Evaporation Variation in the Shiyang River Basin over the Past 60 Years and Analysis of Its Causes: Postprint

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Abstract

Evaporation is a critical component of the water cycle, and understanding its variation and underlying causes is of great significance for the sustainable utilization of water resources. Using the Shiyang River Basin as a case study, data from four meteorological stations (Wushaoling, Yongchang, Wuwei, and Minqin) distributed along a decreasing altitude gradient from south to north over the past 60 years (1958–2017) were selected to analyze the spatiotemporal variation characteristics of evaporation and their causes in the Shiyang River Basin based on an improved PenPan model. The results indicate that: (1) Spatially, an altitude effect exists in evaporation variation in the Shiyang River Basin, with evaporation decreasing significantly as altitude increases at a rate of approximately 38 mm $\cdot$ $(100\text{m})^{-1}$; temporally, evaporation variation exhibits obvious piecewise characteristics, decreasing from 1958 to 1970 and increasing since the 1970s, most notably in the plain areas. (2) The improved PenPan model can satisfactorily simulate evaporation variation at daily and monthly scales at each station (R^2>0.85); to further improve simulation accuracy, the wind speed function in the model needs to be revised. (3) The radiation component calculated by the improved PenPan model shows little interannual variation, whereas the aerodynamic component exhibits a fluctuating upward trend, which is consistent with the variation trends of temperature and vapor pressure deficit, indicating that temperature rise is the main cause of increased evaporation in the Shiyang River Basin since the 1970s. This suggests that under the background of climate warming, evaporation in the Shiyang River Basin will continue to increase, placing greater pressure on future intensification of water resource management to ensure sustainable development.

Full Text

Analysis of Evaporation Change and Its Causes in the Shiyang River Basin Over the Past 60 Years

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Abstract

Evaporation is a key component of the water cycle, and understanding its variation and causes is crucial for sustainable water resource utilization. Taking the Shiyang River Basin as an example, this study selected meteorological data from four stations along a north-south altitudinal gradient (Wushaoling, Yongchang, Wuwei, and Minqin) for the past 60 years (1958-2017). Based on the PenPan model, we analyzed the spatiotemporal variation characteristics of evaporation and their causes in the Shiyang River Basin. The results show that: (1) Spatially, evaporation variation exhibits an altitudinal effect, decreasing significantly with increasing elevation at a rate of approximately 38 mm per 100 m increase in altitude. Temporally, evaporation shows distinct stage characteristics, decreasing from 1958-1970 but increasing since the 1970s, particularly in plain areas. (2) The PenPan model can effectively simulate daily and monthly evaporation variations at each station ($R^2 > 0.85$), though the wind speed function requires further modification to improve simulation accuracy. (3) The radiative component calculated by the PenPan model shows little interannual variation, while the aerodynamic component fluctuates and increases, consistent with temperature and vapor pressure deficit trends, indicating that temperature rise is the main cause of increased evaporation in the Shiyang River Basin since the 1970s. This suggests that under climate warming, evaporation in the Shiyang River Basin will continue to increase, placing greater pressure on future water resource management and sustainable development.

Keywords: pan evaporation; PenPan model; component splitting; Shiyang River Basin

1. Study Area Overview

The Shiyang River Basin is located in the eastern part of the Hexi Corridor in Gansu Province [Figure 1: see original paper], west of the Wushaoling Mountains and at the northern foot of the Qilian Mountains, with geographical coordinates of 101°41 -104°16 E and 36°29 -39°27 N. The terrain slopes from southwest to northeast, with elevations ranging from 1182 to 5214 m and a total basin area of 4.16$\times10^{4}$ km^2. The basin comprises eight tributaries from east to west: Dajing River, Gulang River, Huangyang River, Zamu River, Jinta River, Xiying River, Dongda River, and Xida River. From south to north, the basin encompasses three distinct climate zones: the southern Qilian Mountains represent a high-cold semi-arid and semi-humid zone at 2000-5000 m elevation, with mean annual temperatures of 2-6°C, annual precipitation of 300-600 mm, and aridity indices of 0.25-1; the central Hexi Corridor plain is an arid zone at 1500-2000 m elevation, with mean annual temperatures of 6-8°C, annual precipitation of 150-300 mm, annual evaporation of 1300-2000 mm, and aridity indices of 1-7; the northern region is an extremely arid zone at 1200-1500 m elevation, with mean annual temperatures exceeding 8°C, annual precipitation below 150 mm, annual evaporation of 2000-2600 mm, and aridity indices of 7-25. The Minqin oasis in the northernmost part receives only 50 mm of annual precipitation, with uneven seasonal distribution and 70% of precipitation concentrated in summer.

2. Data and Methods

2.1 Meteorological Data

The Shiyang River Basin contains four national meteorological stations distributed from south to north along the altitudinal gradient: Wushaoling, Yongchang, Wuwei, and Minqin stations . Due to relatively short time series at hydrological stations within the basin, which limit long-term trend analysis, we selected complete and consistent meteorological data from 1958-2017 as our analytical dataset, obtained from the National Meteorological Science Data Center (http://data.cma.cn).

2.2 Water Surface Evaporation Observation

Water surface evaporation observations followed the *Standard for Observations of Water Surface Evaporation* (SL 630-2013): during the non-freezing period (April-October), 20 cm evaporation pans were used, while during the freezing period (November-March), E-601 evaporation pans were employed. Both instruments were observed simultaneously during the pre-freezing (November) and post-thawing (March) periods to calculate conversion coefficients between 20 cm and E-601 pans. In data compilation, November and March small pan observations were converted using measured conversion coefficients from October and April, respectively, while December-February small pan data were converted using the November measured coefficient [26].

2.3 PenPan Model and Parameterization

Rotstayn et al. [11] developed a physical model coupling radiative and aerodynamic components to accurately simulate Class A pan evaporation (hereafter "PenPan model"). The model calculates daily Class A pan evaporation (PenPan, mm · d^{-1}) as:

$$PenPan = \frac{s}{s+\gamma} \cdot \frac{R_{n,Pan}}{\lambda} + \frac{\gamma}{s+\gamma} \cdot f(u) \cdot (e_s - e_a)$$

where s is the slope of the saturation vapor pressure curve ($\mathrm{kPa} \cdot {}^\circ\mathrm{C}^{-1}$), γ is the psychrometric constant ($\mathrm{kPa} \cdot {}^\circ\mathrm{C}^{-1}$), $R_{n,Pan}$ is net radiation over the pan ($\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$), λ is the latent heat of vaporization ($\mathrm{MJ} \cdot \mathrm{kg}^{-1}$), $f(u)$ is the wind speed function, and $(e_s - e_a)$ is the vapor pressure deficit (kPa).

The wind speed function $f(u)$ is expressed as a function of wind speed at 2 m height (u_2, $\mathrm{m} \cdot \mathrm{s}^{-1}$) [11]:

$$f(u) = 1.202 + 1.621u_2$$

The PenPan model splits evaporation into two components: the radiative term (primarily influenced by net radiation) and the aerodynamic term (primarily influenced by wind speed and vapor pressure deficit).

The calculation of $R_{n,Pan}$ is most critical and can be expressed as:

$$R_{n,Pan} = R_{s,Pan} - R_{l,Pan}$$

where $R_{s,Pan}$ is the total shortwave radiation received by the pan and $R_{l,Pan}$ is the net longwave radiation.

The shortwave radiation $R_{s,Pan}$ is calculated as:

$$R_{s,Pan} = (1 - \alpha_{Pan}) \cdot R_{dir} + (1 - \alpha_A) \cdot R_{dif}$$

where α_{Pan} is the albedo of Class A pan water surface (taken as a constant 0.08), α_A is the albedo of the ground surrounding the pan, R_{dir} is direct radiation, and R_{dif} is diffuse radiation.

The direct radiation R_{dir} is:

$$R_{dir} = -0.11 + 1.31 \cdot \frac{n}{N} \cdot R_{rad}$$

where n/N is the sunshine duration percentage and R_{rad} is extraterrestrial radiation.

The pan radiation factor f_{rad} is expressed as:

$$f_{rad} = 1.32 + 4 \times 10^{-5} \cdot |lat| + 8 \times 10^{-6} \cdot |lat|^2$$

where $|lat|$ is the absolute latitude.

In the above formulas, calculations for s, γ, λ, e_s, and e_a follow standard methods [23].

Sun et al. [19] proposed that when simulating E-601 pan evaporation, directly using $R_{n,Pan}$ instead of $R_{s,Pan}$ (hereafter "modified model") simplifies the model, improves applicability, and enhances accuracy. The calculation of $R_{n,Pan}$ requires site latitude, longitude, elevation, and sunshine duration, with detailed methods provided in [19].

2.4 Model Evaluation

We employed three commonly used metrics to evaluate hydrological model performance: coefficient of determination (R^2), root mean square error (RMSE), and Nash-Sutcliffe efficiency coefficient (NSE):

$$R^2 = \left[\frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \right]^2$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

where X_i represents observed evaporation values, Y_i represents simulated values, and $\bar{X}$ and $\bar{Y}$ are the respective means. All statistical analyses and parameter calculations were performed using IBM SPSS Statistics 19.0 (IBM SPSS Statistics, Inc, USA) and SigmaPlot 14.0 (Systat Software, Inc, USA), with NSE > 0 indicating acceptable model performance and high credibility.

3. Results and Analysis

3.1 Evaporation Variation

Annual evaporation decreases significantly with increasing altitude [Figure 2: see original paper]. The Minqin station in the downstream plain exhibits the highest annual evaporation at 1174.5 mm, while the Wushaoling station in the upstream mountainous area shows the lowest at 500 mm. The central Yongchang and Wuwei stations have moderate values around 800 mm. Notably, evaporation at Wuwei and Yongchang stations differs little despite Wuwei' s lower elevation; Wuwei' s relatively low evaporation may be attributed to its location within an urban area with lower wind speeds and insufficient aerodynamic components. Excluding Wuwei station, the remaining three stations show a significant negative linear relationship between annual evaporation and altitude (R^2 = 0.96, p

< 0.001), with a decreasing rate of 38 mm per 100 m elevation increase. Regarding altitudinal effects, Wang et al. [20] reported that evaporation in the Qilian Mountain forest zone (\$ \$20 cm pan) decreased at 29.6 mm per 100 m across 1680–3800 m, lower than our result due to our study area’ s greater altitudinal gradient. Altitude indirectly influences evaporation spatiotemporal variation through temperature and humidity, while station location and human activities also contribute (e.g., Wuwei’ s slightly lower evaporation).

Daily average evaporation at the four meteorological stations along the Shiyang River Basin’ s altitudinal gradient are 2.44\$$\pm 0.16 mm \cdot d^{\{\text{-1}\}, 3.20\pm 0.16 mm \cdot d}\{\text{-1}\}, 3.21\pm 0.14 mm \cdot d^{\{\text{-1}\}, and 4.19\pm 0.19 mm \cdot d}\{\text{-1}\}$\$, increasing gradually from south to north. All stations show consistent intra-annual variation patterns, increasing from March, peaking in June–July, then decreasing through winter [Figure 3: see original paper]. Cumulative annual evaporation shows similar patterns across stations before June, after which differences emerge and growth rates slow post-August. Monthly average evaporation also increases from south to north, with lowest values in winter, highest in summer, and intermediate in spring and autumn . Seasonal patterns show: spring (Mar–May) > summer (Jun–Aug) > autumn (Sep–Nov) > winter (Dec–Feb).

Interannual evaporation variation shows distinct spatial differences [Figure 4: see original paper]. While upstream Wushaoling and downstream Minqin stations exhibit decreasing trends (-4.67 mm • a^{-1} and -0.58 mm • a^{-1}, respectively), central Yongchang and Wuwei stations show significant increasing trends (17.86 mm • a^{-1} and 13.95 mm • a^{-1}). However, cumulative anomaly curves reveal clear breakpoints: Yongchang, Wuwei, and Minqin evaporation divided into two stages—decreasing before 1970 (negative anomalies) and increasing thereafter (positive anomalies); Wushaoling decreased until 1990 then increased. These results differ from Liu et al. [21], who found decreasing evaporation across all stations.

3.2 Model Simulation and Validation

Previous studies demonstrate that the modified PenPan model effectively simulates E-601 pan evaporation [19]. Our results confirm this [FIGURE:5, FIGURE:6]. At daily scale, the modified model shows significant linear relationships with observations ($R^2 > 0.85$ for all stations) but generally overestimates evaporation by 10–20%, particularly at high evaporation rates. Model performance is better in plain areas than mountainous regions, with increasing overestimation at higher altitudes (e.g., Wushaoling station shows the highest bias). This performance exceeds that of Sun et al. [19] for upstream reservoir evaporation. At monthly scale, model performance improves ($R^2 > 0.90$), though overestimation persists, particularly for high-altitude Wushaoling station (overestimated by 20%), likely due to altitude-increasing wind speeds affecting the aerodynamic component. In summary, the modified PenPan model adequately simulates evaporation across different altitudes in the Shiyang River Basin, though further refinement of the wind speed function $f(u)$ is needed, as its expression varies regionally [11, 13, 16].

3.3 Causes of Evaporation Change

Evaporation is influenced by multiple factors [11-12, 21], broadly categorized into radiative and aerodynamic factors [13, 16, 26]. Based on modified Pen-Pan model calculations, the radiative and aerodynamic components of evaporation in the Shiyang River Basin exhibit distinct characteristics: the radiative component (controlled by net radiation) remains relatively stable, while the aerodynamic component (controlled by vapor pressure deficit and wind speed) fluctuates and increases [Figure 7: see original paper]. High-altitude Wushaoling and Yongchang stations have relatively low radiative components comparable in magnitude to aerodynamic components, whereas low-altitude Wuwei and Minqin stations show radiative components significantly exceeding aerodynamic components at Wuwei but the opposite at Minqin. Comparison with [Figure 8: see original paper] reveals that aerodynamic component variation is the primary cause of interannual evaporation differences. According to the PenPan model, the main factors affecting aerodynamic component variation are vapor pressure deficit and wind speed. Meteorological factor anomalies show that temperature and vapor pressure deficit decreased before 1970, then increased rapidly from the early 1980s, while wind speed showed opposite trends. Net radiation remained largely unchanged except at Wushaoling station. Thus, temperature is the main driver of evaporation change in plain areas, creating a positive feedback loop: global warming → temperature rise → increased vapor pressure deficit → increased evaporation. However, the high-altitude Wushaoling station shows opposite patterns, suggesting complex climate system interactions at the intersection of the Loess Plateau, Qinghai-Tibet Plateau, and Inner Mongolia Plateau require further investigation.

4. Conclusions

Accurate quantification of water surface evaporation is crucial for rational water resource scheduling and refined water management. Using the modified PenPan model, this study analyzed spatiotemporal evaporation variation and its causes in the Shiyang River Basin, yielding the following conclusions:

1) Evaporation exhibits significant altitudinal effects, decreasing at 38 mm per 100 m elevation increase. Temporal variation shows clear stage characteristics: decreasing before 1970 but increasing since the 1970s, particularly in plain areas.

2) The modified PenPan model effectively simulates daily and monthly evaporation across stations ($R^2 > 0.85$), though the wind speed function requires further refinement for improved accuracy.

3) Component analysis reveals that increased evaporation since the 1970s primarily results from aerodynamic component increases. Temperature and evaporation show positive feedback in mid-lower plain areas, contrasting

with high mountain areas. Future temperature increases will likely drive continued evaporation increases, necessitating comprehensive consideration of evaporation impacts in agricultural irrigation, major water project planning (especially reservoirs), and climate change adaptation policies.

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