Article

Spatial-Temporal Change of Actual Evapotranspiration and the Causes Based on the Advection–Aridity Model in the Weihe River Basin, China

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Abstract: Evapotranspiration is a key process between the atmospheric hydrological cycle and the energy cycle, which has a great significance in understanding climate change and the rational use of water resources, especially for the Weihe River basin (WRB) (a basin in China experiencing a shortage of water resources). We investigated the spatial-temporal change of actual evapotranspiration (ET_a) based on the daily meteorological variables of 22 meteorological stations and the annual streamflow of three hydrological stations from 1970 to 2018 in the WRB. The contributions of key meteorological variables to ET_a changes and the sensitivity coefficient are also quantified. The temporal trends of ET_a showed an increasing trend from 1970 to 2018, and the spatial distribution of ET_a increased from northwest to southeast in the WRB. Increasing trends were detected in the multi-year average, spring, and winter, but only a few stations passed the significance test. Summer and autumn showed a decreasing trend, but this trend was not significant. Solar radiation is the most sensitive meteorological variable, followed by vapor pressure, wind speed, and mean temperature. Vapor pressure contributes the most to ET_a changes, followed by solar radiation. In general, vapor pressure (relative humidity) is the dominant meteorological factor affecting ET_a in the WRB. In addition to meteorological factors, the ET_a is also affected by combined and complicated factors caused by precipitation and human activities. As an important part of the hydrological cycle, ET_a has important research significance for water resources management, economy, agriculture, and ecology and results of this study may be helpful to further clarify the climate change and human activities impacts on the basin hydrological cycle.

Keywords: evapotranspiration; complementary relationship; Advection–Aridity model; Weihe River Basin

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1. Introduction

Evapotranspiration is a complex hydrological process, which closely links surface water balance and energy balance and is an important component of the hydrological process and energy cycle in the ecosystem [1]. It is estimated that with land surface evapotranspiration of more than $6 \times 10^4 \text{ km}^3$, nearly 70% of the precipitation on land will return to the atmosphere in the form of evapotranspiration each year [2]. The changes in climate factors and terrestrial surfaces (vegetation and soil characteristics) are the most direct factors affecting evapotranspiration during the hydrological cycle [3,4]. Accurately estimating the changes in ET_a and the attribution of different meteorological factors to ET_a is significant for the research of regional climate change, water resource management, and the construction of water conservancy projects. Almost every aspect of forestry, agriculture, and

water resource allocation is related to terrestrial and water surface evapotranspiration [5–8]. Therefore, the study of the regular patterns and mechanisms related to evapotranspiration is becoming increasingly important.

In recent centuries, the global climate has experienced a significant warming trend, and the issue of climate change has drawn much attention from the public, academic circles, and governments [9]. The fifth report of the IPCC noted that during the years from 1880 to 2012, the global average temperature on land and sea increased by 0.85 °C. According to paleo climatological data, the years from 1983 to 2012 may have been the warmest in the past 1400 years [10]. In this context, it is believed that global warming will dry out the surface atmosphere and increase the evapotranspiration of the soil surface and the crop, which will cause a series of water cycle changes [1,11]. A large number of current results show that there has been a continuous decrease in the evapotranspiration of evaporating pans around the world. The rate of this decrease was about $-1 \sim -5 \text{ mm} \cdot \text{a}^{-10}$ in the past 50 years [12–14]. The potential evapotranspiration (ET_p) in many countries and regions also shows a decreasing trend, while the temperature shows an increasing trend: Italy [15], India [16], Australia [17], Israel [12], New Zealand [18], the Canadian Prairies [19], and Japan [20], as well as some regions of China, have observed the same phenomenon [21–23]. Roderick (2002) called this the “evapotranspiration paradox” for the first time, as a hydrological phenomenon featuring a significant increase in air temperature accompanying a significant decrease in evapotranspiration [24]. The same phenomenon was also reported in studies on the analysis of ET_p and the actual evapotranspiration ET_a , such as the reference evapotranspiration in the middle and southwest areas of the Yellow River Basin [25]; potential and pan evapotranspiration in the Changjiang (Yangtze River) catchment [26]; ET_p in the eastern plain area of the Aksu River Basin [27]; ET_a in the pearl river basin [28]; and ET_a in the Yangtze River [29]. The results of existing studies showed that the attributions of different factors to the trend of evapotranspiration are inconsistent among different studies. Some studies reported solar radiation was the dominant factor for the decrease of evapotranspiration in the Iran [30], northeast India [31] and middle-lower Yellow River Plain [25]; Liu [32] observed a decrease of evapotranspiration in the Haihe River Basin attributed to wind speed; and some other studies reported that relative humidity is the dominant factor decreasing evapotranspiration in the Aksu and Heihe River Basins [27,33]. In addition, Irmak et al. [34] and Jung et al. [35] found that limited moisture supply could be the dominant factor driving changes in ET_a .

During the past several decades, considerable attention has been given to the tendency, spatiotemporal distribution, and influencing factors of pan evapotranspiration (ET_{pan}) and ET_p . Only a few studies have focused on the long-term changes and driving factors of ET_a changes, and it is difficult to obtain sufficient and reliable data for ET_a at a large scale using fixed meteorological observatories. The current estimation of ET_a mainly relies on model estimations and satellite data because lysimeters are costly to install and maintain [36,37]. The water balance method is also used to estimate the ET_a , but it cannot be applied to situ measurements and needs mass data (e.g., the water consumption of human activities); moreover, some data are not available to the public. Therefore, this method cannot be used in the spatial analysis of ET_a [38]. In 1963, Bouchet first outlined the complementary hypothesis that the relationship between ET_a and evapotranspiration capacity (ET_p) in a given area are complementary [39]. This complementary relationship states that, over areas at a regional scale and away from any sharp environmental discontinuities, the external energy will remain unchanged. With adequate water status, the process of ET_a will increase with an increase of the water supply; under this condition, ET_a will eventually equal ET_p , which is defined as wet surface evapotranspiration (ET_w) [40]. Once ET_a decreases as the water supply becomes less abundant, the air becomes drier, and the excess energy heats up the atmosphere, leading to an increase in ET_p and excess energy equal to the increase in ET_p —i.e., the results of the complementary relationship between ET_p and ET_a . This phenomenon can be applied to estimate ET_a with routinely recorded weather data without the need for additional, less common measurements of the moisture status of the

vegetation or soil. As one of the relevant methods, the Advection–Aridity (AA) model has been verified in many regions [40–42]. This method relies solely on routine meteorological observations. Local temperature and humidity gradients in the atmospheric boundary layer respond to—and obviate the necessity for information regarding—the conditions of moisture availability at the surface. These models bypass the complex and poorly understood soil–plant processes and thus do not require data on soil moisture, stomatal resistance properties of the vegetation, or any other aridity measures, nor do they require the local calibration of parameters, beyond those built into the models. Therefore, this method is the practical and easier preferred method relatively used in the calculate of ET_a .

The Weihe River Basin (WRB) is located in the transition area from semi-arid to semi-humid in an economically developed area in Northwest China, which is also an ecologically fragile area. In recent years, under the influence of climate warming and human activities, the ecological environment of the basin has been rapidly degraded. Most of the existing studies on hydrology and water resources have been done on precipitation [43,44], runoff [45], and ET_p in this basin [46,47], with few studies on ET_a . Therefore, the main objectives of this study were to (i) analyze the spatial distribution and temporal variation of ET_a ; (ii) quantitatively assess the impacts of climate variables on ET_a , including the degree of sensitivity and contributions of meteorological factors; and (iii) determine the dominant climatic variables that affect the changes of ET_a . The results derived from this study will help us better estimate and analyze the spatial and temporal variations of ET_a in this region. This study provides a foundation for understanding the causes of drought and flooding, developing scientific irrigation processes and protecting ecological systems, and improving the utilization rate of water resources in this basin.

2. Study Area and Dataset

2.1. Study Area

As the largest tributary of the Yellow River, the WRB is located in the lower midstream of the Yellow River. The total area is approximately $1.348 \times 10^5 \text{ km}^2$, and the main stream is 818 km in length. The basin originates from the Niaoshu Mountain of Gansu Province and Baiyu Mountain in the north, reaches Tongguan in the east and the Qinling Mountains in the south, and flows through the three provinces of Shaanxi, Gansu, and Ningxia. The basin is divided into three larger sub-basins with distinct geographic and climatic conditions: the Wei River, the Jing River, and the Beiluo River, known as the Jing-Luo-Wei Region. Among them, the Wei River has the largest area, $7.23 \times 10^4 \text{ km}^2$, and is located to the south of the whole basin with a long east–west direction belonging to the Guanzhong Plain. Jing River is the next largest, with an area of $4.54 \times 10^4 \text{ km}^2$, and is located on the north bank. The smallest area is the Beiluo River, $2.69 \times 10^4 \text{ km}^2$, located in the eastern part of the whole basin and accounting for 20% of the total basin area. The Wei River Basin is located in the transition zone between arid and humid regions. It belongs to a typical continental monsoon climate, making it dry and cold in winter and humid and hot in summer. The average annual rainfall in the area is 572 mm. The interannual variation of the rainfall is large, and the distribution is uneven during the year, mainly in summer (July–October), accounting for more than 60% of the annual rainfall. In winter (December–February), the rainfall is scarce, accounting for about 4% of the annual rainfall (Figure 1).

2.2. Data Sets

In this study, meteorological data from 22 national meteorological stations, provided by the National Meteorological Information Centre of China (NMIC) (<https://www.nmic.cn/>), including the daily average/maximum/minimum temperature, relative humidity, sunshine duration, wind speed, and precipitation during 1970–2018, were used in this study to estimate the ET_a in the WRB. These data were verified by the NMIC before being issued. Detailed information about these stations and datas are given in Tables 1 and 2. The division of seasons is based on the meteorological weather seasons—that is, spring runs from March

to May, summer from June to August, autumn from September to November, and winter from December to February of the following year.

Figure 1. Location of the Weihe River Basin.

Table 1. Information for the National Meteorological Observatory Stations used in this study.

Sub Basins	Station Number	Station Name	Longitude (°E)	Latitude (°N)	Altitude (m)	Catchment Area (km ²)
Wei River	52986	Lintao	35.37	103.87	1886.6	0.16
	52996	Huajialing	35.38	105.02	2450.6	0.72
	56093	Minxian	34.43	104.02	2314.6	0.38
	57143	Shangxian	33.87	109.97	742.2	0.08
	57134	Foping	33.52	107.98	1791.8	0.11
	57144	Zhenan	33.43	109.15	985.6	0.01
	57006	Tianshui	34.58	105.75	1141.7	0.93
	57036	Xian	34.27	108.95	410.0	0.72
	57016	Baoji	34.35	107.13	612.4	0.85
	53903	Xiji	35.97	105.72	1901.3	0.42
	57034	Wugong	34.25	108.22	505.4	0.79
	57046	Huashan	34.48	110.08	2064.9	0.51
Jing River	53821	Huanxian	36.57	107.30	1543.6	1.09
	53923	Xifeng	35.73	107.63	1421.9	0.93
	53929	Changwu	35.20	107.80	1206.3	0.92
	53915	Kuntong	35.55	106.67	1346.6	0.99
	53723	Yanchi	37.80	107.38	1347.8	0.10
	53817	Guyuan	36.00	106.27	1753.2	0.34
Beiluo River	53738	Wuqi	36.92	108.17	1331.4	1.05
	53845	Yanan	36.60	109.47	957.1	0.28
	53942	Luochuan	35.77	109.42	1158.3	1.02
	53947	Tongchuan	35.08	109.07	978.9	1.00
	57046	Huashan	34.48	110.08	2064.9	0.51

The hydrological data in this study include the annual streamflow during 1970–2018 from three hydrological stations provided by the Yellow River Water Resources Commission. The Huaxian station belongs to the main stream of Wei River, the Zhuangtou station belongs to the Beiluo River, and the Zhangjiashan station belongs to the Jing River. Detailed information on the hydrological stations is shown in Table 3.

Table 2. Characteristics of meteorological and hydrological data in Wei River Basin.

Decades	Streamflow (10 ⁸ m ³)			Precipitation (mm)	Wind Speed (m/s)	Average Temperature (°C)	Relative Humidity	Sunshine Duration (h)
	Huaxian	Zhuangtou	Zhangjiashan					
1970–1979	59.41	6.08	17.43	541.78	2.22	9.79	64.75	6.38
1980–1989	79.13	7.39	17.02	558.79	1.94	9.75	65.47	5.83
1990–1999	43.79	7.11	14.02	506.45	1.99	10.44	64.42	6.20
2000–2010	45.04	5.01	9.28	526.77	1.88	10.92	63.75	6.23
2010–2018	55.04	5.78	11.38	573.34	1.94	11.06	63.62	6.03
Mean	56.51	6.29	13.87	540.78	2.22	9.79	64.75	6.38
Max	131.00	13.09	26.05	760.97	2.36	11.69	70.79	6.62
	(1983)	(1988)	(1975)	(2003)	(1970)	(2013)	(1989)	(1979)
Min	16.83	3.09	4.51	369.49	1.78	9.04	59.38	5.13
	(1997)	(1973)	(2000)	(1997)	(2002)	(1984)	(1995)	(1989)
SD	25.92	2.44	5.39	82.30	0.14	0.69	2.21	0.34

SD: Standard Deviation.

The hydrological data in this study include the annual streamflow during 1970–2018 from three hydrological stations provided by the Yellow River Water Resources Commission. The Huaxian station belongs to the main stream of Wei River, the Zhuangtou station belongs to the Beiluo River, and the Zhangjiashan station belongs to the Jing River. Detailed information on the hydrological stations is shown in Table 3.

Table 3. Basic information of the hydrological station in the study area.

Hydrological Stations	Sub-Basins	Longitude (°E)	Latitude (°N)	Catchment Area (km ²)
Huaxian	Wei River	34°35′	109°46′	106,500
Zhuangtou	Beiluo River	35°02′	109°50′	25,600
Zhangjiashan	Jing River	34°38′	108°36′	43,200

3. Methodology

3.1. Evapotranspiration Estimation

Based on the complementary hypothesis proposed by Bouchet in 1963, Brutsaert and Stricker [47] provided a conceptual model based on the hypothetical non-advective evaporative power of the air, where the excess power in ET_p is equal to the deficit of power in ET_a . The evapotranspiration under this condition is defined as wet environment evapotranspiration (ET_w), which provides the complementary relationship between ET_a and ET_p in Equation (1). This relationship provides an index of the aridity of the atmosphere in a given region. Therefore, this approach is referred to herein as the “Advection–Aridity” (AA) model, which is applied to calculate the ET_a in the basin:

$$ET_a = ET_p = ET_w \quad (1)$$

This equation can be used to calculate the annual, monthly [48], and daily ET_a [47], as well as the ET_a for shorter time steps. For example, Parlange and Katul reported changes in ET_a over 20 min time steps [49]. The ET_p is calculated by the following equation originally proposed by Penman [50] for a free water surface:

$$ET_p = \frac{\Delta}{\Delta + \gamma} Rn + \frac{\gamma}{\Delta + \gamma} E_a \quad (2)$$

where Δ is the slope of the saturation vapor pressure curve of the air temperature calculated using the mean air temperature, which is an important parameter for describing

vaporization and used in the equations for calculating the ET_p from climatic data. γ is the psychrometric constant and kept constant for each location, given by

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \quad (3)$$

where P is the atmospheric pressure, R_n is the net radiation near the surface expressed as the equivalent vaporization rate, which is the difference between the incoming net shortwave radiation and the outgoing net longwave radiation. E_a is the drying power of the air, which, in general, can be written as

$$E_a = f(u)(e_a^* - e_a) \quad (4)$$

where e_a^* , e_a are the vapor pressure at the evaporating surface and the vapor pressure in the atmosphere above, respectively; $f(u)$ is a function of the horizontal wind velocity; and u_r is the wind speed at a height of r meters above the ground surface. The data of the wind speed measured by the China Meteorological Observatory stations are generally taken at a height of 10 m (U_{10}), which needs to be converted into a wind speed at a height of 2 m, which can be described as [50]

$$f(u) = 0.35(1 + 0.54U_{10}) \quad (5)$$

In Equation (1), Morton (1976) proposed calculating the wet environment evapotranspiration (ET_w) with the Priestley–Taylor formula [51], where α is the Priestley–Taylor evapotranspiration coefficient, the value of α depends on the surface vegetation coverage and regional micro-meteorological conditions, and α has a highly nonlinear relationship with soil moisture content, as well as significant temporal and spatial variability. The value ranges from 0.72 in the forest environment to 1.57 under strong advection conditions. Therefore, α generally adopts adjusted values in different areas:

$$ET_w = \alpha \frac{\Delta(R_n - G)}{\Delta + \gamma} \quad (6)$$

by combining Equations (2) and (5), ET_a can be written as

$$ET_a = (2\alpha - 1) \frac{\Delta}{\Delta + \gamma} (R_n - G) - \frac{\gamma}{\Delta + \gamma} E_a \quad (7)$$

Next, we calibrate α in the AA model according to the closed basin water balance formula and then calculate the annual actual evapotranspiration (ET_a) of the entire basin as

$$ET_a = P - R - \Delta S \quad (8)$$

where P , R are the annual precipitation, the net stream flow at the basin outlet, this can be calculated through the outlet runoff of three control hydrological stations in this basin divided by the area controlled by the stations (catchment areas), and ΔS is the water storage changes in a catchment, respectively. Here, the change in water storage is negligible in a given water year. Considering that α has the characteristics of time and spatial variation, the different sub-areas are calibrated separately. The values of α were determined by the minimum relative error between the multiyear average ET_a estimated by the AA model and the multiyear average ET_a calculated by the water balance method. The relative error of the parameter calibration can be expressed as:

$$\mu = \frac{ET^{WB} - ET_a^{AA}}{ET^{WB}} \times 100\% \quad (9)$$

where ET^{WB} is the actual multi-year average evapotranspiration calculated by the water balance method, and ET_a^{AA} is the actual multi-year average evapotranspiration calcu-

lated by the AA model. Here, 1970–1994 is the calibration period, and 1995–2018 is the verification period.

The calculated ET_a is analyzed in both time and space. In the spatial analysis, the interpolation method was used to realize the conversion of point data to area data of meteorological factors. The Kriging interpolation method was applied in this study since the uneven distribution of meteorological stations. Compared with inverse distance weighted and spline methods, Kriging is mainly used for the interpolation analysis of uneven points, and the ordinary Kriging interpolation method is the most commonly used method in geoscience statistics, and also has more applications in the spatial analysis of meteorological factors.

3.2. Trend Detection

Non-parametric Mann–Kendall rank correlation tests were used to detect the trend changes of ET_a [52,53]. This method does not require the data to have the characteristics of a normal distribution. Instead, it requires the sequence to be random and independent, so the probability distribution is equivalent and not disturbed by a few outliers. A positive value of Z indicates an upward trend, while a negative Z value indicates a downward trend. This can relatively objectively determine the trend of long-term sequence data changes and is widely used in hydrology [54,55].

3.3. Sensitivity Analysis

The sensitivity coefficient of ET_a is an important index used to measure the impact of climate factors, such as the mean temperature (T_{mean}), wind speed (U_2), solar radiation (R_s), and actual vapor pressure (e_a), on ET_a . Different variables in the Penman–Monteith model have different meanings, so the sensitivity coefficient can be used to make each factor dimensionless and thereby compare the relationship between different climatic factors. To understand the influence of different factors on ET_a , the dimensionless sensitivity coefficient defined by the dimensionless partial derivative with respect to the independent factors is used in this study. McCuen (1974) and Beven (1979) transformed the partial derivative into a non-dimensional form to determine the sensitivity of the variables:

$$SV_i = \lim_{\Delta V_i \rightarrow 0} \left(\frac{\Delta ET_a / ET_a}{\Delta V_i / V_i} \right) = \frac{\partial ET_a}{\partial V_i} \times \frac{V_i}{ET_a} \quad (10)$$

where SV_i is the sensitivity coefficient, and V_i is the i th variable. The sensitivity coefficient represents the variable of ET_a caused by changes in meteorological factors. A positive value of SV_i indicates that ET_a increases with increases in the meteorological factor, and vice versa. This method has been widely used in evapotranspiration studies [22,23,32,54].

3.4. Trend Attribution

The contribution amount of each meteorological variable to evapotranspiration can be expressed as the partial derivative of ET_a to the factor multiplied by the slope of the factor change and can be calculated by the following total differential equation [32]:

$$\frac{dET_a}{dt} = \sum \frac{\partial ET_a}{\partial x_i} \frac{dx_i}{dt} = \sum f_i' \frac{dx_i}{dt} \quad (11)$$

If we let $TR_y = dy/dt$ and $TR_i = dx_i/dt$ be the long-term trends in y and x_i , then Equation (10) can be rewritten as

$$TR_y = \sum f_i' TR_i = \sum C(x_i) \quad (12)$$

If TR_y and TR_i are estimated as the slope of the linear regression for y and x_i against time t , $C(x_i)$ can then be estimated as the contribution of x_i to the long-term trend in y , which is exactly the product of the partial derivative and long-term trend in x_i :

$$\frac{dET_a}{dt} = \frac{\partial ET_a}{\partial U_2} \frac{dU_2}{dt} + \frac{\partial ET_a}{\partial R_s} \frac{dR_s}{dt} + \frac{\partial ET_a}{\partial T_{mean}} \frac{dT_{mean}}{dt} + \frac{\partial ET_a}{\partial e_a} \frac{de_a}{dt} \quad (13)$$

This can be simplified to

$$L(ET_a) = C(U_2) + C(R_s) + C(T_{mean}) + C(e_a) \quad (14)$$

where the left side of the equation represents the change in ET_a during the study period, and the right side is the sum of the contributions of the four meteorological factors. Here, $C(U_2)$, $C(R_n)$, $C(T_{mean})$, and $C(e_a)$ represent the contributions of U_2 , R_s , T_{mean} , and e_a contributed to the long-term ET_a changes, respectively. If the contribution value is positive, the ET_a increased with the long-term changes of the meteorological variables, and if the contribution value is negative, then the result is the opposite.

In addition, the contribution rate of a meteorological factor to the long-term trend of ET_a is

$$P(x) = \frac{c(x)}{c(T_{mean}) + c(R_n) + c(e_a) + c(U_2)} \times 100\% \quad (15)$$

where $P(x)$ is the contribution rate of a meteorological factor to the long-term trend of ET_a .

4. Results and Discussion

The hydrological and precipitation data were available from 1970 to 2018 for the whole basin, these data were used for calibration only and the results listed in Table 4. The calibration period was selected from 1970 to 1994, and the validation period was from 1995 to 2018 for the Wei River basin. Considering that the model parameters varied spatially, the Wei River Basin was divided into three larger sub-areas, the Wei River, Jing River, and Beiluo River, to calibrate the model parameters, respectively. The value of α ranged from 0.5 to 1.5, with a step size of 0.01, taking the α when the relative error between the multi-year ET_a calculated by the AA model and the multi-year ET_a calculated by the water balance reached the minimum. The AA model calibration results are shown in Table 3. The values of α in the Wei River, Jing River, and Beiluo River are 0.93, 0.88, and 0.96, respectively. Compared with the calibration period, the relative error of ET_a in the validation period ranged within $\pm 10\%$ in three sub-areas. Meanwhile, the absolute errors during calibration period were 26.04 in Jing River, -14.59 in Beiluo River, -2 in Wei River, the absolute error in the validation period ranged with -5.36 – -0.46 in three sub-basins. Consequently, the ET_a estimated by the AA model was reasonable.

Table 4. The Advection–Aridity (AA) model calibration results in the Weihe River Basin.

Sub-Areas	Hydrological Station	Area (km ²)	α	Calibration Period (1970–1997) Annual Mean ET_a (mm)				Validation Period (1998–2018) Annual Mean ET_a (mm)			
				Water Balance	AA Model	Absolute Error	Relative Error (%)	Water Balance	AA Model	Absolute Error	Relative Error (%)
Wei River	Huaxian	63,300	0.93	525.83	527.84	-2.00	-3.1	526.33	528.97	-2.46	-2.5
Jing River	Zhangjiashan	43,200	0.88	489.67	463.63	26.04	2.4	450.25	450.89	-0.64	-4.1
Beiluo River	Zhuangtou	25,600	0.96	559.18	573.77	-14.59	-4.4	545.78	551.41	-5.63	-4.3

4.1. Temporal Change

The temporal changes in annual and seasonal ET_a from 1970–2018 are given in Figure 2a. The annual average ET_a in the WRB was 522.73 mm, with an insignificant increasing trend from 1970 to 2018. The averages of ET_a for spring, summer, autumn, and winter were 166.32 mm, 226.1 mm, 83.87 mm, and 34.77 mm, respectively, accounting for 31.82%, 43.25%, 16.04%, and 6.65% of the annual ET_a . The seasonal ET_a also showed an insignificant increasing trend over the study period, except for the ET_a in autumn, which showed an insignificant decreasing trend. The inter-annual variation of ET_a showed that the ET_a increased from January to July but decreased from August to December, with the largest ET_a from April to September (Figure 2b).

Figure 2. The variation of the annual, seasonal and monthly ET_a in the Weihe River Basin from 1970 to 2018. (a): Annual and seasonal; (b): Monthly.

4.2. Spatial Distribution of Seasonal and Annual ET_a

The spatial distribution of seasonal and annual ET_a in the WRB is shown in Figure 3, based on data interpolated by the Ordinary Kriging interpolation method (a method widely used in geoscience statistics [52]) from 22 meteorological stations during 1970–2018. The mean annual ET_a ranged from 436.8 mm to 601.8 mm, with the high annual ET_a values distributed in the eastern part of the whole basin and the southern part of the Wei River and low annual ET_a values mostly found in the western and central areas of the WRB. The ET_a decreased from southeast to northwest in the WRB. The distribution patterns of seasonal ET_a were similar to the annual patterns, which were roughly consistent in different regions. In summer and autumn, the distribution of ET_a was basically consistent with the spatial changes in the annual ET_a values. In spring and winter, higher ET_a values were found in the eastern part of the whole basin, while lower ET_a was observed in the central and northwestern areas of the whole basin, decreasing from east to west. The annual, summer, and autumn distributions of ET_a seem to be related to the elevation change of the basin. The ET_a value was found to be higher at lower altitudes and lower at higher altitudes.

Figure 3. Spatial distribution of annual and seasonal ET_a in the Weihe River Basin ((a): Annual, (b): Spring, (c): Summer, (d): Autumn, (e): Winter).

In spring, summer, and autumn, ET_a was higher in the east and south of the basin and lower in the central and western regions. In the east of the basin is the Beiluo River, which was the first demonstration site for the implementation of the Grain for Green program in China. This area has high forest coverage, and its interception evaporation and vegetation transpiration increase with the increasing of large-scale vegetation restoration. The south of the basin near the north of the Qinling Mountains belongs to a warm temperate semi-humid climate zone. There are a large number of warm temperate deciduous broad-leaved forests in the area with good vegetation coverage. In addition, the Guanzhong Plain lies in the southern part of the basin, which is one of the major grain-producing areas in Shaanxi province; the farmland irrigation also leads to an increase of ET_a . Therefore, the increase in cultivated land and woodland have enhanced the ET_a in the east and south of the basin. Some studies have shown that vegetation restoration resulted in an increase of the ET_a in the Loess Plateau [56]. The land type in the west and north is mainly grassland, and the evapotranspiration in grassland is less than that in woodland and cultivated land. Grassland is less disturbed by human activities than other types, so the ET_a change is relatively constant in the west and north of the basin. The decrease of ET_a in the northern part of the basin is also related to a decrease in sunshine and wind to a certain extent [57]. Compared with other seasons, the ET_a decreased in winter in the central and eastern basins, mainly due to the low temperature decreasing the vegetation transpiration and water demands in agricultural irrigation regions.

4.3. The Trends of ET_a Change

The trend of ET_a tested by the Mann–Kendall method is shown in Figure 4. Here, the trend of ET_a for the WRB is characterized by complicated spatial variability. The annual ET_a increased at 17 stations, with six (27%) stations significant at a 95% confidence level

(the values of MK test over the 2.76). The annual ET_a decreased at five stations, mainly distributed in the southern part of the basin. In spring, the ET_a increased significantly at 22 stations, with 11 of those stations dominated by significant increasing trends at a 95% confidence level. In summer, the ET_a of the 16 stations presented a decreasing trend, but most of them presented no obvious significance. Most stations in the autumn presented an increasing trend, mainly distributed in the upper area of Jing River and the northern part of the whole basin, accounting for 59% of all stations, but the significance was not very high. For the winter, the ET_a increased at 20 stations (10 of which were statistically significant at a 95% confidence level, accounting for 45.5% of all stations), whereas only two stations decreased with a low-significance confidence level.

Figure 4. The values of Mann–Kendall test results of the ET_a during 1970–2018 ((a): Annual, (b): Spring, (c): Summer, (d): Autumn, (e): Winter).

In terms of the different watersheds, the ET_a on the main stream of the Wei River mainly increased in spring and winter, the Beiluo River showed an increasing trend in other seasons (except for summer and autumn), and the Jing River showed an increasing trend in other seasons, except for summer.

4.4. Impact Factors of ET_a

4.4.1. Sensitivity of the ET_a to Meteorological Variables

The average annual values of the sensitivity coefficients for the mean temperature, solar radiation, wind speed, and vapor pressure were -0.02 , 0.30 , 0.16 , and -0.18 over the whole basin, respectively (Table 5). These results indicate that solar radiation is the most sensitive meteorological variable for ET_a changes, followed by vapor pressure, wind speed, and mean temperature in this basin. Annually, the ET_a showed a positive correlation with the mean temperature, solar radiation and wind speed and a negative correlation with the

vapor pressure, indicating that the ET_a increases with an increase of mean temperature and vapor pressure but decreases with a decrease of solar radiation and/or wind speed. For example, when mean temperature, solar radiation, and wind speed increased by 10% and vapor pressure reduced by 10%, ET_a will increase by 0.02%, 0.3%, 0.16%, and 0.18%, respectively. Seasonally, spring and winter are the most sensitive to solar radiation and wind speed, while summer and autumn are the most sensitive to solar radiation and vapor pressure. In general, both years and seasons are the most sensitive to solar radiation and the least sensitive to mean temperature. Another study also confirmed that solar radiation [58,59] and relative humidity [35,60] are the most sensitive factors affecting evapotranspiration changes in some regions, such as most parts of China [61,62], the Upper Heihe River Basin [63], and India [16]. Recently, Zhao (2018) [64] reported that relative humidity is the most sensitive meteorological variable for evapotranspiration changes in the north, northeast, and northwest of China, followed by wind speed, while in central, southwest, and eastern China, relative humidity is the most sensitive factor, followed by solar radiation. Fan Junliang (2016) showed that hours of sunshine is the most sensitive factor in plateau areas, while relative humidity is the most sensitive factor in temperate continental climate zones, temperate monsoon climate zones, and subtropical monsoon climate zones [65]. Therefore, the changes in evapotranspiration and sensitivity to different meteorological factors are quite different in different regions.

Table 5. The mean Sensitivity coefficients for mean temperature, solar radiation, wind speed, vapor pressure in the whole basins of Wei River Basin, which were represented as $S(T)$, $S(R_n)$, $S(U)$ and $S(ea)$, respectively.

Variables	Spring	Summer	Autum	Winter	Annual
$S(T)$	0.003	0.003	0.002	−0.001	0.020
$S(R_n)$	0.214	0.195	0.281	0.486	0.300
$S(U)$	0.124	0.070	0.102	0.329	0.160
$S(ea)$	−0.141	−0.111	−0.153	−0.324	−0.180

The monthly sensitivity coefficients of the meteorological variables showed that the sensitivity coefficients of ET_a to solar radiation and wind speed are positive, indicating that ET_a experiences an increasing trend with an increase in solar radiation and wind speed (Figure 5). The ET_a sensitivity coefficient to solar radiation is between 0.19 and 0.53, with the maximum in December and the minimum in August. The sensitivity coefficient to wind speed is between −0.01 and 0.53, with the maximum and minimum values in January and August, respectively. The sensitivity coefficients of ET_a to mean temperature and vapor pressure all have negative values (except for the positive temperatures in December), indicating that the ET_a decreases with an increase in mean temperature and vapor pressure during the year. The sensitivity coefficient of ET_a to mean temperature is between −0.03 and 0.02. The maximum occurs in December, and the minimum occurs in June. The sensitivity coefficient to vapor pressure is between −0.36 and 0.09; the maximum occurs in June, and the minimum occurs in December. In addition, the change curve for the sensitivity coefficient of ET_a to solar radiation and vapor pressure changes symmetrically.

The spatial distribution of the annual sensitivity coefficient of the ET_a in the WRB from 1970 to 2018 is shown in Figure 6. The sensitivity of ET_a to different meteorological variables has a certain zone distribution. Based on the distribution analysis of the ET_a to the mean temperature sensitivity coefficient, the sensitivity coefficient value is distributed between −0.03 and 0.02. The high-value areas mainly occur around the Baoji station and the main stream of the Wei River, where the sensitivity coefficient values are positive, while the rest of the stations in the basin have negative values, and low-value areas are mainly distributed in the southeast of the basin. Based on the distribution analysis of the ET_a for the solar radiation sensitivity coefficient $S(R_n)$, the sensitivity coefficients are mainly distributed between 0.16 and 0.39; the high value areas are mainly distributed in the upper reaches of the Jing River, and the sensitivity coefficients of the whole basin all

have positive values, indicating that the ET_a of the entire basin increases with an increase in solar radiation. The low-value areas are mainly distributed around Wuqi station in the upper reaches of Beiluo River, with an area smaller than the high-value area. In addition, a similar spatial distribution of sensitivity value changes can be observed for wind speed and vapor pressure, which have a coherent spatial pattern, and both show a decreasing trend from west to east. The high-value areas are mainly located in the middle east of the basin, while the low-value areas are located in the west side of the basin. The high-value areas of wind speed and vapor pressure account for nearly half of the basin's area.

Figure 5. Variation of monthly mean sensitivity coefficient in Weihe River Basin.

4.4.2. Contribution of the ET_a to Climatic Variables

Table 6 shows the contributions of each meteorological variable to ET_a changes. Annually, the increase in mean temperature and vapor pressure should have led to -0.0033 and $-0.0001 \text{ mm} \cdot \text{a}^{-1}$ decreases in ET_a , respectively; however, the decreases of solar radiation and wind speed instead yielded -0.0058 and $-0.0006 \text{ mm} \cdot \text{a}^{-1}$ decreases in ET_a . The total contribution of different meteorological variables led to a decrease of $-0.0046 \text{ mm} \cdot \text{a}^{-1}$ in ET_a . It is thus concluded that solar radiation is the dominant factor decreasing the annual ET_a . The contribution rates of mean temperature, solar radiation, wind speed, and vapor pressure to the long-term trends for annual ET_a were 2.79%, 12.69%, 12.89%, and 71.64%, respectively. This indicates that in the long term, solar radiation is the most crucial factor (except autumn) for ET_a changes over the WRB, followed by vapor pressure, wind speed, and mean temperature.

Seasonally, the contributions of each meteorological variable in summer and autumn (the warm season) are larger than those in spring and winter, and the total contributions of each season are negative, except for winter. The contribution of each factor in the first half of the year was greater than that in the second half of the year, indicating that the ET_a changes in the basin were mainly affected by the summer and autumn. For annual contributions, solar radiation was found to be the dominant factor affecting the seasonal contributions to ET_a in the study area, except for autumn, followed by vapor pressure, mean temperature, and wind speed. For example, in spring, the mean temperature, solar radiation, vapor pressure, and wind speed led to a 0.0024 , -0.0082 , 0.0011 , and $-0.0104 \text{ mm} \cdot \text{a}^{-1}$ decrease in ET_a , respectively. Wind speed, on the other hand, showed a positive effect on ET_a . This effect was offset by decreases in the mean temperature, solar radiation, and vapor pressure. The combined effects of the four meteorological factors resulted in a $-0.0199 \text{ mm} \cdot \text{a}^{-1}$ decrease in ET_a . Based on the contribution rates of different meteorological variables to the long-term trends in seasonal and annual ET_a , vapor pressure was found to be the dominant factor (except in autumn) for ET_a changes over the WRB, followed by solar radiation, wind speed, and mean temperature.

Figure 6. Spatial distribution of the mean annual sensitivity coefficients of the Weihe River Basin.

Table 6. Contributions of meteorological variables to the long-term trend in ET_a .

Period	Contribution				
	$C(T)$	$C(R_n)$	$C(U_2)$	$C(ea)$	$C(ET_a)$
Spring	−0.0024	−0.0082	0.0011	−0.0104	−0.0199
Summer	−0.0006	0.0099	−0.0002	−0.0024	−0.0153
Autumn	−0.0001	−0.0085	−0.0002	−0.0072	−0.0160
Winter	0.0004	−0.0091	−0.0001	0.0057	0.0485
Annual	−0.0001	−0.0058	−0.0006	−0.0033	−0.0046
Period	Proportional Contribution (%)				
	$P(T)/\%$	$P(R_n)/\%$	$P(U_2)/\%$	$P(ea)/\%$	P_{sum}
Spring	12.05	41.16	−5.48	52.28	100.00
Summer	3.60	−64.33	1.46	159.27	100.00
Autumn	0.79	52.94	1.36	44.92	100.00
Winter	0.90	−18.69	−0.21	118.01	100.00
Annual	2.79	12.69	12.89	71.64	100.00

Note: $C(T)$, $C(R_n)$, $C(ea)$ and $C(U_2)$ respectively represent the contribution of the average temperature, net solar radiation, actual water vapor pressure and wind speed to the long-term trend of ET_a , $C(ET_a)$ represents the sum of the contribution of the four meteorological factors over the years; $P(T)$, $P(R_n)$, $P(ea)$ and $P(U_2)$ represent the contribution rate of mean temperature, net solar radiation, actual water vapor pressure and wind speed to the long-term trend of ET_a , respectively; P_{sum} are the total contribution rate of average temperature, net solar radiation, actual water vapor pressure and wind speed to the long-term trend of ET_a .

The sensitivity coefficient of ET_a to meteorological factors refers to the changes of ET_a caused by the unit changes of the meteorological variables, while the actual contributions of these variables to the changes of ET_a also depend on their own variability. Therefore, whether or not a single meteorological variable is the main factor affecting the changes in long-term ET_a depends on the combined effect of the sensitivity of this meteorological variable to ET_a and the slopes of the variable itself. For example, although vapor pressure is the second-most sensitive variable to annual ET_a changes in this region, it presents the largest impact (contribution) to ET_a changes compared to other climatic variables in spring. Generally, solar radiation is the dominant factor affecting the changes in annual ET_a , followed by vapor pressure.

Overall, the change of different meteorological variables during 1970–2018 showed in Figure 7, it can be concluded from the above analyses that the increasing vapor pressure or decreasing relative humidity is primarily responsible for the ET_a changes in the WRB. The relative humidity is mainly determined by the vapor pressure, so the relative humidity is the dominant meteorological factor that affects the ET_a in the WRB. Similarly, differences in the controlling climatic factors have also been identified in many other regions. Jung et al. (2010) [35] and Marshall (2012) [66] found that the general global average annual evapotranspiration increased from 1982 to 1997, but after the strongest El Niño phenomenon happened in 1998 the global evapotranspiration growth trend seems to have stopped, and the global average land evapotranspiration decreased. This change in evapotranspiration is mainly due to the moisture limitations in the southern hemisphere, especially the weakening of water vapor sources in Africa and Australia (Jung et al., 2010) [35]. On the other hand, this study region located in the southeast portion of the Yellow river, where the moisture introduced by the southeast monsoon from the South China sea and/or Bohai combined with topographic factors can directly influence the relative humidity [58]. Relative humidity is affected by vapor pressure, and saturated vapor pressure has a direct relationship with temperature. Therefore, increasing the temperature would lead to increasing the saturated vapor pressure, further causing a decrease in relative humidity and eventually an increase in evapotranspiration. Zhang (2011) [67] also found that relative humidity is the most sensitive factor for changes in the reference evapotranspiration in northwest China and attributed the decrease in relative humidity in NW China to increases in precipitation. NW China is characterized by an arid climate, and a reduction in precipitation will cause an increase in relative humidity.

Figure 7. Cont.

Figure 7. Annual trends of ((a): Relative humidity, (b): Wind speed, (c): Sunshine duration, (d): Mean temperature) in Weihe River Basin.

Based on the previous results, it can be seen that the total contribution of meteorological factors to the ET_a changes is negative, but the ET_a in this study area is increasing. Therefore, the factors affecting the changes of ET_a in the WRB are complicated and comprehensive and are caused by a combination of climatic conditions and land surface conditions. Changes in precipitation are also closely related to changes in ET_a . Similar to the changes in the average multi-year ET_a , the precipitation changes also showed a slight increase (Figure 8). The spatial distribution of precipitation in the WRB is shown in Figure 9a, where it can be seen that precipitation in the WRB decreases from southeast to northwest. Similar changes can be observed in the average multi-year, summer, and autumn ET_a values. The precipitation in the WRB is mainly concentrated in summer and autumn, especially from June to August, indicating the ET_a in summer and autumn, to a certain extent, is affected by precipitation.

Figure 8. Spatial distribution of average precipitation from 1960–2018 in Weihe River Basin.

Rainfall mainly promotes evapotranspiration in two ways. On the one hand, it increases soil water content [68]. The decline in global land surface evapotranspiration from 1998 to 2008 was mainly due to the decrease of soil moisture [35]. On the other hand, rainfall can also promote vegetation growth. Using Pearson's correlation analysis, the correlation between precipitation and ET_a in the whole basin reached a significance level of 0.01 ($p = 0.50$), and the ET_a increased with an increase in precipitation. Evapotranspiration plays an important role in water and energy balance, and changes in evapotranspiration will also cause changes in the hydrological cycle. The Aridity index (AI) is usually used to evaluate the wet and dry state of a basin and is commonly expressed as the ratio of potential evapotranspiration to precipitation [69]. It can be seen from Figure 9b that the climate in this basin is experiencing a state of long-term drought (AI greater than 1), although the AI presents opposite characteristics of

change compared to the precipitation, as the overall trend of change is relatively gentle. There was, however, a significant increase in 1997 and 1995, mainly due to the decrease in rainfall during this period.

Figure 9. Variation of average precipitation and Aridity index from 1960–2018 in Weihe River Basin. (a): average precipitation; (b): Aridity index.

Some studies have also shown that vegetation change is another important factor affecting the changes of evapotranspiration in a watershed [70]. Since 1999, China has implemented a series of ecological restoration projects to alleviate ecological deterioration, such as surface water loss, soil erosion, land desertification, and grassland degradation. In particular, the implementation of large-scale Grain for Green and Nature Forest Protection programs resulted in the rapid restoration of vegetation in the WRB. The local climate has, therefore, changed, and the increase in the coverage of large areas of vegetation has further led to a rapid increase in local evapotranspiration [65]. Effective vegetation restoration resulted in a significant increase in evapotranspiration in the northeast and central parts of Xilinguole League, China [71]. Under the influence of the Grain for Green programs, the evapotranspiration in different catchments showed an increasing trend with the increase of vegetation coverage in the Loess Plateau of China. At the same time, these activities also caused changes in land use types in the watershed; likewise, the changes in evapotranspiration under different landscape patterns are different. Zhou et al. (2019) [56] estimated the ET_a of the Loess Plateau through MODIS data and found that the annual average evapotranspiration of different land use types in the Loess Plateau is forest land > farmland > grassland. The irrigation area of farmland is another

important evapotranspiration area. Large areas of irrigated farmland (accounting for 72% of Shaanxi Province) and low-efficiency irrigation measures (flood irrigation) have caused a large amount of water to experience evapotranspiration.

In this study, the ET_a values estimated by the AA model were calibrated via the annual scale water balance method. The calculation of the runoff depth in terms of water balance was mainly based on the runoff data in the China Hydrological Yearbook. However, in this study we can only use the existing data to estimate the runoff depth, and some data are not available to the public. Therefore, without affecting the estimation, we used the water balance to estimate the runoff depth. Meanwhile, the measured runoff in recent years deviated from the “natural” runoff gradually, since the specific water amount used in reservoir storage and drainage, agricultural irrigation, and industrial domestic applications is difficult to estimate. In addition, this study focused on an analysis of the ET_a changes in the WRB based on meteorological factors but did not consider the adjustment of the crop planting belt, growth period changes, urban layout, or other related aspects caused by changes of meteorological factors.

5. Conclusions

This study calculated the ET_a of the WRB with the AA model based on complementary assumptions, and the water balance method was used to calibrate the parameters of the model. The estimated ET_a was in good agreement with the ET_a calculated by the water balance formulation. The ET_a in this basin showed a slight increasing trend in the long-term, and the spatial pattern of ET_a was shown to increase from northwest to southeast. In terms of spatial changes over the years, except for some stations in the southern part of the basin, the remaining stations showed a significant increase. Solar radiation is the most sensitive meteorological variable for ET_a changes in the basin, followed by actual vapor pressure, wind speed, and temperature. Actual vapor pressure is the meteorological variable that contributes the most to ET_a changes, followed by solar radiation. This indicates that the actual vapor pressure is the dominant factor that affects ET_a changes in the basin, in addition to climatic conditions, they are also affected by factors such as precipitation and landscape. This study provided a quantitative method to determine the relationship between meteorological variables and ET_a . The results are vital for understanding the effects of climate and human activity on hydrological processes and provides important information for water resources management in China. However, due to the uncertainty and limitations of the study, to some extent there is still much work needed to obtain a more accurate actual evapotranspiration model. In the future, further research into the utilization forms of water resources in the basin and the issues related to climate resource changes and their environmental effects is needed.

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