

Postprint: Simulation, Validation and Analysis of Hydrological Components in the Jingbo River Basin Based on CMDAS-Driven SWAT Model

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Abstract

Quantitatively describing the variation patterns of land surface-related variables using atmospheric and hydrological models has always been a research focus in the atmospheric science and hydrology communities. However, due to the scarcity of stations in western China, traditional meteorological observation stations can no longer meet the demands for high-precision simulation and analysis of large-scale land surface components. This study establishes the China Meteorological Assimilation Driving Datasets for the SWAT model (CMADS) to drive the SWAT (Soil and Water Assessment Tool) model (hereinafter referred to as the CMADS+SWAT model), selects the Xinjiang Jingbo River Basin, which is scarce in traditional meteorological stations, as the target area, and completes the calibration, validation, and spatiotemporal relationship extraction and analysis of various land surface components (such as soil moisture, snow depth, and snowmelt) in the basin. Analysis reveals that the CMADS dataset can effectively drive and calibrate the SWAT model to complete localization. Specifically, the overall NSE efficiency coefficients of the CMADS+SWAT model range from 0.659 to 0.942 at the monthly scale, and from 0.526 to 0.815 at the daily scale. Correlation analysis of soil moisture and snowmelt processes within the basin reveals that soil moisture in the Jingbo River Basin reaches its first peak during March-April, primarily contributed by alpine snowmelt phenomena within the basin; after the snowmelt period ends, precipitation in the basin increases, and phenomena such as rising temperatures cause soil temperature to exhibit fluctuating trends; by mid-October, the passage of cold air generates substantial precipitation (snow), ultimately transforming soil water into frozen soil until the approach of the snowmelt period in the following year, when soil water increases again until the snowmelt process concludes. On one hand, this demonstrates that the CMADS+SWAT model can effectively improve the performance of the SWAT hydrological model in arid regions of northwestern China (areas with

scarce stations); on the other hand, it clarifies the spatiotemporal evolution patterns of relevant land surface components (soil moisture, evaporation, etc.) in the Jingbo River Basin. This study will provide certain scientific impetus for the development of atmospheric hydrology as a discipline in China.

Full Text

Preamble

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Simulation, Validation, and Analysis of Hydrological Components in the Jingbo River Basin Based on the SWAT Model Driven by CMADS

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Abstract

Quantitatively describing the changing patterns of land surface variables using atmospheric and hydrological models has long been a research focus in atmospheric and hydrological sciences. However, traditional meteorological stations in western China are too sparse to meet the requirements for high-precision, large-scale simulation of land surface components. This study selected the Jingbo River Basin in Xinjiang—a region with scarce conventional meteorological stations—as the target area and employed the China Meteorological Assimilation Driving Datasets for the SWAT model (CMADS) to drive the Soil and Water Assessment Tool (SWAT). The model completed calibration, validation, and spatiotemporal analysis of various surface components, including soil moisture content, snow depth, and snowmelt. Our analysis demonstrated that the CMADS dataset can effectively drive and calibrate the SWAT model to complete localization in the Jingbo River Basin. The Nash-Sutcliffe efficiency (NSE) coefficients of the CMADS-driven SWAT model generally ranged between 0.659 and 0.942 at the monthly scale and between 0.526 and 0.815 at the daily scale. Furthermore, our analysis revealed that soil moisture content reaches its first annual peak between March and April, primarily caused by snowmelt in the high mountains. After the snowmelt period ends, increased precipitation and rising temperatures cause soil temperature to fluctuate until mid-October, when cold air brings considerable precipitation and snow. This eventually transforms soil water into frozen soil until the snowmelt period of the following year, after which soil water increases again until the end of snowmelt. This study verifies that CMADS+SWAT can enhance the performance of the SWAT model in arid regions of northwestern China that lack weather stations, while also clarifying

the spatiotemporal evolution patterns of relevant land surface components in the Jingbo River Basin. These findings will promote the development of atmospheric and hydrological sciences in China.

Keywords: CMADS; SWAT; Jingbo River Basin; surface component

Introduction

Globally, ecosystems and water resources face severe crises. Changes in land surface processes in arid regions significantly impact both inland river water cycles and ecological environment evolution. Accelerated water quality deterioration has also led to frequent sudden water events in these areas. The unique oasis structure of arid zones gives water and energy cycles their own distinct patterns. Systematic analysis of the spatiotemporal changes in surface water resource components in Xinjiang' s arid regions is of great significance, providing an important scientific basis for achieving sustainable eco-hydrological development in China' s inland arid basins.

The Jingbo River Basin is located in western Xinjiang, with a total closed basin area of 11,275 km². Surrounded by mountains on all sides, its topography is macroscopically integrated with the Junggar Basin and can be broadly divided into three geomorphic units: mountains, basins, and plains. The basin is situated in the downdraft channel of strong winds from the Alashankou Pass, making wind disasters the primary meteorological hazard. The basin' s extremely fragile ecological structure leads to frequent sandstorms, salinization, and desertification. Accelerated climate warming and continuous human reclamation activities have reduced inflow to Ebinur Lake, causing its area to shrink by nearly 1,500 km², with wetland area decreasing sharply and lake water mineralization rising rapidly. According to incomplete statistics, Ebinur Lake has lost nearly 678 km³ of water storage. This sharp decline in water resources has reduced the lake' s climate regulation function, caused severe damage to the basin ecosystem and local residents' living environment, and ultimately led to rapid ecological deterioration, including food chain disruption, biodiversity reduction, and accelerated desertification.

Given the Jingbo River Basin' s significant contributions to Xinjiang' s ecological balance and socio-economic development, using high-precision atmospheric data to drive mature hydrological models can provide sustainable development decision-making support for the basin and promote restoration strategies for surface process components. However, due to scarce traditional meteorological stations, heterogeneous underlying surfaces, and the impacts of climate change and human activities, uncertainty in model outputs and assessments is increased in this region. Numerous studies have proven that atmospheric assimilation datasets integrating more observational data can substantially improve model output accuracy. Various atmospheric reanalysis products exist globally, including NCEP/NCAR reanalysis, NCEP-DOE reanalysis, ERA-15, ERA-40, ERA-Interim, JRA-25, and Princeton reanalysis datasets. Although these re-

analysis datasets provide important data support for climate scenario analysis in meteorologically ungauged areas, their accuracy for regional refined simulation needs improvement. For instance, Pal et al. used the RegCM3 regional climate model to simulate and evaluate monthly precipitation variations during winter and summer monsoon seasons in East Asia, finding significant precipitation errors, particularly in winter. Zhao et al. evaluated the applicability of NCEP reanalysis surface pressure and temperature elements in China and found obvious seasonal and regional differences. Shi et al. assessed the applicability of various reanalysis datasets in China and found that wind field data anomaly errors showed negative correlation with altitude. These studies indicate that while reanalysis products can reflect large-scale meteorological element spatial patterns, most do not utilize all regional automatic stations in China and thus cannot accurately represent near-surface meteorological conditions. Using atmospheric datasets closer to China's actual meteorological fields to drive mature hydrological models can better enable detailed analysis of large-scale spatiotemporal evolution patterns of surface components in China.

This study uses the Jingbo River Basin—with its scarce stations and heterogeneous underlying surface—as a typical validation and analysis area. The CMADS dataset drives the widely used SWAT model to provide effective eco-hydrological system restoration strategies for the basin while validating CMADS applicability in western China.

1. Study Area Description

The Jingbo River Basin is located on the northern slope of the western Tianshan Mountains ($81^{\circ}46' - 83^{\circ}51' E$, $44^{\circ}02' - 45^{\circ}10' N$). Precipitation in the basin mainly originates from water vapor from the Arctic Ocean and Atlantic Ocean. The glacier areas of the Jinghe and Bortala Rivers are 96.2 km^2 and 110.3 km^2 , respectively, accounting for 20.6% and 21.4% of total river runoff. The mineralization of Ebinur Lake water is increasing annually, and the conflict between ecological and domestic water use is becoming increasingly prominent. Approximately $1,500 \text{ km}^2$ of the basin has degraded into saline desert, with salinization area reaching 20.6% and land degradation being severe.

Previous research on the Jingbo River Basin and even the entire Xinjiang region has relied on various reanalysis datasets or traditional meteorological observation data. With only two meteorological stations in the basin, no reasonable and credible hydrological process simulation and analysis has been conducted for this region. This study will use the high-resolution CMADS atmospheric forcing dataset to drive SWAT for detailed simulation of hydrological components in the Jingbo River Basin, aiming to systematically analyze spatiotemporal evolution characteristics of surface elements and lay a solid foundation for research on complex hydrological models driven by high-resolution meteorological data or regional climate models in China.

[Figure 1: see original paper] Schematic diagram of the Jingbo River Basin

2. Materials and Methods

2.1 Model Input Data

2.1.1 Digital Elevation Model Data Model input data primarily include digital elevation model (DEM), land use data, and meteorological forcing fields. The DEM was selected from SRTM (90 m) data obtained from the CGIAR-CSI SRTM 90m elevation database (<http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp>).

[Figure 2: see original paper] Elevation of the study area and input data for the SWAT model

2.1.2 Soil Distribution in the Jingbo River Basin Soil physical properties determine water production in different hydrologic response units (HRUs) of the SWAT model. This study used soil input data from the Harmonized World Soil Database (HWSD) based on the World Soil Database. Land use data were obtained from the Jingbo River Basin Management Office and superimposed with China's second glacier inventory dataset. To ensure consistent resolution, soil and land use data were uniformly resampled to the same spatial resolution, with the planar projection coordinate system set to WGS_1984_UTM_Zone_44N.

[Figure 3: see original paper] Soil distribution and land use distribution in the Jingbo River Basin

2.1.3 Atmospheric Driving Data This study used the CMADS (China Meteorological Assimilation Driving Datasets for the SWAT model) as atmospheric input data. This dataset incorporates the China Land Data Assimilation System (CLDAS), ensuring the reliability of meteorological input data. The dataset provides daily average relative humidity, daily cumulative solar radiation, and daily cumulative precipitation. The original spatial range covers 0–65°N, 60–160°E, with spatial resolutions of 1/3°, 1/4°, 1/8°, and 1/16°. This study used the 1/3° spatial resolution covering the Jingbo River Basin (81°46'–83°51' E, 44°02'–45°10' N) from January 1, 2008 to December 31, 2014. The basin contains 22 CMADS stations.

Information of CMADS driving data

CMADS station distribution in the Jingbo River Basin

2.1.4 Hydrological Validation Data This study used daily flow data from hydrological stations within the Jingbo River Basin as model calibration and validation data, including two stations: Wenquan and Jinghe.

Hydrological station information in the Jingbo River Basin

2.2 SWAT Model Description

The SWAT model conceptualizes homogeneous units with identical land cover, soil distribution, and management practices as the same type of hydrologic response unit (HRU). The model assumes consistent water balance processes within each HRU. SWAT provides three potential evapotranspiration calculation methods: Penman-Monteith, Priestley-Taylor, and Hargreaves. Since CMADS provides all required input elements including solar radiation—unlike traditional meteorological stations that require weather generators to simulate radiation—this study selected the physically based Penman-Monteith method to maximize simulation accuracy.

2.3 SWAT Model Configuration

The study area basin area is 2,482,366.4052 hm², divided into 24 sub-basins and 263 HRUs using ArcGIS. Surface runoff was calculated using the runoff curve number model, with runoff from different HRUs converging into the main channel. The Muskingum method based on the continuity equation was selected for main channel water routing. Since precipitation input data are daily, the weather generator method was used to spatially discretize single-point meteorological data across the basin. To reduce errors from spatial interpolation, particularly in high-altitude areas, multiple elevation bands were defined to accurately identify precipitation distribution across different elevation zones.

Based on the overlapping period of CMADS driving field temporal scale and runoff observation data (2008–2014), the warm-up period was set to 2008 to allow hydrological processes to reach equilibrium from initial conditions. The calibration period was 2009–2010, and the validation period was 2011–2014.

2.4 Sensitivity Analysis and Calibration

This study used the SWAT-CUP program for model calibration. SWAT-CUP is an automatic calibration and uncertainty analysis program developed by the EAWAG research institute specifically for the SWAT model. In this study, 11 runoff-related parameters were calibrated using SWAT-CUP to obtain final parameter values.

During the calibration period (2009–2010), parameters were calibrated simultaneously at two basin stations while considering the relationship between annual evaporation and runoff to ensure simulation results approximated actual annual totals. Macro adjustments were made first, followed by monthly calibration, then daily parameter calibration and fine-tuning. The optimal precipitation lapse rate (PLAPS) parameter was 44.5 mm/km, and the temperature lapse rate (TLAPS) was -4.3039°C/km, consistent with the basin's multi-year actual mean values.

Final parameter values within the SWAT model

2.5 Model Evaluation

This study selected the Nash-Sutcliffe Efficiency (NSE) coefficient and R^2 determination coefficient as model evaluation metrics, which are widely used to assess model performance. NSE is a normalized statistic that reflects the fit between observed and simulated values, calculated as:

$$NSE = 1 - [\Sigma(Q_m - \bar{Q})^2] / [\Sigma(Q_s - \bar{Q})^2]$$

where Q represents runoff variables, subscripts m and s represent observed and simulated values, and \bar{Q} represents the mean observed runoff. NSE ranges from 0.5 to 1.0, with values above 0.5 indicating acceptable model results and values approaching 1.0 indicating perfect agreement. The R^2 determination coefficient represents the correlation between variables. Many studies consider $NSE > 0.5$ and $R^2 > 0.5$ as satisfactory model criteria, while some consider $NSE > 0.4$ acceptable. This study adopted $NSE > 0.5$ as the standard for acceptable simulation results.

3. Results Analysis

3.1 Runoff Simulation Validation and Analysis Based on CMADS+SWAT

This study used CMADS to drive the SWAT model for runoff simulation at two hydrological control stations in the basin: the Jinghe mountain pass control station and the Wenquan station. Observation data were used for parameter calibration and validation. At the monthly scale, the CMADS-driven SWAT model achieved satisfactory results at both control stations in the Jingbo River Basin. During the calibration period, the model performed excellently at Jinghe ($NSE = 0.939$, $R^2 = 0.942$) and well at Wenquan ($NSE = 0.904$, $R^2 = 0.934$). During the validation period, NSE and R^2 values were slightly lower than in the calibration period but remained acceptable.

Compared with the Jinghe mountain pass control station, the Wenquan station's simulation accuracy was lower due to the significant influence of upstream alpine glaciers in the high-cold mountainous area. While the model's degree-day factor provides detailed consideration of snowmelt, the glacier meltwater recharge rate is smaller than at the Wenquan control station.

[Figure 4: see original paper] Monthly simulation results (2009–2013) at Jinghe control station driven by CMADS+SWAT, where 95PPU represents the percentage of measured data bracketed by the 95% prediction uncertainty

[Figure 5: see original paper] Determination coefficient between monthly observation and simulation at Jinghe control station

After completing monthly scale calibration and validation, this study applied the optimal monthly parameter values to the SWAT model for daily fine-tuning calibration. The results showed that the modeled runoff matched daily observations well in both hydrological sub-basins. During the calibration period, the CMADS+SWAT model performed well at Jinghe ($NSE = 0.801$, $R^2 = 0.815$)

and acceptably at Wenquan ($NSE = 0.526$, $R^2 = 0.592$). During the validation period, the model achieved acceptable results at both stations ($NSE = 0.796$, $R^2 = 0.791$ at Jinghe; $NSE = 0.659$, $R^2 = 0.592$ at Wenquan).

[Figure 6: see original paper] Monthly simulation results (2009-2013) at Wenquan control station

[Figure 7: see original paper] Determination coefficient at Wenquan control station

[Figure 8: see original paper] Daily simulation results (2009-2013) at Jinghe control station

[Figure 9: see original paper] Daily observation-simulation determination coefficient at Jinghe control station

[Figure 10: see original paper] Daily simulation results (2009-2013) at Wenquan control station

[Figure 11: see original paper] Daily observation-simulation determination coefficient at Wenquan control station

3.2 Soil Moisture and Related Variables Analysis Based on CMADS+SWAT

After localizing the SWAT model for the Jingbo River Basin, this study analyzed the model's capability to simulate spatiotemporal evolution of soil moisture and snowmelt variables, while quantitatively analyzing response relationships among various components. The study focused on the Jinghe sub-basin as the main analysis object.

3.2.1 Snowmelt Process and Soil Moisture Response in the Jingbo River Basin To investigate the impact of snowmelt on soil moisture, this study extracted spatial variation maps of soil moisture and corresponding snowmelt amounts for the entire Jingbo River Basin on March 18, 2012. Analysis revealed that the basin's overall soil moisture was in a relatively wet state on that day, with soil moisture in the Wenquan control sub-basin at 57 mm, while soil moisture in the Jinghe control station and nearby sub-basins was relatively lower. Examination of the corresponding snowmelt spatial distribution showed extensive snowmelt occurring on the northern slope of the western Tianshan Mountains, which coincided with areas of higher soil moisture.

To quantitatively analyze the magnitude and direct response relationship between snowmelt and soil moisture, this study conducted time series analysis of various surface components in the Jinghe control sub-basin, including soil moisture, potential evapotranspiration, precipitation, and snowmelt. Taking the Jinghe mountain pass control station as an example, snowmelt began in mid-March, with significant snowmelt events occurring on March 18 (18 mm/d). On this day, soil moisture in the Jinghe control sub-basin also reached a high annual level (56 mm). The analysis found that the primary contribution to soil moisture increase in the Jingbo River Basin comes from mountain snowmelt,

with only minimal contribution from precipitation. Soil moisture and potential evapotranspiration show an inverse relationship in magnitude.

[Figure 12: see original paper] Spatial correlation analysis of soil moisture and snowmelt in the Jinghe River Basin

[Figure 13: see original paper] Time series analysis of various components in the Jinghe River Basin (taking Jinghe control station as an example)

3.2.2 Precipitation and Soil Moisture Response in the Jingbo River Basin While snowmelt significantly impacts soil moisture in the Jinghe control sub-basin, precipitation contributions cannot be ignored. This study focused on analyzing the effects of summer and late autumn precipitation on soil moisture. Since soil moisture fluctuates for extended periods from post-snowmelt to October, and exhibits sudden increases followed by constant periods, this study extracted and analyzed spatiotemporal response relationships between precipitation and soil moisture during these two phases.

Taking July 30, 2010 as an example, precipitation in the Jinghe mountain pass control sub-basin reached 30.1 mm, while soil moisture climbed to 24.8 mm. The rapid increase in soil moisture in the sub-basin fully demonstrates that large precipitation events cause rapid soil moisture increases in the short term. A similar situation occurred on October 15, 2011, when precipitation in the Jinghe mountain pass control sub-basin approached 40 mm and soil moisture reached 22 mm. After this event, soil moisture remained constant, indicating that late-year precipitation contributes significantly to soil moisture changes.

[Figure 14: see original paper] Spatial correlation analysis of soil moisture and precipitation in the Jinghe River Basin

[Figure 15: see original paper] Time series analysis of soil moisture and precipitation in the Jinghe River Basin (taking Jinghe control station as an example)

3.2.3 Annual Cycle Analysis of Soil Moisture Changes Analyzing soil moisture changes from an annual cycle perspective revealed that the snowmelt period occurs from March to April each year in the study area. Snow depth experiences an initial increase followed by a decrease, approaching zero after the snowmelt period, which is consistent with observed snow depth data extracted from the Jinghe station. After the snowmelt period, as the climate warms and the rainy season arrives, soil moisture in the study area climbs rapidly. Since air temperatures are relatively high during this period, frozen soil begins to melt while evaporation increases and accelerates soil water reduction, causing soil moisture to exhibit fluctuating trends. In mid-October, the basin experiences large-scale precipitation due to cold and humid air flow, significantly increasing soil water content. As cold air arrives, soil liquid water content freezes, producing frozen soil. Seasonal frozen soil persists until the next year's snowmelt period, when frozen soil melts again and part of it converts back to soil liquid water.

Overall, soil moisture in the basin reaches its first high level in March-April each year, mainly caused by snowmelt from basin snow cover. After the snowmelt period ends, increased precipitation and rising air temperatures cause soil moisture to fluctuate, eventually converting soil water to frozen soil. Until the next snowmelt period, soil liquid water increases again until snowmelt ends. The mid-October cold air passage producing substantial precipitation causes frozen soil formation.

[Figure 16: see original paper] Snow depth and frozen soil observations at Jinghe control station (2010 and 2011)

Assessment of monthly and daily runoff simulation results from CMADS+SWAT

4. Discussion and Conclusion

This study used the CMADS+SWAT model to conduct runoff simulation and validation at two hydrological control stations in the Jingbo River Basin. The CMADS+SWAT model analyzed various surface components in the Jinghe control sub-basin, including soil moisture, potential evapotranspiration, precipitation, and snowmelt, deepening understanding of the spatial evolution patterns of each component in the sub-basin and explaining the changing mechanisms of soil moisture across different seasons. The NSE coefficients of the CMADS+SWAT model ranged from 0.659 to 0.942 at the monthly scale and from 0.526 to 0.815 at the daily scale, indicating that the model can effectively simulate runoff in the Jingbo River Basin.

In the later stages of this research, more observational data (such as satellite remote sensing data) will be considered to enhance the reliability of CMADS+SWAT model results. At the current stage, the output data from the CMADS-driven SWAT model hold significant meaning for studying high-resolution meteorological data driving complex hydrological models. It is expected that this dataset will provide data support for detailed hydrological and ecological simulation research in China.

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