Influence of snow ablation and frozen ground on spring runoff generation in the Mogot Experimental Watershed, southern mountainous taiga of eastern Siberia

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Abstract Snowmelt runoff is one of the most important discharge events in the southern mountainous taiga of eastern Siberia. The present study was conducted in order to understand the interannual variations in snowmelt infiltration into the frozen ground and in snowmelt runoff generation during the snowmelt period in the southern mountainous taiga in eastern Siberia. Analysis of the obtained data revealed the following: (1) snowmelt infiltration into the top 20 cm of frozen ground is important for evaluating snowmelt runoff generation because frozen ground absorbed from 22.9% (WY1983) to 61.5% (WY1981) of the maximum snow water equivalent. The difference in snowmelt infiltration for the two years appears to have been caused by the difference in snowmelt runoff generation; (2) the snowmelt runoff ratio increased with (i) increase in the fall soil moisture just before the soil surface froze and (ii) increase in the maximum snow water equivalent. The above results imply that the parameters governing snowmelt infiltration in the boreal taiga region in eastern Siberia are fall soil moisture and the maximum snow water equivalent, as is the case in the simple model presented by Gray *et al.*

Keywords Eastern Siberia; runoff ratio; snowmelt; snowmelt infiltration into frozen ground; soil moisture

Acronyms

FORSGC	Frontier Observational Research System for Global Change
SHI	State Hydrological Institute
SWE	Snow Water Equivalent
TDR	Time Domain Reflectrometry
WY	Water Year

Introduction

Recently, Peterson *et al.* (2002) showed that Arctic river discharge increases as surface air temperature increases. Furthermore, Yang *et al.* (2002) showed that variations in the monthly runoff of the Lena River also increase with the increase of winter runoff. Ma *et al.* (2000) showed that more than 60% of river runoff from the Lena River basin comes from the southern mountainous region and that this region is located in the permafrost zone.

There have been numerous hydrological studies of permafrost regions (e.g. Roulet and Woo 1986; Woo and Winter 1993; Kuchment *et al.* 2000). Kuchment *et al.* (2000) developed a distributed hydrological model for the Kolyma River basin in Russia. The model included several hydrological processes in the permafrost region, such as snowmelt infiltration into frozen ground.

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One of the most important runoff events is snowmelt runoff. Numerous studies have investigated snowmelt runoff and sublimation from the snowpack. Alexeev *et al.* (1973) and Motovilov (1979) showed that snowmelt infiltration into frozen ground is important for evaluating snowmelt runoff. However, it is not clear how snowmelt infiltration into frozen ground affects snowmelt discharge in the southern mountainous taiga of eastern Siberia, where an important water source for the Arctic Ocean is located. The southern mountainous taiga in eastern Siberia is the source of the Baikal and Lena Rivers watershed, and the Lena River basin is a large source of freshwater that discharges into the Arctic Ocean. We conducted our study using the Mogot Experimental Watershed, which is located in the southeastern mountainous region of Siberia and which was established by the State Hydrological Institute (SHI) in 1976. The SHI carried out long-term observations of the water and energy balances in the Mogot Experimental Watershed from 1976 to 1985 inclusive (Sokolov and Vuglinsky 1997). These datasets are used to analyze the characteristics of the runoff ratio and snow ablation. Furthermore, the Frontier Observational Research System for Global Change (FORSGC) and SHI conducted intensive observations in the Mogot Experimental Watershed, which was established by SHI in 1976, from August 2000 to May 2002.

The present study had two objectives: (1) to evaluate the effect of snow ablation and permafrost on interannual variations in spring runoff, and (2) based on the results of this evaluation, to understand the interannual variability in spring runoff generation in the southern mountainous region.

Methodology

Site description

The Mogot Experimental Watershed is located in the southern mountainous region of eastern Siberia (55.5°N, 124.7°E), approximately 60 km north of Tynda, in the Amur region of Russia, in the Nelka River basin. The watershed is situated at the drainage divide between the Lena and Amur River basins. However, the Nelka River basin may be taken to be included in the Amur River basin. The basin is 12 km long and 2.5 km wide, with a total area of approximately 30.8 km^2; the slopes are exposed to the northeast and southwest. In this basin, altitudes range from 580 m to 1130 m a.s.l. Hydrometeorological observations were carried out in this region from August 2000 to May 2002. Furthermore, we accessed the hydrometeorological data from 1976 to 1985 that were collected by the SHI. The latest project, from 2000 to 2002, was conducted jointly by the FORSGC of Japan and the SHI of Russia.

Figure 1 shows the location of the study site. The dominant land cover is larch forest (*Larix cayanderi*), although ridges are partially covered by birch and pine forests. Forest covers nearly 90% of the watershed, and the remaining area is covered by grassland. The soils contain permafrost and are covered by a 10–15 cm thick layer of moss. The porosity of the upper 20 cm of soil exceeds 85% in most of the watershed, and these layers contain organic soil. The deeper layer is sandy soil. Since we had no data concerning the porosity of the deeper, sandy layer, we assumed that the porosity of this layer would be less than 85%. Meteorological observations were carried out at an open site in the watershed at an altitude of approximately 610 m a.s.l. from 1975 to 1985, and in the larch forest and at open sites from 2000 to 2002.

Observational and historical data

In order to evaluate the water and energy fluxes above and below the larch canopy, an 18.6 m high tower was installed at a site in the sparse larch forest in the middle of August 2000. From August 2000 to May 2002, hydrometeorological observations were carried out from

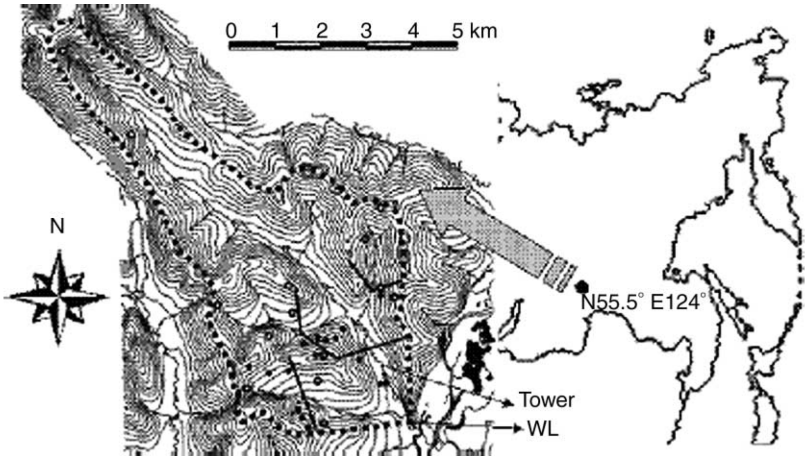

Figure 1 Location of the Mogot Experimental Watershed. WL and Tower denote the cross section and meteorological observational sites, respectively. Thick and broken lines denote snow and soil survey courses and closed circles denote the location of the observation site

this location at the bottom of the main valley. The site was located near the previous meteorological observation site, which had been used from 1976 to 1985.

Russian traditional meteorological observation was also carried out at an open site, where the historical meteorological data were collected. The daily data for hydrometeorological elements (air temperature, relative humidity, wind speed, total and low layer cloudiness, ground surface temperature, air pressure, river discharge, soil moisture, ground thaw depth and snow water equivalent) were available from 1976 to 1985 and from 2000 to 2002. Measurements of air temperature, relative humidity and wind speed were taken 2 m above the soil surface. Soil moisture was measured by taking 100 cm^3 soil samples every 5 cm within the soil layer from depths of 0–20 cm, using a soil pit and then drying the samples to evaluate the volumetric soil moisture from 1976 to 1983. In 2001, the soil moisture was measured by a time domain reflectometry (TDR) sensor and soil sampling, using a soil pit. In 1981 and 1983, the winter soil moisture below a snowpack was also measured using the same method. Snow water equivalent was obtained by conducting a snow survey at three snow courses (shown in Figure 1).

Yang and Ohata (2001) considered wind-induced under-catch of solid precipitation to be important. Therefore, we adopted the bias-correction method described by Yang and Ohata (2001) for the Tretyakov precipitation gauge, as follows:

$$CR(snow) = 103.10 - 8.67W_s + 0.30T_{\max} \tag{1}$$

$$CR(mixed) = 96.99 - 4.46W_s + 0.88T_{\max} + 0.22T_{\min} \tag{2}$$

$$CR(rain) = 100.00 - 4.77W_s^{0.56} \tag{3}$$

where CR is the catchment ratio of a Tretyakov precipitation gauge (%) for each type of precipitation, W_s is the daily mean wind speed ($\mathrm{m\ s^{-1}}$), and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperatures (°C), respectively. Here, the transition air temperature between snow and rain was assumed to be 1.5°C.

The snow water equivalent was measured in a snow survey along three snow courses from 1975 to 1985 and along one snow course from 2000 to 2002. The thaw depth in the surface soil was observed at more than 18 points within the watershed from 1975 to 1983 and at two points at the bottom of the valley from 2000 to 2002, using cryopedometers as instruments for measuring the depth to which the soil is frozen. Each cryopedometer consisted of an outer tube

Table 1 Annual precipitation, annual discharge, maximum snow water equivalent, spring discharge (April to May), and annual and snowmelt runoff ratios from WY 1979 to WY1983 and from WY2001 to WY2002. NA denotes missing data. '*' denotes no bias correction on the winter precipitation

Water year	Annual precipitation (Oct.–Sep.) (mm)	Annual Discharge (Oct.–Sep.) (mm)	Maximum snow water equivalent (mm)	Fall soil moisture within upper 20 cm (mm)	Spring discharge (Apr.–May) (mm)	Annual runoff ratio (Oct.-–Sep.)	Snowmelt runoff ratio (Apr.–May)
1979	542	261	80	96	30	0.48	0.38
1980	578	326	95	142	69	0.56	0.73
1981	594	397	65	44	17	0.67	0.26
1982	696	422	62	77	42	0.61	0.68
1983	531	282	105	169	91	0.53	0.87
2001	557*	214	62	NA	19	0.38	0.31
2002	NA	NA	104	101	90	NA	0.87
Mean	583	317	82	105	51	0.54	0.63

containing an inner rubber tube filled with distilled fresh water. The water freezes when the soil temperature falls below 0°C and melts when temperature rises above 0°C. Therefore, the cryopedometer can detect the position of the upper and lower limits of soil freezing/thawing. The standard depth of seasonal frost in Russia is 150 cm. In the present study, cryopedometers were installed at depths of up to 150 cm.

Runoff ratio

The ratio of precipitation into the watershed to discharge from the watershed, i.e. the runoff ratio, is one of the most important factors for understanding the hydrological cycle in the watershed, and in particular the rainfall–runoff event. A runoff ratio of less than 1 indicates that the precipitation is spent by the increase of evapotranspiration or soil moisture. We defined the period of the snowmelt season to be from 1 April to 31 May. The runoff ratio (R) is defined as

$$R = D/P \tag{4}$$

where R is the runoff ratio, D is the discharge (mm), and P is the precipitation (mm).

We considered the properties of snowmelt runoff based on the runoff ratio. The snowmelt runoff ratio (R_{SM}) is defined as

$$R_{\mathrm{SM}} = D_{\mathrm{Apr-May}}/SWE_{\mathrm{max}} \tag{5}$$

where R_{SM} is the snowmelt runoff ratio, $D_{\mathrm{Apr-May}}$ is the discharge from 1 April to 31 May (mm) and SWE_{max} is the observed maximum snow water equivalent (mm).

Snowmelt was estimated using the following equation:

$$SM_n = SWE_n - SWE_{n-1} \tag{6}$$

where SM is the snowmelt (mm), SWE is the snow water equivalent (mm) and the subscripts n and $n-1$ indicate present day and previous day values, respectively. We ignored sublimation during the snowmelt period and assumed that snow ablation was equivalent to the amount of snowmelt. When snowfall occurs during a thaw, snow ablation will exceed the maximum snow water equivalent.

Results and discussion

Characteristics of hydrological elements in the watershed

We considered a water year (WY) to run from 1 October in one year to 30 September in the next. So, for example, WY1979 runs from 1 October 1978 to 30 September 1979. From November to April, the river was completely frozen. According to the average hydrometeorological behavior, runoff began at the end of April or in early May. The maximum snow water equivalent generally occurred at the end of March or April, because there was little precipitation during the winter period. The characteristics of discharge, SWE and precipitation from WY1979 to WY1983 and from WY2001 to WY2002 are depicted in Figure 2. The maximum discharge occurred from July to September during a summer precipitation event. When SWE was large, there were three peaks in the annual discharge. One peak was caused by snowmelt and the others by summer and autumn precipitation. While SWE was being released, snowmelt discharge was significant in WY1983 and WY2002, but snowmelt discharge was small. Snowmelt discharge varied from year to year. Table 1 shows the annual precipitation and discharge, the maximum snow water equivalent, spring discharge, and annual and snowmelt runoff ratios from WY1979 to WY1983 and from WY2001 to WY2002. (Data for the annual runoff ratio for 2002 were unavailable.) According to the annual precipitation and discharge figures, 38–67% of precipitation contributed to the discharge. The range of the maximum snow water equivalent was 62–105 mm. In contrast,

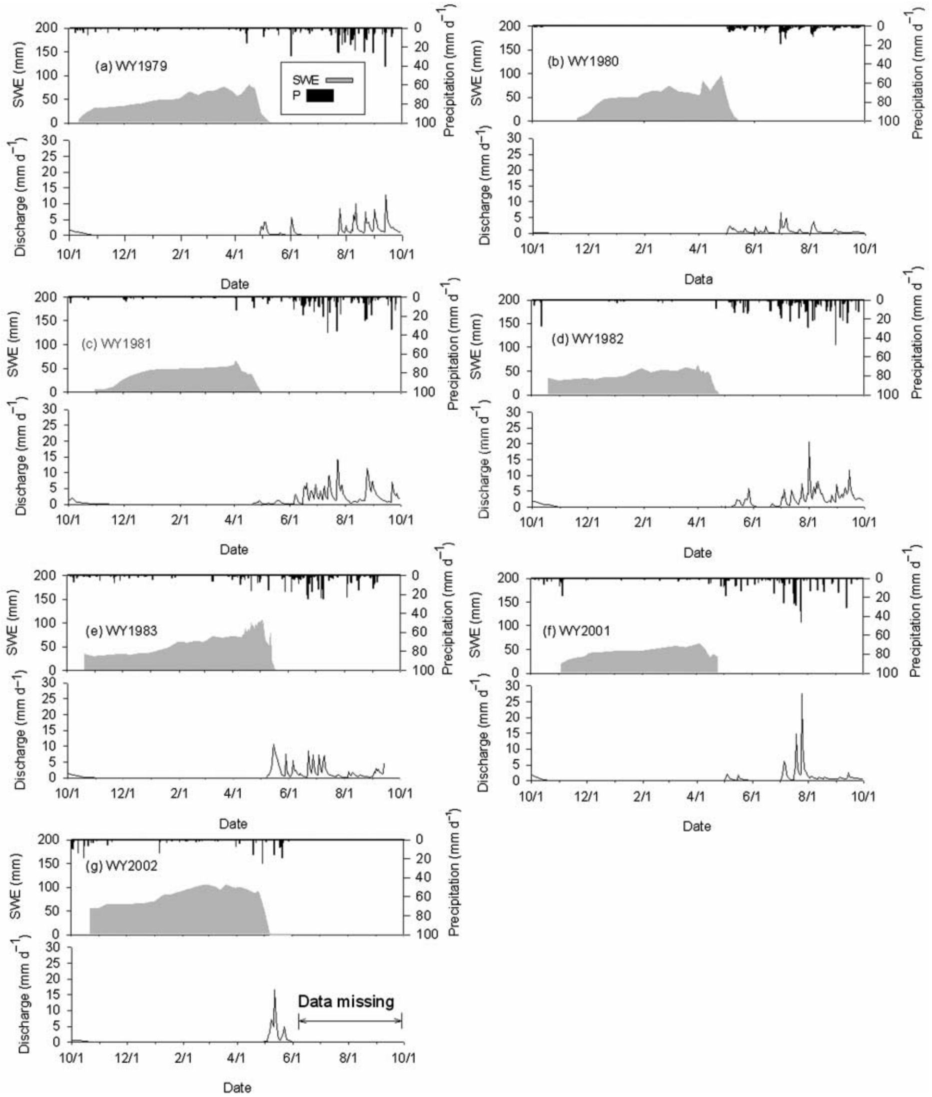

Figure 2 Temporal variations in accumulated snow ablation, discharge, precipitation and snow water equivalent from WY1979 to WY1983 and from WY2001 to WY2002. Data for WY2002 was from 1 October 2001 to 31 May 2002. Accumulated snow ablation was estimated by the accumulated decreases in snow water equivalent

spring discharge ranged from 17–91 mm. The snowmelt runoff ratio ranged from 0.26–0.87. The range of the snowmelt runoff ratio was slightly larger than the annual runoff ratio. The average snowmelt runoff ratio for the six years for which we have complete annual datasets was slightly larger than the annual runoff ratio for those six years. However, the differences between the two runoff ratios were small. Carey and Woo (1998) showed that, if the surface soil contains an organic layer, the snowmelt easily infiltrates into the frozen ground when the soil surface is frozen. Next, we will show in greater detail the temporal change of snowmelt discharge and interannual variability in snowmelt runoff ratio.

Effect of snow ablation and soil moisture changes on snowmelt runoff generation

Figures 3(a, b) show the temporal variations in discharge, snow water equivalent, thaw depth and soil moisture within the upper 20 cm of the soil layer during thaws in WY1981 and

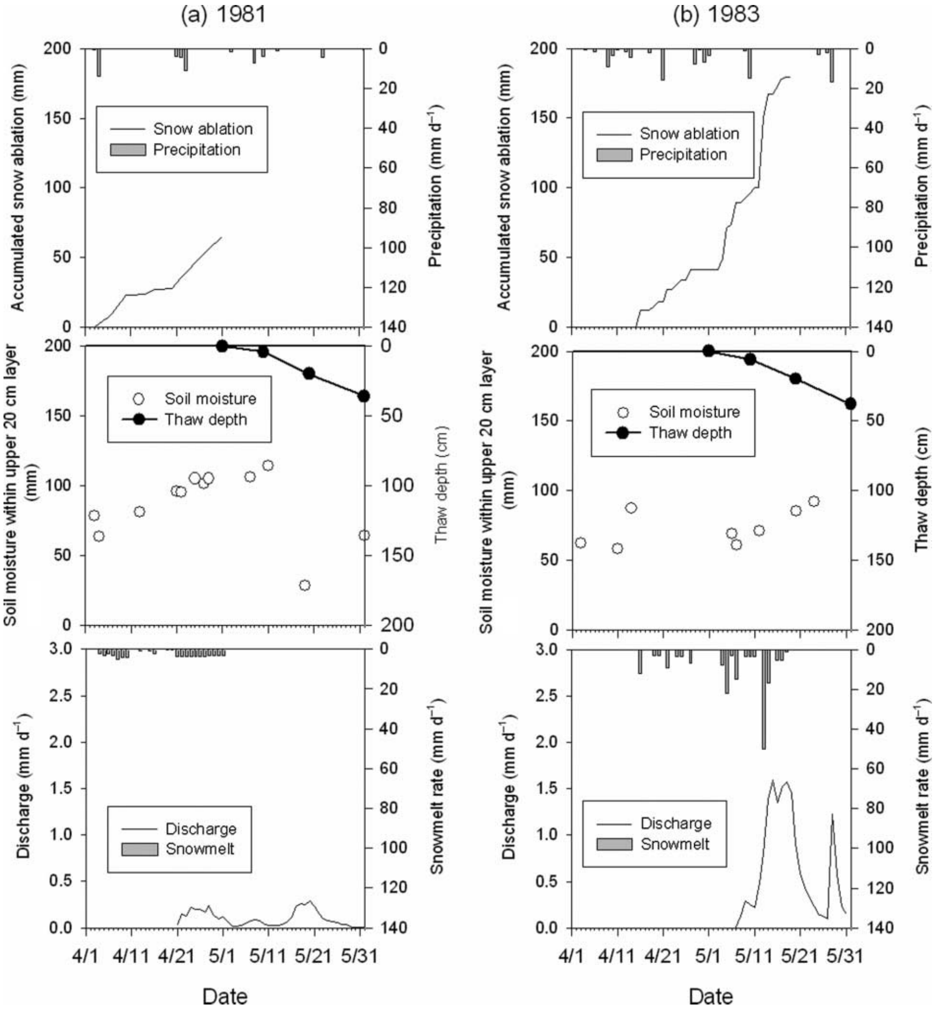

Figure 3 Temporal variations in accumulated snow ablation, precipitation, discharge, snow water equivalent, thaw depth and soil moisture within the upper 20 cm of the soil layer in WY1981 (a) and WY1983 (b)

WY1983. The minimum value for the snowmelt runoff ratio during the seven years analyzed occurred in WY1981, and the maximum snow water equivalent was 40 mm less than in WY1983. The thaw depth in both years was shallow. Once the snowpack disappeared, the thaw depth increased. There was little snowmelt discharge during a thaw in WY1981, while soil moisture within the upper 20 cm of the soil layer clearly increased as accumulated snow ablation increased (Figure 3(a)). The increase in soil moisture within the upper 20 cm was 40 mm, and the proportion of the increase in soil moisture to the maximum snow water equivalent was 62%. It was evident that the low snowmelt runoff ratio for WY1981 was caused by the snowmelt infiltration into the frozen ground. In contrast, Figure 3(b) shows that the large discharge in WY1983 was a result of snowmelt. In WY1983, the soil moisture within the upper 20 cm of the soil layer increased only slightly, by 24 mm, and the percentage of the increase in soil moisture to the maximum snow water equivalent was 23%. The spring discharge for WY1983 was 74 mm larger than for WY1981. Thus, we concluded that the spring discharge is primarily the result of the absorbed snowmelt water into the surface soil and the maximum snow water equivalent.

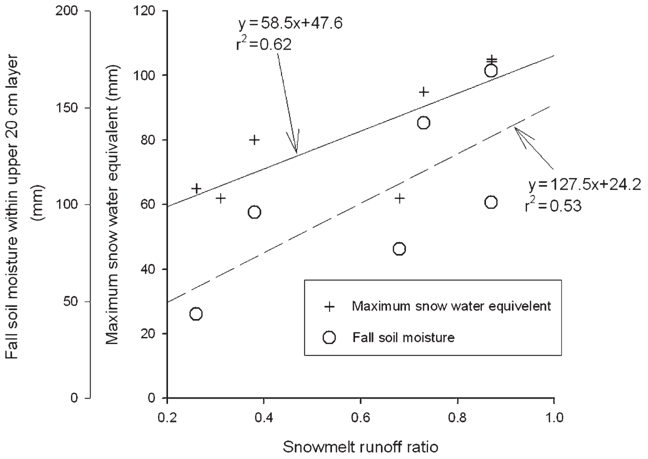

Figure 4 Relationship between snow water equivalent, soil moisture within the upper 20 cm of the soil layer and snowmelt runoff ratio. Closed and open circles denote the maximum snow water equivalent and soil moisture within the upper 20 cm of the soil layer, respectively. Thick and broken lines denote regression curves for the maximum snow water equivalent and soil moisture within the upper 20 cm of the soil layer, respectively

Interannual variability in snowmelt runoff ratio

In the above section, the snowmelt infiltration was demonstrated to affect the generation of snowmelt runoff. Gray *et al.* (1985) constructed a simple model of the snowmelt infiltration into the frozen ground of Canadian prairies using an empirical relationship between the infiltration, the fall soil moisture and the maximum snow water equivalent. Here, we show how the snowmelt runoff ratio depends on these parameters. Figure 4 illustrates the relationship between the maximum snow water equivalent or fall soil moisture within the upper 20 cm of the soil layer before the soil surface freezes and the snowmelt runoff ratio. The snowmelt runoff ratio increased in relation to increases in both the fall soil moisture and the maximum snow water equivalent. This result implies that the parameters governing snowmelt infiltration in the boreal taiga region in eastern Siberia were also fall soil moisture and the maximum snow water equivalent, as is the case in the simple model of Gray *et al.* (1985). This relationship is based on the fact that the ability of the organic layer to store snowmelt water was determined by the ice contents of that layer, which was due to the fall soil moisture. Furthermore, when the maximum snow water equivalent exceeded the ability of the organic layer to store snowmelt water, snowmelt water increased the surface runoff and produced a higher runoff ratio. These relationships correspond to the results present by Carey and Woo (1998). The correlation coefficient between the maximum snow water equivalent and the snowmelt runoff ratio was higher than the coefficient between fall soil moisture and the snowmelt runoff ratio. Thus, the maximum snow water equivalent was more effective in determining the snowmelt runoff ratio, rather than fall soil moisture. However, our data were limited and the snowmelt discharge and snowmelt infiltration into frozen ground were rarely reported in the southern mountainous taiga region of eastern Siberia. Further research is required in order to clarify the impact of snowmelt infiltration into frozen ground on the snowmelt discharge.

Conclusions

Analysis of the obtained data yielded the following results:

(1) The mean snowmelt runoff ratio was similar to the annual ratio, and the variation in the snowmelt runoff ratio was larger than that in the annual ratio.

(2) Snowmelt infiltration into the upper 20 cm of frozen ground is important for evaluating snowmelt runoff generation because frozen ground absorbed from 23% (WY1983) to 62% (WY1981) of the maximum snow water equivalent. This difference in snowmelt infiltration in the two years appears to have caused the difference in snowmelt runoff generation.

(3) The snowmelt runoff ratio increased with increases in (i) the fall soil moisture just before the soil surface froze and (ii) the maximum snow water equivalent. These results imply that the parameters governing snowmelt infiltration in the boreal taiga region in eastern Siberia were also fall soil moisture and the maximum snow water equivalent, as in the simple model of Gray *et al.* (1985). Further study is necessary in order to understand such processes as snowmelt infiltration into the frozen ground and soil moisture changes below the snowpack in winter.

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