

Postprint of a Study on a Simple Snowmelt Model Based on Air Temperature Variation

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Abstract

In arid regions, snow and ice melt constitute the primary source of water resource formation. Consequently, the formation, transformation, and utilization of snow resources represent important components of water resources development and utilization research in Xinjiang, while hydrological models serve as critical approaches for determining water resource formation and transformation quantities. Using the field experimental area of the Tianshan Snow Station of the Chinese Academy of Sciences as the research base, with meteorological data as independent variables and snowmelt amount as the dependent variable, this study investigated a temperature-based snowmelt model. The established single-factor simple model was calibrated and validated, while multi-year snowmelt variation patterns in the experimental area and the response process of snowmelt to temperature were analyzed. The results indicate that snowmelt still occurs during winter under certain low-temperature conditions. The critical value of daily mean temperature for snowpack ablation in the study watershed of the Tianshan Mountains is approximately -7°C ; when the daily mean temperature falls below -7°C , snowmelt essentially enters a suspended state, reflecting the characteristics of snowmelt in arid regions. Regarding the model, the single-factor simple snowmelt model constructed based on temperature demonstrates good representativeness in simulating mountain snowmelt amounts. During the calibration period (2016–2020), the correlation parameters between observed and simulated snowmelt amounts—bias, mean absolute error, root mean square error, Nash–Sutcliffe efficiency coefficient, and determination coefficient—were -0.037 , 0.367 , 0.482 , 0.870 , and 0.876 , respectively; while during the validation period, these values were -0.210 , 0.292 , 0.577 , 0.845 , and 0.811 , respectively. The simulation results and correlation coefficients from the validation period demonstrate that the model's simulated values exhibit good consistency and stability with observed values. Its advantage lies in the ability to estimate watershed snowmelt amounts using readily accessible meteorological data. The

research findings provide a relatively simple algorithm for snowpack ablation calculations in arid regions and offer a simple yet effective snowmelt sub-module for hydrological models. This study holds important reference value for understanding local snowmelt variation patterns and for subsequent snowmelt runoff simulation and forecasting.

Full Text

A Simple Snowmelt Model Based on Temperature Variation

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Abstract: In arid regions, snowmelt constitutes the primary source of water resource formation. Consequently, the formation, transformation, and utilization of snow resources represent critical research topics for water resource development and utilization in Xinjiang, while hydrological modeling serves as the key approach for quantifying these processes. Using the field experimental area of the Tianshan Snow Station, Chinese Academy of Sciences as the study site, this research develops a temperature-based snowmelt model with meteorological data as independent variables and snowmelt amount as the dependent variable. The simple single-factor model was calibrated and validated, while multi-year snowmelt variation patterns and the response of snowmelt to temperature were analyzed. Results indicate that snowmelt continues to occur during winter within certain low-temperature ranges. In the study watershed of the Tianshan Mountains, the critical daily mean temperature for snowpack ablation is approximately °C. When daily mean temperature falls below °C, snowmelt essentially ceases, reflecting the distinctive characteristics of snowmelt in arid environments. Regarding model performance, the temperature-based single-factor snowmelt model demonstrates good representativeness for simulating mountain snowmelt. During the calibration period (2016–2020), the correlation parameters between observed and simulated snowmelt values were: bias = 0.037, MAE = 0.367, RMSE = 0.482, NSE = 0.870, and $R^2 = 0.876$. During the validation period, these values were 0.210, 0.292, 0.577, 0.845, and 0.811, respectively. The simulation results and correlation coefficients during validation demonstrate good consistency and stability between simulated and observed values. The primary advantage of this model is its ability to estimate watershed snowmelt using readily available meteorological data. The research findings provide a relatively simple algorithm for snowmelt calculation in arid regions

and an effective snowmelt submodule for hydrological models, offering important reference value for understanding local snowmelt patterns and subsequent snowmelt runoff simulation and forecasting.

Keywords: temperature variation; snowmelt model; Tianshan Mountains

Global climate change and water resource issues represent shared concerns for governments and academic communities worldwide, constituting a critical bottleneck for leapfrog development in northwest China's arid regions. Xinjiang's water resource formation and hydrological cycle processes exhibit unique characteristics in these arid environments, with high mountains intercepting atmospheric moisture to generate precipitation that feeds numerous rivers. The negative temperature conditions in alpine zones cause precipitation to occur as either rainfall or snowfall, with a portion of snowfall temporarily or permanently stored in mountainous areas, developing extensive glaciers that provide relatively abundant and stable runoff. Snowpack serves as a crucial freshwater resource; although global snow precipitation accounts for only about 5% of total precipitation, this proportion is substantially higher in Xinjiang's Tianshan region, approaching nearly half of total precipitation. The Tianshan Mountains, a high-altitude range representing the primary region of runoff formation in Xinjiang, experience rapid spring warming that triggers rapid snowmelt at mid-low elevations and piedmont plains, generating snowmelt floods that disrupt or damage transportation, animal husbandry, agricultural infrastructure, and human lives. In recent decades, the Ili River Valley has experienced severe spring snowmelt flood disasters. Therefore, understanding snowpack and snowmelt patterns is essential for water resource assessment, regulation, and snowmelt flood prevention in this region.

Current research on Tianshan snowpack primarily focuses on remote sensing of snow cover at watershed scales, application and evaluation of extended products, improvement of retrieval methods, runoff sequence simulation, and parameter modification in snowmelt runoff models (SRM). Snowmelt models generally fall into two categories: degree-day models and energy balance models. Degree-day models, typical statistical models, have been widely applied in snow and ice melt research. However, these models have limitations: when applied to different watersheds, model parameters require calibration, yet mountainous areas with limited accessibility often lack observation stations, making it difficult to obtain meteorological data on temperature, precipitation, snowpack, and snowmelt in high-cold mountainous regions. Consequently, empirical and semi-empirical degree-day factors are difficult to acquire, affecting result reliability. To address these limitations, this study conducted experimental research on snowpack, snowmelt, and related meteorological elements in the western Tianshan Mountains, aiming to quantify the relationship between snowmelt amount and temperature, develop a simple temperature-based snowmelt model, reveal mountain snowmelt variation patterns and temperature response mechanisms, and provide a simple algorithm for watershed snowmelt flood simulation and forecasting.

1. Study Area Overview

The study area is located on the northern slope of the Tianshan Mountains in Xinjiang, China, covering a watershed area of approximately 2 km². Specifically, it comprises the field experimental watershed west of the Tianshan Snow and Avalanche Research Station, with elevations ranging from 1100 to 3100 m and topography that is high in the south and low in the north. The watershed exhibits distinct semi-arid mountainous hydrological characteristics.

2.1 Data Acquisition

Meteorological data were automatically collected using a Campbell CR1000 data logger, measuring air temperature, humidity, atmospheric pressure, rainfall, wind speed, and wind direction. Snowmelt amount was measured using a Sommer snow water equivalent (SWE) instrument, which determines snow weight changes at different times through pressure sensors; melted snow water drains through numerous small holes in the device. Snowfall was measured using a weighing rain gauge that records cumulative snowfall, with temporal variation obtained by calculating differences between measurements. Snow surface sublimation was first measured using an eddy covariance system to determine latent heat, then calculated indirectly through formulas. Snow surface temperature was measured using Apogee SI-111 temperature sensors, while ground surface temperature was measured using HydraProbe. Soil moisture was obtained through a moisture sensor probe integrated into the Campbell system. To ensure universality and representativeness of snowmelt data, analysis was conducted using data from complete hydrological years. Three meteorological stations and snowfall/snowmelt instruments were installed at different elevation zones within the watershed, with the highest station at 2120 m. The watershed outlet hydrological station is at approximately 1175 m elevation. The region experiences large diurnal temperature variations, with an annual mean temperature of 8.7 °C. Snowmelt primarily occurs between March and May. Observations indicate multi-year average precipitation of about 550 mm and average wind speed of 1.5 m · s⁻¹, with annual average radiation around MJ · m⁻² · d⁻¹, demonstrating typical semi-arid mountainous climate characteristics.

2.2 Research Methods

Based on collected data, this study divided snowmelt into different stages, plotted snowmelt variation curves using Origin software, and analyzed fundamental snowmelt patterns in the study area. Long-term temperature and corresponding snowmelt data were linearly fitted using the least squares method to construct a simple single-factor snowmelt model, which was then divided into calibration and validation periods for evaluation and analysis. Field observations revealed that temperature contributes more to snow ablation than radiation.

3.1 Response Patterns of Snowmelt to Temperature

Precipitation resources in Xinjiang's mountainous areas constitute the primary source of oasis water resources, with high-mountain snow and ice melt serving as the "blood maker" of perennial rivers. Consequently, snowmelt runoff research has become a main focus of hydrological process studies in arid regions. Figure 2 illustrates the correlation between snowmelt rate and ambient temperature, with both environmental temperature data (air temperature, snow surface temperature, and ground surface temperature) and snowmelt rate data ($\text{mm} \cdot \text{d}^{-1}$) presented as daily averages. The results show synchronous resonance between snowmelt rate variation trends and ambient temperature fluctuations—as environmental temperature decreases or increases, snowmelt rate follows accordingly. When air temperature rises to certain values, intermittent snowmelt occurs due to complete snowpack depletion; therefore, modeling only considers effective snowmelt from winter onset to spring thaw. Simultaneously, snowmelt occurs even during winter at certain low temperatures, indicating that the critical temperature for snow ablation in this Tianshan watershed is not around 0°C . Experimental data show that snowmelt essentially ceases when air temperature falls below -12°C , which is significantly lower than the critical temperature for snowmelt, reflecting snowmelt characteristics in arid mountainous environments. Snow surface temperature and air temperature exhibit synchronous fluctuation trends. Given the advantage of easy data acquisition for air temperature, it was selected as the primary factor influencing snowmelt amount.

3.2 Daily Variation Patterns of Snow Water Equivalent

Figure 3 shows the annual snow ablation trend line for the Araltobe watershed in the Tianshan Mountains from 2016 to 2021. Observations reveal that the proportion of snowfall to total precipitation varies across hydrological years. The cumulative snowpack growth process is directly related to snowfall amount and temperature, while the ablation process is primarily temperature-dependent. The multi-year average precipitation in the experimental area is approximately 570 mm, with winter snowfall of 200 mm, accounting for about 35% of average annual precipitation. Thus, winter snowfall contributes more to water resources in arid regions than other seasons, particularly at higher elevations. Using data from the 1175 m elevation outlet station as an example, the snowmelt process divides into three stages: complete ablation stage, non-complete ablation stage, and complete ablation stage. The complete ablation stage features significant temperature contributions to snowmelt, causing cumulative snowmelt to equal cumulative snowfall, representing an unstable snow period. The non-complete ablation stage features lower temperatures insufficient for complete snow ablation, resulting in cumulative snowmelt less than cumulative snowfall, representing a stable snow period. In early March, with sudden temperature increases, mountain snowmelt increases dramatically until complete depletion. Air temperature and solar radiation are the primary drivers of snowmelt. The critical temperature for snow surface sublimation (evaporation) in this study is $^\circ\text{C}$.

3.3 Snowmelt Model Based on Temperature Variation

This study investigates the interaction between snowmelt amount and temperature, establishing a temperature-based snowmelt model through the intrinsic relationship between daily cumulative snowmelt and daily mean temperature. Since the complete ablation stage represents an unstable snowmelt period with temperature contributions exceeding actual snowmelt, model calculations would overestimate actual snowmelt. Therefore, model development must focus on the non-complete ablation stage, though the calibrated model remains applicable to all snowmelt stages, provided snowpack exists on the ground surface.

3.3.1 Model Construction

Extensive field observations reveal a significant linear relationship between snowmelt amount and temperature (correlation coefficient reaches 0.87). Other uncertainty factors including net solar radiation and vegetation index contribute minimally to snowmelt and were therefore excluded. This study selected the non-complete ablation stage of snowpack as the modeling basis, constructing a simple single-factor snowmelt model with temperature as the independent variable and snowmelt amount as the dependent variable: $y = ax + b$, where y is snowmelt amount (mm), x is temperature ($^{\circ}\text{C}$), and a and b represent model slope and intercept, respectively. Through least squares fitting of long-term temperature and corresponding snowmelt data, the following snowmelt model was derived: $\text{SM} = 0.232a + 1.7488$, where SM is snowmelt amount (mm). Considering the snowmelt critical temperature (T_c), the formula was further modified to: $\text{SM} = 0.232r + 3.4659$.

3.3.2 Model Calibration

Using the established formula, simulated snowmelt results for the calibration period (2016–2020) in a typical Tianshan watershed were obtained. Due to interannual temperature variation, snowmelt values differ across years. Figure 4 shows that during the calibration period, simulated and measured values exhibit consistent fluctuation trends, though some extreme snowmelt values show noticeable deviations. Snowmelt amounts were larger in certain years, closely related to higher temperatures and greater snowfall. The model demonstrates reliable simulation results for the entire hydrological year's daily snowmelt data.

3.3.3 Model Validation

Figure 5 presents the simulated snowmelt results for the winter of 2020–2021 (validation period). Compared with the calibration period, the model shows some deviation between simulated and observed values during validation, underestimating peak snowmelt amounts. This discrepancy relates not only to model uncertainties (radiation, wind speed, etc.) but also to hardware weighing and software conversion errors in observation equipment. For a single-factor

(temperature) linear model, the simulation results are satisfactory, enabling approximate snowmelt estimation using simple temperature data. The model is suitable for long-term snowmelt process simulation.

3.3.4 Model Accuracy Analysis

Figures 6 and 7 present correlation comparisons between observed and simulated snowmelt values for calibration and validation periods. Both periods show high correlation ($R^2 > 0.8$), though the model underestimates values. Compared with the calibration period, validation period simulations are lower and deviate more from the 1:1 line. Further analysis reveals that when snowmelt amount is less than 5 mm, simulated values closely match observations (approaching the $y = x$ line), while for values exceeding 5 mm, simulations are lower than observations (approaching the x-axis), indicating better performance under low snowmelt conditions. Overall, the model achieves satisfactory validation for single-factor input with high simulation efficiency ($R^2 > 0.8$), providing a simple and effective snowmelt submodule for distributed hydrological models.

3.3.5 Model Evaluation Criteria

To validate model effectiveness, five evaluation metrics were adopted: bias, mean absolute error (MAE), root mean square error (RMSE), Nash-Sutcliffe efficiency coefficient (NSE), and coefficient of determination (R^2). These metrics are expressed as:

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (z_i - z_i^*)$$

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |z_i - z_i^*|$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (z_i - z_i^*)^2}$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^N (z_i - z_i^*)^2}{\sum_{i=1}^N (z_i - z_{i,ave}^*)^2}$$

$$R^2 = \left[\frac{\sum_{i=1}^N (z_i - z_{i,ave})(z_i^* - z_{i,ave}^*)}{\sqrt{\sum_{i=1}^N (z_i - z_{i,ave})^2 \sum_{i=1}^N (z_i^* - z_{i,ave}^*)^2}} \right]^2$$

where z_i represents simulated values, z_i^* represents observed values, $z_{i,ave}$ and $z_{i,ave}^*$ represent mean simulated and observed values, respectively, and N is the

data quantity. Table 1 presents the correlation evaluation between observed and simulated snowmelt values for calibration and validation periods. Overall performance is good, with most metrics within acceptable ranges. Bias remains low, particularly during calibration (around 0.037), while validation period bias exceeds 0.2. Both MAE and RMSE are less than 0.6. NSE and R^2 values exceed 0.8 for both periods (0.870 and 0.876 for calibration; 0.845 and 0.811 for validation), indicating good consistency between simulated and observed values.

In summary, during the second snow ablation stage (non-complete ablation), atmospheric temperature contributes most significantly to snowmelt amount ($R^2 > 0.8$), followed by solar radiation, underlying surface conditions, and other factors. The nonlinear functional relationship between snowmelt amount and multiple factors (temperature, solar radiation, underlying surface conditions, etc.) will be addressed in future work; this study focuses specifically on the response process and patterns of snowmelt amount to temperature.

4 Conclusions

Using meteorological data from the field research station affiliated with the Ili Station as independent variables and snowmelt amount as the dependent variable, this study developed a temperature-based snowmelt model, revealing multi-year snowmelt variation patterns and temperature response processes. The conclusions are as follows:

- 1) Extensive observations reveal that snowmelt continues to occur during winter within certain low-temperature ranges. In the study watershed of the Tianshan Mountains, the critical daily mean temperature for snowpack ablation is not around 0 °C. Experimental data show that snowmelt essentially ceases when daily mean temperature falls below -12 °C. The critical daily mean temperature for snow surface sublimation (evaporation) in this study is °C, significantly lower than the critical temperature for snowmelt, reflecting snowmelt characteristics in arid mountainous environments.
- 2) Regarding snow water equivalent, the snowmelt process divides into three stages: complete ablation stage → non-complete ablation stage → complete ablation stage. The complete ablation stage features significant temperature contributions, causing cumulative snowmelt to equal cumulative snowfall, representing an unstable snow period. The non-complete ablation stage features lower temperatures resulting in cumulative snowmelt less than cumulative snowfall, representing a stable snow period.
- 3) A single-factor temperature-based snowmelt model was constructed. To ensure model integrity, only effective snowmelt from winter onset to spring thaw (non-complete ablation stage) was considered during model development. However, the calibrated model is applicable to all snowpack conditions and provides reliable simulation results (validation period $R^2 = 0.811$).

- 4) Model evaluation shows good overall performance for both calibration and validation periods, with R^2 values of 0.876 and 0.811, respectively. The model demonstrates good consistency between simulated and observed values, with the advantage of estimating watershed snowmelt using readily available meteorological data. The research provides a simple algorithm for snowmelt calculation in arid regions, an effective snowmelt submodule for distributed hydrological models, and technical support for watershed snowmelt flood simulation and forecasting.

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