Analysis of Intra-annual Runoff Variation in Typical Glacial Regions of the Tian Shan: Postprint

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Abstract

Based on hydrological and meteorological data from the Urumqi River Source Glacier No. 1 region in the Tianshan Mountains during 1980–2016, this study analyzed the variation characteristics and causes of runoff in the glacierized area at monthly, daily, and hourly scales. The results indicate: (1) During 1980–2016, runoff during the ablation period (May–September) exhibited an overall increasing trend, with a trend rate of 3.44$×10^{4}$ $m^3 \cdot a^{-1}$, among which the increasing trend was particularly significant from June to August. Over the 37-year period, August contributed the most to runoff increase, followed by June and July, while May and September contributed the least. Runoff in the ablation period increased significantly in 1993, and runoff from May to August all experienced abrupt changes in the 1990s. (2) Daily runoff increased significantly from the 1980s through the 1990s to the 2000s, but decreased during 2010–2016. The timing of daily runoff peaks showed a clear advancing trend from the 1980s–1990s, but stabilized during 2010–2016. (3) During 2011–2016, diurnal flow variations in July and August were more significant. The daily flow curve exhibited a "peak-valley" diurnal variation pattern, with peak occurrence times in July and August earlier than those in June and September. (4) During 1980–2016, both temperature and precipitation in the ablation period in this basin showed increasing trends. Correlation analysis indicated that runoff from June to August was significantly positively correlated with temperature. Overall, intra-annual runoff in the glacierized area demonstrated good synchrony with temperature and precipitation at monthly and daily scales, indicating that its variation is primarily controlled by concurrent temperature and precipitation conditions.

Full Text

Preamble

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Temporal Inner-Annual Runoff Variation in the Typical Glacier Region of the Eastern Tianshan Mountains, China

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Abstract

Based on hydrological and meteorological data from 1980 to 2016, this study analyzed the variation characteristics and driving factors of runoff in the Urumqi Glacier No. 1 region at monthly, daily, and hourly scales. The results indicate that runoff during the ablation period (May–September) exhibited an overall increasing trend with a rate of 3.44$\times10^{-1}$, with August showing the lowest baseline flow but the most significant upward trend. Runoff increased markedly after 1993, with monthly discharge in June, July, and August all showing significant increases. August contributed the most to the total runoff increase, followed by June and July, while May and September contributed minimally. Daily runoff data revealed that discharge increased substantially during the 1980s and 1990s, decreased slightly in the 2000s, but remained elevated overall. The timing of daily peak flow advanced noticeably during the 1980s–1990s but stabilized after the 1990s. Hourly-scale analysis demonstrated pronounced diurnal flow variations, particularly in July and August, with flow curves exhibiting distinct peak-valley patterns. Both temperature and precipitation during the ablation period showed upward trends. Correlation analysis revealed significant positive relationships between monthly runoff and temperature from June to August. Overall, runoff, temperature, and precipitation demonstrated strong synchrony at monthly and daily scales, indicating that short-term runoff variations are primarily controlled by concurrent temperature and precipitation conditions.

Keywords: Tianshan Mountains; Urumqi Glacier No. 1; inner-annual runoff variation; climate change

Introduction

Glaciers serve as critical "solid reservoirs" that sustain river discharge and agricultural irrigation in arid regions. The Tianshan Mountains, often called the "Central Asian Water Tower," contain extensive glaciers that constitute a vital component of water resources in Central Asian arid zones. Under climate warming, Tianshan glaciers have experienced significant retreat, with approximately 18% area loss and 26% mass loss since the 1960s. This retreat has altered annual runoff patterns, increasing flood risks and intensifying seasonal water supply contradictions. Previous studies have documented rising river discharge in winter, spring, and summer across various Tianshan tributaries, with peak flows shifting significantly.

Glacier runoff exhibits complex inner-annual variations spanning monthly, daily, and hourly scales. For instance, the Koxkar Glacier in the Tomur-Khan Tengri region shows maximum daily discharge occurring 4–10 hours after peak temperatures, with minimum flows at 7:00–10:00 and maximum flows at 15:00–18:00. Such variations directly impact agricultural irrigation and socioeconomic sustainability in downstream arid regions. Accurately characterizing these inner-annual patterns is essential for water resource management and disaster prevention, yet systematic long-term observations remain limited due to harsh environmental conditions.

Urumqi Glacier No. 1 (hereafter "Urumqi Glacier") is among the longest-monitored and most systematically observed reference glaciers in the Tianshan Mountains and globally. Since 1959, the glacier has retreated by 26% and split into eastern and western branches, with a combined area of 1.54 km^2 in 2018. As the headwater of the Urumqi River, its runoff variations critically affect regional industrial, agricultural, and municipal water supplies. While previous research has established temperature as the primary control on runoff, particularly summer temperatures, systematic analysis of inner-annual (monthly, daily, hourly) runoff characteristics remains lacking. This study leverages comprehensive hydrometeorological data from the Tianshan Glaciological Station to analyze runoff allocation and variation patterns, aiming to elucidate hydrological responses to accelerated glacier melt under climate warming and provide scientific references for water resource assessment across the Urumqi River basin and Central Asia.

1. Study Area, Data, and Methods

1.1 Study Area

Urumqi Glacier No. 1 (43°07 33.98 -43°07 34.155 N, 86°48 35.456 -86°48 20.896 E) is located on the northern slope of Tianger Peak in the central Tianshan Mountains, serving as the source of the Urumqi River. The hydrological monitoring section, established in the 1980s, is situated 300 m from the glacier terminus at 3,693 m elevation, controlling a 3.34 km^2 basin comprising Urumqi Glacier, moraine deposits, and exposed bedrock. The region exhibits a continental climate with hot, rainy summers and cold, dry winters. According to Daxigou Meteorological Station (43°06 N, 86°50 E, 3,539 m), the multi-year mean precipitation is 480 mm (concentrated in May–September) and mean annual temperature is -4.7 °C.

1.2 Data Sources

Hydrological observations at Urumqi Glacier began in 1959 following national standards (SL 58-2014 and GB/T 50138-2010). A CS456 pressure-type water level sensor recorded water levels every 10 minutes during the ablation period (May–September). Flow velocity was measured using propeller and Doppler current meters to establish stage-discharge rating curves. Observations were suspended after 1993 but resumed in 1998. To ensure data continuity, this study uses daily discharge data from 1998–2016, supplemented by reconstructed 1980–1997 data from previous modeling studies. Hourly meteorological data (2011–2016) were obtained from a monitoring tower near the glacier terminus.

1.3 Methods

Linear trend analysis and Mann-Kendall (M-K) trend tests were employed to detect runoff trends during the ablation period and individual months. The linear trend method uses regression to identify increasing or decreasing patterns, while the M-K test statistically evaluates trend significance. For the M-K test, the null hypothesis (H_0) assumes no trend in dataset X, while the alternative hypothesis (H_1) indicates a monotonic trend. The test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where sgn(xj - xi) equals +1, 0, or -1 when xj - xi is greater than, equal to, or less than zero, respectively. For large samples, S is transformed to Zc:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} & S < 0 \end{cases}$$

Trend significance is assessed at 95% (|Zc| > 1.96) and 99% (|Zc| > 2.58) confidence levels. The M-K mutation test identifies abrupt changes by constructing a rank sequence Sk and standardized statistic UFk. The intersection point between UFk and its reversed sequence UBk within critical lines indicates the mutation time.

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2. Results

2.1 Monthly-Scale Runoff Variation

During the ablation period (May–September), runoff exhibited a significant increasing trend at a rate of 3.44$×10{-1}, thoughmonthlypatternsvaried(Figure3).Augustshowedthehighestincreaserate(1.52×1 1}), followedbyJuneandJuly(both0.98×10{-1}), whileMayandSeptemberhadminimalincreases(0.02×10{- 1}$ and 0.21$×10^{-1}$, respectively). Consequently, August contributed most to total runoff increase (53%), followed by June (27%) and July (20%). M-K tests confirmed significant upward trends in June, July, and August at the 99% confidence level, while May and September showed no significant trends (Table 1).

Table 1 Mann-Kendall test statistics for ablation period and monthly runoff of Urumqi Glacier No. 1 (1980–2016)

The accumulated difference curve revealed that ablation period runoff remained consistently high after 1993, with slight declines after 2000. Specifically, runoff increased by 27% after 1993 and 35% after 1997. M-K mutation tests indicated that monthly runoff for June, July, and August underwent abrupt changes in the 1990s, consistent with the accumulated difference analysis, while May and September mutations occurred later (2002 and 2005, respectively).

2.2 Daily-Scale Runoff Variation

Daily runoff data show that multi-year average discharge begins in early May, peaks around July 20, and declines until late September, lasting approximately 153 days. Daily runoff increased substantially during the 1980s (1.74$×10^{-1}$) and 1990s, decreased slightly in the 2000s, but maintained an overall upward trend (Figure 2). The 1990s exhibited the largest increase, particularly in July and August, while the 2000s showed reduced but still elevated flows compared to the 1980s.

The timing of daily peak flow advanced significantly during the 1980s–1990s but stabilized after the 1990s. In the 1980s, peak flow occurred on July 20, advancing to July 15 in the 1990s—a 5-day advance. However, from the 1990s onward, the peak timing remained stable at July 15-16. This stabilization coincides with reduced interdecadal temperature and precipitation increases during the 2000s. Flow duration curves widened across decades, indicating more sustained high flows, with the most pronounced fluctuations occurring in 1996 when temperature and precipitation variability peaked.

2.3 Hourly-Scale Runoff Variation

Hourly observations (2011-2016) revealed that daytime discharge (9:00-20:00) consistently exceeded nighttime discharge (21:00-8:00) throughout the ablation period (Figure 4). July and August showed the largest diurnal amplitude, with daytime flows 1.3-1.5 times greater than nighttime flows. The diurnal cycle exhibited clear peak-valley patterns, with minimum flows at 8:00-9:00 and maximum flows at 15:00-18:00. Peak arrival time was shortest in July and August (6-7 hours) and longest in June and September (9-10 hours), reflecting faster melt response to temperature during peak summer months.

2.4 Basin Climate Change

From 1980-2016, ablation period temperature increased significantly at 0.5 °C per decade ($P < 0.01$), with a mutation point in the mid-1990s. Precipitation also increased at 7.5 mm per decade ($P < 0.01$), with a mutation around 1995. Daily-scale analysis shows temperature increases became particularly pronounced after July 15, while precipitation remained relatively stable across decades. The 1990s experienced the most significant temperature rise, though precipitation increases were modest compared to temperature.

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3. Discussion and Conclusions

3.1 Discussion

Glacier runoff comprises meltwater from snow/firn in the accumulation zone, ice melt from the ablation zone, and runoff from exposed slopes. Climate conditions, particularly temperature and precipitation, drive these processes. At monthly scales, June-August runoff showed significant positive correlations with temperature ($r > 0.6$) but weak correlations with precipitation (Table 2). While May temperature trends were insignificant despite precipitation increases, June-August runoff increases occurred with strong warming and minimal precipitation change, confirming temperature as the dominant control.

Table 2 Correlation coefficients between monthly runoff and temperature/precipitation (1980-2017)

At daily scales, runoff patterns closely tracked interdecadal temperature variations. The advancement of peak flow timing during the 1980s-1990s reflects accelerated melt response to warming, while stabilization after the 1990s suggests a new equilibrium where increased melt is sustained throughout summer. The diurnal peak-valley pattern, with 6–10 hour lags behind temperature peaks, reflects meltwater transit time through the glacier system.

3.2 Conclusions

This study reveals distinct inner-annual runoff variation patterns in the Urumqi Glacier No. 1 region from 1980–2016:

1. **Monthly scale**: Ablation period runoff increased significantly (3.44$×10^{-1}$), with August contributing most (53%) to the increase. June, July, and August showed significant upward trends, while May and September exhibited minimal change. Runoff increased abruptly after 1993, with monthly mutations occurring in the 1990s.
2. **Daily scale**: Runoff increased during the 1980s–1990s, decreased slightly in the 2000s, but remained elevated overall. Peak flow timing advanced by approximately 5 days during the 1980s–1990s (from July 20 to July 15) but stabilized after the 1990s. Flow duration curves widened, indicating more sustained summer discharge.
3. **Hourly scale**: Diurnal variations were pronounced, with daytime flows exceeding nighttime flows by 30–50% in July and August. Peak flows occurred at 15:00–18:00, with 6–10 hour lags behind temperature maxima.
4. **Climate controls**: Ablation period temperature and precipitation both increased significantly, with mutations in the mid-1990s. Runoff correlated strongly with temperature at monthly and daily scales, while precipitation effects were secondary. Short-term runoff variations primarily reflect combined temperature and precipitation conditions in the glacierized basin.

These findings underscore the sensitivity of glacier runoff to climate warming and highlight the importance of high-resolution observations for understanding hydrological responses in Central Asian water resources.

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Note: Figure translations are in progress. See original paper for figures.