

Postprint Study on the Applicability of Hargreaves-Samani Regression-Corrected Crop Reference Evapotranspiration Calculation

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Abstract

To improve the accuracy of the Hargreaves-Samani (H-S) model for calculating reference evapotranspiration, regression correction was applied to the H-S model using daily meteorological data from 128 weather stations in the Northwest Yellow River Basin and the Middle-Lower Yangtze Plain from 1961 to 2010. With the Penman-Monteith (P-M) model as the benchmark, the computational accuracy of the improved H-S model (H-SCORR) was evaluated, and the future adaptability of the H-SCORR model was assessed using climate models from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The results show that: after correction, during the validation period, the average mean absolute error (MAE) and root mean square error (RMSE) for the four sub-regions of the Middle-Lower Yangtze Plain decreased by $6.21 \text{ mm} \cdot \text{month}^{-1}$ and $6.38 \text{ mm} \cdot \text{month}^{-1}$, respectively; the average MAE and RMSE for the four sub-regions of the Northwest Yellow River Basin decreased by $9.26 \text{ mm} \cdot \text{month}^{-1}$ and $9.23 \text{ mm} \cdot \text{month}^{-1}$, respectively; and the coefficient of determination (R^2) after correction in the two study regions improved by at least 1% compared to before correction. Under future climate scenarios from CMIP6 climate models, R^2 values all exceeded 0.98, demonstrating good adaptability. The corrected model method developed in this study can provide a higher-accuracy reference evapotranspiration estimation method for regions with only temperature data, offering a relatively accurate data foundation for high-frequency irrigation.

Full Text

Applicability Study of Reference Crop Evapotranspiration Calculation Based on Hargreaves-Samani Regression Correction

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Abstract

The Hargreaves-Samani (H-S) model for calculating reference crop evapotranspiration (ET_0) was regressed and corrected using daily meteorological data from 128 meteorological stations in the Northwest Yellow River Basin and the middle and lower reaches of the Yangtze River from 1961–2010. The calculation accuracy of the upgraded H-SCORR model was evaluated using site data from 2011–2020 with the Penman-Monteith model serving as the reference standard. The ACCESS-CM2 model and future test scenario SSP2-4.5 from the Sixth International Coupled Model Intercomparison Project (CMIP6) climate simulation experiment were also used to assess the H-SCORR model's future adaptability. The results show that the mean absolute error (MAE) of the four subdomains in the middle and lower reaches of the Yangtze River decreased from 2.58–7.99 $\text{mm} \cdot \text{month}^{-1}$ to 1.53–6.38 $\text{mm} \cdot \text{month}^{-1}$ after correction, while the root mean square error (RMSE) decreased from 3.22–24.56 $\text{mm} \cdot \text{month}^{-1}$ to 1.96–9.27 $\text{mm} \cdot \text{month}^{-1}$ during the validation period. On average, both MAE and RMSE decreased by 6.21 $\text{mm} \cdot \text{month}^{-1}$ and 6.38 $\text{mm} \cdot \text{month}^{-1}$, respectively. For the Northwest Yellow River Basin, the MAE of four subregions decreased from 2.51–34.1 $\text{mm} \cdot \text{month}^{-1}$ to 1.11–8.94 $\text{mm} \cdot \text{month}^{-1}$, and the RMSE decreased from 3.02–41.71 $\text{mm} \cdot \text{month}^{-1}$ to 1.43–10.46 $\text{mm} \cdot \text{month}^{-1}$, with average monthly reductions of 9.26 $\text{mm} \cdot \text{month}^{-1}$ and 9.23 $\text{mm} \cdot \text{month}^{-1}$, respectively. In both study areas, the coefficient of determination (R^2) exceeded 0.9 for most months and 0.8 for the remaining months, with the corrected R^2 values improving by at least 1% compared to pre-correction values. Under future climate scenarios from the CMIP6 climate model, R^2 values all exceeded 0.98, demonstrating strong adaptability. Therefore, the H-SCORR model shows improved performance in both the Northwest Yellow River Basin and the middle and lower reaches of the Yangtze River, better simulating the seasonal cycle and long-term trends of ET_0 while improving calculation accuracy for reference crop evapotranspiration.

Keywords: reference crop evapotranspiration; Hargreaves-Samani model; Penman-Monteith model; model validation; applicability

Introduction

Reference evapotranspiration (ET_0) represents a critical parameter in numerous applications including climatology, hydrology, and water resources planning. Accurate estimation of ET_0 is essential for irrigation system design, water resource management, agricultural and hydro-meteorological research, and water budget determination. Among calculation methods, the Penman-Monteith (P-M) model is recognized as the standard approach, having demonstrated reliability across various climates when compared with lysimeter measurements and other model outputs. However, the P-M model's computational complexity and extensive meteorological data requirements—including maximum and minimum temperatures, sunshine duration, wind speed, and relative humidity—limit its application in many regions where complete observational data are unavailable.

The Hargreaves-Samani (H-S) model has emerged as one of the most widely used temperature-based methods due to its simplicity and reduced data requirements. Nevertheless, the model's accuracy is often influenced by local meteorological conditions beyond just temperature extremes, particularly wind speed and humidity. Research has shown that the H-S model's calibration coefficients vary monthly across different climate zones. While previous studies have conducted calibrations and validations under various global climate conditions, many have focused on general parameter distribution patterns without comprehensive daily evaluation across numerous stations. For instance, studies in the Guadalquivir Valley irrigation district demonstrated that using corrected equations could reduce water consumption compared to original formulations. Similarly, research in Ningxia determined site-specific empirical coefficients through least-squares regression, while other work implemented monthly and regional coefficient corrections using linear regression analysis.

To address these limitations, this study employs long-term daily meteorological data sequences from 128 national stations to calibrate and validate the H-S model, enhancing its responsiveness to temporal climate factor variations. The research systematically compares the model's computational accuracy and adaptability between the arid/semi-arid Northwest Yellow River Basin and the humid middle-lower Yangtze River Plain. Furthermore, future adaptability of the calibrated model is assessed using CMIP6 climate projections.

Study Area and Data Sources

Study Area Overview

The study encompasses two distinct regions: the Northwest Yellow River Basin and the middle-lower Yangtze River Plain. The Northwest Yellow River Basin, characterized by high west-east topography with plateau-dominated landscapes

and glacial coverage above 4000 m, receives 200–650 mm of annual precipitation decreasing from southeast to northwest. With average annual temperatures of 12–14°C, the region experiences cold, dry winters and hot summers with scarce precipitation, making it ecologically vulnerable. Annual evaporation ranges from 845.93–1225.07 mm, with Gansu and Ningxia representing areas of maximum evaporation within China and forming a critical component of Central Asian arid zones.

The middle-lower Yangtze River Plain comprises the Jiangnan Plain, Dongting Lake, Poyang Lake, Wan-Su riverine areas, Lixiahe region, and the Yangtze River Delta, spanning Hubei, Hunan, Jiangsu, Jiangxi, Zhejiang, Anhui, and Shanghai. Located in the subtropical zone of the Northern Hemisphere at elevations of 5–100 m, the region receives 1000–1500 mm of annual precipitation with average temperatures of 14–18°C. Abundant rainfall and lower evaporation (1040.91–1091.65 mm) create humid conditions, making it one of China's most water-rich regions.

Data Collection

This study utilized daily meteorological data from 1961–2020 obtained from the China Meteorological Data Service Center (<http://data.cma.cn>) for 128 stations across both regions (station locations shown in [Figure 1: see original paper]). The dataset includes maximum temperature, minimum temperature, wind speed, rainfall, sunshine duration, and relative humidity. Data from 1961–2010 were used for model calibration, while 2011–2020 data served for validation. Rainfall, as the primary water input to ecosystems, influences net radiation distribution among energy components (sensible and latent heat fluxes), thereby altering atmospheric water-heat conditions and vapor pressure deficit to achieve comprehensive ET_0 regulation. Based on annual rainfall data from all stations, inverse distance weighting interpolation was applied to partition the study areas into different moisture condition zones ([Figure 2: see original paper]).

Methods

Reference Evapotranspiration Calculation Methods

The Penman-Monteith model, recommended by the Food and Agriculture Organization as the standard method for calculating and evaluating ET_0 , was implemented using ET_0 Calculator software. The equation is expressed as:

$$ET_{0-PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where R_n is net radiation at the canopy surface ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), G is soil heat flux density ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), T is mean air temperature ($^{\circ}\text{C}$), U_2 is wind speed at 2 m height ($\text{m} \cdot \text{s}^{-1}$), γ is the psychrometric constant ($\text{kPa} \cdot ^{\circ}\text{C}^{-1}$), Δ is the

slope of the vapor pressure curve ($\text{kPa} \cdot ^\circ\text{C}^{-1}$), e_s is saturation vapor pressure (kPa), and e_a is actual vapor pressure (kPa).

The Hargreaves-Samani model, an empirical formula requiring fewer meteorological inputs, was also employed:

$$ET_{0-HS} = 0.0023 \cdot (T_{mean} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot R_a$$

where T_{mean} , T_{max} , and T_{min} are mean, maximum, and minimum temperatures ($^\circ\text{C}$), respectively, and R_a is extraterrestrial radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$). The extraterrestrial radiation is calculated as:

$$R_a = \frac{24 \times 60}{\pi} \cdot G_{sc} \cdot d_r \cdot [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)]$$

where G_{sc} is the solar constant ($0.082 \text{ MJ} \cdot \text{m}^{-2} \cdot \text{min}^{-1}$), d_r is the inverse relative Earth-Sun distance, ω_s is the sunset hour angle, ϕ is latitude in radians, and δ is solar declination.

Model Correction Method

While the H-S model's simplicity enables broader application, its lower accuracy relative to P-M necessitates correction. This study employs nonlinear least squares regression to develop the H-SCORR model. The correction process involves calculating modified coefficients and analyzing errors, followed by future ET_0 prediction using the calibrated model.

A 50-year calibration period (1961-2010) was selected, with monthly ET_0 from the P-M model serving as the dependent variable and H-S model outputs as the independent variable. The correction equation is established as:

$$ET_{0-PM} = a + b \cdot ET_{0-HS}$$

Calibration coefficients a and b are derived through regression, and the corrected H-S model (H-SCORR) is expressed as:

$$ET_{0-HSCORR} = a + b \cdot ET_{0-HS}$$

The H-SCORR model was subsequently validated using 2011-2020 meteorological data and compared against P-M calculations. Future adaptability was assessed using the ACCESS-CM2 model from CMIP6 under the SSP2-4.5 scenario, which represents medium social vulnerability and medium radiative forcing, commonly employed for regional downscaling and decadal climate predictions. The algorithm improvement flowchart is presented in [Figure 3: see original paper].

Accuracy Evaluation Criteria

Using the P-M model as reference, three statistical metrics evaluate the H-SCORR model performance:

Mean Absolute Error (MAE):

$$MAE = \frac{1}{n} \sum_{i=1}^n |ET_{0-HS}(i) - ET_{0-PM}(i)|$$

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (ET_{0-HS}(i) - ET_{0-PM}(i))^2}$$

Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^n (ET_{0-HS}(i) - ET_{0-PM}(i))^2}{\sum_{i=1}^n (ET_{0-HS}(i) - \overline{ET_{0-HS}})^2}$$

where n is the sample size, $ET_{0-HS}(i)$ and $ET_{0-PM}(i)$ are monthly ET_0 values calculated by the respective models, and $\overline{ET_{0-HS}}$ is the mean H-S model value. R^2 reflects the correlation between estimated values, indicating consistency in trends and distribution patterns, while MAE and RMSE quantify deviation magnitude.

Results

Spatial Variation Distribution Patterns of ET_0

The spatial distribution of ET_0 across the middle-lower Yangtze River Plain shows a gradual increase from south to north, ranging from 1041-1092 mm. High-value centers occur at Laohekou and Fangxian (1081-1089 mm), primarily due to local topography and high sensitivity to wind speed and sunshine duration. Low-value centers at Yongzhou, Changning, and Daoxian (1041-1065 mm) result from higher relative humidity and shorter sunshine hours. In the Northwest Yellow River Basin, ET_0 ranges from 846-1225 mm, increasing from west to east. Notable high-value areas at Huinong, Taole, Yulin, Hengshan, and Yanchi (1030.62-1225.07 mm) correspond to centers of maximum sunshine duration and lower relative humidity in the region.

Model Accuracy Analysis

Statistical metrics for the original and corrected H-S models reveal distinct error characteristics during calibration and validation periods. Longer calibration sequences reduce errors from climate variability and validation applications,

making extended data periods more favorable for model stability. Consequently, the 50-year calibration period (1961–2010) was adopted.

Post-correction improvements in MAE, RMSE, and R^2 are evident across all subdomains ([Figure 5: see original paper],). In the middle-lower Yangtze River Plain, MAE decreased from 2.58–7.99 $\text{mm} \cdot \text{month}^{-1}$ to 1.53–6.38 $\text{mm} \cdot \text{month}^{-1}$, while RMSE declined from 3.22–24.56 $\text{mm} \cdot \text{month}^{-1}$ to 1.96–9.27 $\text{mm} \cdot \text{month}^{-1}$. Average monthly reductions of 6.21 $\text{mm} \cdot \text{month}^{-1}$ and 6.38 $\text{mm} \cdot \text{month}^{-1}$ were achieved for MAE and RMSE, respectively. The Northwest Yellow River Basin exhibited even stronger correction effects, with MAE decreasing from 2.51–34.1 $\text{mm} \cdot \text{month}^{-1}$ to 1.11–8.94 $\text{mm} \cdot \text{month}^{-1}$ and RMSE from 3.02–41.71 $\text{mm} \cdot \text{month}^{-1}$ to 1.43–10.46 $\text{mm} \cdot \text{month}^{-1}$, representing average monthly reductions of 9.26 $\text{mm} \cdot \text{month}^{-1}$ and 9.23 $\text{mm} \cdot \text{month}^{-1}$. R^2 values exceeded 0.9 for most months post-correction, with minimum improvements of 1% over pre-correction values. These results demonstrate that H-SCORR calculations are substantially more accurate than the original H-S model, particularly in the Northwest Yellow River Basin where correction effects were more pronounced than in the middle-lower Yangtze River Plain.

Application of the H-SCORR Model

Given the strong adaptability of H-SCORR in the Northwest Yellow River Basin, this region was selected for future applicability assessment. Using ACCESS-CM2 model data from CMIP6 under the SSP2-4.5 scenario, the H-SCORR model's predictive capacity was evaluated for 2021–2030. The model successfully simulated both seasonal cycles and long-term trends, achieving R^2 values exceeding 0.98 ([Figure 6: see original paper], [Figure 7: see original paper]), confirming its robust future applicability.

However, despite significant accuracy improvements, spatial variability persists in some areas requiring further refinement. The H-SCORR model exhibits clear spatial heterogeneity, and differences in temporal and spatial scales across study regions necessitate additional investigation. While this study employed correction coefficients to mitigate effects of wind speed, rainfall, and humidity, the method cannot directly reflect relationships between meteorological factors and ET_0 , warranting further discussion.

Discussion

Accurate ET_0 estimation is crucial for water resource management, agricultural planning, and hydro-meteorological research. The H-SCORR model is not intended to replace the P-M model but rather to provide effective ET_0 estimation when only temperature data are available. The calibration approach significantly improves accuracy, particularly benefiting high-frequency irrigation applications.

The model demonstrates superior performance in the Northwest Yellow River Basin compared to the middle-lower Yangtze River Plain, likely due to more sta-

ble climate patterns in arid/semi-arid regions. Future research should examine calibration accuracy across different temporal scales and investigate correction coefficients for smaller sub-regions, especially given the complex geography and large spatial extent of this study. While the correction coefficients effectively account for regional climate influences, more explicit representation of meteorological factor interactions remains an area for improvement.

Conclusions

1. The H-SCORR model significantly improved ET_0 calculation accuracy, with results much closer to P-M standards. In the middle-lower Yangtze River Plain, average MAE and RMSE decreased by $6.38 \text{ mm} \cdot \text{month}^{-1}$ and $6.21 \text{ mm} \cdot \text{month}^{-1}$, respectively. In the Northwest Yellow River Basin, corresponding reductions of $9.26 \text{ mm} \cdot \text{month}^{-1}$ and $9.23 \text{ mm} \cdot \text{month}^{-1}$ were achieved. Most months showed $R^2 > 0.9$, with corrected R^2 values improving by at least 1% over original values.
2. The H-SCORR model demonstrates strong future applicability under CMIP6 climate scenarios, with R^2 values exceeding 0.98. This enables reliable ET_0 forecasting for the study regions, supporting advanced evapotranspiration research and water resource management.
3. While absolute error performance varies across specific sites, overall errors decreased significantly in both regions. The correction proved more effective in the Northwest Yellow River Basin, indicating the H-SCORR model's particular suitability for arid and semi-arid environments.

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