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Soil temperature-threshold based runoff generation processes in a permafrost catchment

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Abstract

The contributing-area concept was the universal approach in rainfall–runoff processes modelling. However, it is unclear of the role of permafrost in controlling runoff generation processes. The areas that contribute to runoff generation are complex, variable and difficult to determine in permafrost catchments, and thus, there is no suitable quantitative approach for the simulation of runoff generating dynamics. To understand how thaw-freezing cycle in permafrost catchment effect the runoff generation processes, a typical catchment of continuous permafrost on the Tibetan Plateau was measured, and the spring and autumn season when runoff generation obviously differs from non-permafrost regions were focused on in this study. By introducing soil temperature threshold functions for surface saturation excess runoff generation and subsurface groundwater discharge, two dominant runoff generation types for permafrost catchments in different seasons are analysed, and corresponding simple quantitative approach related to the thawing and freezing periods are presented. The results show that the new approach can exactly identify the runoff generation dynamics of spring thawing and autumn freezing processes. In the permafrost headwater catchments of alpine meadows, the surface soil temperature or thawed depth threshold for variable runoff generation area depend on the zero thawing isotherms, which reach a depth of 40 cm. The subsurface groundwater discharge, which is controlled by soil temperature, contributes more than 85 % of the total river discharge in the autumn freezing period. The crucial variable for the spatial–temporal variation of runoff contributing area in the permafrost catchment is the soil temperature rather than soil moisture.

1 Introduction

A variety of runoff generating mechanisms occur in different environments and in the same environment at different times. However, a comprehensive understanding of the delivery mechanism of runoff at various scales and within different environments still remains elusive (Beven, 2002; Latron and Gallart, 2007), which is one of the most challenging obstructions to the solution of hydrological scale issues and the development of distributed hydrological models. The variable contributing area concept, defining areas as being the most relevant for runoff generation within the catchment, has become popular in the last two decades and has been used to determine the spatial and temporal dynamics of runoff generation controlling factors (Güntner et al., 2004; Latron and Gallart, 2007; Penna et al., 2011). Accounting for variations in the runoff generation areas at the catchment scale is one of the most difficult challenges in the development of watershed hydrological models and in the improvement of hydrological scale issues (Dickinson et al., 1970; Dawdy et al., 1978; Blazkova et al., 2002). Two types of runoff contribution areas, infiltration excess runoff and saturation excess runoff, have often been implicitly used as indices for indicating variable contributing areas (Ward and Robinson, 1990; Latron and Gallart, 2007; Penna et al., 2011). Because the saturation excess runoff and stored-full runoff (over the depression and soil-zone storage) are closely correlated with the soil moisture regime (Leavesley et al., 1983), threshold relations between surface soil moisture and surface runoff generation have been revealed by recent studies and are acknowledged as having a critical role in understanding the runoff generation mechanism and in improving hydrological models (Zehe et al., 2010; Detty and McGuire, 2010; Penna et al., 2011). Field investigations of the runoff generation mechanism and its controlling factors in permafrost conditions are rare, and there is lack of knowledge about how to indicate the variable contributing area of runoff generation in continuous permafrost catchments (Wright et al., 2009).

Permafrost, defined as ground at or below the freezing point of water 0 °C (32 °F) for two or more years, is the frozen ice-saturated or oversaturated soil or bedrock that acts as a relatively impermeable layer, above which the seasonal ice in the active layer decreases the hydraulic conductivity, the available storage capacity of the soil, and the water infiltration capacity (Woo and Winter, 1993; Quinton and Mash, 1999). The drainage of precipitation and meltwater inputs primarily formed the thawed water-saturated layer perched above the frost table. The depth and distribution of the frost table within the active layer controls the position of the water-saturated zone, which descends through the soil profile during soil thawing. On the slope scale, uneven or progressive soil thawing on frozen slopes heavily affects the mode and rate of water flow downslope and the flow concentrations in rivers (Quinton et al., 2004; Wright et al., 2009; Woo, 2012). Thus, the distribution of the frost table depth controls the surface saturation excess runoff and stored-full runoff generation processes and is the critical factor in determining the processes of the watershed flow concentration. However, there is difficulty in quantifying the effects of the spatial and temporal variability of the frost table depth in terms of runoff generation. It is unclear if and how the variable contributing area concept could be used in a permafrost catchment. Consequently, the goal of the present study is to provide new scientific insights into the seasonal dynamics of runoff-contribution areas in a continual permafrost headwater catchment and to develop a method to quantify the runoff generation processes and to identify the effects of the freeze–thawing cycle of the active soil layer on river discharge.

2 Methods

2.1 Study area description

The Fenghuoshan watershed, which is located in the central regions of the Qinghai-Tibet Plateau (93°3′–92°50′ E and 34°40′–34°48′ N), is underlain by continuous permafrost (Fig. 1.). One of the first tributaries with a total catchment area of 1.62 km^2 was selected for this study and observation systems were implemented. The altitude of the watershed ranges from 4780 to 5143 m a.s.l., the annual mean air temperature is −5.2 °C, and the mean annual precipitation is 358 mm, with more than 85 % falling in summer (July to September). Alpine meadows and swamps are formerly the most widespread types of vegetation in the experimental catchment, with an average coverage of 60 to 97 %. The active layer thickness ranged from 2.1 m in the valley to 0.8 m on the mountain ridge. The slopes are moderate, between 15 and 35 %, in most of the catchment.

In the study catchment, 1.6 m deep boreholes were drilled at different elevation points from the river valley to the mountain ridge at two side slopes and at different distance points from the river outlet to the source region in the valley (Fig. 1), and soil moisture and temperature sensors were installed at depths of 0.05, 0.20, 0.40, 0.80, 1.0, 1.20, and 1.60 m. The general point conditions are listed in Table 1. Soil moisture was determined by a frequency domain reflectometer (FDR) with a calibrated soil moisture sensor that was equipped with a theta-probe (Holland Eijkelamp Co.). Volumetric soil moisture was derived from changes in the soil dielectric constant and converted to a millivolt signal with an accuracy of ±2 %. The soil temperature was monitored using a thermal resistance sensor that was sensitive to temperature changes in the range of −40 to 50 °C and had an overall system precision of ±0.02 °C. One portable, micro-meteorological station (HOBO Weather Station, ONSET Co., USA) was established in the experimental catchment. Two snow-monitoring sensors (SR50A, Campbell Co., USA) with an accuracy of 0.25 mm were established at the valley and mountain ridge, respectively. At the outlet of the catchment, a V-notch weir was established and the runoff processes were monitored three times per day.

2.2 Analysis approach

In this study, variable runoff-contributing areas are defined as areas that have effective hydrological connections with streams and, thus, directly contribute to the runoff measured at the catchment outlet (Ambroise, 2004; Rui, 2004). In non-permafrost regions, the nonlinear variation curve of the water-storage capacity and water-saturation capacity are generally used as indices to indicate the saturation excess runoff generating processes, whereas the soil infiltration capacity nonlinear curve is used to indicate the infiltration excess runoff generating processes (Rui, 2004). In general, the water-storage capacity-based runoff production for saturation excess runoff can be estimated from the water balance equation as follows (Ward and Robinson, 1990; Rui, 2004; Brutsaert, 2005):

$$R = (P - E) - \int_0^{P-E} \left[1 - \varphi\left(W'_m\right)\right] dW'_m \qquad (1)$$

where R is the runoff production in catchment. P and E are precipitation and actual evapotranspiration (mm), respectively. W'_m is the soil water content at field water capacity. $\varphi\left(W'_m\right) = \alpha$ is the water-storage capacity curve, which refers to the ratio of areas with $\le W'_m$ to the total catchment area. If we know the infiltration capacity curve f_p and the rainfall intensity p_i at time T in a rainfall process, the infiltration excess runoff production can also simply be estimated (Rui, 2004; Brutsaert, 2005). However, all of those indices are linked to the relationships between soil hydraulic properties and precipitation, which are obviously not suitable to permafrost catchments in which active soil freezing-thawing cycles have important effects on runoff generating processes. Therefore, it is necessary to determine new methods to clarify the unique runoff generation mechanism and its spatiotemporal variability in permafrost regions.

2.2.1 During the thawing period

In the spring and early summer seasons, along with the active soil layer thawing, the surface soil water content increases quickly and reaches its peak values (Yi et al., 2009; Wang et al., 2012). When the thawed active layer is within a certain depth, the surface soil layer can maintain a water-saturated condition. Then, the saturation excess runoff generating processes can occur. Because the soil water dynamics are controlled by temperature rather than precipitation, there are no significant relationships between soil moisture and precipitation and no obvious relationship between precipitation and runoff (Wang et al., 2009). If the threshold of the surface soil temperature is T_0, the saturation excess runoff generation (SERG) can occur when the actual surface soil temperature T'_s is less than or equal to T_0. Under the soil temperature condition, snowmelt water Q_s is an important water balance factor participating in the runoff contributing area (DeBeer and Pomeroy, 2010). Thus, Eq. (1) can be expressed in terms of soil thawing processes as follows:

$$R = \int_0^{T_0} (P + Q_s - E)[1 - f(T_s')]\,dT_s' \quad (2)$$

where $f(T_s')$ is defined as the soil temperature-threshold curve, which refers to the ratio of areas with surface soil temperature $\leq T_0$ to the total catchment area. $f(T_s')$ is a dimensionless function, referred to catchment area with soil water-saturated condition. Obviously, the application of Eq. (2) abides by the hypotheses: (1) once the surface soil temperature increased from below 0 °C to equal to 0 °C, the frozen soil begins to thaw, and until the temperature reaches to T_0, the thawed surface soil layer remains in the water-saturated condition. (2) During the spring and early summer season, the saturation excess runoff generation was the dominant type of runoff generation at a catchment scale when the active surface soil was thawing.

2.2.2 During the freezing period

In contrast to the thawing processes of active soil, the freezing process occurs in two directions, i.e. top and bottom. The downward ground freezing controls the surface runoff generation, whereas the upward ground freezing affects the groundwater (especially, the suprapermafrost groundwater) discharge, feeding the surface runoff. In the autumn season, along with the active soil undergoing freezing, the discharge of suprapermafrost groundwater covers approximately 70–90 % of the total runoff in the autumn recession process of many Qinghai-Tibetan Rivers (Liu et al., 2012; Wang et al., 2009). A few studies also found that the groundwater discharge was responsible for more than 70–80 % of the total river runoff in the autumn in many arctic river basins (Walvoord and Striegl, 2007; Muskett and Romanovsky, 2009; Lapp, 2015). By using the relationship between the recession rate and the active soil depth proposed by Lyon and Destouni

(Lyon et al., 2009, 2010), the equation for the groundwater discharge of recession runoff related to deep active soil temperature (a proxy for the freeze–thaw depth of the active soil layer) $g(T_{SD})$ was developed. Besides the groundwater discharge, surface runoff production (including subsurface interflow) is also the main feeding source of river runoff before surface soil freeze. It is similar to thawing processes, the saturation excess runoff generation is re-occupied the dominant type of surface runoff generation when surface soil temperature T_s' is over 0 °C but less than or equal to T_0. Thus, the runoff production during autumn freezing period is primarily comprised by surface saturation excess runoff generation and groundwater discharge. The Eq. (1) can be expressed for the freezing period as follows:

$$R = \int_{T_0}^{0} (P + Q_s - E) f\left(T_s'\right) \mathrm{d}T_s' + g(T_{SD}) \tag{3}$$

where T_{SD} is the deep active soil temperature. To effectively indicate the variation in the thickness (or storage capacity) of the groundwater aquifer (i.e. mostly the suprapermafrost groundwater), the depth at which T_{SD} is detected is suggested for the selection of the approximate 2/3 thickness of the suprapermafrost groundwater aquifer due to indicate the effect of downward ground freezing on groundwater system. Equation (3) is a mixture function integrating the surface saturation excess runoff generation and subsurface groundwater discharge processes, both of which are controlled by the soil freeze–thaw cycle.

2.3 Parameters determination

In the experimental catchment, Wang et al. (2009, 2012) found that the surface soil moisture (top 20 cm) was at its spring peak volume of 40 to 60 % (volumetric soil moisture) when the thawing zero isotherms were above a depth of 40 cm. Furthermore, there were significant correlations between the soil temperature and runoff processes in the thawing period (from April to June) when the thawing depth of the active layer was within 60 cm. Thus, the surface soil temperature threshold, T_0, was determined as the point where the zero isotherms reached a depth of 40 cm during the thawing period. Chang et al. (2015) monitored the dynamics of suprapermafrost groundwater in the study catchment and found that the thickness of the suprapermafrost groundwater aquifer was 110–130 cm along the slope. The thickness of the suprapermafrost groundwater aquifer at the mid-slope point of 4900 m could be approximately regarded as the mean groundwater aquifer thickness of the whole catchment. Therefore, the soil temperature at a depth of 2/3 of the suprapermafrost groundwater aquifer thickness at the point of 4900 m was used to identify T_{SD}.

The actual daily evapotranspiration (E) was assessed through field observations using micro-lysimeter systems (Weighing lysimeters) with three vegetation coverage scenarios of 93, 67 and 30 % in the study catchment (Wang et al., 2010). Because the experimental catchment has a relatively large vegetation coverage of 60–97 %, the field observed daily E with 93 % vegetation coverage was selected for use in this study as the actual average daily evapotranspiration. In winter, precipitation in the study region was less than 30 mm (November–March), whereas evaporation exceeded 40 mm. Thus, the snow cover was irregular, filmy and discontinuously distributed over the ground surface, even in the middle of winter (Sato, 2001; Wang et al., 2010). The impacts of winter snow on runoff processes were different from those reported in other permafrost regions, such as those in North America and Siberia (Woo, 2012; Christensen et al., 2004) and were ignored in this study. However, the precipitation increased with the snow content and the mixed snow and rain content in the spring season; thus, the role of snow in runoff generation could not be ignored. The snow was identified in two ways: from the snow monitoring sensor data and from the estimation of daily precipitation using the threshold air temperature method (Chen et al., 2014).

3 Results

3.1 Runoff generation processes during the thawing period

After identifying the parameters of Eq. (2) using the field measured and monitoring data from the small permafrost catchment in the Qinghai-Tibet Plateau, it was found that $f\left(T'_s\right)$ varied as an exponential curve with time. Based on the daily precipitation P, snowmelt water Q_s and actual evapotranspiration E, the daily runoff of the study catchment was simulated using Eq. (2) for the thawing period from June to July, and the results are shown in Fig. 2a. By comparing the results with the observed field runoff, it was found that the new runoff generation model was improved by accounting for variations in the runoff generation area due to the soil thawing processes; the improved model could produce excellent simulation accuracy. The correlation coefficient (R^2) between the simulated and observation runoff was 0.92, and the relative error was only 10 % (Fig. 2b). This result indicates that the new approach modified by the active soil thawing area can be successfully used to simulate and predict spring runoff generation processes in the permafrost catchment. The new approach quantitatively clarified the essence and processes of the active soil temperature variation effects on spring runoff generation and revealed the role of the soil temperature threshold for controlling runoff generation and its spatial–temporal dynamics in the permafrost catchment.

During the thawing period, the ratio of areas with the surface soil temperature $\leq T_0$ to the total catchment area ($f\left(T'_s\right)$) decreased exponentially with the increasing surface soil (upper 20 cm) temperature (Fig. 3). When the surface soil temperature was above the threshold, the thawed depth of the active soil layer was extended to 40 cm in the study catchment. Along with the gradual drying of the surface soil layer, the area of saturation excess runoff generation (SERG) decreased. The infiltration excess runoff generation (IERG) replaced the saturation excess runoff generation to become the dominating runoff generation type when the active soil temperature was over the threshold in most of the catchment areas. Then, a large portion of the precipitation infiltrated into the active soil layer to replenish the soil moisture, which reduced the runoff coefficient (Wang et al., 2009). Therefore, the surface soil temperature has an important role in controlling runoff processes, and the correlative coefficient between precipitation and total runoff was insignificant during the spring season (Fig. 3, $R^2 = 0.24$, $p > 0.15$). Using parameterized Eq. (2), the deduction of runoff produced from active soil thawing was estimated, and the results are shown in Fig. 3. The decrease in the ratio of the SERG area to the total catchment area was associated with the increase in runoff deduction. From 19 to 30 June, the depth of the thawed active layer was lower than 60 cm in most areas of the catchment, and the modelled runoff was 0.5–1.0 times lower than the observed runoff. However, after 10 July, the runoff was 2–3 times lower than the observed runoff. This may be the reason that the runoff coefficient decreased from 0.6 to 0.8 in June to 0.2 to 0.40 in July (Wang et al., 2009). Considering that the runoff coefficient was generally higher than 0.8 and that the direct runoff was lower than 2.0 mm in May (Wang et al., 2009, 2010), the runoff reduction should be less than 30 % of the total observed runoff in May. Thus, during the spring season, the initial thawing action, including thawing of the surface active soil layer and snow melt, enhanced the increase in the surface runoff generation but restricted runoff generation after the active thawing depth reached the threshold point. This confirmed the hypothesis that the surface soil temperature dynamics controlled the spring runoff processes by changing the saturation excess runoff generation area, and the effects indicated a valid threshold range for the thawed depth of the active soil.

3.2 Runoff generation processes during the freezing period

After using the regression methods of Levenberg–Marquardt and Universal Global Optimization (Price et al., 2005; Nocedal and Wright, 1999), the following $g(T_{SD})$ was obtained: $g\ (T_{SD}) = 0.62e^{0.67T_{SD}}$. Equation (3) was then parameterized and used to simulate the runoff processes during the freezing period from 8 September to 10 October, and the results are shown in Fig. 4. The function of the mixed surface and subsurface (i.e. suprapermafrost groundwater) runoff generation processes could subtly describe the runoff recession in the autumn freezing period. Although the simulation of the mixed

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model lightly overstated the low water flow, the simulation runoff graph was consistent with the actual fluctuation of runoff processes (Fig. 4a). The correlation coefficient and the coefficient of determination between the measured and the estimated runoff data were 0.90 and 0.81, respectively (Fig. 4b). The fit RMSE (root-mean-square error) was only 0.66 mm, and the RE (relative error) was 8.7 %. These results indicate that Eq. (3), which includes the variations in the surface runoff generation and subsurface groundwater discharge areas, has good accuracy and high validity in the simulation of the effects of soil freezing processes on the surface runoff in a permafrost catchment and could be thought of as a good alternative runoff modelling and prediction approach during freezing periods.

A few studies used stable isotope separation technology to document the fact that groundwater discharge covered most or all of the river base flow, even the total river flow in freezing season (Boucher and Carey, 2010; Liu et al., 2012; Lapp, 2015). However, it is difficult to numerically simulate the subsurface or groundwater discharge and composition of river flow in permafrost regions due to the complex dynamics of subsurface aquifers and water movement (Moo, 2012). The function $g(T_{SD})$ in Eq. (3) is used to determine the river flow variation caused partly by soil temperature changes in the deep active layer, which was used as a proxy for the variation in the groundwater discharge in this study. Thus, the function $g(T_{SD})$ could be used to separate the groundwater discharge from the total surface runoff (Fig. 5a). It was estimated that the groundwater discharge contributes approximately 85.5 % of the total river runoff during the autumn recession process in the permafrost headwater catchment. This result is consistent with the results of Liu et al. (2012) in the same watershed and Lapp (2015) in arctic rivers using stable isotope separation. Figure 5a shows that the hydrograph of groundwater discharge is similar to the distribution curve separated by the traditional direct runoff division method (Rui, 2004). The direct runoff, formed by quick interflow and surface runoff fed directly by rainfall, accounts for only 14.5 % of the total runoff. Figure 5b shows that there is a weak correlation between precipitation and total runoff during the autumn freezing period ($R^2 = 0.34$, $p > 0.1$), whereas the correlation between precipitation and direct runoff is extremely significant ($R^2 = 0.82$, $p < 0.001$). This result indicates that the deep soil temperature controls the total runoff of the autumn season and that precipitation only plays a small role in the direct runoff.

4 Summary and conclusions

In permafrost catchments, the variation in the area contributing to runoff is not produced by the soil moisture regime but rather by the soil temperature dynamics in the freeze–thaw cycle of the active layer. This behaviour differs from non-permafrost catchments because there are two different variations in the runoff generation area: the surface soil freezing–thawing conversion, which controls the saturation excess runoff generation during the spring and autumn, and the deep active soil freezing–thawing conversion, which controls the subsurface groundwater discharge processes that are crucial to autumn runoff generation and recession processes. In this study, we couple the two runoff generating variations to develop a variable contributing area theory and quantitative approach for permafrost headwater catchments and examine the effects of the active soil freeze–thaw cycle in terms of runoff generation and seasonal variation. The new approach incorporates variable contributing areas for the surface saturation excess runoff generation and subsurface groundwater discharge as functions of seasonal soil temperature and variation in the soil water saturation.

Using the quantitative runoff generating function, the runoff dynamics during the spring thawing and autumn freezing processes in the permafrost headwater catchment are identified exactly. During the spring thawing period, the area contributing to saturation excess runoff generation decreases exponentially in response to the increasing soil temperature. The direct runoff is reduced by 1–3 times to that of the measured river discharge and converted into soil moisture and recharged into the subsurface groundwater in the thawed active layer. In the Qinghai-Tibet Plateau, the soil temperature or thawed depth threshold for the variable runoff generation area is determined by the zero isotherms, reaching a depth of 40 cm in the permafrost headwater catchment of an alpine meadow. In the autumn freezing period, the subsurface groundwater discharge is the dominating source of runoff generation, contributing more than 85 % of the total river runoff of the permafrost headwater catchment. The results of the runoff generation modelling, which integrates the surface saturation excess runoff generation and subsurface groundwater discharge, indicate that the deep soil temperature variation (average depth of 90 cm in the study region) control the autumn runoff recession processes, whereas precipitation only plays a role in the direct runoff, which contributes less than 15 % of the total river runoff. These results imply that the spatiotemporal dynamics of the areas that contribute to runoff generation in permafrost catchments are functions of seasonal surface soil ice water saturation, soil temperature in the profile of the active layer and subsurface groundwater storage and discharge; the most crucial variable is the soil temperature. In the future, with increased warming, there will be more advanced, faster and shorter spring runoffs with more groundwater discharge into rivers in the autumn and winter seasons.

Runoff generation processes are the one of the most important part in watershed hydrological processes. In the rainfall–runoff modeling systems, the contributing-area concept was the universal approach in runoff modelling whether linear or nonlinear relationship with soil moisture (Dickinson et al., 1970; Dawdy et al., 1978; Leavesley et al., 1983; Blazkova et al., 2002). However, the contributing-area concept is defined by this study as a nonlinear relationship with soil temperature rather than soil moisture in permafrost catchment. For spring thawing and autumn freezing periods, the new runoff generation functions with the nonlinear relationships of soil temperature produced excellent accuracy performance in the simulation of runoff generating dynamics. The results indicated that those functions are suitable to permafrost catchment, and successfully fulfil the quantitative approach gap in hydrological processes modelling of cold regions (Wright et al., 2009; Zhou et al., 2014). As a consequence, the new approaches and findings in this study can be used for both the calibration and improvement of the distributed hydrological models used for permafrost regions.

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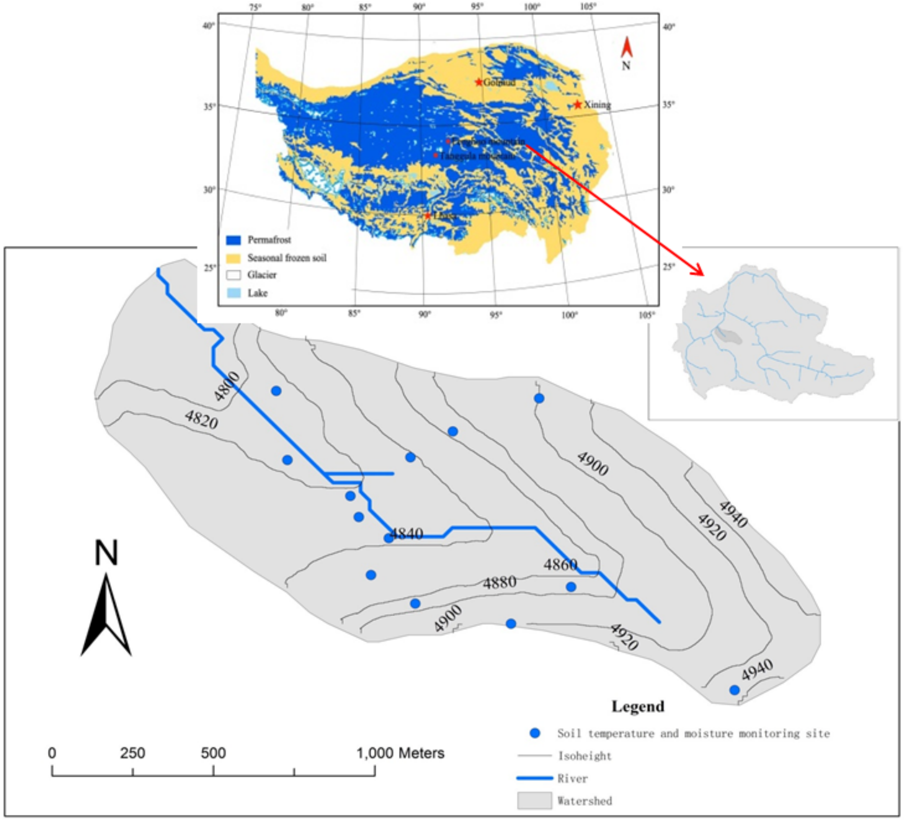

Figure 1. Location of the experimental Fenghuo watershed in permafrost region of Qinghai-Tibet plateau, China. The soil temperature and moisture monitoring sites in the headwater catchment are used in this study.

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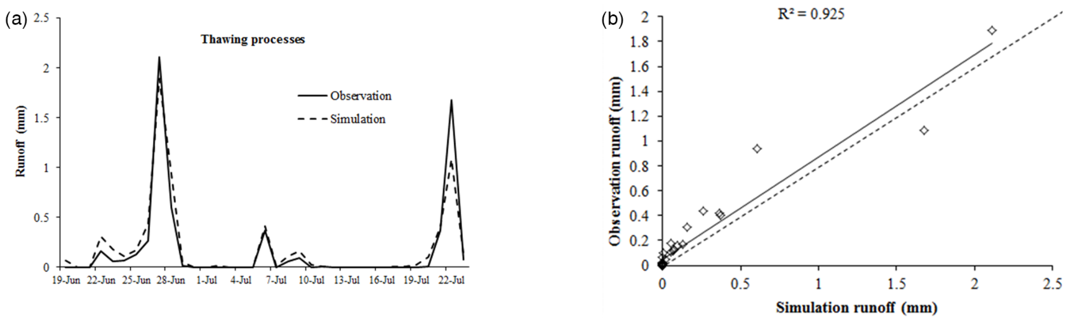

Figure 2. Modelled runoff generation compared with field observed runoff during the spring thawing period in a permafrost catchment. **(a)** referred runoff hydrograph comparison, while **(b)** is the simple scatter of statistical analysis.

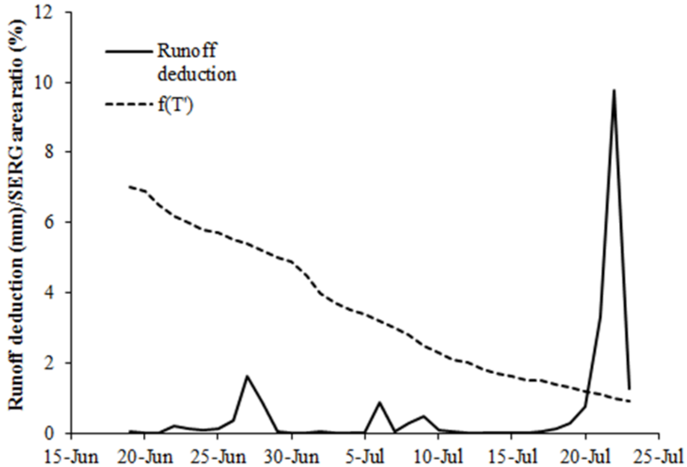

Figure 3. The variation in the saturation excess runoff generation (SERG) area ratio and runoff reduction during the thawing period in a permafrost catchment.

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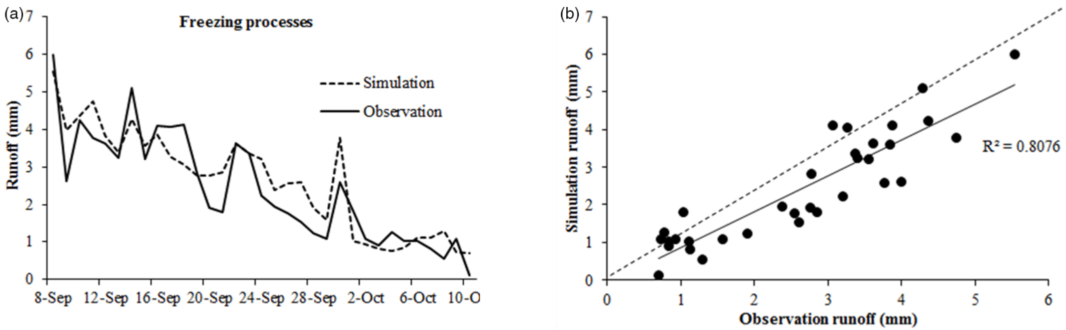

Figure 4. Modelled runoff generation compared with field observed runoff during the autumn freezingperiods in a permafrost catchment. **(a)** referred runoff hydrograph comparison, while **(b)** is the simple scatter of statistical analysis.

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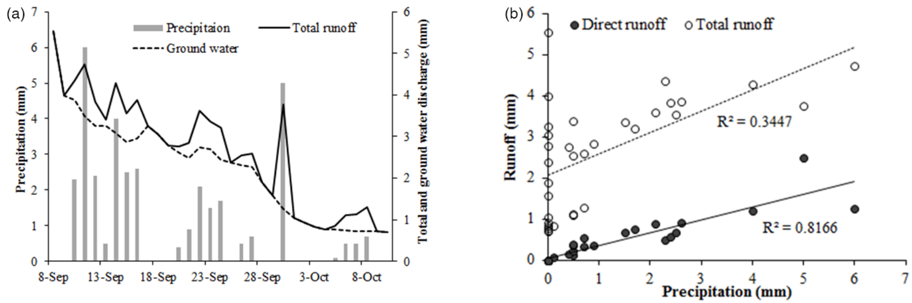

Figure 5. The hydrograph of the total runoff with precipitation patterns and the separation of total runoff and the groundwater discharge using the new approach of integrated surface runoff generation and subsurface groundwater discharge **(a)**. After separating the daily direct runoff from the total runoff, the correlation between the precipitation and the total runoff/direct runoff was scattered and statistically analysed **(b)**.