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ORIGINAL ARTICLE

The relationship between runoff and ground temperature in glacierized catchments in China

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Abstract A single parameter index method, in which ground temperature and air temperature is the sole input variable, respectively, is used to evaluate and compare the glacial runoff in three typical glacier catchments, Dongkemadi glacier catchment in Tibetan plateau, Koxkar glacier catchment and the headwater catchment of Urumqi River catchment in Tianshan Mountains in West China. The method based on ground temperature is an attempt to evaluate glacier runoff in elevated terrains, as few studies have focused specifically on the association between glacier runoff and ground temperature. The results identify ground temperature versus a certain depth, which is a critical factor that affected glacier hydrological processes and showed that runoff data is much better correlated with ground temperature than air temperature. Especially, at the latter two catchments, the largest coefficients of exponential relationship R^2 between glacier runoff and ground temperature are 0.9 and 0.83, respectively. The accuracy of the method makes it possible to estimate the glacier runoff with a certain depth ground temperature at a certain site, which may provide a new approach to evaluate the glacier runoff for areas where there is a lack of observation data.

Keywords Air temperature · Ground temperature · Glacier catchment · The so-called optimal depth

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Introduction

From a water resources perspective, meltwater from the seasonal snow cover and the glacier ice is one of the important water sources in many alpine regions of western China. The glacier runoff induced by ice and snowmelt depends mainly on the meteorological conditions above the surface, especially air temperature (Yang and Zeng 2001; Ohmura 2001). Many studies have analyzed the closed linkage between the air temperature and ablation, and indicated that the melt rate could be parameterized simply as an empirical function of the air temperature in melt and runoff models (Braithwaite 1995; Hock 1999, 2003, 2005; Ohmura 2001). For most glaciers in western China, the mass and energy balance observations are rare. Even in some monitored glaciers, there is still a lack of continuous datasets for various climate variables. It suggests that the estimation of glacier runoff should employ a more pragmatic method with low data requirement.

Generally, the statistical methods based on air temperature, which are the most available meteorological data, are usually the most direct and simplest ways to estimate the melt rates and runoff. In the past 20 years, numerous researches have studied the problem and shown that air temperature had a good relation with glacier ablation and discharge in China. The studies aim at simulating ablation determined that there was a good power function relationship between glacier melt and air temperature at daily resolution on many glaciers in the Qilian Mountain region and Tianshan Mountains region in Western China (Yang and Zeng 2001). Other studies using a simple statistical method to evaluate the runoff based on short observation data, although relatively satisfactory results were usually received at coarse time resolution, also revealed a good exponential function relationship between the glacier runoff and air temperature on various glaciers in Western China, such as the Rongbuk glacier on Mount Everest (Liu et al. 2006), the Qiyi glacier in the Qilian Mountains (Song et al. 2008), the Koxkar glacier in Tianshan Mountains (Chen et al. 2008). Although there have been abundant studies using air temperature to estimate glacier ablation and discharge, surprisingly few studies have focused specifically on the association between the glacier runoff and ground temperature. The reason why few literatures have discussed the relationships between ground temperature and glacier runoff is the lack of systematic monitoring of ground temperature at most glacier catchments (Chen et al. 2008). Moreover, most researches are mainly concerned with the glacier itself (mainly focused on melt, energy observation etc.), as well as the model based on the observed data, but not the observation near or far from the glacier.

Ground temperature and its temporally evolving are closely related to air temperature and play a major role in a wide range of environments. For example, from a consideration of the energy balance, ground surface temperature would directly affect the sensible heat fluxes and surface long-wave radiation, resulting in a considerable influence on surface heat fluxes and atmospheric circulation patterns. The diurnal and annual variability of ground temperature also affects snowmelt and distribution, permafrost melt, active layer thickness and depth, all of which also contribute water to discharge (Boone et al. 2006; Liston and Elder 2006; Harris 2001). It is known that there is a time lag from the melting at the glacier surface to the meltwater arriving at the outlet of the glacier, while the temporal variability of ground temperature also often lags surface heat fluxes due to the soil's low thermal conductivity. Therefore, there may be a relationship between the ground temperature and glacial runoff, and the relationship could be better than that of air temperature. Previous study had determined that there was a good correlation between hourly ground temperature and runoff during a no rain period for a short-term on Koxkar glacier (Xie 2005). However, it is unwise to form a judgment on the basis of the short-term observation in one glacial catchment and neglect the rain process, which also plays a significant role in inducing the flood process during the ablation period (Chen et al. 2008). With research carried out in three glacierized catchments recently, these data series are longer and more representative, which make it possible to analyze how ground temperature affects the runoff.

The main aims of this research are twofold. First, the relationships between daily runoff and daily air temperature as well as between daily runoff and daily ground temperature at three alpine glacier catchments using a simple statistical method were evaluated and compared, since the glacial discharge regime is characterized by pronounced diurnal cycles. Second, the variation regime of statistical relation at various depths and spatial distribution is analyzed to determine the best empirical formula which makes it possible to estimate glacier runoff with a certain depth ground temperature at a certain site.

Investigated catchments and data description

For comparisons of analytical results, three alpine catchments are selected with different glacierized areas in Western China. These are Koxkar glacier catchment in Western of Tianshan Mountains, Dongkemadi glacier catchment in Tibetan plateau, and the Headwater catchment of Urumqi River in Central Tianshan Mountains (Fig. 1).

Koxkar glacier catchment

Recently, detailed fieldwork was undertaken since 2003 on Koxkar glacier, a typical dendrite valley glacier with an elevation range of about 3,020–6,300 m at the south of Tumor Mountain, Xinjiang, China. The catchment has an area of 117.6 km^2, of which 83.6 km^2 is glacierized (Fig. 1a). From about 3,750 m, the glacier is almost

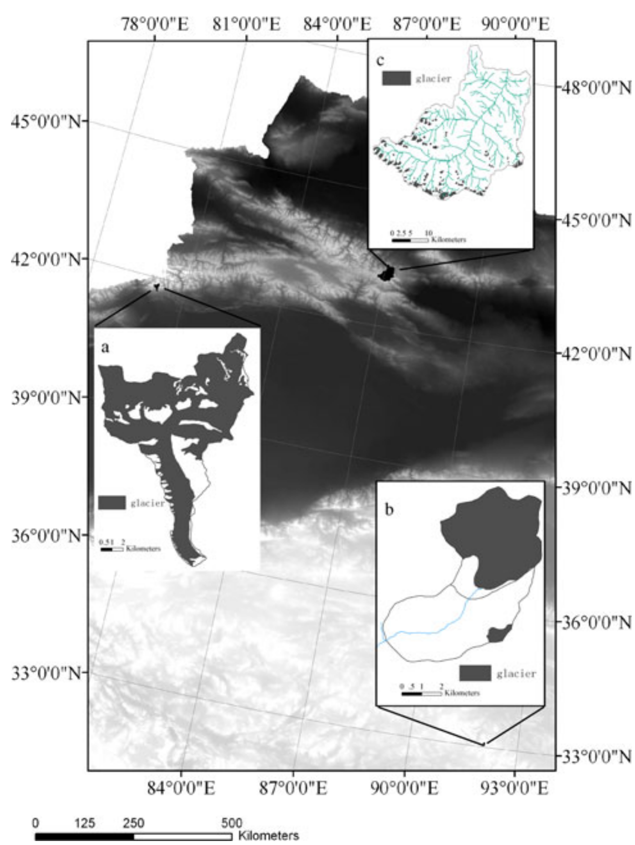

Fig. 1 Location of the target areas and the glacierized areas

Table 1 Position information of the hydro-meteorological stations for the headwater catchment of Urumqi River

Station	U1	U2	U3	U4	U5	U6	The deep borehole	Outlet section
Longitude (°)	86°49′E	86°49′E	86°49′E	86°51′E	87°07′E	87°05′E	86°50′E	87°12′E
Latitude (°)	43°06′N	43°06′N	43°07′N	43°07′N	43°12′N	43°34′N	43°06′N	43°21′N
Altitude (m)	3,544	3,659	3,805	3,408	2,131	2,161	3,900	1,942

covered by debris, and the thickness of debris decreases gradually along altitude gradient. For these analyses, data from four automatic weather stations referred as K1, K2, K3, and K4, whose location information are shown in Table 2, were used. The stations K2, K3, and K4 are located in the debris area, whereas station K1 is located in an alpine meadow area. At each station, air temperature, relative humidity, wind speed and direction, incoming and reflected radiation, and ground temperature are recorded. The profile measurements of ground temperature at these stations are shown in Table 6. Measurements are taken every 10 s and the 1-h averages are stored on data loggers. Glacial runoff is monitored approximately 80 m downstream of the glacier terminus near the weather station K1. The catchment has the most detailed ground temperature data among the three catchments, but some stations do not work for some intervals due to harsh weather conditions and several sensors were moved for other research aims (Table 2).

Dongkemadi glacier catchment

Dongkemadi glacier is in the middle of Tanggula Mountain, Tibetan Plateau, where the equilibrium line altitude is near 5,600 m. The catchment covers an area of 39.1 km^2 of which 43% is glacierized (Fig. 1b). For the collection of discharge data from the study glacier, a discharge gauging site (5,140 m) was established about 4,650 m downstream of the snout of the glacier. Discharge data are collected for four ablation seasons (2005–2008). An automatic weather station near the discharge-gauging site is established to collect air temperature and underground temperature at 0, 15, 30, 45, 60, 70, 90 cm (Table 3).

The headwater catchment of Urumqi River

The headwater catchment of the Urumqi River is in the central part of Tianshan Mountains and represents the upper part of the Urumqi River basin. The catchment covers an area of 924 km^2 of which 4.1% is glacierized (Fig. 1c), including cirque glaciers, hanging glaciers, and small valley glaciers. The No. 1 glacier is a small valley glacier, which has the longest mass balance records in China. There are five long-term air temperature monitoring gauges in the catchment (station U1–U5) and one gauge around the catchment (station U6), whose location information is shown in Table 1. However, a set of short-term data of ground temperature was collected from 22 May to 30 November 2001 at the deep borehole (Table 1) near the station U2. Therefore, the relationship between the runoff and air temperature, and ground temperature are also investigated at Urumchi, Dabancheng, Bayinbuluke and Turpan, which are all far away from the catchment and have datasets of ground temperature from 1 January 2000 to 30 November 2001.

Results

Relationships between the glacial runoff, air temperature, and ground temperature in three glacier catchments

Koxkar glacier catchment

To compare the differences in the two relationships, the most continuous and longest data of air temperature at 2 m height and ground temperature at 0.2 m depth (from 20 May 2004 to 31 March 2005) from station K1 with the corresponding record of glacial runoff were chosen for analysis. During this period, the maximum and average daily air temperatures were 16.4 and −0.3°C, respectively, while the maximum and average daily ground temperatures were 10.6 and 2.9°C, respectively.

Figure 2 shows the discrepancies of the two relationships, and the corresponding efficiency criteria R^2. The relationships between runoff and ground temperatures, as well as between runoff and air temperatures, reveal a good exponential function relationship, and the R^2 of the empirical formula is expressed as 0.76 and 0.93, respectively. Employment of ground temperature improves the model performance considerably.

Furthermore, the comparison of the two relationships between glacial runoff, air temperature, and ground temperature for all stations in Koxkar glacier catchment are also summarized in Table 2. It concludes that the relationship between runoff and ground temperatures versus a certain depth at all stations, regardless if the underlying surface is debris or alpine meadow, presents a superior linkage compared with that between runoff and 2 m air temperature under the same climate conditions.

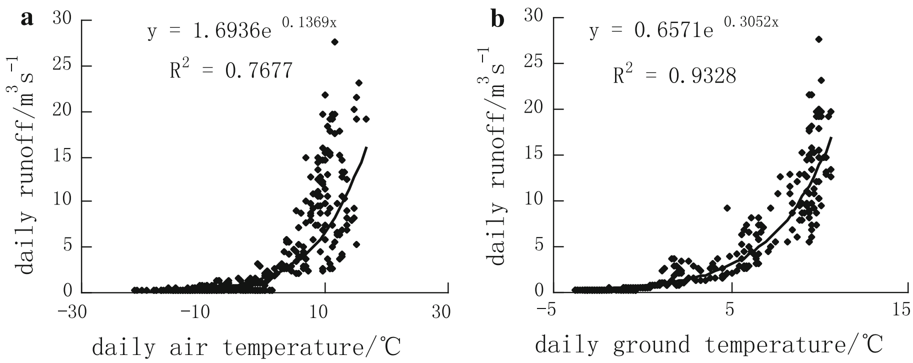

Fig. 2 The relationships between runoff, ground temperatures at 0.2 m depth and 2 m air temperature above surface from 20 May 2004 to 31 March 2005 in Koxkar glacier catchment

Table 2 Relationships between glacial runoff, air temperature and ground temperature in Koxkar glacier catchment

Station	Location information	Period	Air temperature–runoff	Ground temperature–runoff	Ground depth (cm)	Data pairs	Surface type
K1	41°42′N, 80°10.3′E, 3,007 m	26 Jul 2007–23 Nov 2008	$y = 1.3553e^{0.1308x}$	$y = 0.8499e^{0.2122x}$	20	487	Alpine meadow
			$R^2 = 0.74$	$R^2 = 0.86$			
K2	41°42.5′N, 80°08.7′E, 3,212 m	29 Jun 2003–12 Sep 2003	$y = 1.605e^{0.1474x}$	$y = 1.4323e^{0.2555x}$	100	477	Debris
		8 Aug 2007–14 Sep 2008	$R^2 = 0.77$	$R^2 = 0.86$			
K3	41°43.4′N, 80°07.8′E, 3,342 m	14 Apr 2004–30 Jun 2004	$y = 0.41x + 1.4549$	$y = 0.639x + 1.77$	80	48	Debris
			$R^2 = 0.54$	$R^2 = 0.83$			
K4	41°47.4′N, 80°02.9′E, 4,219 m	7 Jul 2003–11 Sep 2003	$y = 4.6914e^{0.1719x}$	$y = 3.9295e^{0.2817x}$	60	470	Debris
		28 Apr 2004–27 Sep 2004	$R^2 = 0.78$	$R^2 = 0.90$			
		16 Aug 2005–20 Jun 2006					

Dongkemadi glacier catchment

Table 3 shows the statistical discrepancies of the relationships between runoff and ground temperatures versus different depths and air temperature at 1.5 m above surface. Whether it is the whole data series (463 data pairs) or the example period (132 data pairs) for the ablation season in 2008, the linkage between runoff and ground temperatures, especially the ground temperature at 0.3 m depth, is better than that between runoff and air temperature. However, the exponential function for the ablation period during 2005–2008 is dissatisfactory due to insufficient knowledge about winter discharge data compared with Koxkar glacier. In addition, the higher average altitude and more harsh weather conditions at Dongkemadi glacier, compared with Koxkar glacier, may be the reasons that all statistical coefficients were small.

The headwater catchment of Urumqi River

The fitting results of the six air temperature gauge sites and the deep borehole for daily runoff are shown in Table 4, and the relationship coefficients are also given in Table 4. The largest R^2 at 0.4 m depth is 0.83 and greater than the R^2 at all air temperature gauge sites in the reported data series. It can be seen that the value of R^2 at station U2 near the deep borehole is 0.75. The improvement in performance also implies that the result-based ground temperature dependent is excelled above the air temperature dependent.

Another analysis on the relationships between runoff and ground temperature, as well as air temperature, was performed at Urumchi, Dabancheng, Bayinbuluke and Turpan, as the data series of the deep borehole are too short (Table 5). It was surprising to find that the relationship between runoff and ground temperature is still better than that between runoff and air temperature, even those stations are far away from the catchment.

Summary and discussion

As stated earlier, the model to estimate glacial runoff with an empirical formula in which ground temperature is the sole measured input variable reveals a more significant

Table 3 Relationships between glacial runoff, air temperature and ground temperature in Dongkemadi glaicer catchment

Period	Ablation seasons during 2005–2008 (from early June to early October)						
Relationship between runoff and air temperature			$y = 1.2699e^{0.148x}$		$R^2 = 0.31$		
Relationship between runoff and ground temperature	$R^2 = 0.31$	$R^2 = 0.40$	$R^2 = 0.51$	$R^2 = 0.06$	$R^2 = 0.09$	$R^2 = 0.02$	$R^2 = 0.03$
Ground depth (cm)	0	15	30	45	60	75	90
Period	1 Jun 2008–12 Oct 2008						
Relationship between runoff and air temperature			$y = 1.6081e^{0.0453x}$		$R^2 = 0.27$		
Relationship between runoff and ground temperature	$R^2 = 0.14$	$R^2 = 0.36$	$R^2 = 0.70$	$R^2 = 0.65$	$R^2 = 0.18$	$R^2 = 0.35$	$R^2 = 0.09$
Ground depth (cm)	0	15	30	45	60	75	90

Table 4 Relationships between glacial runoff, air temperature and ground temperature in the headwater catchment of Urumqi River

Station	Air temperature–runoff	R^2	Ground temperature–runoff	R^2	Ground depth at deep borehole (cm)
U1	$y = 6.1855e^{0.0996x}$	0.71	$y = 6.7649e^{0.0986x}$	0.79	0
U2	$y = 7.1379e^{0.096x}$	0.75	$y = 7.0908e^{0.1167x}$	0.82	20
U3	$y = 7.3596e^{0.1025x}$	0.77	$y = 6.935e^{0.1298x}$	0.83	40
U4	$y = 6.2833e^{0.0939x}$	0.75	$y = 6.9984e^{0.1446x}$	0.80	60
U5	$y = 3.5523e^{0.0824x}$	0.77	$y = 7.2552e^{0.1684x}$	0.74	80
U6	$y = 3.4122e^{0.0736x}$	0.69	$y = 7.691e^{0.1886x}$	0.66	100
			$y = 7.9472e^{0.2086x}$	0.58	120
			$y = 8.9891e^{0.2578x}$	0.44	160

Table 5 Relationships between glacial runoff, air temperature and ground temperature in the station, which are all far away from the headwater catchment of Urumqi River (1 Jan 2000–30 Nov 2001)

Station	Location information	Air temperature–runoff	Ground temperature–runoff	The so-called best ground depth (cm)	Remark
Urumchi	43°47′N, 87°39′E, 935 m	$y = 2.80e^{0.0557x}$ $R^2 = 0.66$	$y = 1.64e^{0.0869x}$ $R^2 = 0.83$	80	
Dabancheng	43°21′N, 88°19′E, 1,103.5 m	$y = 2.66e^{0.0667x}$ $R^2 = 0.69$	$y = 1.96e^{0.0815x}$ $R^2 = 0.80$	20	The deepest observation depth
Bayinbuluke	43°02′N, 84°09′E, 2,458 m	$y = 5.43e^{0.0532x}$ $R^2 = 0.64$	$y = 3.82e^{0.1028x}$ $R^2 = 0.78$	40	The deepest observation depth
Turpan	42°56′N, 89°12′E, 34.5 m	$y = 1.74e^{0.0568x}$ $R^2 = 0.69$	$y = 1.14e^{0.0711x}$ $R^2 = 0.78$	40	

relation than that of air temperature in three alpine catchments. Especially, at Koxkar glacier catchment and the headwater catchment of Urumqi River, the largest coefficients R^2 are 0.9 and 0.83, respectively, which basically meet the requirement of glacier runoff estimation.

The important characteristic of why the equations based on underground temperature performed better than models based on air temperature is that ground temperature is an average variable dependent on a number of other variables or parameters, including meteorological conditions such as surface global radiation and air temperature, soil physical parameters such as surface reflectivity, water content, topographical variables such as elevation, slope and aspect, and other surface characteristics (Kang et al. 2000), while glacier runoff tends to scale with recent air temperatures and not individual point readings. The other reasons may lie in: (1) the fluctuation of ground temperature is more stable than air temperature during the non-ablation period due to low thermal conductivity and high heat capacity; (2) rainfall also plays a significant role in the process inducing

Table 6 The variations of relationship between runoff and ground temperature in Koxkar glacier catchment (station number and data series were same as Table 2)

Station	0 cm	20 cm	40 cm	50 cm	60 cm	80 cm	100 cm	The so-called optimal ground depth (cm)
K1	$y = 0.93e^{0.16x}$ $R^2 = 0.80$	$y = 0.85e^{0.21x}$ $R^2 = 0.86$	$y = 0.83e^{0.26x}$ $R^2 = 0.81$		$y = 0.77e^{0.29x}$ $R^2 = 0.65$	$y = 0.85e^{0.28x}$ $R^2 = 0.40$	$y = 1.026e^{0.21x}$ $R^2 = 0.16$	20
K2	$y = 1.15e^{0.13x}$ $R^2 = 0.74$	$y = 1.24e^{0.15x}$ $R^2 = 0.79$		$y = 1.36e^{0.18x}$ $R^2 = 0.84$			$y = 1.43e^{0.26x}$ $R^2 = 0.86$	100
K3		$y = 1.96e^{0.06x}$ $R^2 = 0.40$	$y = 1.66e^{0.11x}$ $R^2 = 0.65$		$y = 1.59e^{0.13x}$ $R^2 = 0.71$	$y = 1.89e^{0.17x}$ $R^2 = 0.76$		80
K4		$y = 2.71e^{0.18x}$ $R^2 = 0.78$	$y = 3.35e^{0.23x}$ $R^2 = 0.86$		$y = 3.93e^{0.28x}$ $R^2 = 0.90$	$y = 4.18e^{0.28x}$ $R^2 = 0.88$		60

the flood process during the ablation period (Chen et al. 2008). In that case, the air temperature usually decreased significantly and the runoff obviously increased. The empirical formula using air temperature may introduce an additional error into the runoff estimation. However, the results based on ground temperature with the empirical equation will be improved due to ground temperature having no obvious changes under the same condition. (3) The sub-diurnal and sub-seasonal variations in the internal drainage system affect the confluence time, causing the time when the runoff peaks occur are all constantly changing, while the occurrence time of the maximum air temperature and the peak ground temperature are relatively stable in a day. It indicates that using an average variable of multi-variables as ground temperature will obtain better results than air temperature.

The spatial variation of the relationship between ground temperature and glacial runoff

As shown in Tables 3, 4, 5, 6, the coefficient R^2 of the empirical equation based on ground temperature shows a very similar regime at any station in three investigated catchments. The value of R^2 first increases with depth, and then declines until the ground depth reaches a threshold, presenting parabolic curve regularity with depth, which indicates there exists a so-called optimal depth having best performance with the largest coefficient of determination. For instance, the optimal depth is about 0.3 m at the weather station in Dongkemadi glacier catchment, while the optimal depth for the headwater catchment of Urumqi River is about 0.4 m at the deep borehole, 0.8 m at station Urumqi, as well as 0.4 m at station Turpan. In Koxkar glacier catchment, the optimal ground depths at stations K1 and K4 are about 0.2 and 0.6 m, respectively, whereas the exact depth cannot be validated at stations K2 and K3 due to the lack of deep ground temperature observation data.

Table 6 shows that the optimal depth at K1 stations is shallower than that at the other three stations in Koxkar glacier catchment. The result may be caused by the different thermal conductivity between alpine meadow and debris. Results from the three stations in the debris present that the optimal depth decreases with the ascent of the altitude, which might be attributed to two different factors. First, the percent of debris coverage is smaller at high altitude positions compared with low altitude stations, which induces much more of the incoming solar radiation being reflected back to space at high altitude and may result in a considerable affection on surface heat fluxes and ground temperature. Second, with the debris thickness decreasing gradually along altitude gradient, the ice temperature under debris covers would play an important role in the variation of debris temperature.

In general, the so-called optimal ground depth at all stations in three catchments, except station K1 in Koxkar glacier catchment, decreases with increasing altitude. There exists a linear relationship between the so-called optimal ground depth y and altitude x, which could be described using a linear formula $y = -0.0361x + 203.16$ and defined with the R^2 of 0.81.

Conclusions

Soil characterized by low thermal conductivity and high heat capacity would make ground temperature lag behind air temperature and more steady than air temperature as a good filter. However, the linkage between the glacier runoff and soil temperature have not had much attention to study as various glacial models have been developed. The recent investigations carried out in three glacierized catchments in China make it possible to evaluate the association between the glacial runoff and ground temperature. For the whole data series at three alpine catchments, it is determined that association between the runoff and ground temperature reveals a more significant relationship than that of air temperature, indicating ground temperature versus a certain depth as a critical factor that affects glacier hydrological processes. This relationship could be described by an exponential function with a high accuracy, which basically meets the requirement of glacier runoff estimation. The accuracy of the method makes it possible to estimate glacier runoff with a certain depth ground temperature, and provides a new approach to evaluate glacier runoff for an area lacking observed data. However, the spatial variation of the so-called optimal ground depth and accurate position to obtain the best estimated result in a catchment are still not clear due to many uncertain factors. Therefore, more detailed field measurements and universality investigations are needed to analyze the linkage and association between ground temperature and glacial runoff for different types of glaciers.

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