Evaluation of potential evapotranspiration in the Weihe River Basin based on statistical downscaling

Y G Liu¹,²,³, S X Wang¹, Y Wang⁴ and H N Hu¹

¹Collage of Geography and Environment, Baoji University of Arts and Sciences, Baoji 721013, China
²Key Laboratory of Disaster Monitoring and Mechanism Simulating in Shaanxi Province, Baoji University of Arts and Sciences, Baoji 721013, China

E-mail: yingeliu@163.com

Abstract. The Hargreaves method of using the average temperature (Tₘ) was used to calibrate the estimation of potential evapotranspiration (PE) for daily meteorological data of 35 weather stations from 1951 to 2015 in the Weihe River Basin and a statistical downscaling model was applied to downscale the Hadley Centre Sea-Atmosphere Coupled Model (HadCM3) output data to each station. The future temporal and spatial variations of temperature and evapotranspiration under different climate change scenarios were evaluated for the periods of 2016–2039, 2040–2069, and 2070–2099. The results show that the downscaling method is well suited for estimating the PE and that the PE in the Weihe River Basin is larger in May–July and smaller in autumn and winter. The mean annual temperature and annual PE exhibit an increasing trend for the high greenhouse gas emission scenario (RCP8.5) and low greenhouse gas emissions scenario (RCP4.5) and the magnitude of increase is greater for the RCP8.5 scenario. Greater increases in the PE were mainly distributed in the south of the Weihe River, the upper reaches of the Beiluo River, and the middle reaches of the Jinghe River, whereas most of the northern reaches of the Weihe River exhibited smaller changes that were located in the lower reaches of the Jing River. The regional distribution of the PE is consistent with the temperature changes. This study provides the basis for regional water resource management planning.

1. Introduction
Regional hydrologic cycles are very sensitive to climate change and both climate change and human activities are the main driving factors of hydrologic cycles and changes in water resources [1-3]. Climate warming will exacerbate the water cycle, drive the variability of hydrological factors, increase the frequency and intensity of hydrological events, and change the balance of the regional water volume, which will have a great impact on the distribution of regional water resources and socio-economic development. For this reason, potential changes in the hydrological cycle have attracted the attention of researchers and many studies have been conducted on the spatial and temporal distribution patterns of the atmospheric circulation and the hydrological cycle [4-6]. Evapotranspiration is an important part of the water cycle and is also a key input factor for hydrological models [7-9]. To date, research methods of regional climate change on the hydrological cycle have included hydrodynamic models, regional climate models(GCM), statistical downscaling, and dynamical downscaling [10-14]; these methods have been used to analyze the impact of climate change on runoff and the response of...
water resources to climate change by assuming future climate change scenarios. Due to the influence of the arid climate and human activities, the runoff and sediment load in the Weihe River basin have decreased significantly and the hydrological processes have undergone great changes; these effects have had a huge impact on the local industrial and agricultural production, as well as the ecology of the river basin. Thus, based on 60 years of daily meteorological data of the Weihe River basin, we estimate the daily potential evapotranspiration (PE) of each station and predict the PE trend for future climate change scenarios. The results of this study will provide a basis for water resource management and governmental decision-making.

2. Study area and methods

2.1. Study area and data
The Weihe River is the largest tributary of the Yellow River. It is located at 104°00′E–110°20′E, 33°50′N–37°18′N and originates in the Niaoshu Mountain in Weiyuan County in the Gansu Province in figure 1. The Weihe River flows through the Gansu, Ningxia, and Shaanxi provinces and eventually flows into the Yellow River in Tongguan County in the Shaanxi Province. The river basin encompasses 134767 km² and covers the loess plateau in the north and the Qinling Mountains in the south. The Weihe River has many tributaries, among which the Jinghe River is the largest with a length of 455.1 km, a basin area of 45400 km², and a proportion of the total basin area of 33.7%. The North Luo River is the second largest tributary of the Weihe River with a length of 680 km, a basin area of 26900 km², and a proportion of the total basin area of 20%. The Weihe River basin is located in the transitional zone of the arid and humid regions and has a continental monsoon climate. Due to human activities and climate warming, the water resources of the Weihe River basin are greatly threatened. Therefore, the study of PE in the Weihe River basin is of great significance for the socioeconomic and environmental development.

![Figure 1. Meteorological stations in the Weihe River basin.](image)

The data used in this study include daily temperature, pressure, relative humidity, wind speed, and sunshine hours and consists of meteorological data from the Hadley Centre Sea-Atmosphere Coupled
Model (HadCM3) output and the National Centers for Environmental Prediction (NCEP) reanalysis data. The meteorological data originate from 35 weather stations in the Weihe River basin and the surrounding area collected during 1959–2016. The locations of the weather stations are shown in figure 1. The NCEP data are daily data for 1961–2000 and include 26 parameters, including average sea level pressure, surface air temperature, specific humidity, relative humidity, ground speed, wind direction, latitudinal wind speed, meridional wind speed, vorticity, divergence, 500 hPa and 850 hPa geopotential height, and 500 hPa and 850 hPa relative humidity. The NCEP grid size is 1.875°×1.875°, which is not compatible with the HadCM3 grid size. Therefore, the NCEP grid data were converted into a grid size of 2.50°×3.75° for compatibility with the HadCM3 data. The GCM output data consists of daily data from 1961 to 2099 of the HadCM3 of the Met Office (data were obtained from http://www1cics1uvic1ca/scenarios/index1cg2i Scenarios). The grid size is 2.50°×3.75° and the data includes two climate scenarios: high greenhouse gas emissions (RCP8.5) and low greenhouse gas emissions (RCP4.5). The forecast factor is the same as for the NCEP.

2.2. Methods
Statistical downscaling is achieved by establishing empirical relationships between the large-scale forecast factors and the regional or site-scale forecast factors to be applied to the temperature and PE predictions. In the statistical downscaling model (SDSM), weather generators and multiple regression methods were applied to the model calibration and verification; subsequently, future climate scenarios were generated and the PE was estimated. The approach consists of two parts: 1) establishing statistical relationships between the forecasters factors (regional or site meteorological data) and the forecast factors (atmospheric circulation factor), and 2) using GCM output data and the SDSM model to generate future time series data. In this study, we use the daily average temperature (Tav) as the forecast factor. A correlation analysis and scatter plots were used to determine the fit between the predicted value and the 26 NCEP predictors for each site. The statistical relationships and the model parameters were determined based on the measurements (forecast amount) of the daily data from 1961 to 1990 and the determined sequence of the NCEP forecast factors. The daily data from 1991 to 2000 were used to verify the model parameters. Finally, the HadCM3 daily data from 2016 to 2099 were input to the SDSM, thus simulating the daily Tav sequences for the RCP8.5 and RCP4.5 scenarios at each site. The period of 1961–2015 was identified as the base period to estimate the temperature series data and the temperature data were then used to estimate the change in the PE.

The Food and Agriculture Organization (FAO) Penman–Monteith (FAO-PM) method and the Hargreaves method [15,16] were used to estimate the PE because the FAO-PM method has a high accuracy in arid or humid areas. The formula is as follows:

\[
PE = \frac{0.408 \cdot k(R - G) + \frac{900}{T + 273} \cdot \nu_2(P_s - P_a)}{k + \tau + 0.34 \cdot \nu_2} 
\]

where \( PE \) represents the PE (mm/d); \( R \) represents the solar net radiation (MJ/m²·d); \( G \) represents the soil heat flux (MJ/m²·d); \( T \) represents the average temperature (°C); \( \nu_2 \) represents wind speed at a height of 2 m (m/s); \( P_s - P_a \) represents the saturated vapor pressure difference (KPa); \( k \) represents the slope of the saturated vapor pressure curve (KPa/°C); \( \tau \) represents a wet/dry constant (KPa/°C).

The Hargreaves method only requires temperature and geo-location data as input and reflects the radiation term based on the temperature difference. Therefore, it has been widely used when information is missing. The formula is as follows:

\[
PE = \sqrt{\alpha R_s T_d} \cdot (T_u + 17.8)
\]
Where $PE$ represents the PE ($mm/d$); $\alpha$ is parameters, and the initial value is 0.0023, $T_a$ represents the average temperature ($^\circ C$); $T_d$ represents the temperature difference ($^\circ C$); $R_a$ represents the top-of-atmosphere radiation ($MJ/m^2\cdot d$).

3. Evaluation of PE

3.1. Calibration of the PE estimation method

The estimation of the PE for the future scenarios requires a method with fewer input variables and higher accuracy. Based on the mean absolute error (AE), the average relative error (RE), mean square error (SE), and the coefficient of determination ($R^2$) were used as evaluation indices. The AE, RE, and SE must be as small as possible. After correction, the parameters were revised to be in the range of 0.0007–0.0069, the AE was in the range of 17.12%–36.12%, the SE was in the range of 0.38–1.02, and the $R^2$ was in the range of 0.74–0.89. The results indicate that the corrected Hargreaves method has a small simulation error at each station and that the simulation result is satisfactory. The mean monthly distribution of the PE based on the weights of the sites is shown in Figure 2. As can be seen, the mean monthly distribution of the PE is in good agreement for the two methods, thus the corrected Hargreaves method can be used to estimate the PE for future climate change scenarios in the Weihe River basin. The values of the PE during May to August were greater than 100 mm and accounted for 42% of the annual PE.

![Figure 2. Distribution of monthly PE, a: FAO-PM method, b: Hargreaves method.](image)

The parameters of the SDSM model are determined according to the forecast factors selected for each station. To simulate temperature of each station, the $R^2$ and validation period of the measured sequence are great. The simulation results of the SDSM were good and were used in the downscaling of the GCM output; this was then used as in input into the corrected Hargreaves model to generate PE sequences for each station for the two scenarios of RCP8.5 and RCP4.5.

3.2. PE estimation

Figure 3 shows the monthly $T_{av}$ and PE for the two scenarios. The $T_{av}$ in the Weihe River basin shows an upward trend and the warming rate gradually increases over time, except for the period from 2010 to 2039; however in April and May; the $T_{av}$ decreases slightly. The PE also shows a clear increasing trend from May to October and reaches a peak in July. However, during 2016–2039 and 2040–2069, the PE increases slightly, has no significant change from November to next April, and shows a decrease during 2016–2039. Figures 4 and 5 show the spatial distributions of the daily $T_{av}$ and PE under the RCP4.5 scenario. The spatial distribution of the RCP8.5 scenario is basically the same except for the magnitude of the change. As can be seen, the upstream area of the Weihe River and the North Luohe River have a larger increase in the $T_{av}$ and a greater increase is observed in the middle reaches and a smaller in the lower reaches of the river basin. Over time from 2016 to 2090, the areas
of higher temperatures gradually expand from the upper reaches of the Weihe River to the middle and upper reaches. The range of higher temperatures in the upper reaches of the North Luo River gradually decreases. The range of lower temperatures remains relatively stable. The larger increases in $T_{av}$ are concentrated in the upper reaches of the Weihe River, Jinghe River, and North Luohe River, whereas areas of lower temperatures are mainly distributed in the lower reaches of the Weihe River near Xi’an.

**Figure 3.** Trends of monthly temperature and PE for different climate change scenarios.

**Figure 4.** Spatial distributions of annual temperatures in the Weihe River basin under the RCP4.5 scenario.

**Figure 5.** Spatial distributions of annual PE in the Weihe River basin under the RCP4.5 scenario.
The PE shows an increasing trend with increasing temperatures, whereas the spatial distribution of the PE is relatively stable in different regions. Larger increases in the PE are located in the south of the Weihe River, the upper reaches of the North Luo River, and the middle reaches of the Jinghe River. Moreover, the maximum PE is eight times that of the minimum PE. During 2016–2039, 2040–2069, and 2070–2099, the largest increases are 187.09 mm, 217.19 mm, and 257.78 mm, respectively. These results show that the rate of PE will slow down after the 2080s. In most areas of the north Weihe River, the PE increases at a slower rate and these areas are located in the middle and lower reaches of the Jinghe River.

4. Conclusion
The monthly variations in the PE and the spatial and temporal variations of the PE under different climate change scenarios are estimated for the Weihe River basin using an SDSM. The following conclusions are drawn.

The changes in the temperature are small in May and June and larger in the other months. The PE is largest in the summer and smaller in the winter; the PE in the summer accounts for 42% of the annual PE. The PE is relatively large in the upper reaches of the Weihe River, the lower reaches of the north, and the southern part of the middle reaches; in contrast, the PE is smaller in the northern midstream areas. The maximum PE is about eight times that of the minimum PE. The PE has a wide range of change from May to September; the largest value occurs in July, whereas the changes are small in autumn and winter. The PE experiences an increasing trend under the two climate change scenarios and this is consistent with the trend of the temperature changes. The $T_{\text{av}}$ and PE in the Weihe River basin show a significant upward trend. The increase in the PE is greater for the RCP4.5 scenario. The area of the temperature increase greatly expands at different times. The PE exhibits an increasing trend in different regions during the different time periods with a larger increase in the south of the Weihe River and a smaller increase in the north of the Weihe River.

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