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Snowmelt-Coupled Xin'anjiang Model for Runoff Simulation in Arid Regions: A Postprint

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Abstract

Within the Xiying River basin above the Jiutiaoling Station, daily data from gridded precipitation and air temperature datasets for the period 2011–2018 were utilized to develop a method for correcting anomalous gridded precipitation points through exploration of the precipitation-runoff causal relationship, and a snowmelt module was coupled with the three-source Xin'anjiang model to investigate the watershed's daily runoff simulation process. Simulation performance was evaluated using two assessment criteria: the Nash-Sutcliffe efficiency coefficient and relative error. The simulation performance after precipitation correction and after snowmelt coupling was compared with that of the unimproved model to analyze the applicability of the snowmelt-coupled Xin'anjiang model in the Xiying River basin. The results indicate that gridded precipitation correction based on the precipitation-runoff causal relationship improved runoff simulation accuracy, with the Nash-Sutcliffe efficiency coefficient of simulated runoff increasing in 75% of the years. The snowmelt-coupled Xin'anjiang model performed well in the study area, yielding better simulations than the unimproved model in over 75% of the years, with the Nash-Sutcliffe efficiency coefficient exceeding 0.6 in over 87% of the years. The snowmelt-coupled Xin'anjiang model provides a decision-making reference for forecasting and early warning of snowmelt runoff in the Xiying River basin.

Full Text

Runoff Simulation in an Arid Area Using the Xin'anjiang Model Coupled with Snowmelt

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Abstract

Using daily grid-based precipitation and temperature datasets from 2011 to 2018 in the upstream watershed of the Jiutiaoling hydrological station in the Xiying River Basin, this study explores a correction method for abnormal grid precipitation points based on the causal relationship between precipitation and runoff. A snowmelt module was coupled with the three-source Xin'anjiang model to simulate daily runoff processes in the watershed. Simulation performance was evaluated using two criteria: the deterministic coefficient and relative error. The results after precipitation correction and snowmelt coupling were compared with those from the unmodified model to analyze the applicability of the improved Xin'anjiang model in the Xiying River Basin. The findings indicate that grid precipitation correction based on precipitation-runoff relationships improved runoff simulation accuracy, with the deterministic coefficient increasing in 75% of the years. The snowmelt-coupled Xin'anjiang model performed well in the study area, showing better simulation results than the original model in over 75% of years, with deterministic coefficients exceeding 0.6 in more than 87% of years. This improved model provides a decision-making reference for snowmelt runoff forecasting and early warning in the Xiying River Basin.

Keywords: Xiying River Basin; grid precipitation; snowmelt module; improved Xin'anjiang model

Introduction

Rivers in northwestern China predominantly originate in mountainous regions, where snowmelt serves as a crucial spring water source. The Xiying River, located in Gansu Province, derives its runoff primarily from snowmelt in the eastern Qilian Mountains and precipitation in mountainous areas. While most existing research on the Xiying River Basin has focused on ecological and water conservancy issues in the irrigation district, hydrological modeling studies remain scarce, necessitating the development of suitable hydrological models for this region. When applying hydrological models in this basin, the influence of spring snowmelt must be considered.

The Xin'anjiang model, widely used in China, features a clear structure and hierarchical design that has been continuously refined through practical applications, making it suitable for hydrological simulation in data-scarce regions. Liu et al. summarized the model's development characteristics, noting its evolving architectural diversity, component evaluation, and expanding application scope. Previous studies have demonstrated that the Xin'anjiang model can be enhanced through various approaches: Lyu et al. combined particle swarm optimization with ensemble Kalman filter data assimilation for batch parameter estimation in data-scarce cold regions; Han et al. integrated a variable dynamic storage coefficient method for river flood routing; and others have successfully applied the model in the Feng River Basin and Urumqi River in Xinjiang, proving its applicability extends beyond humid regions to northwestern China. Zhao et al. further enhanced the model's versatility by incorporating infiltration-excess runoff mechanisms for the Juma River Basin.

Regarding snowmelt runoff modeling, widely used models include SRM and SWAT, while MIKE SHE incorporates snowmelt modules. However, SRM primarily performs well for spring snowmelt and is mostly limited to short-term intra-annual runoff forecasting. MIKE SHE is relatively complex, requiring extensive input data including digital elevation, land use, snow cover characteristics, soil properties, and meteorological data—making it difficult to implement in data-scarce basins like Xiying River. Jiang first applied snowmelt runoff simulation with the Xin'anjiang model in the Chedek Basin, and subsequent researchers considered energy concepts for high-cold mountainous regions. However, these approaches still require extensive analysis of solar radiation, topographic effects, and snow cover area, posing challenges for data-limited mountain regions. This study selects the widely used, structurally clear Xin'anjiang model and incorporates a temperature-threshold-based snowmelt module to expand its applicability.

In data-scarce regions like the Xiying River Basin above Jiutiaoling Station, the absence of precipitation observations and significant topographic variation means that precipitation at the Jiutiaoling hydrological station cannot represent the entire watershed. Accurate precipitation forcing data is crucial for hydrological simulation as it directly affects simulation accuracy. This study first corrects grid precipitation data, then couples a snowmelt module with the Xin'anjiang model, and uses the corrected precipitation data to drive the coupled model for runoff simulation.

1.1 Study Area

The Xiying River, located in the southwest of Wuwei City, is a tributary of the Shiyang River Basin. Its upstream section consists of the Ningchang and Shuiguan rivers, originating from the Lenglongling section of the eastern Qilian Mountains. The basin features a high-cold semi-arid and semi-humid climate, with runoff primarily composed of alpine snowmelt and Qilian Mountain precipitation. The multi-year average runoff at the mountain outlet reaches 3.184×10^8 m^3, ranking first among the eight upstream rivers of the Shiyang River Basin and accounting for 22.3% of the total. The Jiutiaoling hydrological station, situated near the mountain outlet, is the only station above the outlet and is unaffected by artificial facilities, with long-term hydrological measurement records. The area above Jiutiaoling Station has good vegetation cover and minimal soil erosion. Due to topographic differences, precipitation varies significantly between this area and the upstream region, with annual precipitation reaching 500–800 mm upstream but only 200–400 mm at Jiutiaoling Station. Runoff from March to May originates mainly from spring snowmelt, while June to September runoff is generated by mountain precipitation. This study focuses on the watershed above Jiutiaoling Station (Figure 1), with a drainage area of 1077 km².

1.2 Data Sources

The precipitation and temperature data used as inputs for the improved Xin'anjiang model were obtained from datasets released by the National Meteorological Information Center. Precipitation data were derived from the China Ground Precipitation Daily Value 0.5°×0.5° Grid Dataset (V2.0, code: SURF_CLI_CHN_PRE_DAY_GRID_0.5), while temperature data came from the China Ground Temperature Daily Value 0.5°×0.5° Grid Dataset (code: SURF_CLI_CHN_TEM_DAY_GRID_0.5). Additionally, daily evaporation and flow data for the Jiutiaoling hydrological station from 2011 to 2018 were obtained from the Hydrological Yearbook of Inland Rivers in the Hexi Region of Gansu Province, published by the Ministry of Water Resources.

1.3 Methods

1.3.1 Grid Precipitation Data Correction Method The grid dataset is primarily produced by interpolating precipitation from high-density meteorological stations across China using the thin-plate spline method, which introduces certain errors. Zhao Yufei, the dataset developer, noted that errors are more pronounced in summer than in other seasons. When using grid precipitation data for precipitation (snowmelt) runoff simulation, a few runoff anomalies occur in summer, necessitating precipitation data correction.

Conventional correction methods involve comparison with nearby station data. However, in the Xiying River Basin, nearby meteorological stations are located far from the watershed (Figure 2), mostly distributed in the northeast and northwest directions, lacking representative stations in the southwestern mountainous area that constitutes the primary precipitation and runoff source. Therefore, this study explores an alternative approach using the precipitation-runoff relationship for correction.

Through years of grid precipitation-runoff simulation experiments, we identified two constraints—annual maximum precipitation and runoff coefficient—that can detect significant grid precipitation anomalies. Points violating both constraints are identified as anomalies:

Constraint 1 (Precipitation): $P < 0.7 \times P_{\max}$
Constraint 2 (Runoff coefficient): $\alpha > 0.3$

where R represents the measured daily runoff depth at the Jiutiaoling outlet (mm), P is daily grid precipitation (mm), and α is the runoff coefficient. The precipitation constraint uses the 3σ principle: with an average annual runoff coefficient μ of 0.3 and standard deviation σ of 0.1, values below $\mu - 3\sigma$ (0.27% probability) are considered outliers. For years where the maximum daily grid precipitation exceeds 40 mm, if this point is anomalous, it affects anomaly detection under the precipitation constraint. In such cases, the second-largest annual precipitation value is used as the base for the precipitation constraint, multiplied by a calibrated coefficient of 0.7.

Although complex underlying surface and climatic conditions affect precipitation-runoff relationships, rainfall and runoff maintain a strong causal relationship that can serve as a preliminary evaluation reference. After identifying anomalous points, we correct them using the precipitation-runoff relationship curve drawn from data with anomalies removed (Figure 3). This approach is particularly valuable in arid and semi-arid regions with limited station data, where national meteorological datasets can be used despite inherent errors. Correcting a few significantly biased grid precipitation points using precipitation-runoff curves improves data usability and simulation accuracy.

1.3.2 Coupling Snowmelt Module with Xin'anjiang Model Based on the Xin'anjiang model, we added a snowmelt module comprising five components: snowmelt calculation, evapotranspiration computation, saturation-excess runoff generation, three-source separation, and flow concentration.

1) Snowmelt Module

The improved Xin'anjiang model incorporates a snowmelt module before the first layer, primarily using the degree-day factor method. This method assumes a significant linear relationship between snowmelt and temperature:

$M = \text{DDF} \times (T - T_0)$ when $T > T_0$

where M is snowmelt water amount ($\text{mm} \cdot \text{d}^{\ 1}$), T is air temperature (°C), T_0 is the snowmelt threshold temperature (°C), and DDF is the degree-day factor ($\text{mm} \cdot {}^{\circ}\text{C}^{\ 1} \cdot \text{d}^{\ 1}$). The module's primary inputs are temperature and precipitation. Snowmelt energy originates mainly from net radiation (including longwave and shortwave) and sensible heat flux. Since near-surface longwave radiation and sensible heat flux dominate snowmelt, and temperature is the primary factor influencing surface longwave radiation, this method directly uses readily available temperature as the model driver. After snowmelt calculation, the combined liquid water from snowmelt and rainfall serves as input for subsequent model components.

2) Evapotranspiration Calculation

The model employs a three-layer evaporation mode, where evapotranspiration capacity is calculated as the product of an evaporation conversion coefficient and observed values from the Jiutiaoling station:

$\text{EP} = \text{KC} \times E_{\text{pan}}$

where EP is evapotranspiration capacity (mm), KC is the evapotranspiration conversion coefficient, and E_{pan} is pan evaporation observed at the evaporation station (mm). This approach is based on the principle that soil evaporation capacity maintains a linear relationship with water surface evaporation under identical meteorological conditions.

3) Saturation-Excess Runoff Generation
The saturation-excess runoff mode assumes runoff generation begins only after the vadose zone reaches field capacity. Since water storage capacity varies across the watershed, partial area runoff occurs when precipitation plus initial vadose zone storage is less than the maximum watershed water storage capacity; full watershed runoff occurs when this sum exceeds the maximum capacity:

$R = \mathrm{PE} - (\mathrm{WMM} - W) + \mathrm{WMM} \times (1 - (\mathrm{PE} + W)/\mathrm{WMM})^{1+B}$ when $\mathrm{PE} + W < \mathrm{WMM}$
$R = \mathrm{PE} - (\mathrm{WMM} - W)$ when $\mathrm{PE} + W \geq \mathrm{WMM}$

where A is the ordinate corresponding to watershed initial vadose zone storage (mm), WMM is the maximum single-point water storage capacity in the watershed (mm), B reflects the non-uniformity of vadose zone water storage capacity distribution (smaller B indicates more uniform distribution), R is runoff (mm), W is watershed storage (mm), and PE is net rainfall after evapotranspiration (mm). Note that P in PE refers to the liquid water amount after snowmelt calculation.

4) Three-Source Separation
Runoff separation follows the traditional Xin'anjiang model approach, dividing runoff into surface flow, interflow, and groundwater. Considering the runoff area's influence and underlying surface conditions, we use a parabolic approximation similar to the previous module to represent the distribution of free water capacity in the runoff area. Free water, comprising capillary and gravitational water, can flow freely under force. The separation formulas are:

$\mathrm{RS} = (\mathrm{PE} - S) \times U$ when $\mathrm{PE} > S$
$\mathrm{RS} = 0$ when $\mathrm{PE} \leq S$

where RS is surface runoff (mm), S is free water storage (mm), and U is a unit conversion coefficient (constant).

5) Flow Concentration Calculation
Surface runoff flows directly into the river network:

$\mathrm{QS}(i) = \mathrm{RS}(i) \times U$

where QS is surface runoff concentration ($m^3 \cdot s^{1}$), i denotes the day, and the timescale is daily.

Interflow concentration uses a linear reservoir method:

$\mathrm{QI}(i) = \mathrm{CI} \times \mathrm{QI}(i-1) + (1 - \mathrm{CI}) \times \mathrm{RI}(i) \times U$

where QI is interflow concentration ($m^3 \cdot s^{1}$), CI is the interflow recession coefficient, RI is interflow runoff (mm), and U is the unit conversion coefficient.

Groundwater concentration also employs the linear reservoir method:

$\text{QG}(i) = \text{CG} \times \text{QG}(i-1) + (1-\text{CG}) \times \text{RG}(i) \times U$

where QG is groundwater runoff concentration ($\text{m}^3 \cdot \text{s}^{-1}$), CG is the groundwater recession coefficient, and RG is groundwater runoff (mm).

1.3.3 Evaluation Criteria Based on hydrological forecasting evaluation standards, we employed relative error (RE) and deterministic coefficient (DC) for assessment:

$$\text{RE} = \frac{\sum Q_{\text{sim}} - \sum Q_{\text{obs}}}{\sum Q_{\text{obs}}} \times 100\%$$

$$\text{DC} = 1 - \frac{\sum (Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum (Q_{\text{obs}} - Q_{\text{obs\_mean}})^2}$$

where Q_{sim} is the simulated flow ($\text{m}^3 \cdot \text{s}^{-1}$), Q_{obs} is the observed flow at Jiutiaoling Station ($\text{m}^3 \cdot \text{s}^{-1}$), RE is relative error, and DC is the deterministic coefficient.

2.1 Analysis of Grid Precipitation Correction Results

Based on the watershed's location within precipitation grids, we extracted grid precipitation data within the basin. Using the anomaly identification and correction method, we corrected grid precipitation data. Anomalies were identified within the region defined by the constraint conditions. Although few grid points required annual correction, these points represented precipitation data that deviated significantly from the precipitation-runoff relationship curve.

Analysis of the 2018 grid precipitation correction (Figure 4) shows that only two days required correction (marked in red). The correction improved the deterministic coefficient for that year. Grid precipitation correction enhanced simulation performance in years where the deterministic coefficient was below 0.6, with improvements observed in 75% of years. However, in years where the deterministic coefficient already exceeded 0.6, the improvement was minimal.

2.2 Snowmelt Runoff Simulation Analysis

We conducted simulations using the Xin'anjiang model before and after snowmelt module integration, both with and without precipitation correction. The results (Table 1) demonstrate that the snowmelt-coupled model generally outperformed the traditional Xin'anjiang model. Notably, improvements in the deterministic coefficient and reductions in relative error were not always synchronized, as parameter optimization prioritized the deterministic coefficient as the objective function, which better reflects the simulation process and the proportion of flow variation captured. Relative error primarily evaluates the relationship between total simulated and observed flow, focusing on volume control.

Using 2011–2015 as the calibration period and 2016–2018 as the validation period, parameter optimization employed a genetic algorithm with the deterministic coefficient as the objective function. Table 2 presents the optimized parameters. In the calibration period, the deterministic coefficient reached 0.82, and this parameter set was applied to the validation period, achieving a deterministic coefficient of 0.71, demonstrating the model's applicability in the Xiying River Basin.

After snowmelt coupling and grid precipitation correction, the average deterministic coefficient for the 8-year simulation period was 0.76, compared to 0.60 for the original Xin'anjiang model—a significant improvement of 0.16. In the calibration period, the deterministic coefficient improved from 0.78 to 0.82 after correction, while in the validation period, it increased from 0.66 to 0.71. The snowmelt-coupled Xin'anjiang model successfully simulated spring snowmelt runoff. In the validation period, although overall performance was generally lower than in the calibration period, spring runoff was still well-simulated, indicating effective functioning of the snowmelt module.

The model effectively simulated summer flood peaks, likely because the Xiying River Basin has a thin runoff generation layer, and in most cases, daily precipitation produces same-day outflow with short watershed concentration delays. In the validation period, the overall simulation performance was generally inferior to the calibration period, but spring runoff remained well-simulated, confirming that the temperature-based snowmelt module adequately calculates spring runoff in the study area.

3. Conclusions

Considering the actual conditions of the study area, this study incorporated a snowmelt module into the Xin'anjiang model to account for snowmelt effects on runoff. Additionally, due to the scarcity of hydrological stations in the study area, grid precipitation and temperature datasets were used as driving data for the improved model. During application, we explored methods for identifying and correcting anomalous points, using corrected grid precipitation as model input for hydrological simulation. We then analyzed simulation performance before and after model improvement and precipitation data correction, reaching the following conclusions:

1) In arid and semi-arid regions with limited station data, national meteorological datasets can address data scarcity issues. Correcting a few significantly biased grid precipitation points using precipitation-runoff relationship curves improves data usability, with the deterministic coefficient increasing in 75% of years. However, the correction method has limitations: in 2018, only 4.3 mm of precipitation was corrected, with minimal difference before and after correction. This occurs because the correction method does not consider smaller precipitation values, and the two constraints cannot identify trend issues in low precipitation events—an aspect requiring further investigation.

2) Coupling a snowmelt module with the Xin'anjiang model requires minimal driving data and is simple to implement. The Xin'anjiang model achieved annual deterministic coefficients above 0.6 in the Xiying River Basin. Af-

ter snowmelt coupling and grid precipitation correction, over 87% of simulation years had deterministic coefficients above 0.6, and over 75% had coefficients above 0.7. The average deterministic coefficient improved from 0.60 for the original model to 0.76 after improvements, demonstrating good overall performance and applicability in the Xiying River Basin.

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Figures

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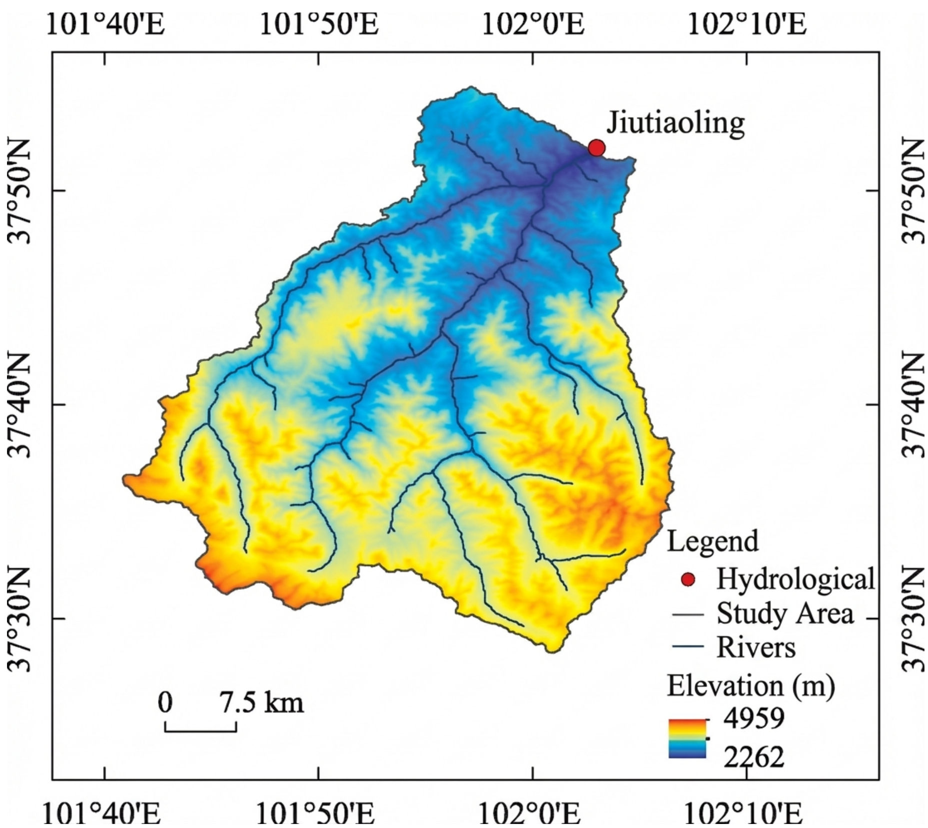

Figure 1: Figure 1

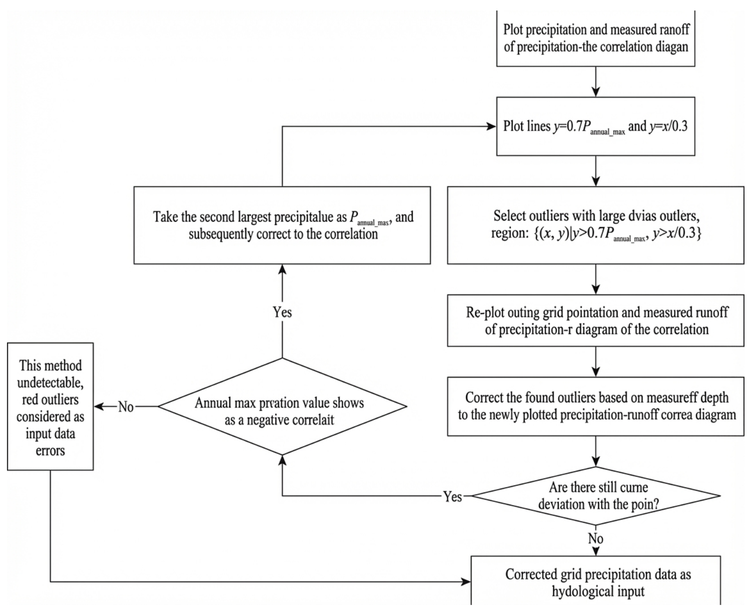

Figure 2: Figure 3