Postprint: Runoff Variation Characteristics During the Ablation Season in the Laohugou Watershed, Western Qilian Mountains

Authors: Jin Zizhen, Qin Xiang, Zhao Qiudong, Li Yanzhao, Liu Yushuo, Chen Jizu, Lihui Wang, Wang Qiang, Qin Xiang

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Abstract

Based on runoff data from the Laohugou watershed cross-section in the western Qilian Mountains and meteorological data from the Base Camp meteorological station, this study analyzed the correlation between glacier runoff and meteorological elements, established a multivariate exponential nonlinear regression equation to reconstruct runoff and compensate for missing data, and examined the interannual, seasonal, and diurnal variation characteristics of glacier runoff. The results show: (1) Glacier runoff exhibits the highest correlation with air temperature (0.86), followed by water vapor pressure (0.81), relative humidity (0.46), and precipitation (0.27), indicating that runoff is most strongly influenced by air temperature. (2) Observations from the 21st century indicate a daily average runoff of 2.10 $m^3 \cdot s^{-1}$, representing an increase from 1.65 $m^3 \cdot s^{-1}$ in the late 1950s, primarily attributable to a 0.75 °C temperature rise during the ablation season. Interannual runoff variation is more pronounced during the intense ablation period (July–August) and less variable at the beginning (May–June) and end (September) of the ablation season. Runoff contribution percentages during the ablation season (May–September) are 5.3%, 16.1%, 37.3%, 35.1%, and 6.2%, respectively. (3) The multivariate exponential nonlinear regression equation satisfactorily simulates daily runoff (average Nash-Sutcliffe efficiency coefficient of 0.70). After filling gaps in the runoff record, diurnal runoff variation is found to be smaller at the beginning and end of the ablation season but larger during the intense ablation period. Regarding runoff time-lag effects, monthly runoff during the ablation season in the Laohugou watershed displays a 'valley-peak' diurnal pattern. The time interval between maximum air temperature and maximum runoff is longer at the beginning and end of the ablation season and shorter during the intense ablation period, with the maximum difference of 3 hours occurring in June at the beginning of the ablation season. Understanding the variation characteristics of glacier meltwater is

crucial for water resource management, ecological protection, and sustainable socioeconomic development in arid regions.

Full Text

Preamble

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Characteristics of Runoff Variation During Ablation Season in Laohugou Watershed, Western Qilian Mountains

JIN Zizhen[1],[2], QIN Xiang[1], ZHAO Qiudong[3], LI Yanzhao[1],[2], LIU Yushuo[1], CHEN Jizu[1], WANG Lihui[1],[2], WANG Qiang[1]

[1] Qilian Shan Station of Glaciology and Eco-environment, State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China
[2] University of Chinese Academy of Sciences, Beijing, China
[3] Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China

Abstract: Based on runoff data from the Laohugou watershed cross-section and meteorological data from the Base Camp weather station in the western Qilian Mountains, this study analyzed the correlation between glacierized area runoff and meteorological elements, and established a multivariate exponential nonlinear regression equation to reconstruct missing runoff data. Additionally, the characteristics of interannual, seasonal, and diurnal scale runoff variations in the glacierized area were examined. The results demonstrate that: (1) Runoff exhibits the highest correlation with air temperature (0.86), followed by water vapor pressure (0.81), relative humidity (0.46), and precipitation (0.27), indicating that temperature is the dominant control on runoff. (2) The mean daily runoff in the 21st century is 2.10 $m^3 \cdot s^{-1}$, which is higher than the 1.65 $m^3 \cdot s^{-1}$ observed in the late 1950s, primarily due to a 0.75°C increase in ablation season temperature. Interannual runoff variation is substantial during the strong ablation period but relatively small during the early (May-June) and late (September) ablation season. Runoff generation from May through September accounts for 5.3%, 16.1%, 37.3%, 35.1%, and 6.2% of the total ablation season runoff, respectively. (3) The multivariate exponential nonlinear regression equation effectively simulates daily runoff (mean Nash-Sutcliffe efficiency coefficient = 0.70). After supplementing missing runoff data, diurnal runoff variation is small during the early and late ablation period but large during the strong ablation period. Regarding the time-lag effect, monthly runoff in Laohugou watershed shows a distinct "valley-peak" diurnal pattern during the ablation season. The time interval between maximum temperature and maximum runoff is long during the early and late ablation period, but short during the strong ablation period, with the maximum difference reaching 3 hours in June. Clarifying glacier meltwater variation characteristics is crucial for water resource management, ecological protection, and sustainable socioeconomic development in arid regions.

Keywords: runoff reconstruction; climate change; runoff variation; Laohugou watershed

Introduction

Glaciers serve as "solid reservoirs" that constitute important water resources for river replenishment and agricultural irrigation, while also acting as natural recorders and early warning indicators of climate change. Glacier meltwater is a critical water resource in the arid regions of northwest China, playing a vital role in maintaining ecological balance and supporting sustainable socioeconomic development. Global warming has caused most glaciers worldwide to retreat. In the western Qilian Mountains, glacier area decreased by 14.1% between 1956 and 2017, with the most significant retreat occurring after 2000. During the 1960s-1970s, glacier area and volume losses accounted for 10.3% of the total. Laohugou Glacier No. 12 is the largest valley glacier in the Qilian Mountains, spanning 9.7 km in length with an area of 20.37 km^2 and an elevation range of 4250-5483 m. As a continental glacier, it has experienced substantial mass loss and retreat in recent decades, with the terminus retreating 403 m and the area decreasing by 1.54 km^2 since 1957. The equilibrium line altitude averaged 4380 m historically but rose to 5015 m by 2010. Such glacier changes inevitably impact water resources in arid regions. As glaciers evolve, their meltwater contribution to water resources follows a "first increase then decrease" trend. For instance, modeling in the Yarkant River basin since 1961 shows glacier runoff has generally increased, accounting for 51.1% of total runoff, though the "turning point" has not yet emerged. The timing of this turning point depends on glacier size and coverage: watersheds with low glacier coverage and small glaciers (e.g., Shiyang River, Manas River, and sources of the Nu River, Yellow River, and Lancang River on the Tibetan Plateau) have already reached peak meltwater, while watersheds dominated by larger glaciers (e.g., Kuche River, Muzart River, Shule River, and Yangtze River source) will likely reach peak meltwater in 10-20 years. Additionally, glacier meltwater can trigger natural disasters such as glacial lake outburst floods and debris flows. Therefore, understanding hydrological characteristics in glacierized areas and quantifying current and future glacier meltwater contributions are essential for water resource management and disaster prevention.

Runoff in glacierized areas originates primarily from glacier meltwater, seasonal snowmelt, rainfall, and groundwater. However, runoff generation is influenced not only by meteorological factors but also by underlying surface conditions, subglacial drainage systems, supraglacial stream networks, and active permafrost layers. Due to observational limitations, understanding of runoff generation and concentration processes remains limited. Hydrological models based on degree-day and energy balance approaches can simulate and predict glacierized area runoff, including distributed energy balance models, distributed enhanced degree-day models, and precipitation-runoff-evapotranspiration models. However, in alpine regions, limited observational data restrict the applicability of most hydrological models. In practice, assessing and predicting runoff based on relationships between meteorological elements and runoff is crucial. Time series correlation analysis is an important method for determining these relationships. Previous studies in glacierized areas have established regression relationships between runoff and meteorological elements, demonstrating that meteorological variables can successfully simulate glacierized area runoff. Laohugou watershed is located in the high-altitude mountains of the western Qilian Mountains with harsh natural conditions. Runoff observation instruments (water level gauges) are vulnerable to damage from riverbed gravel during summer, resulting in missing data. Previous studies on Laohugou watershed have focused on single-year runoff variations and only considered temperature and precipitation for data reconstruction. Therefore, establishing regression models between runoff and meteorological elements is critical for extending runoff time series, filling data gaps, and analyzing runoff at different temporal scales. This study systematically analyzes the relationships between runoff and meteorological elements using statistical methods, develops a multivariate exponential nonlinear regression model to reconstruct missing runoff data, and comprehensively examines interannual, seasonal, diurnal, and time-lag characteristics of runoff.

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1. Study Area Overview

Laohugou watershed is located in the upper Shule River region on the northeastern edge of the Tibetan Plateau in the western Qilian Mountains (39°25 - 39°30 N, 96°31 -96°33 E). The watershed is controlled by the mid-latitude westerlies year-round, characterized by perennial low temperatures and abundant precipitation. The hydrological cross-section is established between Base Camp and the terminus of Laohugou Glacier No. 12 at an elevation of 4180 m. According to the First Glacier Inventory, the watershed glacier area is 37.59 km^2 with a coverage of 65.15%. The current cross-section has been operational since 2007, controlling a watershed area of approximately 37.58 km^2 with 65.17% glacier coverage. A historical cross-section from 1958 was located about 5-10 m downstream of the current section, controlling 37.67 km^2 with 65.01% glacier coverage. Although the cross-section location has changed slightly, it remains near the same elevation with minimal changes in catchment area and glacier coverage, ensuring that observed runoff reflects glacier runoff variations. Laohugou Glacier No. 12, with the glacier code 5Y448D0004, is the largest valley glacier in the Qilian Mountains. In recent decades, the glacier has experienced significant mass loss and retreat, with the terminus retreating 403 m and area decreasing by 1.54 km^2 since 1957. The equilibrium line altitude averaged 4380 m historically but rose to 5015 m by 2010.

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2. Data and Methods

2.1 Meteorological and Hydrological Monitoring

Automatic weather stations were installed at 4550 m and 5040 m in Laohugou watershed. This study uses data from the Base Camp station at 4180 m (Fig. 1). The automatic weather station employs a Campbell CR1000 data logger, with temperature measured by an HMP45C sensor (accuracy $±0.2°C)andprecipitationrecordedbyaT200Bautomaticrain/snowgauge(accuracy0±$0.1 mm) at 30-minute intervals. Precipitation data were corrected using the method proposed by Ye et al. [21] for Chinese precipitation observation errors. Temperature, precipitation, and runoff data from 2008-2017 were used as historical observations. Hydrological monitoring involves velocity and water level measurements. Velocity is measured using an LS25-1 propeller-type current meter, while water level is observed with a water level gauge and verified with a staff gauge to establish a stage-discharge relationship curve for calculating ablation season discharge. The primary hydrological data used are daily runoff values from 2008-2017.

2.2 Research Methods

Autocorrelation and cross-correlation coefficients were used to analyze relationships between runoff and meteorological elements. The autocorrelation coefficient (Rk) and cross-correlation coefficient (rk) are calculated as:

$$R_k = \frac{\sum_{i=1}^{n-k}(X_i - \bar{X})(X_{i+k} - \bar{X})}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

$$r_k = \frac{\sum_{i=1}^{n-k}(X_i - \bar{X})(Y_{i+k} - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where Rk is the autocorrelation coefficient, n is the number of time series data points, k is the time lag, Xi is the daily time series data, $\bar{X}$ is the mean, Xi+k is the time series data with lag k, rk is the cross-correlation coefficient, Yi+k is the time series data with lag k, and $\bar{Y}$ is the mean.

The coefficient of variation (Cv) quantifies the dispersion of time series data:

$$C_v = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2}}{\bar{X}} \times 100\%$$

where Cv is the coefficient of variation and n is the number of data points.

The Nash-Sutcliffe efficiency coefficient (NSE) and relative error (Er) evaluate model performance:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2}$$

$$E_r = 100 \times \frac{\sum_{i=1}^{n}(Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^{n} Q_{obs,i}}$$

where NSE is the Nash-Sutcliffe efficiency coefficient, Er is the relative error, Qobs is the observed value, Qsim is the simulated value, and $\bar{Q}_{obs}$ is the mean observed value.

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3. Results and Analysis

3.1 Temperature and Precipitation Characteristics

Meteorological observations of temperature and precipitation are fundamental to hydrological research. In high-altitude regions with complex terrain and harsh environments, meteorological observations are scarce, yet precipitation significantly contributes to runoff and glacier meltwater is highly sensitive to temperature. Moreover, the spatial distribution of temperature and precipitation differs from plain areas. Therefore, enhanced meteorological observation in high-altitude regions is crucial for analyzing runoff changes under climate change. Base Camp observations show that the mean annual temperature from 2008-2017 was -5.33°C, with maximum and minimum temperatures of 2.24°C and -10.74°C, respectively. Mean annual precipitation was 383.9 mm. Temperature variations are relatively stable, while precipitation showed a decreasing trend before 2013 but has increased annually since then (Fig. 2). Daily mean temperatures exceed 0°C from May to September, defining the ablation season, with June-August as the strong ablation period. For the ablation season, daily mean temperatures are 0.50°C, 3.55°C, 6.00°C, 5.53°C, and 0.50°C from May to September, respectively. Minimum temperatures are -2.11°C, 3.05°C, 7.46°C, 3.53°C, and -4.98°C. Monthly precipitation is 36.3 mm, 60.7 mm, 82.8 mm, 79.6 mm, and 39.3 mm, accounting for 77.5% of annual precipitation. Temperature increases gradually before August and decreases thereafter, while precipitation increases before July and decreases afterward (Fig. 2).

3.2 Relationship Between Runoff and Meteorological Elements

To clarify meteorological influences on glacierized area runoff, correlations between runoff and temperature, precipitation, and other indices were analyzed.

Fig. 3 shows runoff autocorrelation and correlations with meteorological elements. Runoff autocorrelation coefficients range from 0.82 to 0.93, indicating strong persistence where daily runoff is highly correlated with previous days' runoff, reflecting the glacier' s role as a "solid reservoir." Runoff shows the strongest positive correlation with temperature (0.86), followed by water vapor pressure (0.81), relative humidity (0.46), and precipitation (0.27). Temperature is the dominant control on runoff. Water vapor pressure, representing atmospheric moisture content, is an important greenhouse gas that alters radiation balance by absorbing shortwave and longwave radiation, thereby increasing meltwater runoff. Relative humidity, calculated as the percentage of actual vapor pressure to saturation vapor pressure, indirectly affects runoff through vapor pressure. The weak correlation with precipitation (0.12-0.27) occurs because precipitation on glaciers is primarily snow, which increases albedo and inhibits melt. Even liquid precipitation contributes less to runoff than temperature-driven melt. No correlation exists with shortwave radiation. Cross-correlations decrease with increasing time lag for all elements except shortwave radiation. These findings align with studies in the Tianshan Mountains and Parlung Glacier No. 4.

Due to data gaps in some years, multivariate regression equations were developed to reconstruct missing runoff. Following previous research, a multivariate exponential nonlinear regression equation using temperature and vapor pressure as independent variables effectively simulates glacierized area runoff. This study uses temperature, precipitation, and vapor pressure as independent variables, achieving the highest correlation. Separate equations were established for each ablation season (2008-2017) and for the mean state (Table 1). The 2008-2010 equations used only temperature and precipitation due to limited observations. Results show that R^2 values from multivariate exponential nonlinear regression exceed those from linear regression. The mean-state equation simulates 2008-2017 runoff with NSE values of 0.70 and relative errors of -1.2% to 38.2% (mean = 19.1%). Year-specific equations perform better, with NSE values of 0.72 and relative errors of -1.9% to -12.4% (mean = -1.3%). Simulated peaks are generally lower than observed due to underestimated precipitation and vapor pressure at Base Camp (4180 m) compared to glacier elevations (4250-5483 m), and because subglacial drainage systems are not considered. Fig. 4 compares observed and simulated runoff.

3.3 Interannual, Seasonal, and Diurnal Runoff Variation

Based on reconstructed and observed data, interannual, seasonal, and diurnal runoff variations were analyzed. Mean ablation season runoff was 1.45 $m^3 \cdot s^{-1}$ in 2008, 1.85 $m^3 \cdot s^{-1}$ in 2013, and 2.30 $m^3 \cdot s^{-1}$ in 2016. The 21st century mean (2.10 $m^3 \cdot s^{-1}$) exceeds the late 1950s value (1.65 $m^3 \cdot s^{-1}$). The coefficient of variation quantifies interannual variability: monthly values are 0.72, 0.66, 0.48, 0.49, and 0.76 for May-September, respectively, with a mean of 0.62, indicating relatively small interannual variation overall.

Seasonal variation shows runoff increasing from May, peaking in July, then decreasing rapidly (Fig. 5). May-September runoff accounts for 5.3%, 16.1%, 37.3%, 35.1%, and 6.2% of the ablation season total, respectively. July contributes the most (37.3%). This aligns with studies showing continental glaciers peak in July-August, accounting for ~72.4% of annual runoff.

Diurnal variation characteristics are shown in Fig. 6. At the beginning and end of the ablation season (May, June, September), diurnal variation is small with flat hydrographs. Minimum and maximum runoff occur at 06:30-07:20 and 15:50-17:00, respectively. During strong ablation (July-August), diurnal variation increases substantially (standard deviations of 0.66 and 0.64 vs. 0.20-0.33 in other months), with rapid rises and falls. Minimum and maximum occur at 06:20-07:00 and 15:00-15:50, respectively. The larger variation results from higher temperatures, enhanced solar radiation, reduced snowfall, and developed supraglacial drainage networks that reduce meltwater retention.

3.4 Time-Lag Effect of Runoff

The time-lag effect refers to the time interval between daily temperature maximum and runoff maximum. Fig. 7 shows monthly diurnal variations of temperature and runoff during the ablation season. Runoff exhibits a distinct "valley-peak" diurnal pattern. In early ablation (May-June), the time interval is large, especially in June when temperature peaks at 14:00 but runoff peaks at 17:00 (3-hour lag). This occurs because heavy snowfall (64.4% of precipitation) and underdeveloped supraglacial drainage delay meltwater transport. In strong ablation (July-August), snowfall decreases, rainfall increases, and surface drainage develops, reducing the time lag. Temperature peaks at 15:00 and runoff peaks at 15:00-15:50, making the curves nearly synchronous. At the end of ablation (September), the interval increases again as temperatures drop and snowfall resumes, though the developed drainage system still allows relatively rapid transport.

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4. Discussion

Runoff observed at the glacier terminus includes contributions from the ablation zone, accumulation zone, and exposed slopes. When the exposed slope area is small, observed runoff approximates glacier meltwater runoff. The cross-section is located ~5-10 m from the terminus, so observed flow primarily reflects glacier meltwater. During the ablation season, runoff variation is mainly controlled by meteorological elements. Runoff correlates most strongly with temperature (0.86), moderately with vapor pressure (0.81) and relative humidity (0.46), and weakly with precipitation (0.27), consistent with studies in the Tianshan Mountains.

The 21st century mean ablation season temperature is 2.10°C, 0.75°C higher than the 1950s-1960s mean of 1.35°C, driving increased runoff from 1.65 to 2.10

$m^3 \cdot s^{-1}$. During strong ablation (July-August), runoff accounts for 72.4% of the ablation season total due to high temperatures (mean 5.8°C), high vapor pressure (0.55 kPa), high relative humidity (64.4%), and substantial precipitation (50.8% of seasonal total). Early and late ablation periods (May-June, September) contribute 16.1% and 6.2%, respectively, with lower temperatures (0.33°C and -0.18°C) and more snowfall. The rain-snow separation temperature in northwest alpine regions is 3.5-5.5°C, so although June precipitation (39.3 mm) exceeds August (36.3 mm), the higher snowfall proportion and lower temperatures result in less runoff.

The time-lag effect is influenced by snowfall, temperature, and supraglacial drainage development. In early ablation, heavy snowfall (64.4% in June) and immature drainage networks maximize the lag. In strong ablation, reduced snowfall and developed drainage minimize the lag. At ablation end, increased snowfall and lower temperatures increase the lag again, though developed drainage partially offsets this effect. Therefore, glacierized area runoff is influenced by temperature, vapor pressure, relative humidity, precipitation, and snow conditions, all of which should be considered in future studies.

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5. Conclusions

1) Temperature in Laohugou watershed showed a decreasing trend before 2013 but has increased recently. Precipitation decreased before 2013 then increased. Runoff autocorrelation coefficients range from 0.82 to 0.93, indicating strong persistence. Runoff correlates most strongly with temperature (0.86), moderately with vapor pressure (0.81) and relative humidity (0.46), and weakly with precipitation (0.27), confirming temperature as the dominant control.

2) Multivariate exponential nonlinear regression equations established for each year using temperature, vapor pressure, and precipitation effectively simulate daily runoff (mean NSE = 0.72, mean relative error = -1.3%). The 21st century mean ablation season runoff (2.10 $m^3 \cdot s^{-1}$) exceeds the 1950s-1960s value (1.65 $m^3 \cdot s^{-1}$), primarily due to a 0.75°C temperature increase. Interannual variation is large during strong ablation but small during early and late ablation periods.

3) Seasonal runoff distribution shows May-September contributions of 5.3%, 16.1%, 37.3%, 35.1%, and 6.2%, respectively. Diurnal variation is small during early and late ablation but large during strong ablation. The time-lag between temperature and runoff peaks is longest in early ablation (maximum 3 hours in June), shortest during strong ablation, and intermediate at ablation end, influenced by temperature, precipitation phase, vapor pressure, relative humidity, and supraglacial drainage development.

Understanding glacier meltwater variation characteristics is essential for water resource management, ecological protection, and sustainable development in arid regions.

References

[1] Huss M, Hock R. Global scale hydrological response to future glacier mass loss[J]. Nature Climate Change, 2018, 8(2): 135-140.

[2] Oerlemans J, Anderson B, Hubbard A, et al. Modelling the response of glaciers to climate warming[J]. Climate Dynamics, 1998, 14(4): 267-274.

[3] Liu Chaohai, Kang Ersi, Liu Shiyin, et al. Study on the glacier variation and its runoff responses in the arid region of northwest China[J]. Science in China Series D, 1999, 29(Suppl. 1): 55-62.

[4] Zhang Jiutian, He Xiaojia, Shangguan Donghui, et al. Impact of intensive glacier ablation on arid regions of northwest China and its countermeasure[J]. Journal of Glaciology and Geocryology, 2012, 34(4): 848-854.

[5] Liu Shiyin, Shen Yongping, Sun Wenxin, et al. Glacier variation since the maximum of the little ice age in the western Qilian Mountains, northwest China[J]. Journal of Glaciology and Geocryology, 2002, 24(3): 227-233.

[6] Liu Y S, Qin X, Chen J Z, et al. Variations of Laohugou Glacier No.12 in the western Qilian Mountains, China, from 1957 to 2015[J]. Journal of Mountain Science, 2018, 15(1): 25-32.

[7] Ren Cai, Long Aihua, Yu Jiawen, et al. Effects of climate and underlying surface changes on runoff of Yarkant River Source[J]. Arid Land Geography, 2021, 44(5): 1373-1383.

[8] Zhao Q D, Ding Y J, Wang J, et al. Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the glacier inventory data and observed streamflow[J]. Journal of Hydrology, 2019, 573: 60-81.

[9] Zhang S Q, Gao X, Zhang X W. Glacial runoff likely reached peak in the mountainous areas of the Shiyang River Basin, China[J]. Journal of Mountain Science, 2015, 12(2): 382-395.

[10] Zhang Z H, Deng S, Zhao Q D, et al. Projected glacier meltwater and river runoff changes in the upper reach of the Shule River Basin, north eastern edge of the Tibetan Plateau[J]. Hydrological Processes, 2019, 33(7): 1059-1074.

[11] Chen J Z, Kang S C, Qin X, et al. The mass balance characteristics and sensitivities to climate variables of Laohugou Glacier No.12, western Qilian Mountains, China[J]. Sciences in Cold and Arid Regions, 2018, 9(6): 543-553.

[12] Kang E. Relationship between runoff and meteorological factors and its simulation in a Tianshan glacierized basin[J]. International Association of Hydrological Sciences Publication, 1991, 205: 189-197.

[13] Hock R, Holmgren B. A distributed surface energy balance model for complex topography and its application to Storglaciären, Sweden[J]. Journal of Glaciology, 2005, 51(172): 25-36.

[14] Reijmer C H, Hock R. Internal accumulation on Storglaciären, Sweden, in a multi-layer snow model coupled to a distributed energy and mass balance model[J]. Journal of Glaciology, 2008, 54(184): 61-72.

[15] Pellicciotti F, Buergi C, Immerzeel W W, et al. Challenges and uncertainties in hydrological modeling of remote Hindu Kush Karakoram Himalayan (HKH) basins: Suggestions for calibration strategies[J]. Mountain Research and Development, 2012, 32(1): 39-50.

[16] Singh P, Kumar A, Kumar N. Hydro-meteorological correlations and relationships for estimating streamflow for Gangotri Glacier basin in western Himalayas[J]. International Journal of Water Resources and Environmental Engineering, 2010, 3(2): 60-69.

[17] Srivastava D, Kumar A, Verma A, et al. Analysis of climate and runoff in Dunagiri glacier of Garhwal Himalaya (India)[J]. Water Resources Management, 2014, 28(10): 3035-3055.

[18] Shi Y F, Liu C H. The glacier inventory of China[J]. Annals of Glaciology, 2010, 50: 1-4.

[19] Kang X, Ding L. Relation of mass balance, ELA and climate in Tianshan Mountain and Qilian Mountain[J]. Journal of Glaciology and Geocryology, 1981, 3(1): 53-56.

[20] Qin Dahe. Introduction to cryospheric science[M]. Beijing: Science Press, 2017: 322-323.

[21] Ye Baisheng, Yang Daqing, Ding Yongjian, et al. China rainfall observation error analysis and correction[J]. Journal of Geographical Sciences, 2007, 62(1): 3-13.

[22] Qin Xiang, Cui Xiaoqing, Du Wentao, et al. Variations of the alpine precipitation during 1960—2006 recorded in Laohugou ice core in western Qilian Mountains, China[J]. Journal of Geographical Sciences, 2014, 9(5): 681-689.

[23] Basistha A, Arya D S, Goel N K. Spatial distribution of rainfall in Indian Himalayas: A case study of Uttarakhand Region[J]. Water Resources Management, 2008, 22: 1325-1346.

[24] Solomon, Rosenlof, Portman, et al. Contributions of stratospheric water vapor to decadal changes in the rate of global warming[J]. Science, 2010, 327(5970): 1219-1223.

[25] Li S H, Yao T D, Yang W, et al. Melt season hydrological characteristics of the Parlung No.4 Glacier, in Gangrigabu Mountains, southeast Tibetan Plateau[J]. Hydrological Processes, 2016, 30(8): 1252-1263.

[26] Li Z, Wang W, Zhang M, et al. Observed changes in streamflow at the headwaters of the Urumqi River, eastern Tianshan, Central Asia[J]. Hydrological Processes: An International Journal, 2010, 24(2): 217-224.

[27] Liu Shuangshuang, Li Zhongqin, Zhang Hui, et al. Temporal inner-annual runoff variation in the typical glacier region of the eastern Tianshan Mountains, China[J]. Arid Zone Research, 2020, 37(6): 1388-1395.

[28] Zhang Xiaopeng, Qin Xiang, Wu Jinkui, et al. Response of glacier runoff to climate change in the Laohugou Basin, Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2017, 39(1): 148-155.

[29] Zhang Xueyan, Qin Xiang, Wu Jinkui, et al. Analysis of the characteristics of runoff yield and confluence in the Laohugou Basin, Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2017, 39(1): 140-147.

[30] Chen Rensheng, Kang Ersi, Ding Yongjian. Some knowledge on and parameters of alpine hydrology[J]. Advances in Water Science, 2014, 25(3): 308-317.

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