Controlling Factors and Characteristics of Peak Runoff in an Alpine Headwater Under the Asian Monsoon Climate

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Understanding the mountain hydrological cycle, including runoff processes, is important for water-related disaster prevention. Although the process of peak runoff generation is closely related to water hazards, this process has not been clarified in alpine headwaters with large amounts of precipitation. In this study, we conducted hydrological observations to clarify runoff characteristics and factors that determine peak runoff in an alpine headwater under the Asian monsoon climate. Total precipitation during the summer period (3 months) was 1581.4 mm, and the water runoff responded quickly and clearly to rainfall events. Focusing on baseflow, the runoff was terminated when the snow cover area decreased. This suggested that snowmelt water plays an important role in maintaining baseflow in alpine headwaters under the Asian monsoon climate, like other alpine areas worldwide. In addition, peak runoff was not significantly correlated with soil wetness (as indicated by the antecedent precipitation index), whereas it was correlated with the amount of rainfall just before the generation of peak runoff. Therefore, the amount of rainfall before peak runoff in a single event was important in determining peak runoff. Focusing on the snowmelt season, we confirmed that the runoff increased even during small rainfall events. This indicated that snowpack melting is another factor determining peak runoff when the snowpack remains in the catchment. Considering the immediate runoff generation after rainfall events, direct observation of hydrometeorological data in situ is crucial to predict water-related disasters and consider countermeasures in alpine regions.

Keywords: *peak runoff; rainfall; snowmelt; alpine headwater; water-related disaster; Asian monsoon climate.*

Introduction

Mountain regions, known as "water towers," not only supply high-quality and high-quantity water resources to adjacent lowland areas but also contribute to the control of downstream streamflow (Meybeck et al 2001; Viviroli et al 2003; Jimenez-Rodriguez et al 2015; Harrington et al 2018). Thus, understanding the hydrological cycle in mountain regions is vital for the promotion of proper water resource management and water-related disaster prevention.

Worldwide interest in mountain hydrological cycle research is beginning to include low-temperature alpine regions characterized by high amounts and intensities of precipitation compared with lowlands (Tanaka and Suzuki 2008; Kuribayashi et al 2019). In particular, most winter precipitation is fixed to the ground surface as snowpack, so its role in groundwater recharge and water discharge is limited (Spencer et al 2021). However, this situation changes in spring when the snowpack starts to melt and the snowmelt water provides large amounts of liquid water to the alpine ground surface (Suzuki et al 2008; Mankin et al 2015; Webb et al 2018). In addition, the summer climate in many mountain belts worldwide (eg Europe and North America) is characterized by dry weather (Rood et al 2008; Floriancic et al 2018), whereas high-elevation areas affected by the Asian monsoon (eg Japan and Taiwan) experience large amounts of

rainfall in summer (Chen et al 2004). In alpine regions under the Asian monsoon climate, the period from the snowmelt season (spring) to the beginning of the snowfall season (autumn) is generally a short period of around several months. This period is important in the alpine hydrological cycle because water runoff occurs dynamically.

The timing and magnitude of water-related disasters, such as floods and debris flows, are closely related to peak runoff generation during rainstorms (Fang and Pomeroy 2016). Hence, it is important to clarify the mechanisms and characteristics of peak runoff generation under various field conditions. The amount and timing of peak runoff during rainstorms is primarily governed by rainfall intensity, amount, and spatial distribution (Bracken et al 2008); however, peak runoff characteristics in response to rainfall vary depending on the geological setting and the soil wetness before rainfall. Onda et al (2001) observed water runoff in forests during rainstorms in different geological settings (ie granite and shale). They found that the granite catchment was characterized by large and rapid runoff peaks that coincided with rainfall peaks, whereas the shale catchment was characterized by small runoff peaks from single rainfall events followed by maximum peak runoff after a series of rainfall events. In addition, many previous studies have shown that soil wetness before rainfall, often used as an antecedent precipitation index (API) or antecedent soil moisture index,

FIGURE 1 Study catchment with topography and land cover information. (Data source: aerial survey data of elevation with a 1-m spatial resolution obtained from the Matsumoto Soil-Erosion Control Office; Ministry of Land, Infrastructure, Transport and Tourism; Japan)
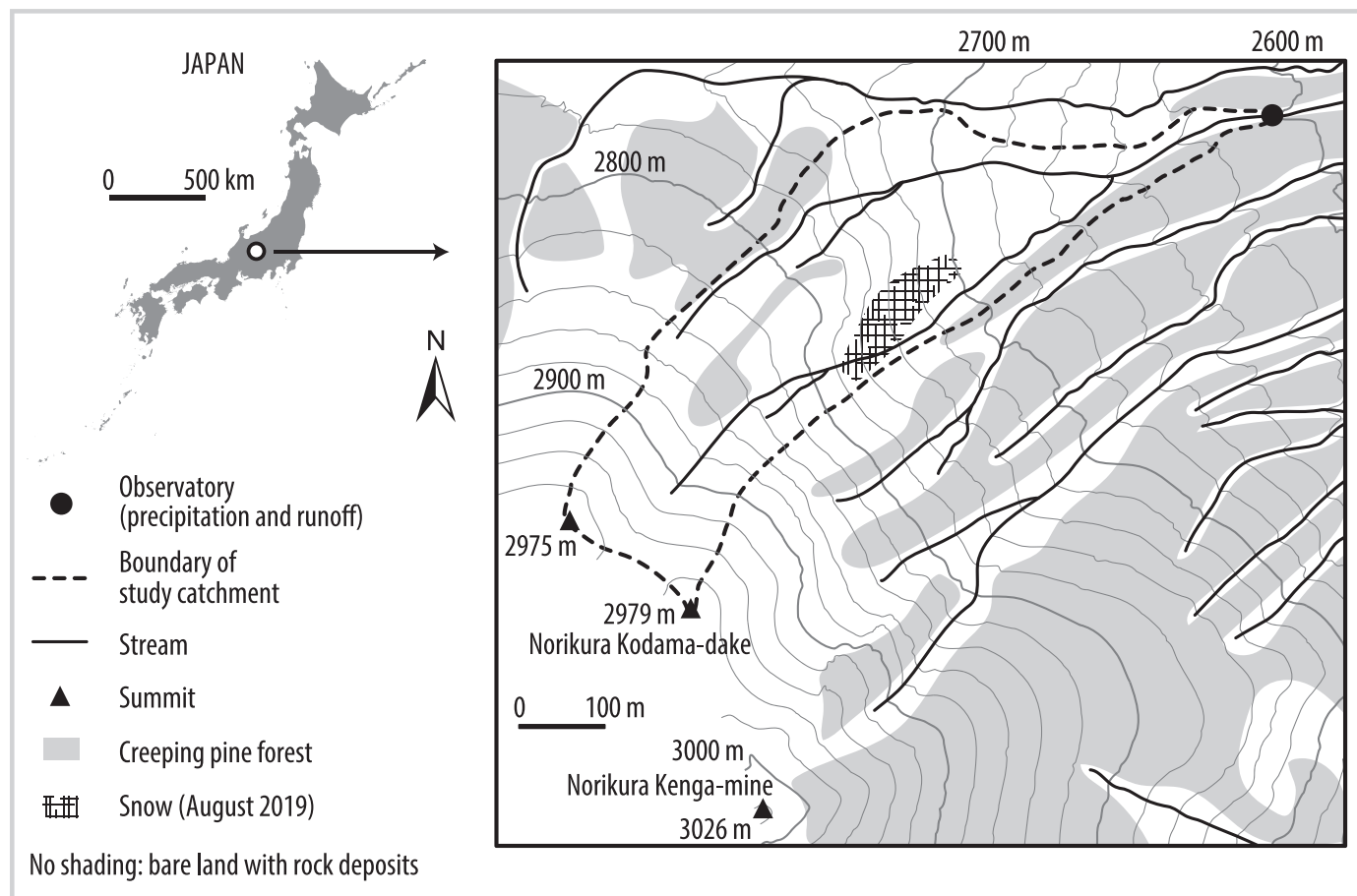
contributes to peak runoff generation (eg Detty and McGuire 2010; Iwagami et al 2010; Scaife and Band 2017). In other words, the wetter the soil moisture conditions before rainfall, the larger the peak runoff will be, linearly with the rainfall amount in areas with developed soil layers.

The time lag between rainfall peak and runoff peak is also an important factor for describing the runoff characteristics of a watershed (Rhea et al 2015). Although the lag depends on geological and topographical conditions, it is generally several tens of minutes to several hours in forested watersheds (Sammori et al 2004). According to studies that examined the role of pipe flow in forests, the lag becomes shorter and the amount of peak runoff increases when pipe flow is generated (Uchida et al 2001). Berne et al's (2004) study of an urbanized watershed mostly covered by an impervious land surface found that the lag between peak rainfall and runoff was short (eg a few minutes). Lundquist et al (2005) and Perkins and Jones (2008) noted that the lag tends to be longer in snow-covered catchments because rainwater is temporarily stored in snow layers.

As described earlier, hydrological characteristics related to peak runoff have been discussed for various fields. However, few observation-based studies have used in situ precipitation and runoff data from alpine areas because of access difficulties and severe weather conditions (Suzuki 2012, 2018; Jong 2015). Many previous studies have focused on regions under dry summer climates; established observation stations in the foothills of watersheds, including

alpine areas; and investigated runoff processes during the snowmelt season (Schmieder et al 2018), baseflow generation processes (Carroll et al 2020), and the groundwater storage function of the geology in alpine areas (Harrington et al 2018). An example of this observation-based research in an alpine headwater with a large amount of rainfall in summer was undertaken by Shimizu et al (2018), who examined the surface flow generation potential in a Japanese alpine area. They found that surface flow was generated by rainfall input of as little as 4 mm of hourly calculated API because of snowmelt-water–oriented subsurface water discharging. However, although attention has been paid to surface flow generation, the characteristics of runoff peaks and their determinants, which are directly related to disaster prevention, have not been investigated in regions beyond forest areas with large amounts of summer rainfall. Therefore, the objectives of this research were to clarify runoff characteristics and factors that control peak runoff in a short summer season in an alpine headwater under the Asian monsoon climate.

Methods

Study area

The study area was an alpine headwater catchment with an area of 0.16 km² on Mt Norikura, in the Japanese Northern Alps, with the highest elevation at Mt Norikura Kodama-

FIGURE 2 Temporal variation of air temperature just downstream of the study catchment (elevation: 2500 m).
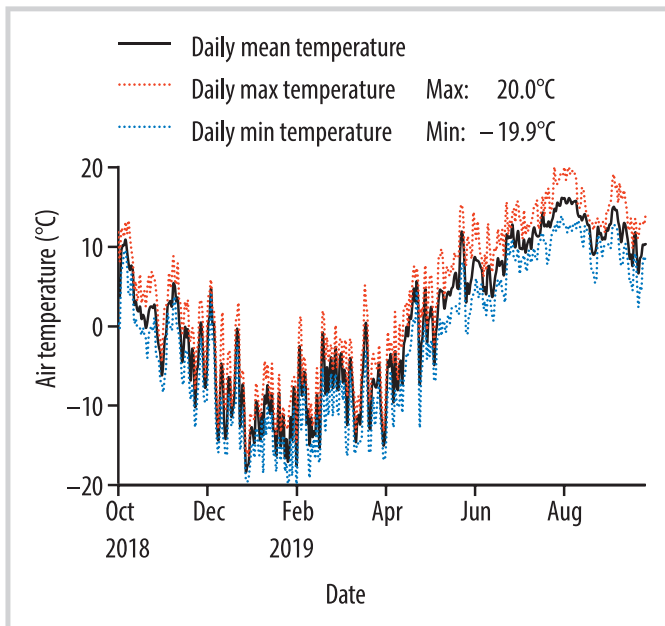
dake of 2979 masl (Figure 1). Mt Norikura is an active Quaternary stratovolcano with multiple volcanic bodies, mainly composed of andesite and dacite (Nakano et al 1995). It is covered with thick andesite and dacite lava flows; however, many rills and gullies have formed on the ground surface because of the erosive action of water. The rainwater or snowmelt water flows selectively and intermittently through these small valleys (Shimizu et al 2018). The land cover is mainly natural bare land with rock deposits and creeping pine forest, an alpine shrub community. During the long winter season (October–June), most land surface is covered with snow because of a large amount of snowfall and low air temperature. A perennial snow patch is found at a valley in the catchment; this recedes to around 2700 masl during the short summer season (July–September).

Hydrological observations and air temperature monitoring

Stream water level (in meters) was recorded every 10 minutes and precipitation (in millimeters) was recorded every 0.2 mm in a creek at 2600 masl using a water table recorder (KADEC21-MIZU, North One, Japan) and a tipping bucket rain gauge (HOBO RG3-M, Onset, Bourne, MA), respectively. The observation period extended from July 2019 to September 2019, when the precipitation mostly fell as rain. The creek is covered with snow from late October to early June because of heavy snowfall in winter; therefore, it is difficult to record hydrological data except in the short summer. Air temperature (in degrees Celsius) was recorded every hour just downstream of the hydrological observatory at 2500 masl from October 2018 to September 2019 using a temperature recorder (RTR502BL, T&D, Japan). The recorder was placed in an appropriate shelter for meteorological observation and installed several meters above the ground surface to avoid the effects of sunlight and snow accumulation.

Daily and hourly precipitation (in millimeters per day and per hour, respectively) were calculated by adding up the

recorded precipitation in 0.2-mm steps for 1 day and 1 hour. The daily mean air temperature was the daily arithmetic mean of the air temperature recorded in the 1-hour step. Daily maximum and minimum air temperatures were extracted from hourly recordings. Moreover, water discharge from the creek was observed 22 times by using a portable electromagnetic current meter (TK-106X, Dentan, Japan) to determine the relationship between water level (in meters) and water discharge (in liters per second). Water discharge during the observation period was then calculated based on the relationship between the observed stream water level and the water discharge (regression equation: $y = 8.6 \times 10^3 \times x^{5.2}$, where y is the discharge [in liters], x is the water level [in meters], and R^2 is 0.62). Finally, water discharge was converted to runoff (in millimeters per day) by dividing it by the catchment area. There are uncertainties in the absolute value of calculated runoff volume during heavy rainstorms because of the difficulty in directly measuring extreme water discharge. This suggests that the peak runoff calculated in this study could be partially overestimated or underestimated. However, considering the positive power approximation between stream water level and water discharge, the calculated runoff should increase as the water level increases. This means that the uncertainty of absolute runoff volume would not affect the main discussion of this study.

Definition of rainfall event and API calculation

Rainfall amounts of 1.0 mm or more per hour were defined as rainfall events, including durations of continuous rainfall. Rainfall events were separated when no rainfall was observed for 1 hour. According to this definition, more than 98.8% of the observed precipitation in this study was determined to be rainfall events.

The API, indicating catchment wetness, is often used to discuss catchment characteristics and rainfall–runoff phenomena in the case of limited observed auxiliary data (Ali et al 2010). Shimizu et al (2018) defined an improved API that considers the temporal variation of catchment wetness with a 10-minute interval to discuss runoff generation in alpine areas. However, the current study used API applied in many previous studies (eg Iwagami et al 2010) to examine peak runoff generation processes and compare the results with previous studies focused on other areas, such as forests and low-elevation mountains and hills. API (in millimeters) is defined as follows:

$$\text{API}(n) = \sum_{i=1}^{n} \frac{P_i}{i} \, (\text{mm}) \qquad (1)$$

where n is the considered number of antecedent days, i is the day count, and P_i is the daily precipitation (in millimeters) i days previously.

Results and discussion

Hydrological characteristics

Air temperature varied between −19.9 and +20.0°C from October 2018 to September 2019 (Figure 2). Focusing on the study period (July 2019–September 2019), it varied between +2.4 and +20.0°C. This means the snowpack melted continuously during the study period. The observed

FIGURE 3 Temporal variations of observed precipitation and runoff.
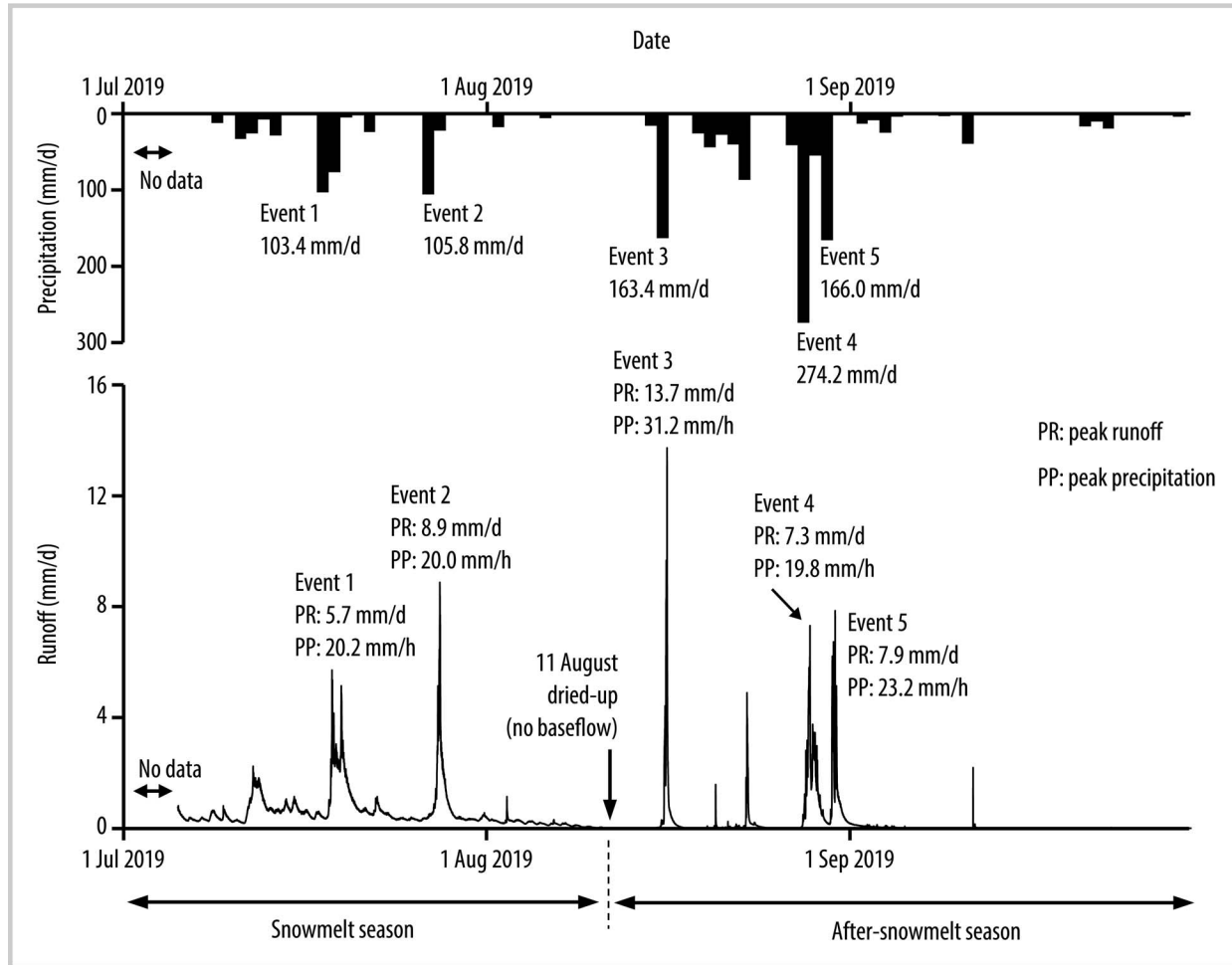
precipitation and runoff are shown in Figure 3. Total precipitation over approximately 3 months (July–September 2019) was 1581.4 mm, which was close to the mean annual precipitation in mountain regions in the United States and European countries (eg Floriancic et al 2018; Carroll et al 2020). Heavy rainfall events with more than 100 mm/d occurred 5 times (events 1–5 in Figure 3) during the observation period. The runoff rate during the study period was calculated to be 2%; total runoff (30.4 mm) was divided by total rainfall (1581.4 mm), indicating most waters (precipitation-related water, including snowmelt water) infiltrate underground because of the high porosity of the volcanic geology (Jimenez-Rodriguez et al 2015).

The runoff characteristics appeared to differ before and after 11 August 2019. The target creek contained water without rainfall until 11 August but dried up during the no-rainfall period after 11 August. In the former period, diurnal runoff variation was observed; peak runoff was found in the afternoon and early evening, and the lowest runoff was found in the early morning. This trend, also reported by Shimizu et al (2018), seemed to reflect the diurnal change in snowmelt volume. Therefore, the cause of the continuous water runoff before 11 August was considered snow that had accumulated upstream, continuously providing water. Then, as the air temperature increased (Figure 2) and the accumulated snow volume decreased, the water supply from

the snow ceased (or was sufficiently weakened) on 11 August, when the creek had no water. Therefore, the periods before and after 11 August were defined as snowmelt season and after-snowmelt season in this study.

Runoff responded to rainfall in both snowmelt and after-snowmelt seasons. The maximum runoff (13.7 mm/d) was observed during event 3. This event (163.4 mm/d) had a smaller daily rainfall amount than event 4 (274.2 mm/d) and event 5 (166.0 mm/d). However, focusing on hourly peak rainfall, event 3 (31.2 mm/h) had a larger rainfall amount than events 1, 2, 4, and 5, with values between 19.8 and 23.2 mm/h. Thus, event 3 was characterized as a high-intensity rainfall event during study period. Therefore, rainfall intensity could be a major factor in determining peak runoff. The next section discusses this topic in detail.

Controlling factors for peak runoff

Based on the definition presented in the Methods section, 53 rainfall events (ie snowmelt season, 20 events; after-snowmelt season, 33 events) were extracted from the observed data. First, to examine the influence of catchment wetness before rainfall, relationships between peak runoff and API 3 (Figure 4A) and API 7 (Figure 4B) were determined. API 3 and API 7 are the APIs for $n = 3$ and $n = 7$ in Equation 1. Each plot in Figure 4 presents data for each rainfall event (white dots, snowmelt season; black dots, after-snowmelt season). The

FIGURE 4 Relationships between peak runoff and (A) API 3 and (B) API 7. The dashed line (snowmelt season) and solid line (after-snowmelt season) represent regression lines.

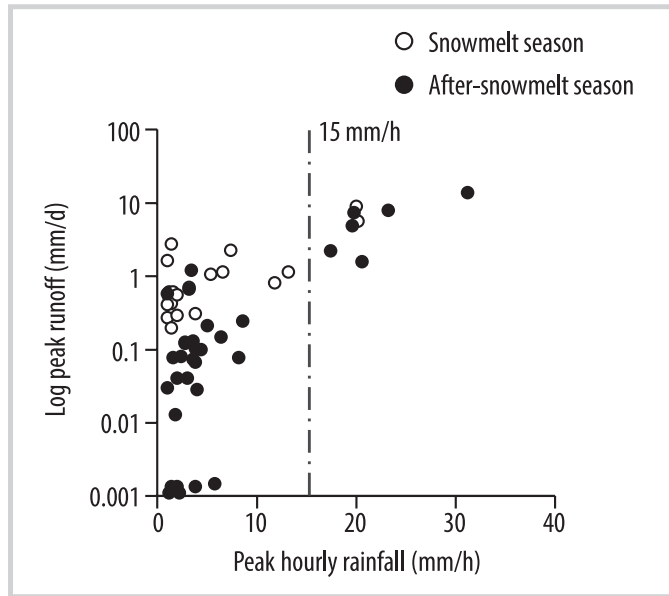FIGURE 5 Relationships between peak runoff and (A) total event rainfall until the time of peak runoff and (B) peak hourly rainfall. The dashed line (snowmelt season) and solid line (after-snowmelt season) are regression lines.
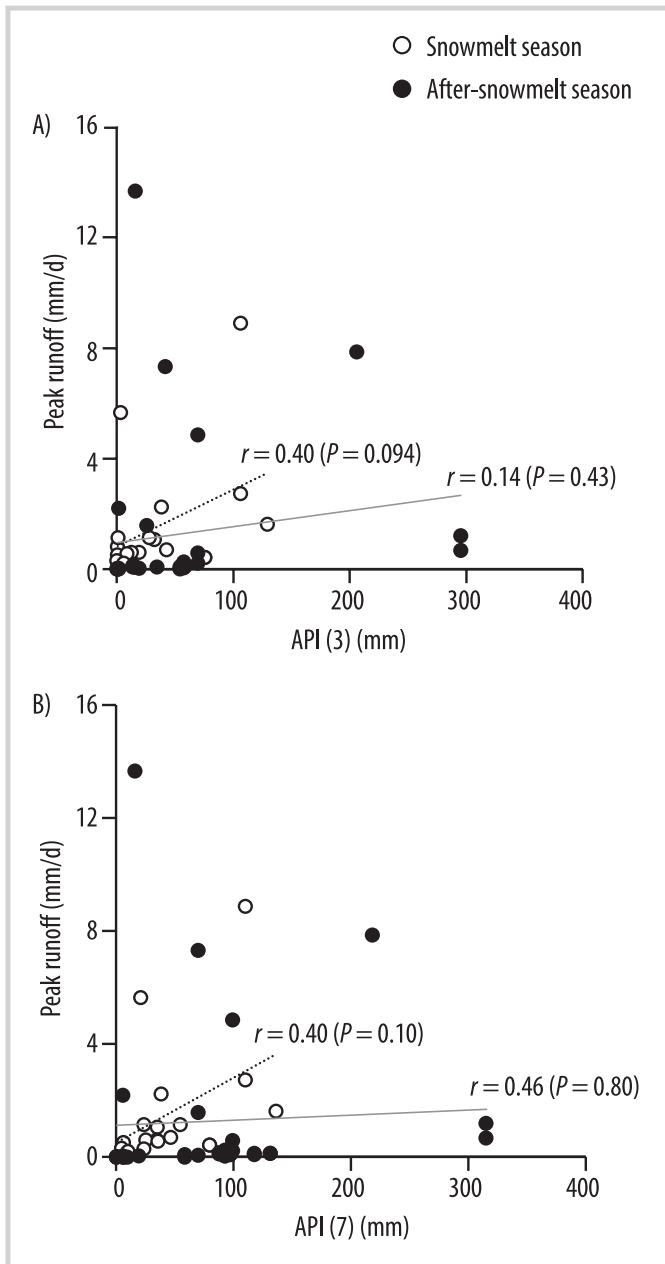
plotted rainfall events were scattered for both API 3 and API 7 cases. Correlation coefficients between API 3 and peak runoff were 0.40 ($P = 0.094$) and 0.14 ($P = 0.43$) for the snowmelt and after-snowmelt seasons, respectively. In addition, correlation coefficients between API 7 and peak runoff were 0.40 ($P = 0.10$) and 0.046 ($P = 0.80$) for the snowmelt and after-snowmelt seasons, respectively. Hence, there was no significant correlation between API and peak runoff in every case. Moreover, the correlation coefficient and its significance in the API 7 case showed almost the same or worse values compared with the API 3 case. This meant that antecedent precipitation for a longer period before a rainfall event might lose its importance for controlling peak runoff, particularly after the snowmelt season.

Considering the API, possible factors controlling the peak runoff of rainfall events seem to relate to phenomena just before or close to the time of peak runoff. Figure 5A presents the relationship between peak runoff and total event rainfall until the time of peak runoff (snowmelt season, $r = 0.93$ and $P < 0.01$; after-snowmelt season, $r = 0.89$ and $P < 0.01$). Figure 5B presents the relationship between peak runoff and peak hourly rainfall (snowmelt season, $r = 0.79$ and $P < 0.01$; after-snowmelt season, $r = 0.89$ and $P < 0.01$). These correlation analysis results show significant and strong positive correlations in all cases in Figure 5.

However, some differences in the tendencies should be noted. If event 4 in Figure 5A is excluded, the trend between peak runoff and total event rainfall until the time of peak runoff appears to be linear. However, there seems to be a threshold of 15 mm/h of peak hourly rainfall. In the case of

FIGURE 6   Relationship between log peak runoff and peak hourly rainfall.

TABLE 1   Rainfall events classified according to the time lag between peak rainfall time and peak runoff time for both snowmelt and after-snowmelt seasons.

Rainfall event	No. of events	% of all events
Snowmelt season		
10-min delay	4	20.0
20-min delay	6	30.0
More than 30-min delay	3	15.0
No clear runoff peak	7	35.0
Total events	20	100.0
After-snowmelt season		
10-min delay	10	30.3
20-min delay	14	42.4
More than 30-min delay	1	3.0
No clear runoff peak	8	24.2
Total events	33	100.0

less than 15 mm/h of peak hourly rainfall, most peak runoff ranged between 0 and 4 mm/d, whereas in the case of more than 15 mm/h of peak hourly rainfall, peak runoff linearly increased as peak hourly rainfall increased. This indicated that there was insufficient power to control peak runoff in the case of less than 15 mm/h of peak hourly rainfall. Considering that the correlation coefficient had a larger value in Figure 5A than Figure 5B, in addition to the linear trend in Figure 5A, it was considered that peak runoff was mainly controlled by the total event rainfall until the time of peak runoff.

Nevertheless, when the hourly rainfall exceeded 15 mm/h, the peak hourly rainfall could also have been a controlling factor of peak runoff. Event 4, which lay outside the linear trend shown in Figure 5A, was characterized by high total event rainfall until the time of peak runoff (237.0 mm) but lower peak runoff (7.3 mm/d). In contrast, event 4 (peak hourly rainfall of 19.8 mm/h) lay at a location similar to that of other rainfall events with more than 15 mm/h of peak hourly rainfall in Figure 5B. Thus, for event 4, it might be more reasonable to say that peak runoff was controlled by peak hourly rainfall. Event 4 continued for 37 hours, with a total rainfall of 354.4 mm per event, which was the longest and largest rainfall event during the observation period. For some long and/or large rainfall events, peak runoff may not be explained by total event rainfall until the time of peak runoff.

The rapid conversion of rainfall input to runoff that results in peak runoff is a characteristic of alpine rainfall–runoff events. This phenomenon is not like that in forests with well-developed soil layers (Iwagami et al 2010) but is similar to that in urban areas (Berne et al 2004) or catchments with granitic geology (Onda et al 2001). Impermeable or low-permeability land surfaces and geological settings allow immediate water discharge after rainfall in urban areas and granitic geology catchments. However, considering the 2% of runoff rate in this study catchment, there seems to be another mechanism of rapid conversion from rainfall to runoff. This could relate to

geological features in alpine areas; therefore, detailed investigations of the sedimentary and geological structures are necessary for further interpretation.

Differences in runoff characteristics between snowmelt and after-snowmelt seasons

In Figure 6, the y-axis of Figure 5B is converted to a logarithmic scale. In cases with less than 15 mm/h of peak hourly rainfall, rain events in the snowmelt and after-snowmelt seasons lie in 2 separate clusters with some exceptions. For the same value of peak hourly rainfall (x-axis), peak runoff appears larger in the snowmelt season (>0.2 mm/d) than in the after-snowmelt season (<0.2 mm/d). This indicates that for events with less rainfall, the peak runoff generation processes were different during the snowmelt season, when the ground surface was covered with snow, compared with the after-snowmelt season, when the ground surface was bare.

Table 1 presents the classification of rainfall events based on the time lag between peak rainfall and peak runoff for both snowmelt and after-snowmelt seasons. During the after-snowmelt season, peak runoff was observed within 20 minutes of peak rainfall for more than 70% of the rainfall events. However, during the snowmelt season, the proportion (50%) of cases delayed by less than 20 minutes was smaller than during the after-snowmelt season, and the proportion of cases delayed by more than 30 minutes and with no clear peak runoff increased. These results indicate that the response of runoff to rainfall was weaker during the snowmelt season than during the after-snowmelt season. The appearance of longer lags when the snowpack dominates the ground surface, similar to the findings of previous studies (eg Lundquist et al 2005; Perkins and Jones 2008), results from the snowpack temporarily storing rainwater. However, the lag resulting from the presence of snowpack was on the order of several tens of minutes at the most in the study area, even though previous research focused on forested catchments below an elevation of 1100 m reported lags on

the order of hours (Perkins and Jones 2008). Even if we take into account that the effect of solar radiation on snowmelt is diurnal (Shimizu et al 2018), the lag was short. This may be attributed to the steep topographic gradient and the climate that produces a large amount of rainfall on the snowpack (Figure 3).

In addition, the larger peak runoff during the snowmelt season compared with the after-snowmelt season, as shown in Figure 6, could have resulted from the supply of snowmelt water. Snowmelt is considered to occur in association with temperature-related diurnal snowmelt (Lundquist et al 2005) and heat supplied by the rain-on-snow phenomenon (Sui and Koehler 2001). Considering that the water storage function of the snowpack relates to the thickness of the snow layer and snow-melting conditions (Lundquist et al 2005), both snow depth and heat balance data are required for further discussion of the runoff process during the snowmelt season in alpine headwaters.

Implications for water-related disaster prevention

Mountain regions are known as principal water resource recharge areas (eg Viviroli et al 2003), and this research supports this: the low runoff rate ($<2\%$) indicated that most rainfall in the short summer season infiltrated underground. However, quick runoff response and sharp runoff peak generation against heavy rainfall have been suggested as rainfall–runoff characteristics in an alpine headwater under the Asian monsoon climate. These hydrological characteristics cause water-related disasters in mountain regions.

When prevention measures are considered, it is essential to know the magnitude and timing of peak runoff generation (Fang and Pomeroy 2016). This research found that peak runoff generation in alpine headwaters relates to the rainfall intensity and amount before the runoff peak, indicating immediate conversion of rainfall to runoff (within several tens of minutes; Table 1). This suggests that rainfall–runoff processes in alpine headwaters are simpler than those in forests and other lower-elevation regions where lots of parameters (eg API and soil thickness; Bracken et al 2008) affect runoff generation. In view of these findings, it is necessary to directly observe meteorological and hydrological data in situ to predict water-related disasters and consider their countermeasures in the alpine regions. The importance of research on rainfall–runoff processes in mountain regions, such as the effect of snowmelt during heavy rainfall and how downstream areas respond to extreme rainfall in the alpine headwaters, is increasing. These topics should be discussed in future works in mountain science.

Conclusions

Runoff characteristics in a short summer season and controlling factors for peak runoff during rainfall events in an alpine headwater under the Asian monsoon climate were investigated by hydrological observation. The findings of this research are as follows:

- Runoff was terminated when the snow cover area decreased. This suggests that snowmelt water plays an important role in maintaining baseflow in alpine headwaters under the Asian monsoon climate, as in other alpine areas worldwide.
- There was no significant correlation between API and peak runoff of each rainfall event, indicating that API does not control peak runoff in the alpine headwater.
- Showing significant correlation, one of the factors defining peak runoff during rainfall events is likely to be the amount of rainfall just before peak runoff generation.
- Peak runoff increased even for small rainfall events during the snowmelt season. This indicates that melting of the snowpack is another factor that determines peak runoff when the snowpack remains in the catchment. For further discussion of snowmelt effects on the runoff processes in alpine headwaters under the Asian monsoon climate, micrometeorological data are needed.
- Because of rapid conversion from rainfall to runoff, direct observation of meteorological and hydrological data in situ is crucial to predict water-related disasters and consider their countermeasures in alpine regions. The way runoff associated with heavy rainfall in alpine regions affects the downstream area should be examined in the future.
- The rainfall–runoff process in alpine headwaters was characterized as a quick runoff response to rainfall. This implies that we can predict water-related disasters and their extent of damage based on precipitation over the previous few hours, which could be used by policymakers in regions with alpine areas to make policy decisions about water hazards.

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