

The simulation of snowmelt runoff in the ungauged Kaidu River Basin of TianShan Mountains, China

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Abstract Snowmelt runoff is an important source of water resources in the arid mountain area. Modelling snowmelt runoff for cold regions remains a problematic aspect because of the lack of data by gauges in large basins. In order to overcome the shortage of measured data in the snowmelt runoff modelling, the temperature interpolation method would greatly help in improving the simulation accuracy and describing the snow-hydrological behaviours of the study catchments. In this study, the temperature is the principal variable used to estimate the importance of the melting of snow cover using the snowmelt runoff model. Five different temperature interpolation attempts were performed over the Kaidu River Basin for the snowmelt season of the year 2000. Three temperature inputs were taken directly from the individual weather stations in or near the study area, and the other two temperature inputs were interpolated from the three weather stations. The results indicated that the temperature estimated from different methods could result in quite a difference in runoffs in comparison with the observed ones. The simulation results using average temperature from the three stations showed good results; the simulation run with the weighted average temperature generated a lower R^2 than the average temperature of three stations and using temperature directly adopted from three individual stations

gave various results. The weather stations used to perform the snowmelt runoff simulation should be located in the place which is most representative of the mountain weather conditions, and the land cover and topography that those stations represented also play an important role in the snowmelt runoff simulation.

Keywords SRM · Snowmelt runoff · Temperature interpolation · Kaidu River Basin · Ungauged basin

Introduction

In the arid area of northwest China, a large fraction of annual stream flow in river basin is generated in the mountains, where the outlet stream was close to total water of the whole basin, which plays a main role of the ecological function (Chen 2001). The snowfall that takes place in the mountains provides a rich and stable snowmelt runoff, and the snowmelt is significant surface water input which is important to many aspects of hydrology including water supply, erosion and flood control (Tarboton et al. 1995), especially in the dry season (Gao and Shi 1992; Chen 2001). In order to forecast the snowmelt runoff, it is necessary to understand the snowmelt process and their response to external inputs by using the hydrological model because they are influenced by both the internal structure of the watershed system and external disturbances (Li and Simonovic 2002).

Temperature is identified as a critical factor that affects watershed hydrological processes, especially snowpack accumulation and snowmelt (Neitsch et al. 2001; Tanasienko and Chumbaev 2008). The runoff generated from snowmelt may follow a general pattern as temperature changes during

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the snowmelt period. Air temperature is presented as the principal variable used to estimate snowmelt in an empirical model such as the snowmelt runoff model (SRM) (Blöschl 1991; Brubaker et al. 1996), and the accurate average temperature at the reference latitude is fundamental for guaranteeing simulation precision, especially for large basins (Rango and Martinec 1981). The air temperature values have a high correlation with the gauge station hydrometric measurements (Richard and Gratton 2001; Zhang et al. 2007). In the Kaidu River Basin, where the streamflow is mainly generated from the mountains, the lack of weather stations makes it difficult to obtain accurate and reliable temperature values for the snowmelt runoff simulation. Hence, the proper temperature description methodology and the appropriate extrapolated approach are required for practical use in estimating snowmelt runoff. A broad consensus of scientists has concluded that the global surface air temperature has increased by about 0.6°C during the twentieth century, and these increases are likely to persist in the twenty-first century, and will probably be accompanied by changes in precipitation and runoff amounts (IPCC 2001). An increase in temperature may affect important changes in hydrologic cycle (Houghton et al. 1996) and water resource availability (Brent and Yu 1999). Higher temperature under climate variation has a serious impact on the hydrologic processes related to the floods caused by snowmelt, which often happens in the Kaidu River Basin (Zhang et al. 2007). More attention should be given to flood risks rather than to droughts in the study region.

Previous studies of snowmelt estimation were based on a temperature index approach with the assumption that temperature is a major driving force in snowmelt processes

(Liu et al. 2006; Li and Wang 2008), but other approaches hypothesize that temperature alone cannot adequately explain the processes of snowmelt (National Engineering Handbook 2004; Zhang et al. 2007), that the elevation and other factors that influence snowmelt, including land use/land cover, aspects and slopes are the dominant ones (Morid et al. 2002; LaMalfa and Ryle 2008). This study aims to simulate snowmelt runoff using the snowmelt module in the SRM according to the average temperature interpolate method. The simulated runoffs using the five different temperature input attempts are compared with each other and with the measured data. Other factors such as land cover influencing snowmelt runoff were also analysed.

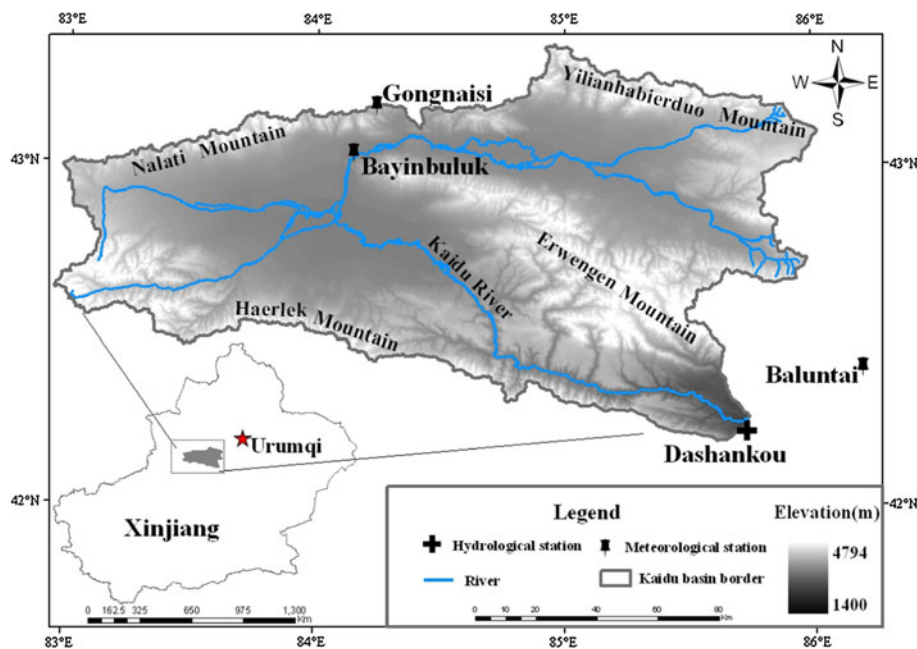
Methodology

Study area and station description

The Kaidu River Basin (Fig. 1), located in the southern slope of Tianshan Mountains, Xinjiang, China, is enclosed between latitudes 42°14'N–43°21'N and longitudes 82°58'E–86°05'E. It spans an area of 1.9×10^4 km². Its major peak is about 5,000 m in elevation, and the deepest depression is 1,400 m.

The region has a complex topography including grassland, marsh and desert, and surrounding mountainous alpine areas. The snow accumulation lasts 5 months from November of every year to March of the next year. With temperatures increasing during April and May, seasonal snowmelt water associated with the rainfalls begins

Fig. 1 Location of the Kaidu River Basin



supplying the river. Snowmelt is the main water source for the germination of the Bayinbuluk pasture, and also the principal source of water required for the economic, social development, and growth of these regions. The hydrologic flow in the Kaidu River Basin is driven by snowmelt in the spring, rainfall/snowmelt in the summer, and perennial glacier melting. The first flood peak appears between March and April, which is mainly governed by snowmelt, while the second flood peak appears between July and August, which is mainly governed by rainfall. Floods resulting from melting event will bring potential hazards for downstream regions because a high volume of flow generates within a short period of time.

Runoff prediction

In order to predict the runoff, the SRM is used in this study. The SRM is a semi-distributed hydrological model which has been applied principally in high mountain environments where it obtains excellent results (Wang et al. 2001). The SRM calculates the daily runoff by computing the water produced from snowmelt and rainfall on all elevation zones and adding them to the recession flow according to the following equation:

$$Q_{n+1} = [cS_n a_n (T_n + \Delta T_n) S_n + cR_n P_n] A \times l(1 - k_{n+1}) + Q_n K_{n+1} \tag{1}$$

where Q ($m^3 s^{-1}$) is the average daily discharge, C is the runoff coefficient expressing the losses as a ratio (runoff/precipitation), with C_S referring to snowmelt and C_R to rain, a_n ($cm \text{ } ^\circ C^{-1} \text{ d}^{-1}$) is the degree-day factor indicating the snowmelt depth resulting from 1 degree-day, T_n ($^\circ C \text{ d}$) is the number of degree-days above the base of $0^\circ C$, ΔT_n ($^\circ C \text{ d}$) is the adjustment by temperature lapse rate for different altitudes of meteorological stations, S_n is the ratio of the snow-covered area to the total area, P_n (cm) is the precipitation contributing to runoff, A_i (km^2) is the area of the basin or zone, k_n is the recession coefficient indicating

the decline of discharge in a period without snowmelt or rainfall, n is the sequence of days during the discharge computation period, $10,000/86,400$ converts $cm \text{ km}^2 \text{ d}^{-1}$ to $m^3 \text{ s}^{-1}$, and m is the number of elevation zones. T , S and P are variables, while others are parameters.

As physical environment varies drastically with increasing altitudes, the basin with a great elevation range was divided into several zones to better describe the physical environment. Previous studies suggested that an interval of less than 500 m is better for the elevation zones, because this can reduce the system error (SRM manual, Martinec et al. 1998; Zhang et al. 2007), while excessively small intervals will increase the modelling complexity. Based on a 1:250,000 scale DEM data, the Kaidu River Basin has been divided into eight elevation zones (Table 1). Climate data are essential for assessing snow-melt runoff. In this study, climate data were acquired from three meteorological stations: one is the Bayinbuluk station which is inside the study region, and the other two stations are Gongnaisi station and Baluntai station, which are near the study region.

In order to run the SRM, information about the snow cover is also required. To estimate the change in snow cover over the Kaidu River Basin, moderate resolution imaging spectroradiometer (MODIS) 8-day snow maximum extent cover imagery was obtained by linearly interpolating to daily snow coverage (Fig. 2). These images are particularly efficient for the estimation of the snow cover (Tekeli et al. 2005).

Temperature estimation for the SRM simulation

Five methods are used in this study to estimate the impact of changing temperature in the hydrological modelling. The first method uses the weighted average temperature from three selected stations. The weighted stations were obtained using SLURPAZ software (slurp model manual, Kite 2003). The weights were determined using the

Table 1 Elevation zones of the Kaidu River Basin

Zone	Elevation range (m)	Area (km^2)	Mean elevation (m)	Station	Land cover
A	1,400–1,825	198.63	1,670.97	Gongnaisi Baluntai	Meadow close to the forest Opening on the meadow
B	1,825–2,250	241.87	2,045.93	–	–
C	2,250–2,675	5,297.16	2,512.73	Bayinbuluk	Opening on the meadow
D	2,675–3,100	5,696.69	2,857.80	–	–
E	3,100–3,525	4,193.95	3,293.17	–	–
F	3,525–3,950	2,454.75	3,689.58	–	–
G	3,950–4,375	619.37	4,056.95	–	–
H	4,375–4,800	22.60	4,424.44	–	–
Entire basin	1,400–4,800	18,725.02	2,924.81	–	–

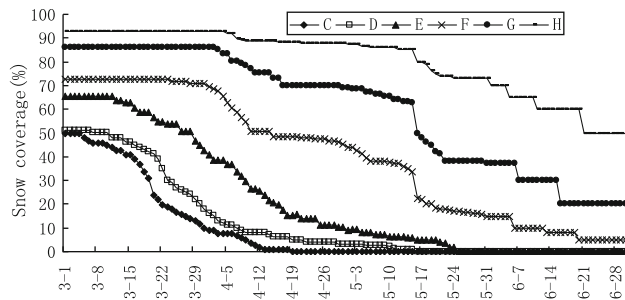


Fig. 2 Snow coverage depletion curve for the Kaidu River Basin in 2000 (Zone C–H)

individual weather stations identified by stations based on the topographic analysis using a digital elevation model (DEM); the land-uses classification of the area and the distances between the individual stations and the drainage basin. The weights were Gongnaisi station: 30%, Bayinbuluk station: 19%, and Baluntai station: 51%. The second one simply averages temperature from three stations. Another three methods use the temperature provided only from each selected station inside or in proximity to the drainage basin. Temperature estimated from first two average methods is used in the zone with an average height of three stations, while the temperature directly adopted from each station in last three methods is used in the zone corresponding to the station's height; then, the temperature estimated in the given zone is used to calculate temperature for other zones by temperature lapse rate. Overall, estimated temperature for all zones from the five methods is used for different runs of the SRM.

Calibration and performance assessment of the model

Different temperature input attempts were performed over the Kaidu River Basin using the SRM for the 2000 snowmelt period (22 March–5 June). Each modelling run was done using the same set of parameter values, which were previously calibrated and adjusted to the basin. Only the temperature and precipitation values were changed between each run. The precipitation values were estimated using the same method which was employed to acquire the temperature data.

The modelling results were evaluated using a determination coefficient (R^2), also known as the Nash–Sutcliffe coefficient:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Q_i - Q'_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \quad (2)$$

where, R^2 represents a measure of the precision of the SRM results, Q_i measured daily runoff, Q'_i stands for the modelled daily runoff and \bar{Q} is the average daily runoff which corresponds to a long-time average of the measured daily runoff.

Results

Relation of runoff with temperature and precipitation

The Bayinbuluk station is located in the Kaidu River Basin, while the Gongnaisi and the Baluntai stations are located near the Kaidu River Basin. The different location and topography of the three weather stations result in the differences in the temperature and precipitation. The annual and snowmelt season precipitation of the Gongnaisi station is the most of the three stations, while the annual and snowmelt season temperature of the Baluntai station is the highest of the three stations. The elevation of Bayinbuluk station is 2,458.9 m, which is higher than both the Gongnaisi and Baluntai stations (Table 2).

In the arid mountain area, the snowfall and snowmelt are the two most important hydrologic components. Precipitation and temperature are the two main factors influencing the snowmelt runoff. The relations of runoff with temperature and precipitation in the Kaidu River Basin are shown in Fig. 3 using the data from Bayinbuluk station. The correlation analysis indicates that the correlation between runoff and air temperature is relatively good with best correlation coefficient reaching 0.7598 during an entire year (Fig. 3b) and 0.7091 during the snowmelt season (Fig. 3d), but it can only reach 0.6959 during an entire year (Fig. 3a) and 0.4254 during the snowmelt season (Fig. 3c) between runoff and precipitation. The runoff during the snowmelt season is not only contributed by rainfall, but also by snowmelt, which results in a low correlation coefficient between runoff and precipitation. The result shows that the air temperature values are crucial to the snowmelt runoff in the study area.

Snowmelt runoff based on different series of temperature values

The determination of temperature lapse rate of Kaidu River Basin was carried out using the three weather stations during the ablation period (March–June) in 1999, 2000, and 2001. The average monthly temperature during the ablation period has been analysed to determine suitable lapse rate of slope temperature for temperature index of the SRM (Table 3). The result showed that the average monthly temperature varies greatly among years, but the temperature decline from the Baluntai to Bayinbuluk was much faster than that from Gongnaisi to Bayinbuluk. This phenomenon is caused by the difference in land cover. The land cover from Gongnaisi to Bayinbuluk is dominated by forest, which has the ability to adjust the temperature and moisture. However, land cover from Baluntai to Bayinbuluk mainly consists of bare land and grassland which have less ability to adjust temperature than forests.

Table 2 The detail information of the three weather stations

Station	Elevation (m)	Longitude	Latitude	Annual P (mm)	Annual mean T (°C)	Snowmelt season P (mm)	Snowmelt season mean T (°C)
Bayinbuluk	2,458.9	84° 09'	43° 02'	275	−5.3	80.4	−2.03
Gongnaisi	1,776	82° 24'	43° 16'	949	1.76	246.3	3.4
Baluntai	1,739.47	86° 18'	42° 44'	211	7	35.3	9.67

T temperature, P precipitation

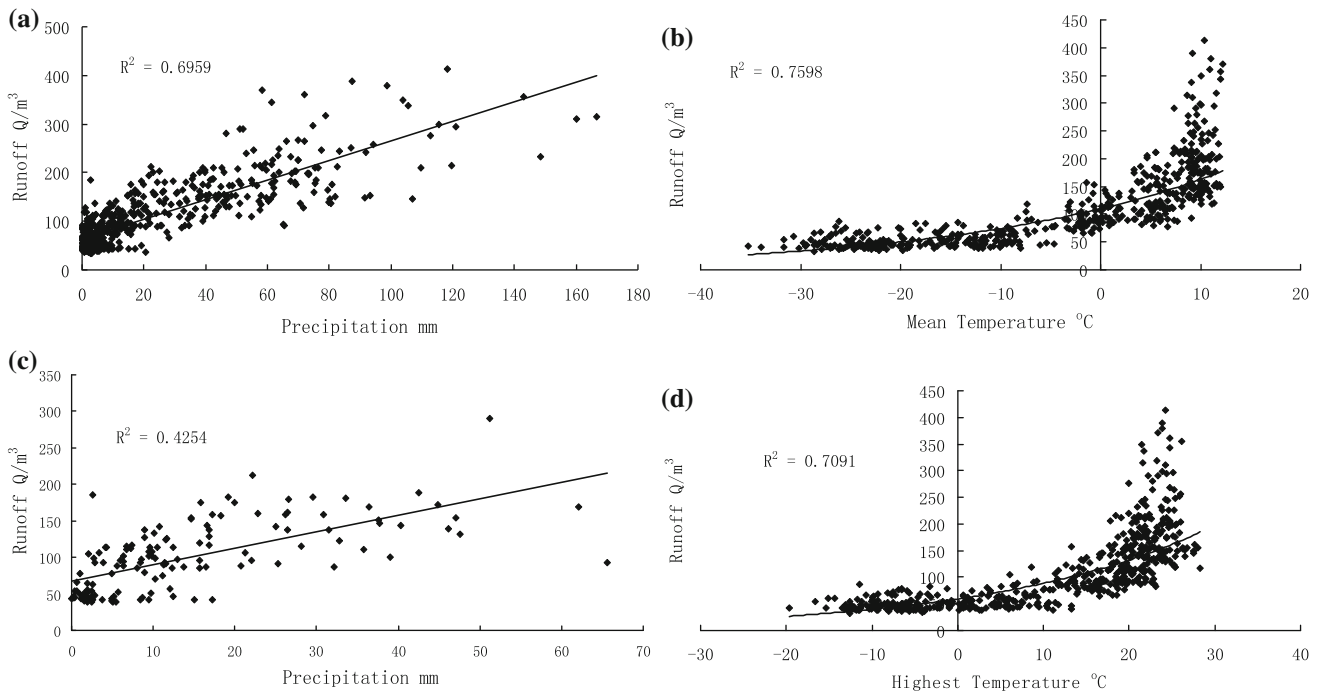


Fig. 3 The correlation between precipitation and runoff, mean temperature and runoff **a, b** during the entire year **c, d** during the snowmelt season

Mean temperature lapse rate within the basin during the ablation period from 1999 to 2001 is used for the SRM. Other parameters were determined with regard to the climatic and hydrological conditions of the study basin and are listed below (Table 4).

The runoffs from SRM simulation with different methods to estimate temperature and precipitation are shown in Fig. 4. The results indicate that the temperature and precipitation estimated from different methods could result in quite a difference in runoffs in comparison to the observed ones.

Using the average temperature of three stations and the temperature of Bayinbuluk station showed a better simulated result than the other three temperature input attempts (Fig. 4). The output runoffs from the average temperature of three stations exhibit a similar trend to the measured values even in the early snowmelt period. The average temperature interpolate method can better catch the peak of the early snowmelt runoff than the other temperature input

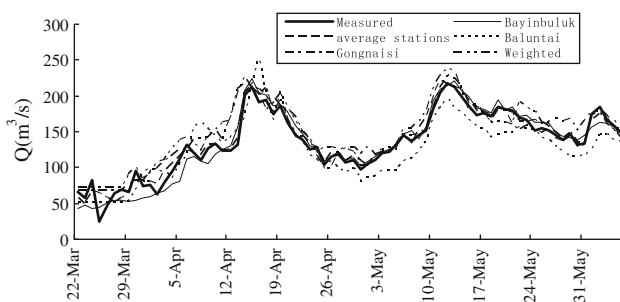
Table 3 Average monthly lapse rate (°C (100 m)⁻¹) for different station pairs during the three year observation

Year	March	April	May	June
Form Gongnaisi to Bayinbuluk				
1999	−0.76	−0.30	−0.94	−0.70
2000	−1.47	−0.44	−0.48	−0.40
2001	−1.34	−0.40	−0.57	−0.48
Form Baluntai to Bayinbuluk				
1999	−1.42	−1.31	−1.22	−1.18
2000	−2.38	−1.18	−1.32	−1.03
2001	−1.95	−1.13	−1.31	−1.40

methods. The weighted average temperature input method showed a higher runoff volume than the measured runoff. The simulation result showed that the smallest error is using the temperature data in Bayinbuluk station, and all simulation runoff is less than the measured data before

Table 4 the parameter values given in the modelling of the Kaidu River Basin

SRM Parameter	Elevation zones							
	A	B	C	D	E	F	G	H
Description								
Degree-day factor ($\text{cm } ^\circ\text{C}^{-1} \text{d}^{-1}$)	0.35	0.35	0.35	0.3	0.25	0.25	0.25	0.25
Snowmelt Runoff coefficient Cs	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9
Rain runoff coefficient Cr	0.75	0.75	0.75	0.75	0.65	0.65	0.6	0.6
Critical temperature ($^\circ\text{C}$)	2	2	2	2	2	2	2	2
Rainfall contributing area	1	1	1	0	0	0	0	0
Time Lag (L, h)	18	18	18	18	18	18	18	18

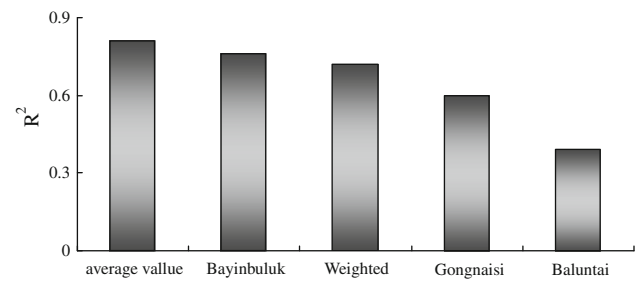
**Fig. 4** Modelling the runoff for the Kaidu River using the five temperature estimation methods

April 10th. In the early snowmelt period, the temperature of individual weather stations cannot reach the peak well.

The results of R^2 varied between 0.34 and 0.81 (Fig. 5). The modelling run using the average temperature of three stations generated the best simulation result with a R^2 of 0.81, while that using the temperature directly adopted from the Baluntai station obtained the lowest R^2 with 0.39. The R^2 from other three methods for estimating the temperature ranges from 0.60 to 0.76.

Discussion and conclusions

The SRM offers a great platform to simulate the snowmelt runoff in mountainous areas where there is a lack of weather stations. The simulation runs of the SRM using temperature estimated by the five methods demonstrate that the temperature plays a crucial role in determining snowmelt runoff. The variations in R^2 were directly attributed to changes in the series of temperature values inserted in the five modelling runs. The results showed how the temperature values influence the simulated results, and the effect of the other factors such as topography and the station environment on the snowmelt process.

**Fig. 5** Modelling precision (R^2) for the Kaidu River Basin

The modelling results using average temperature from the three stations showed good results because the average temperature reduced the local temperature effects of particular stations, which implies that temperature inputs from more stations will improve snowmelt runoff prediction.

Simulation run with the weighted average temperature generated a lower R^2 than the average temperature of three stations and the temperature of the Bayinbuluk station did. The weight in the weighted average temperature method was given according to topography, vegetation cover, and the area of influence of individual stations based on the distance to the drainage basin. The Baluntai station's weight is 51% which occupies more proportion than the Gongnaisi and Bayinbuluk stations, but this station is located near the outlet of the drainage basin, which is more representing of the plane weather conditions with higher temperature and lower precipitation than the mountain weather conditions. The greater weight of the Baluntai station would give a poorer result. The weight selected in the weighted average temperature method had an important impact on the modelling results.

The SRM simulation using temperature directly adopted from three individual stations gave various results. The SRM using the temperature from the Bayinbuluk station generated the best results. The main reason is that the elevation of the station with 2,458 m belongs to zone C, which is much closer to the hypsometric mean elevation of 2,924.81 m, and the station is able to better represent the mountain weather conditions. Gongnaisi station and Bayinbuluk station are located on the two sides of the Sarming Mountain. The topography represented by Gongnaisi station is quite different from Bayinbuluk station, which affects the temperature and precipitation of Gongnaisi station. The mean temperature at the Gongnaisi station during the snowmelt season is above 0°C , and the precipitation is three times than Bayinbuluk's. Higher temperature and more precipitation at the Gongnaisi station influence the snowmelt process, which results in more simulated runoff than other simulation runs do. The worst results came from the Baluntai station which is located near the outlet of the drainage basin. The Baluntai station has

the highest temperature and the lowest precipitation of the three weather stations.

The station represents the plain weather conditions rather than the mountain weather conditions. The local climate conditions of the weather stations play an important role in the precision of runoff simulation.

The other factors, such as land cover, also make effect on the snowmelt simulation. Of all the three stations, only the Bayinbuluk station is located on the open meadow land which is the principal land cover type of the Kaidu basin, while the Gongnaisi and Baluntai stations are located on both the meadow close to the forest area and to bare land, respectively. The forest and bare land environment may influence the temperature and the energy exchange during the snowmelt season. The Bayinbuluk station is located in zone C and the other two located in zone A. The stations located in the lower elevation cannot represent the precipitation event well. The general context and topography of these stations play a more important role than the weighted method does.

Changes in temperature mainly affect snowfall and snowmelt regimes. Snowfall and snowmelt in the arid mountain area are the two most important hydrologic components. The increased temperature increased the rate and intensity of warm season snowmelt, which leads to the changes in peak runoff and its timing within a year.

In the arid mountain environment, the temperature is a more critical factor for runoffs than precipitation, and this fact is much more obvious during the snowmelt season than the whole year. The simulation results indicated that the SRM using five temperature estimation methods is able to generate runoff patterns similar to observed ones, but the numerical results are quite different. Although temperature plays a critical role in the SRM simulation, the local environmental factors such as the general context and topography of stations also has an important impact on the simulation outcomes. Since the SRM does not consider these aspects in terms of parameters, it is expected to take them into account for further study on snowmelt runoff estimation.

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