Impacts of Climate and Underlying Surface Changes on Headwater Runoff of the Yarkant River (Postprint)

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Abstract

Taking the upper headwater region of the Yarkant River basin as the study area, a SWAT distributed hydrological model embedded with a glacier module was constructed to simulate the monthly runoff at Kaqun Hydrological Station from 1968 to 2017, evaluate the applicability of the model in the study area, analyze the interannual variation and intra-annual distribution of glacier runoff based on the simulation results, and quantitatively calculate the contribution rates of climate and underlying surface changes to runoff variation. The results indicate that the model demonstrates good applicability for runoff simulation in the study area, with the coefficient of determination (R^2) being 0.77 and 0.86, Nash-Sutcliffe efficiency (NSE) being 0.76 and 0.85, ratio of root mean square error to standard deviation of observations (RSR) being 0.49 and 0.38, and percent bias (PBIAS) being -7.4% and 0.6% for the calibration period (1968-1992) and validation period (1993-2017), respectively. According to the simulation, glacier runoff in the study area shows an overall increasing trend over the past 50 years, accounting for approximately 51.1% of the total runoff; intra-annual glacier runoff generation occurs primarily from June to September, representing over 90.0% of the annual glacier runoff. Climate and underlying surface changes increased monthly runoff by 6.62 $m^3 \cdot s^{-1}$ and 0.41 $m^3 \cdot s^{-1}$, respectively, with climate change contributing 94.2%, indicating that climate change dominates the impact on runoff in the study area. The research findings can provide a scientific basis for understanding the causes of historical runoff changes and predicting future runoff evolution trends in the study area.

Full Text

Effects of Climate and Underlying Surface Changes on Runoff in the Yarkant River Source Area

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Abstract

Climate and underlying surface changes are the primary factors affecting watershed hydrological cycle processes. Research on runoff evolution responses to these changes across different temporal and spatial scales forms the basis for water resources planning and management. This study focuses on the upper source area of the Yarkant River Basin, where a distributed hydrological model embedded with glacier modules was constructed to simulate monthly runoff at the Kaqun Hydrological Station from 1968 to 2017. The model' s applicability was evaluated, and simulation results were used to analyze interannual variability and intra-annual distribution of glacier runoff, while quantitatively calculating the contribution rates of climate and underlying surface changes to runoff variation.

Results demonstrate strong model performance, with calibration period (1968–1992) and validation period (1993–2017) metrics showing R^2 values of 0.77 and 0.86, Nash-Sutcliffe efficiency (NSE) of 0.76 and 0.85, ratio of root mean square error to standard deviation (RSR) of 0.49 and 0.38, and percent bias (PBIAS) of -7.4% and 0.6%, respectively. Simulations reveal that glacier runoff increased overall during the past 50 years, accounting for approximately 51.1% of total runoff. Glacier runoff primarily occurs from June to September, representing over 90.0% of annual glacier runoff. Climate change and underlying surface change increased monthly runoff by 6.62 $m^3 \cdot s^{-1}$ and 0.41 $m^3 \cdot s^{-1}$, respectively, with climate change contributing 94.2% of the total impact, indicating its dominant role. These findings provide a scientific basis for understanding historical runoff changes and predicting future trends in the study area.

Keywords: climate change; underlying surface change; SWAT model; glacier runoff simulation; Yarkant River Basin

Introduction

Climate and underlying surface changes represent the main factors altering watershed hydrological cycle processes, with runoff evolution under varying climate and underlying surface conditions forming the foundation for water resources planning and management. Current research primarily employs comparative analysis, statistical analysis, and hydrological modeling methods. Among these, physically-based distributed hydrological models can fully reflect watershed spatial heterogeneity, accurately characterize hydrological processes, and reveal internal mechanisms of the water cycle, making them widely used for studying climate and underlying surface change impacts on runoff.

The Soil and Water Assessment Tool (SWAT) is a semi-distributed watershed hydrological model based on physical processes that has been applied in numerous Chinese watersheds, particularly in northwest inland river basins with scarce measured data. However, most studies simulate runoff from rainfall or snowmelt perspectives, with limited research on glacier hydrological processes. In the Tarim River Basin source area, for example, previous applications of MIKE SHE and other models have shown limitations in simulating glacier- and snowmelt-fed river runoff, yielding insufficient accuracy for water management decision-making.

This study addresses the upper source area of the Yarkant River Basin, utilizing glacier inventory data to correct glacier spatial distribution, constructing a SWAT model capable of simulating glacier hydrological processes, and quantifying the contributions of climate and underlying surface changes to runoff evolution. The results provide scientific support for ecological protection, water resources management, and policy formulation in the region.

1.1 Study Area Overview

The upper source area of the Yarkant River Basin lies on the northern slope of the Karakoram Mountains (74°27 -78°24 E, 35°26 -38°18 N), covering 46,404.87 km^2 (46.9% of the total basin area). The terrain slopes from high in the south to low in the north, dominated by alpine snow zones, subalpine and alpine meadow zones, and low mountain hilly zones. Elevations range from 1,450 to 8,537 m, exhibiting pronounced continental climate characteristics [Figure 1: see original paper].

The area hosts 1,447 Quaternary glaciers with total area of 5,315 km^2, total storage of 684.5 km^3, and annual meltwater of 38.24$\times10^{8}$ m^3. The multi-year average temperature is -10.2°C. Precipitation is topography-dependent, with approximately 700 mm in alpine zones, 300 mm in mid-alpine zones, and 150 mm in mid-low mountain zones. The river system is typical of glacier-snowmelt-fed rivers, with the main stream length of 585 km. At the mountain outlet Kaqun Station (76°54 E, 37°59 N), annual runoff is 66$\times10^{8}$ m^3, with glacier-snowmelt accounting for 77.4% of the total. Runoff distribution is extremely uneven intra-annually, with June–September flows representing 73.8%

of the annual total.

1.2 Data Sources

1.2.1 DEM and Glacier Inventory Data Digital Elevation Model (DEM) data were obtained from the International Scientific Data Service Platform at 90 m resolution, used for extracting terrain information, calculating flow direction and catchment area, delineating river networks, and sub-basin division. The first glacier inventory (from 1960s aerial topographic maps) and second glacier inventory (from Landsat TM/ETM+ and ASTER remote sensing imagery) were used to determine glacier spatial distribution during calibration and validation periods.

1.2.2 Underlying Surface Data Domestic underlying surface data were sourced from Geospatial Data Cloud (http://www.gscloud.cn) at 30 m resolution based on Landsat imagery. Foreign data used the Global Land Cover dataset (GLC2000) from the EU Joint Research Centre. Glacier vector data from both inventories replaced glacier types in the original classification. A reclassification index table was established according to SWAT standards , yielding the required underlying surface type map [Figure 2: see original paper].

1.2.3 Soil Data Domestic soil data were obtained from the 1:1,000,000 soil database of the Institute of Soil Science, Chinese Academy of Nanjing. Foreign data used the Harmonized World Soil Database from FAO and IIASA. Glacier vector data replaced ice/snow types, and soil attribute parameters were retrieved using the SPAW software and China Soil Database (http://vdb3.soil.csdb.cn). Reclassification according to SWAT standards produced the required soil type map [Figure 3: see original paper].

1.2.4 Meteorological and Hydrological Data With only one national meteorological station (Taxkorgan) in the study area, its data alone cannot represent the entire regional climate. Therefore, daily precipitation and temperature data from China Ground Precipitation and Temperature Dataset (http://data.cma.cn) were used, interpolated from 2,472 national stations and validated to reflect spatial distribution characteristics. Runoff data for model calibration and validation were monthly observations from Kaqun Station (1968–2017).

1.3 Methods

1.3.1 Trend Analysis of Precipitation, Temperature, and Runoff Linear regression was used to analyze historical trends in climate characteristics and annual runoff, with non-parametric Mann-Kendall tests for significance.

1.3.2 Glacier Module Algorithm The glacier module uses an enhanced temperature-index method for robust calculation at watershed scale with limited data, better explaining spatial heterogeneity from local topography compared to degree-day methods. Key equations include:

Glacier daily melt:

$$M = (c + I_{pot} \times S_{mlt,ice}) \times (T - T_{mlt,ice})$$

where M is glacier daily melt (m^3), c is a constant, I_{pot} is potential solar radiation, $S_{mlt,ice}$ is ice radiation melt factor, T is daily mean temperature (°C), and $T_{mlt,ice}$ is threshold temperature for glacier melt.

Glacier volume:

$$V = \gamma \times S^{1.375}$$

where V is glacier volume (km^3), S is glacier area (km^2), and γ is a dimensionless scaling coefficient.

Glacier mass accumulation:

$$F = W_{se} \times \beta \times (1 + \sin(\frac{2\pi t}{365} - 81))$$

where F is glacier mass accumulation, W_{se} is snow water equivalent, β is base accumulation coefficient, and t is day number.

1.3.3 Hydrological Process Simulation The SWAT model, developed by the USDA Agricultural Research Service, is a physically-based semi-distributed model widely used for watershed simulation and management. The modeling process involves: (1) watershed discretization based on DEM, (2) HRU division using land use, soil, and slope data, and (3) hydrological process simulation driven by meteorological data with parameter adjustment and validation [Figure 4: see original paper].

The SUFI-2 algorithm was used for sensitivity analysis. Fifteen sensitive parameters were auto-calibrated, then manually adjusted based on glacier hydrology processes and reference studies until meeting evaluation criteria. Performance metrics included coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), ratio of RMSE to standard deviation (RSR), and percent bias (PBIAS):

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim,i} - \bar{Q}_{sim})^2}} \right]^2$$

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

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

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

where $Q_{sim,i}$ and $Q_{obs,i}$ are simulated and observed runoff at time step i ($m^3 \cdot s^{-1}$), and $\bar{Q}_{sim}$ and $\bar{Q}_{obs}$ are mean values.

1.3.4 Quantifying Impacts of Climate and Underlying Surface Changes Cross-combination of climate and underlying surface data from different periods created four scenarios to quantify individual and combined effects:

- S_0: Baseline scenario (1968 climate + 1968 underlying surface)
- S_1: Climate change scenario (2017 climate + 1968 underlying surface)
- S_2: Underlying surface change scenario (1968 climate + 2017 underlying surface)
- S_3: Combined change scenario (2017 climate + 2017 underlying surface)

Contribution rates were calculated as:

$$\beta_C = \frac{\Delta Q_C}{\Delta Q_{C+L}} \times 100\%$$

$$\beta_L = \frac{\Delta Q_L}{\Delta Q_{C+L}} \times 100\%$$

where ΔQ_{C+L} is total runoff change under combined effects, ΔQ_C is change due to climate, ΔQ_L is change due to underlying surface, and β_C and β_L are contribution rates.

2 Results and Analysis

2.1 Characteristics of Precipitation, Temperature, and Runoff Changes

Trend analysis of Taxkorgan meteorological and Kaqun hydrological station data (1968–2017) shows significant increases [FIGURE:5, FIGURE:6, FIGURE:7]. Annual precipitation increased by 39.8 mm (significant at α=0.05), mean temperature rose by 2.44°C, and annual runoff increased by 17.20$×10^{8}$ m^3. Mann-Kendall tests confirm all trends are statistically significant.

2.2 Model Simulation Results

2.2.1 Parameter Selection and Calibration SUFI-2 sensitivity analysis identified 15 key parameters for auto-calibration, followed by manual adjustment based on glacier hydrology processes . The 200 km^2 catchment threshold divided the watershed into 31 sub-basins and 185 HRUs. The period 1968–1972 served as model warm-up, 1973–1992 as calibration, and 1993–2017 as validation.

2.2.2 Simulation Evaluation Monthly simulation results for calibration and validation periods are shown in [Figure 8: see original paper] and [Figure 9: see original paper], with performance metrics in . Calibration period statistics (R^2=0.77, NSE=0.76, RSR=0.49, PBIAS=-7.37%) and validation period statistics (R^2=0.86, NSE=0.85, RSR=0.38, PBIAS=0.59%) both indicate "excellent" performance. The glacier-embedded SWAT model accurately captures monthly runoff patterns, though some years with glacial lake outburst floods (e.g., 1998–1999) show larger errors during flood peaks.

2.2.3 Glacier Hydrological Process Analysis Interannual variations show both total runoff and glacier runoff increasing over the past 50 years [Figure 10: see original paper]. Mean annual runoff was 68.26$×10^{8}$ m^3, while mean glacier runoff was 34.87$×10^{8}$ m^3, contributing 51.1% of total runoff (range: 34.0%-70.4%). Intra-annual distribution [Figure 11: see original paper] reveals glacier runoff occurs primarily June–September (>90.0% of annual total), with monthly contributions ranging from 11.9% to 74.0% of total flow. The peak runoff period has advanced by approximately one month over the study period, indicating accelerated glacier melt.

2.3 Impacts of Climate and Underlying Surface Changes on Runoff

Quantitative analysis shows climate change increased monthly runoff by 6.62 $m^3 \cdot s^{-1}$ (94.2% contribution), while underlying surface change increased it by 0.41 $m^3 \cdot s^{-1}$ (5.8% contribution). Under combined changes, monthly runoff increased by 7.03 $m^3 \cdot s^{-1}$. The response shows additive effects, with climate change dominating runoff evolution.

3 Conclusions and Discussion

The Yarkant River source area exhibited significant warming and wetting from 1968–2017, accelerating glacier melt and increasing runoff. Based on SWAT modeling with an embedded glacier module, this study analyzed meteorological and hydrological changes, distinguished and quantified climate versus underlying surface impacts, yielding three main conclusions:

1) Precipitation, temperature, and runoff showed significant increasing trends with annual growth rates of 0.83 mm/yr, 0.05°C/yr, and 0.34$×10^{8}$ m^3/yr, respectively. With 12.6% glacier coverage, glacier hydrological processes must be considered alongside rainfall and snowmelt.

The enhanced temperature-index glacier module demonstrates robust performance in data-scarce watersheds, better explaining topographic heterogeneity than degree-day methods. The glacier-embedded SWAT model achieved "excellent" ratings for calibration, validation, and full-period simulations, though discrepancies remain due to glacial lake outburst floods and input data uncertainties.

2) Simulated annual runoff and glacier runoff both show increasing trends, with glacier runoff comprising 51.1% of total flow—consistent with similar glacier-fed rivers in comparable climates. Monthly glacier runoff contributions range from 11.9% to 74.0%, peaking in July–August and accounting for >90.0% of annual glacier runoff. Notably, the runoff peak has advanced by nearly one month, indicating accelerating glacier melt.
3) Climate and underlying surface changes increased monthly runoff by 6.62 $m^3 \cdot s^{-1}$ and 0.41 $m^3 \cdot s^{-1}$, with contribution rates of 94.2% and 5.8%, respectively. Climate change dominates runoff impacts, with temperature rise and precipitation increase being primary drivers.

Study limitations include: (1) difficulty obtaining meteorological datasets, suggesting future use of remote sensing-assimilated reanalysis data; (2) exclusion of water conservancy projects' impacts on runoff; and (3) lack of future scenario predictions using different climate models. Future research should address these gaps to better support water resources management.

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