatures range from 6.7–7.4°C. Mean air temperature in winter was −3.1°C, varying from −1.5°C to −4.1°C. Annual precipitation is 1062–1810 mm. Total precipitation, sum of amounts of rainfall and snowfall, in winter (January–March) varies between approximately 100–300 mm. Precipitation in winter often occurs during depressions and weather fronts (Tasaka, 1980), unlike the heavy-snow regions facing the Sea of Japan. Maximum snow depth is relatively low at 0–70 cm and the limited snowfall and low temperatures result in soil frosts with a maximum depth of 0–20 cm (Hamada and Tanaka, 2010). The slope of the regression line derived from the relationship between year and mean air temperature in winter was 0.03°C year$^{-1}$ and its correlation coefficient was 0.024 in (sample number n = 17, significance level in t-test p > 0.05).

Observations and data set

Although the installation of the weir was in the 1980’s, deficits were often found in data sets for the winter season presumably due to low temperature of the study site. Several 10’s of cm of ice can be seen in the weir in winter, which is without freeze proofing. We tried to obtain data for years that would enable us to analyze observations from the first of March. Data sets for eight years (1991, 1997, 1998, 2003, 2004, 2006, 2012, 2013) matched this criteria. In the early six years (1991, 1997, 1998, 2003, 2004, 2006), water heights were recorded with a combination of float type water height recorders and water height charts read at 1-hour intervals and converted to water discharge (L s$^{-1}$) and then discharge rate (mm hour$^{-1}$). The capacitance water level sensor (LT-1000, TruTrack) was used from September 2011. All water height data were converted to discharge based on the theoretical equation of a 90° V-notch type weir. Discharge was converted to discharge rate by dividing discharge by watershed area.

Meteorological data were taken partly from the weather station in the Kawakami forest and partly from the Nobeyama station of the nationwide Automated Meteorological Data Acquisition System (AMeDAS). To adjust for missing records (1991 and 1997 air temperature and precipitation and 1998 precipitation), we used data from the Nobeyama AMeDAS, corrected based on the relationship of these data to the Kawakami weather station.

We developed and used a tank model to reproduce the discharge rate (mm hour$^{-1}$). The aims of the model were to validate the observation results, compensate for the lack of observations and reproduce snow water accumulation. Our tank model consisted of a circuit of three tanks with four drainages (Supplement Figure S2). Upper, middle and bottom tanks were assumed to represent surface soil, deeper soil and bedrock, respectively. The equations for calculating numerical quantities are in Supplement Document S1. Statistical significances of correlation coefficients among variables were examined by t-test.

RESULTS AND DISCUSSION

Observation results

Figure 1 shows temporal variation in 10-day average precipitation, 10-day average air temperature, estimated snow water equivalent (SWE), and observed and estimated discharge rates. Hydrograph types differed between the first four years (1991, 1997, 1998, 2003) and the latter four years (2004, 2006, 2012, 2013) (Figure 1). Concentrated runoff in the early years occurred simultaneously with the timing of snowmelt, i.e., a drastic decrease of SWE in the beginning of April. In contrast, in the latter years there were several sporadic peaks and hydrograph shapes were flat. There was no difference between early and later years in the variation in 10-day average air temperatures (p > 0.05). Precipitation in early January and April was greater in early years compared with later years (p < 0.05). We hereafter describe the year groupings by their hydrograph types: concentrated-type hydrograph (early years) and sporadic-type hydrograph (later years).

Concentrated-type hydrographs were similar to those in previous studies that investigated snowmelt runoff in heavy-snow regions, such as Hokkaido in Japan (Suzuki and Kobayashi, 1987) and the Sierra Nevada in the United States (Hunsaker et al., 2012). In concentrated-type hydrographs, active snowmelt decreases SWE to zero as air temperature rises and there is heavy rainfall in the beginning of April. In this period, inputs of water through snowmelt and rainfall appeared to overlap. In contrast to concentrated-type hydrographs, sporadic-type hydrographs lack large discharge peaks in early April and have the midwinter discharge peaks. Midwinter discharge peaks of sporadic-type hydrograph are assumed to be due to winter rainfall (Whitaker and Sugiyama, 2005).

The fact that sporadic-type hydrographs are found in recent years infers an alteration in hydrological processes. To investigate the possibility of altered hydrological processes, we use a tank model to calculate discharge rate and SWE for years lacking observation data (Supplement Figure S3). Table I summarizes the observed and calculated results. Sporadic-type hydrographs have occurred more frequently in recent years. Only two years in the 1990s featured this type, whereas there were 11 between 2000 and 2013. However, discharge rates in April, precipitation in April and maximum SWE varied greatly and lacked a clear trend.

Concentrated-type hydrographs featured relatively high discharge rate during day-of-year (DOY) 91–120. The mean ratio of rainfall to total precipitation during DOY 1–90 was significantly higher in sporadic-type hydrographs than in concentrated-type hydrographs (p < 0.05). Mean maximum SWE was higher in concentrated-type hydrographs (p < 0.05). There was no significant difference in mean air temperature between concentrated- and sporadic-type hydrographs (p > 0.05). The difference in hydrograph shape appears to relate to the ratio and timing of rainfall.

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Relationships between snowmelt discharge and meteorological data

Our results indicate that discharge in April can be the major difference between concentrated-type and sporadic-type hydrographs. We investigated the correlation coefficient between discharge in April (DOY 91–120) and meteorological attributes (Table II). Discharge during DOY 91–120 was significantly correlated with precipitation during DOY 1–30 ($p < 0.01$), precipitation during DOY 91–120 ($p < 0.01$), and maximum SWE during DOY 1–90 ($p < 0.05$). The ratio of rainfall during DOY 1–90 to total precipitation during DOY 1–90 was negatively, but not significantly, related to discharge during DOY 91–120. Maximum SWE was positively correlated with precipitation through all periods except DOY 61–90 ($p < 0.05$), and air temperature had no significant effect on SWE in any period. This was expected because at our high-elevation study site, air temperatures are lower than the threshold for rainfall and snowfall and therefore fluctuations of air temperature were not reflected in SWE. However, air temperature was correlated with precipitation, rainfall during DOY 91–120, and the ratio of rainfall to total precipitation during DOY 61–90 ($p < 0.05$). One possible explanation for the positive correlation between rainfall and air temperature during DOY 91–120 was the passage of a warm front, which brings warm and humid air. The positive correlation between precipitation and maximum SWE during DOY 1–30 ($p < 0.05$) suggests heavy snowfall resulted in a greater maximum SWE.

Despite the lack of temperature trends, our results suggest that increases in midwinter rainfall may lead to more sporadic-type hydrographs. A study on the Sugadairakogen highlands, 80 km from our study site, found that 70% of rainy days during December–February were accompanied by extra-tropical cyclones and suggested a correlation with the Pacific Decadal Oscillation (PDO) index, an index of teleconnection patterns (Sato et al., 2012). Changes in winter cyclone trajectories in the 1990’s may also be correlated with...
midwinter rainfall (Ueno et al., 2010) and helps to explain the increase in sporadic-type hydrographs. Midwinter rainfall processes and their relation to snowmelt runoff should be examined further.

Response to rainfall in midwinter

Previous studies suggest that winter rainfall causes snowmelt and flooding (Sui and Koehlaer, 2001; McCabe et al., 2007), which may result in a loss of water resources in spring and summer. To understand the impacts of midwinter rainfall on streamflow response, we investigated the relationship between the amount of quick flow and event rainfall under two conditions: with and without snow cover (Figure 2). Large amounts of event rainfall increased quick flows both with and without snow cover. The irregular response observed on 8 April 2003 can be attributed to the overlap of
snowmelt and rainfall at the beginning of April.

Excluding the datum of 8 April 2003, the relationship between total quick flow $QF$ (mm) and total event rainfall $ER$ (mm) can be expressed by the following equations:

Without snow cover:

$$QF = 0.24 \times ER - 4.0 \quad (R^2 = 0.60, n = 14) \quad (1)$$

With snow cover:

$$QF = 0.11 \times ER + 0.45 \quad (R^2 = 0.44, n = 14) \quad (2)$$

Our calculated results for runoff events without snow cover are in line with Gomi et al. (2010), who observed that quick flow increased when rainfall exceeded 30 mm. Equation (1) yielded 16 mm as the rainfall threshold that would lead to direct runoff in our study site. The slope of the regression for runoff events with snow cover was smaller than the one for events without snow cover, suggesting that the existence of snow cover can limit immediate runoff during low-intensity rainfall. Very low runoff coefficients were observed on 28 January 2003 and 7 February 2012 and estimated SWEs during both events were large. One possible explanation is that sufficient snow cover may have retained rainwater and decreased direct runoff (Nakatsugawa et al., 2004). It is suggested that a large amount of snow cover moderated runoff during high intensity rainfall in midwinter. However, the high value of the intercept of the regression line suggests that rain water immediately runoffs even in small rainfall events. This could be explained by constant background melts, in addition to direct runoff of rainwater, that occurred during rainfall events in midwinter (Whitaker and Sugiyama, 2005). However, snowpacks on our study site, in contrast to those studied by Whitaker and Sugiyama (2005), were too cold to melt immediately. Further investigation, including snow surveys, are needed to describe snowmelt runoff processes. These results suggest that a decrease in snow cover may accelerate springtime discharge by eliminating a source of water retention.

CONCLUDING REMARKS

In this study, we investigated the variation in snowmelt from the Kurahone watershed, a small, forested watershed in a high-elevation area. We found differences in hydrograph type over the span of 22 years. Early years corresponded to concentrated-type hydrographs and later years to sporadic-type hydrographs. In the concentrated-type hydrographs, active snowmelt and/or intense rainfall resulted in concentrated discharge in the beginning of April. Sporadic-type hydrographs were characterized by discharge peaks in midwinter, assumed to be due to rainfall and no overlap of snowmelt and rainfall in the beginning of April. By analyzing meteorological data, the estimated ratio of rainfall to total precipitation in midwinter was higher in years with sporadic-type hydrographs than in the years with concentrated-type hydrographs. The 21-year tank model-calculated snow melt runoff suggested that sporadic-type hydrographs were more frequent in recent years. Discharge rate in April, precipitation in April and maximum SWE varied considerably and showed no significant trend. Increases in midwinter rainfall and the increased frequency of sporadic-type hydrographs could relate to changes in cyclone patterns, but further investigation is required. The relationship between midwinter rainfall and quick flow suggested that the presence of sufficient snow cover could mitigate direct runoff and that runoff may occur even with small midwinter rainfall events. Future studies should continue to explore hydrological responses to winter rainfall and the links with regional climate change.

SUPPLEMENTS

Figure S1. Maps of the study site
Figure S2. Conceptual diagram of the tank model and a list of parameters. The letter $t$ indicates time with an interval of one hour ($\Delta t = 1$ hour)
Figure S3. Temporal variations in calculated discharge rate and SWE. Years 1993 and 1994 were not calculated because of a lack of AMeDAS data. Asterisks indicate years observation data was available. Underlined numbers indicate concentrated-type hydrographs
Document S1. Equations for the tank model and the explanations for input data

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