Estimation of the Influence of Meteorological Factors on the Potential Evapotranspiration of Yanhe River Basin

Yu Luo[1,3], Peng Gao[1,2,3], Xingmin Mu[1,2,3], Dexun Qiu[1,3]

[1] State Key Laboratory of Soil Erosion and Dryland Agriculture on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, 26 Xinong Road, Yangling, 712100, Shanxi Province, China.

[2] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Northwest A & F University, 26 Xinong Road, Yangling, 712100, Shanxi Province, China.

[3] University of Chinese Academy of Sciences, Beijing, 100049, China

Corresponding Author:

address and email

Prof. Dr. Peng Gao

E-Mail: gaopeng@ms.iswc.ac.cn

Address: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, 26 Xinong Road, Yangling, 712100, Shaanxi Province, China

Phone: +86-29-8701-2875

Prof. Dr. Xingmin Mu

E-Mail: xmmu@ms.iswc.ac.cn

Address: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, 26 Xinong Road, Yangling, 712100, Shaanxi Province, China

Phone: +86-29-8701-2411

Abstract

Potential evapotranspiration (ET_0) is an important expenditure item in the hydrological cycle. Quantitative estimation of the influence of meteorological factors on ET_0 can provide a scientific basis for the study of the impact mechanism of climate change on the hydrological cycle. In this paper, the Penman-Monteith method was used to calculate ET_0. The Mann-Kendall statistical test and the Inverse Distance Weighting method were used to analyze the temporal and spatial characteristics of the sensitivity coefficient of ET_0 to meteorological factors and contribution rate of meteorological factors to ET_0. And the reasons for the change of ET_0 were quantitatively explored in combination with the change trend of meteorological factors. The results showed that the average ET_0 in the Yanhe River Basin from 1978 to 2017 was 935.92mm. Except for Ganquan Station, ET_0 showed an upward trend. Generally, the sensitivity coefficient of air temperature (0.08), wind speed (0.19) and solar radiation (0.42) was positive and the sensitivity coefficient of relative humidity (-0.41) was negative. But there were significant temporal and spatial differences. The upward trend of air temperature and solar radiation contributed 1.09% and 0.55% to ET_0. Respectively, the downward trend of wind speed contributed -0.63% And the downward trend of relative humidity contributed to -0.85% of ET_0. Therefore, the decrease of relative humidity did not cause the increase of ET_0 in Yanhe River basin. The dominant factor of the upward trend of ET_0 was air temperature. But the dominant factors of ET_0 had significant temporal and spatial differences. The downward trend of wind speed at Ganquan Station contributed -9.16% to ET_0, which indicated the dominant factor of "evaporation paradox" in Ganquan area was wind speed. Generally, the increase of ET_0 was related to air temperature, wind speed and solar radiation. And the decrease of ET_0 was related to relative humidity.

Keywords: climate change, the changing trend of meteorological factors, potential evapotranspiration, sensitivity coefficient, contribution rate, dominant factor

1. INTRODUCTION

According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), the earth's surface air temperature has been increasing at a rate of 0.13°C/10a over the past 50 years (1956-2005)(IPCC, 2007). Global warming intensifies the hydrological cycling and affects the spatial and temporal allocation of water resources, so the frequency and intensity of "water" disasters are on the rise(Zhou, 2019). Thus, people's life safety, social and economic development, ecological and environmental protection are facing a series of challenges. Therefore, the research on hydrological cycling is of great significance, which is closely related to people's life and production, and affects many aspects such as social economy and ecology.

Evapotranspiration is an important expenditure item in the water cycle, which is composed of water evaporation and transpiration on the surface, water area and plants, and has an important influence on water balance and energy balance. In practical applications, the concepts discussed are actual evapotranspiration and potential evapotranspiration. Actual evapotranspiration refers to the evapotranspiration under the actual condition of the underlying surface, and potential evapotranspiration refers to the evapotranspiration when the underlying surface is fully supplied with water(FAO, 1998). It is the limit value of actual evapotranspiration in a region(Li, 2013). Respectly, it determines the dry and wet condition of a basin, and is one of the important indicators for estimating the basin evapotranspiration capacity(Zhou, 2019). Under the influence of climate warming, the potential evapotranspiration of the whole world and most regions has shown a decreasing trend, and has not increased as people expected(Roderick & Farquhar, 2002; Roderick & Farquhar, 2004; Burn & Hesch, 2007; Fu et al., 2009). This phenomenon was called the "evaporation paradox". However, evapotranspiration was increasing in some regions, such as western Africa(Onyutha, 2016), Israel(Cohen etal., 2002), and southern China(Yin et al., 2010). Scholars have explored the causes of changes in ET_0 and found that the decline in ET_0 in Australia(Roderick & Farquhar, 2002), Iran(Dinpashoh et al., 2011), southern Canada(Burn & Hesch, 2007) was mainly caused by wind speed. And the decline in potential evapotranspiration in India was most closely related to relative humidity(Chattopadhyay & Hulme, 1997). The most sensitive factor for the decline of ET_0 in China was water vapor pressure(Liu et al., 2012). However, due to the large geographical differentiation of natural geographical conditions in various regions of China, the causes of potential vapotranspiration changes have significant spatial heterogeneity. ET_0 of the Yellow River Basin presented an upward trend, and its changes were most sensitive to solar radiation. But the factor that contributes the most was air temperature(Liu et al., 2010). The most sensitive meteorological factor in the Yangtze River Basin was relative humidity(Gong et al., 2006), but the decrease in solar radiation and wind speed was the main reason for the changes in ET_0 (Wang et al., 2007). The evapotranspiration in the upper reaches of the Heihe River Basin was most sensitive to relative humidity, but its changes were mainly caused by wind speed(Luo et al., 2016). The decrease of ET_0 on the Qinghai-Tibet Plateau was related to the decrease of wind speed, the decrease of net radiation, and the increase of air temperature(Zhang et al., 2007). The potential evapotranspiration of the Loess Plateau was increasing. It was caused by the combined effect of the rise in air temperature and the decline in relative humidity, wind speed, and sunshine hours(Li et al., 2012). The previous studies have found that ET_0 was affected by climate change, the extent of which was related to the change trend of climate factors, and the response of potential evapotranspiration to climate change had significant spatial heterogeneity. Therefore, the influence of climate factors on ET_0 had many uncertainties and was worth further exploration. In addition, Liu et al. (2009) found that the change of ET_0 was not only affected by the climate sensitivity coefficient, but also related to the changing trend of meteorological factors. Only by combining the sensitivity coefficient and the contribution rate can we systematically and quantitatively analyze the causes of change of ET_0(Su et al., 2015).

Since the 1990s, climate change and human activities have had a dramatic impact on the hydrological cycle of the Loess Plateau. The Yanhe River Basin is a typical watershed in the hilly and gully region of the Loess Plateau. Therefore, an in-depth understanding of the impact of climate change on ET_0 in Yanhe River Basin is of great significance for the rational allocation of water resources in Yanhe River Basin, and has guiding significance for the study of water cycle on the Loess Plateau.

In this paper, the Yanhe River Basin was took as the study area. The Penman-Monteith method was used to calculate the ET_0 of the Yanhe River Basin . The objectives of this paper was to analyze sensitivities of ET_0 to four major meteorological variables and the changing trends of various climate factors and quantitatively estimate the contribution rate of climate factors to ET_0. So as to reveal the causes(in terms of meteorological factors) of potential evapotranspiration changes in the Yanhe River Basin in the past 40 years. The study contributed to a more thorough understanding of the impact mechanism of climate change on the water cycle process, and providing a scientific basis for water resources evaluation and management and the composition of agricultural planting structures.

2. DATA AND METHODS

2.1 Study area

The Yanhe River Basin, with length of 286.9km and a total drainage area of 7725 km^2, is a first-level tributary of the middle reaches of the Yellow River. It originates from Zhoushan, Tianciwan Township, Jingbian County, and flows through four counties (cities) including Zhidan, Ansai, Baota and Yanchang. And it enters the Yellow River near the cool bank of Nanhegou Township, Yanchang County. The Yanhe River Basin has a continental monsoon climate, which is dry and windy in spring, warm and rainy in summer, cool and rainy in autumn, and cold and dry in winter(Yang, 2019). In Yanhe River basin, the annual average precipitation is about 520 mm, the average evaporation is 897.7 ~ 1678 mm, the average air temperature is 8.8 ~ 10.2 °C, and the average annual duration of sunshine is 2450 h(Jiao et al., 2017).

2.2 Data

The meteorological data in this paper were from China Meteorological Data Network (http:// data.cma.cn/). The meteorological data included the daily average air temperature (T), the daily maximum air emperature (T_{max}), the daily minimum air temperature (T_{mix}), wind speed of 10 meters (U_{10}), the sunshine duration (n), the daily average relative humidity (RH) and the daily precipitation (P). The U_{10} needs to be converted into wind speed of 2 meters (U_2). The time series of all the data is from 1978 to 2017. The control hydrological stations selected in this paper are Ganguyi station and the meteorological stations are jingbian, Wuqi, Zhidan, Ansai, Yan 'an, Zichang, Yanchuan, Yanchang, Ganquan and Yichuan stations (Figure 1).

[Insert Figure 1]

2.3 Potential evapotranspiration

In this paper, Penman-Monteith method, which was mostly studied as the standard(Zhang et al., 2012), was used to calculate potential evapotranspiration. Its form was:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{\left(T+273\right)} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} (1)$$

Where ET_0 is potential evapotranspiration (mm). R_n is the net radiation (MJ mm^{-2} day^{-1}). G is the soil heat flux (MJ mm^{-2} day^{-1}). $\gamma$is the psychrometric constant (kPa °C^{-1}). T is mean daily air temperature at 2m height(°C). U_2 is wind speed of 2 meters (m s^{-1}). e_s is saturation vapour pressure (kPa). e_a is actual vapour pressure (kPa). Δ is the slope vapour pressure curve(kPa °C^{-1}).

2.4 The calculation method of sensitivity coefficient

The dimensionless sensitivity coefficient(Mccuen, 1974; Beven, 1979; Rana & Katerji, 1998; Hupet & Vanclooster, 2001) was used to characterize the sensitivity of ET_0 to climate change. This method can analyze the impact of a single climate factor change on the ET_0 change under the premise that other climate factors remain unchanged. The sensitivity coefficient (S_i)was calculated as:

$$S_i = \frac{\partial ET_0}{\partial i}\frac{i}{ET_0} (2)$$

Where S_i is the sensitivity coefficient of ET_0 change to climate factor change, which is dimensionless.i is climate factor. $\partial ET_0 / \partial i$ is the partial derivative of potential evapotranspiration ET_0 with respect to climate factor i , indicating the sensitivity of ET_0 to i.

The positive or negative sensitivity coefficient of a variable indicates that ET_0 will increase or decrease as the variable increases. The absolute value of the sensitivity coefficient indicates the degree of influence of climate factors on ET_0. The greater the absolute value of the sensitivity coefficient, the greater the impact of climate factor changes on potential evapotranspiration, and vice versa. If S_i is -0.1, then a 10% increase (decrease) of i would cause a 5% decrease (increase) in ET_0 if the other meteorological variables are fixed.In this paper, the sensitivity coefficients of average air temperature, humidity, wind speed, and solar radiation are calculated and denoted as S_T, S_{RH}, S_{U_2}, S_{R_s}.

2.5 The calculation method of contribution rate

In this paper, the contribution rate of climate factors to potential evapotranspiration was indicated by multiplying S_i by the relative change rate of climate factors(Yin et al., 2010). It was computed as (3) and (4).

$$C_i = S_i \cdot R_i \quad (3)$$

$$R_i = \frac{N \cdot L_i}{M_i} 100\% \quad (4)$$

Where C_i is the contribution rate of change of i to ET_0(%). R_i is the relative change rate of climate factor i. N the number of years in the study period. L_i is the linear trend rate of climate factor i in the study period. M_i is the average value of the climate factor in the study period.

The positive or negative C_i indicates that the positive or negative effect of climate factor i on the change trend of ET_0. The greater the absolute value of C_i, the greater the contribution of climate factor i to the change of ET_0, and vice versa.

2.6 Analytical method

The non-parametric Mann-Kendall statistical test(Mann, 1945; Kendall,) was used to detect the trend of the sensitivity coefficient and contribution rate of potential evapotranspiration in the Yanhe River Basin from 1978 to 2017. The inverse distance weighting method was used to interpolate the sensitivity coefficient and contribution rate of potential evapotranspiration(Lin et al., 2002).

3. RESULTS

3.1 The temporal and spatial characteristics of ET0 and meteorological factors

The characteristics of multi-year average monthly ET_0 and meteorological factors change in Yanhe River Basin are shown in Table 1. The average air temperature of Yanhe River basin from 1978 to 2017 was 9.59°C and the high air temperature month was from June to August. The average relative humidity was 60.05% and the high value month was from August to October. The average wind speed of 2 meters is 1.16 m s^{-1} and the high value month was March to May. The average solar radiation was 5645.81 MJ mm^{-2} day^{-1} and the high value month was from May to July. The average precipitation was 495.19 mm and the high value month was from July to September. From the results of the Mann-Kendall statistical test, it was found that air temperature (significant level of 0.01), solar radiation and precipitation showed an upward trend with the year, while the relative humidity and wind speed of 2 meters showed a downward trend. The average evapotranspiration of Yanhe River basin is 935.92mm and the high value month was from May to July. On the whole, ET_0showed an increasing trend that passed the 0.1 significance level test, while the ET_0 of September and October showed a decreasing trend.

[Insert Table 1]

The average air temperature of Yanhe River Basin from 1978 to 2017 presented a distribution pattern of high in the southeast and low in the northwest and showed an increasing trend(Figure 2). The relative humidity was high in the west and east and low in the north and south. Only the Zichang station and Yanchang station in the basin showed an insignificant rising trend, which indicating that the Yanhe River basin has a significant warming and drying trend. The wind speed of 2 meters was low in the west and east and high in the north-south. The wind speed of 2 meters showed a downward trend as a whole, but the Zichang Station, Yanchang Station, Yanchuan Station and Yichuan Station show an upward trend. The solar radiation in the southeast was smaller than that in the south and showed a downward trend. The solar radiation of Yan 'an station and Jingbian Station were high-value region in the basin and both of them showed an upward trend. The precipitation in the Yanhe River Basin has a distribution pattern of south > southeast > northwest. Yan'an Station and Ganquan Station were the high-value areas of precipitation in the basin. Except for Yan'an Station, precipitation in the basin showed an upward trend. The ET_0 was larger in the southern part and smaller in the western part of the basin. And ET_0showed an upward trend except for Ganquan Station. It can be seen that the characteristics of within year and changing trends of different meteorological elements and ET_0 were different and the spatial heterogeneity was significant. In addition, the ET_0 of Ganquan Station showed a downward trend as the air temperature increased, which indicated that there was an "evaporation paradox" phenomenon in the Ganquan area.

[Insert Figure 2]

3.2 Sensitivity of ET0 to meteorological factors

3.2.1 Temporal characteristics of the sensitivity of ET0 to meteorological factors

The S_T, S_{RH} and S_{R_s} showed a single peak pattern within year, indicating that ET_0 is more sensitive to hydrothermal-heat conditions and sunshine duration in summer than other seasons. In addition, the S_{U_2} showed a single head tilt. It showed that ET_0 was more sensitive to wind speed in winter than in other seasons(Figure 3). On the annual scale, S_T, S_{R_s} and S_{U_2} was positive. And S_{RH} was negative. The absolute value of $S_{R_s}(0.42)$ was the largest, indicating that ET_0 was the most sensitive to solar radiation. $S_{R_s}=0.42$meaned that ET_0 would increases by 4.2% if solar radiation increased by 10% when other factors remain unchanged(Table 2). From the perspective of the year, S_T was positive except in winter. S_{RH} was negative and S_{U_2} was positive in each month. S_{R_s} was positive except for December. From the analysis of the absolute value of the sensitivity coefficient of ET_0 to meteorological factor, we could get that ET_0 in the Yanhe River Basin in spring and summer was mainly affected by solar radiation and it was mainly affected by relative humidity in autumn and winter. From the MK statistics, the monthly sensitivity coefficients of ET_0 to meteorological factor in the Yanhe River Basin were changing. The S_T showed an increasing trend on the annual scale but showed a decreasing trend in March, May, June, July, August and September. S_{RH} showed a decreasing trend on the annual scale but showed a larger trend in March, April , May and June. S_{U_2} showed an increasing trend as a whole but S_{U_2} of October showed a decreasing trend. S_{R_s} mainly decreased on an annual scale and showed an increasing trend in April and May. We can find that in the past 40 years, the sensitivity of ET_0 to air temperature and wind speed had increased and the sensitivity to solar radiation and relative humidity had decreased. The climate sensitivity of ET_0 to climate factors varied from month to month during the year. The trend of sensitivity coefficient of ET_0 varied significantly in each month of the year.

[Insert Figure 3]

[Insert Table 2]

3.2.2 Spatial characteristics of the sensitivity of ET0 to meteorological factors

S_T, $S_{U_2} \wedge S_{R_s}$ at each site in the Yanhe River Basin was positive values. And S_{RH} is negative. The absolute value of S_{RH} of Jingbian Station, Zichang Station, Ansai Station, Yan'an Station, Ganquan Station and Yichuan Station was larger than other factors, which indicated that its ET_0 was most sensitive to relative humidity. The absolute value of S_{Rs} of Wuqi Station, Zhidan Station, Yanchuan Station and Yanchang Station was larger than other stations, which indicated that solar radiation had a high degree of influence on ET_0.S_T showed a tendency to become larger except for Yenan station, Yanchang Station and Yichuan Station. Except for Jingbian station, Wuqi station, Yanan station and Ganquan Station, S_{RH} showed a tendency of getting smaller. Except for Wuqi Station, sensitivity of wind speed of 2 meters was increasing. S_{R_s} of Ansai station, Ganquan Station and Wuqi Station to solar radiation was become larger, while other stations were become smaller(Table 3). Therefore, the ET_0 of the Yanhe River Basin was more sensitive to relative humidity and solar radiation, but the sensitivity is weakening. On the contrary, the sensitivity of ET_0 to air temperature and wind speed is small, but its sensitivity is increasing.

The spatial distribution of sensitivity of ET_0 to climate factor was obtained by spatial interpolation of the sensitivity coefficients of each station (Figure 4). S_T gradually decreased from the southeast to the northwest of the basin and was the largest in the Yanchang area. S_{RH} increased from the middle to the southeast and northwest of the basin and the high value areas of S_{RH} were in Zhidan and Yanchuan respectively. S_{U_2} was roughly opposite to the relative humidity and the samllest value areas of S_{U_2} were in the Zhidan area. The distribution pattern of S_{R_s} was similar to the distribution pattern of sensitivity to S_{RH}. The difference was that areas with high S_{R_s} were in Zhidan, Ganquan and Yanchang. It could be found that the sensitivity of ET_0 to each climate factor varies significantly in space.

[Insert Table 3]

[Insert Figure 4]

3.3 Contribution rate of meteorological factors to ET0

On an annual scale, if the air temperature increased by 14.35%, ET_0 would increase by 1.09%. Since S_{RH} was negative, ET_0 would decrease by 0.85% if relative humidity increase by 2.09%.

If wind speed of two meters decreased by 3.24%, ET_0 Would be decrease by 0.63%. ET_0 would increase by 0.55% when solar radiation increased by 1.32%. In general, the meteorological that contributed the most to ET_0 of Yanhe River Basin from 1978 to 2017 was air temperature. From the perspective of the year, the increase in air temperature of January and February led to an increase in ET_0. The increase of ET_0 in March, July and August was mainly caused by the decrease of relative humidity. The increase in ET_0 in April and May was caused by the decrease in the wind speed of wind speed of two meters. The most significant contribution to ET_0 in June was solar radiation and the increase in ET_0 caused by wind speed of two meters almost offset the decrease caused by the decrease in relative humidity. The most significant contribution to ET_0 in September and October was solar radiation and the decrease in ET_0 was mainly caused by the decline in solar radiation. Air temperature made the most significant contribution to ET_0 in November. Although ET_0 was the most sensitive to relative humidity, its contribution rate was only 0.03%. It can be inferred that the decreasing trend of relative humidity did not cause the decrease of ET_0. The most significant contribution to ET_0 in December was wind speed of two meters. Although ET_0 was sensitive to relative humidity, its decline did not lead to a decrease of ET_0 (Table 4).

The same relative change of the same climate factor had significant differences in the contribution to ET_0. For example, when the relative humidity increased by 0.74%, the ET_0 of the Zichang station decreased by 0.34%, while the ET_0 of the Yanchang station decreased by 0.24%(Table 5). Through comparison, it was found that the meteorological factor, contributing the most to ET_0 of Jingbian Station, Zichang Station, Ansai Station, Ganquan Station, Yanchang Station and Yanchuan Station, was the high wind speed two of meters. Solar radiation contributed the most to ET_0 in Wuqi station. Relative humidity had the had the greatest contribution to ET_0 of Zhidan station, Yan 'an Station and Yichuan Station. Air temperature contributed positively to the increase of ET_0 in the whole basin. While the contribution of relative humidity, wind speed of two meters and solar radiation to ET_0 had significant spatial differences. For example, the contribution rate of relative humidity to the ET_0 of Zichang station and Yanchang station was negative. But the contribution rate of other stations was positive(Table 5). Because ET_0 of Zichang station and Yanchang station had a negative sensitivity coefficient to the relative humidity, the increasing trend of relative humidity has a negative effect on the increase of the ET_0. Conversely, other sites had a positive effect on the increase of ET_0 due to the decreasing trend of relative humidity.

The zonality of the contribution of each meteorological factor to ET_0 is significant. The contribution of air temperature and solar radiation to ET_0 gradually decreased from northwest to southeast of the basin, while the contribution of wind speed of two meters to ET_0 was the opposite. The contribution of relative humidity to ET_0 decreased radially from Zhidan to the surroundings(Figure 5). By combining figure 2 and Figure 5, it can be obtained that the high evapotranspiration in the Yan'an area was mainly caused by the relative humidity and solar radiation. And the low evapotranspiration in the Zhidan area was mainly affected by wind speed of two meters. Because the sensitivity coefficient of ET_0 to relative humidity in Ganquan was negative, the decrease in relative humidity has a positive effect on the increase of ET_0. Similarly, because the sensitivity coefficient of ET_0 to wind speed of two meters and solar radiation was positive, the decreasing trend of wind speed of 2 meters and solar radiation had a positive effect on the decreasing of ET_0. Therefore, the main factors of the "evaporation paradox" phenomenon in Ganquan area were the wind speed of 2 meters and solar radiation.

[Insert Table 4]

[Insert Table 5]

[Insert Figure 5]

4. DISCUSSION

Previous studies have found that the combination of the changing trend of meteorological factors, sensitivity coefficient and contribution rate can better systematically and quantitatively analyze the causes of ET_0 change(Liu et al., 2009; Su et al., 2015).

4.1 Dominant factors of potential evapotranspiration variation in the Yanhe River Basin

In this paper, The absolute value of sensitivity coefficient of ET_0 to climate factors in the Yanhe River Basin was in the order of solar radiation > relative humidity > wind speed of two meters > air temperature. However, there were significant differences in the sensitivity of ET_0 to meteorological factors in each month of the year. For example, the sensitivity coefficient of ET_0 to solar radiation in December is -0.01, but it was as high as 0.7 in July and August. In addition, the sensitivity coefficient of ET_0 to air temperature in winter (December, January, February) was negative, but it was positive in other months. Combined with the results of trend analysis of meteorological factors, it was found that air temperature still had a positive effect on the increase of ET_0, since the air temperature in winter showed a downward trend.

The absolute value of contribution rate of each meteorological factor to ET_0 was in the order of air temperature>relative humidity> wind speed of two meters >solar radiation. The contribution rate of the same meteorological factor to ET_0 in each month of the year was significantly different. For example, the contribution rate of air temperature to ET_0 in January, February and December was 1.95%, 6.68% and 1.46%, but the contribution rate of air temperature to ET_0 in June, July and August was 0.64%, 1.16% and 0.96%. This showed that the contribution of air temperature to the increase of ET_0 in winter was higher than that in summer. Combined with the sensitivity coefficient, it could be found that although the sensitivity coefficient of ET_0 to air temperature was small, its contribution was large. The reason was that the extremely significant (0.01 level) increasing trend of air temperature led to the increase of ET_0. This was similar to the results of study on ET0 climate sensitivity coefficient in the Yellow River Basin(Liu et al., 2010). And in yanhe river basin, although the sensitivity coefficient of ET_0 to solar radiation was the largest, the contribution rate of solar radiation to ET_0 was low due to its the slow increasing rate.

From a spatial point of view, the absolute value of the sensitivity coefficient of ET_0 to air temperature at each station was the smallest among all meteorological factors. But the contribution rate of air temperature to ET_0 was not all the lowest. For example, the contribution rate of air temperature to ET_0 of Jingbian Station, Zichang Station, Zhidan Station, Ansai Station, Yan'an Station, Yanchuan Station, Yanchang Station and Yichuan Station was not the lowest. This was due to the significant increasing trend of air temperature within the control range of each station. At Yanchang station, the sensitivity coefficient of ET_0 to solar radiation (0.45) was the largest. But the contribution rate of solar radiation to the increase of ET_0 (-1.48%) was the lowest of all meteorological factors, which was related to the decreasing trend of solar radiation at Yanchang Station. In conclusion, only by combining the sensitivity coefficient of ET_0 to meteorological factors, the change trend of meteorological factors and the contribution rate of meteorological factors to ET_0 can we correctly and comprehensively understand the causes of changes in ET_0.

In this study, the multi-year average air temperature of the Yanhe River Basin showed an upward trend and sensitivity coefficient of ET_0 to it was positive. The contribution rate of air temperature to ET_0 was 1.09%. The relative humidity showed a downward trend and the sensitivity coefficient of ET_0 to it was -0.41. The contribution rate of relative humidity to ET_0 was -0.85%. It can be seen that the downward trend of relative humidity did not cause the increase of ET_0 in the Yanhe River Basin. The wind speed of two meters showed a downward trend and the sensitivity coefficient of ET_0 to it was positive. The contribution rate of wind speed to the change of ET_0 -0.63%. Solar radiation showed an upward trend and the sensitivity coefficient of ET_0 to it was positive. The contribution rate of solar radiation to ET_0 was 0.55%. It can be concluded that the negative contribution rate of meteorological factors to the increase of ET_0 was less than the positive contribution rate. Therefore, the potential evapotranspiration in the Yanhe Basin has shown an upward trend from 1978 to 2017.In general, the increase of ET_0 in the Yanhe River Basin was related to air temperature, two-meter high wind speed and solar radiation. And the decrease of ET_0 was related to relative humidity.

4.2 Evaporation paradoxes in the Yanhe River Basin

Another point worthy of attention was that the ET_0 of the Yanhe River Basin has shown an upward trend as a whole. But the ET_0 of the Ganquan Station has shown a downward trend, which indicating that the "evaporation paradox" only exists in a local area of the Yanhe River Basin.The absolute value of the sensitivity coefficient of ET_0 to climate factors in Ganquan area was in order of relative humidity > solar radiation> wind speed of two meters >air temperature. And the absolute value of the contribution rate of meteorological factors to ET_0 was in order of wind speed of two meters >relative humidity>solar radiation> air temperature. In Ganquan area, the upward trend of air temperature was significant, but the contribution rate of air temperature to the increase of ET_0 was relatively low. Solar radiation showed a downward trend and the contribution rate of it to ET_0 was -0.74%, which almost offsets the contribution rate of air temperature. The sensitivity coefficient of ET_0 to relative humidity was -0.46 and the contribution rate to ET_0 was 1.37%, which showed that the downward trend of relative humidity had a positive effect on the increase of ET_0. The sensitivity coefficient of ET_0 to wind speed of two meters was only 0.17. But its significant downward trend contributed 9.16% to the decrease of ET_0, indicating that the dominant factor for the downward trend of ET_0 in Ganquan area was the wind speed of two meters. This was similar to what was done by Roderick & Farquhar(2002), Dinpashoh et al. (2011), Burn & Hesch(2007) and Luo et al. (2016).

5. CONCLUSIONS

In this paper, the effects of air temperature, relative humidity, wind speed of two meters and solar radiation on the potential evapotranspiration in the Yanhe River Basin were quantitatively estimated by using sensitivity coefficient and contribution rate, combined with the changing trend of meteorological factors. The main conclusions of this study were summarized as follows:

The absolute value of the sensitivity coefficient of ET_0 to meteorological factor in Yanhe River was in the order of solar radiation>relative humidity> wind speed of two meters >air temperature. The sensitivity of ET_0 to climate factors had significant temporal and spatial differences. The absolute value of the contribution rate of each meteorological factor to ET_0 was in the order of air temperature>relative humidity> wind speed of two meters >solar radiation. The contribution rate of the same climate factor to ET_0 had significant temporal and spatial differences.

The increase of ET_0 in the Yanhe River Basin was related to air temperature, wind speed and solar radiation. And the decrease of ET_0 was related to relative humidity. The dominant factor of the increase of ET_0 in the Yanhe River Basin was air temperature. But the dominant factors of ET_0 in different regions had significant temporal and spatial differences. The dominant factor of the "evaporation paradox" phenomenon in Ganquan area was wind speed.

Only by combining the sensitivity coefficient of ET_0 to meteorological factors, the change trend of meteorological factors and the contribution rate of meteorological factors to ET_0 can we systematically and quantitatively analyze the causes of changes in ET_0.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Burn, D.H., Hesch, N.M., 2007. Trends in evaporation for the Canadian Prairies. Journal of Hydrology, 336(1-2):61-73.

Beven, K., 1979. A sensitivity analysis of the Penman-Monteith actual evapotranspiration estimates. Journal of Hydrology, 44(3-4):169-190.

Cohen, S., Ianetz, A., Stanhill, G., 2002. Evaporative climate changes at Bet Dagan, Israel, 1964-1998. Agricultural and Forest Meteorology, 111(2):83-91.

Chattopadhyay, N., Hulme, M., 1997. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. Agricultural and Forest Meteorology, 87(1):55-73.

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V.P., Kahya, E., 2011. Trends in reference crop evapotranspiration over Iran. Journal of Hydrology, 399(3–4):422-433.

Fu, G., Charles, S.P., Yu, J., 2009. A critical overview of pan evaporation trends over the last 50 years. Climatic Change, 97(1):193-214.

Food and Agriculture Organization of the United Nations, 1998. Crop Evapotranspiration:Guidelines for Computing Crop Requirements. Italy: Food & Agriculture Org.

Gong, L.B., Xu, C.Y., Chen, D.L., Halldin, S., Chen, Y.Q., 2006. Sensitivity of the Penman-Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. Journal of hydrology-amsterdam, 329(3).

Hupet, F., Vanclooster, M., 2001. Effect of the sampling frequency of meteorological variables on the estimation of the reference evapotranspiration. Journal of Hydrology, 243(3-4).

IPCC, 2007. Summary for Policymakers ofClimate Change 2007: The Physical ScienceBasis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Jiao, J.Y., Wang, Z.J., Wei, Y.H., Su, Y., Cao, B.T., Li, Y.J., 2017. Characteristics of erosion sediment yield with extreme rainstorms in Yanhe Watershed based on field. Transactions of the Chinese Society of Agricultural Engineering, 33(13): 159-167.

Kendall, M.G., 1975. Rank Correlation Measures. Charles Grifn, London, UK. 202.

Li X.C., 2013. Spatio-temporal variation of actual evapotranspiration in the pearl, Haihe and Tarim Basins of China. Nanjing, Jiangsu: Nanjing University of Information Science and Technology.

Liu, C.M., Zhang, D., Liu, X.M., Zhao, C.S., 2012. Spatial and temporal change in the potential evapotranspiration sensitivity to meteorological factors in China (1960–2007). Journal of Geographical Sciences, 22(1).

Liu, Q., Yang, Z.F., Cui, B.S., Sun, T., 2010. The temporal trends of reference evapotranspiration and its sensitivity to key meteorological variables in the Yellow River Basin, China. Hydrological Processes, 24(15):2171-2181.

Luo, K.S, Tao, F.L., Deng, X.Z., Moiwo, J.P., 2016. Changes in potential evapotranspiration and surface runoff in 1981-2010 and the driving factors in Upper Heihe River Basin in Northwest China. Hydrological Processes, 31(1).

Li, Z., Zheng, F.L., Liu, W.Z., 2012. Spatiotemporal characteristics of reference evapotranspiration during 1961–2009 and its projected changes during 2011–2099 on the Loess Plateau of China. Agricultural & Forest Meteorology, 154(none):147-155.

Lin, Z.H., Mo, X.G., Li, H.X., Li, H.B., 2002. Comparison of Three Spatial Interpolation Methods for Climate Variables in China. Acta Geographica Sinica, 57(1):47-56.

Liu, X.M., Zheng, H.X., Liu, C.M., Cao, Y.J., 2009. Sensitivity of the potential evapotranspiration to key climatic variables in the Haihe River Basin. Resources Science, 31(9):1470-1476

Mccuen, R.H., 1974. A sensitivity and error analysis cf procedures used for estimating evaporation1. JAWRA Journal of the American Water Resources Association, 10(3).

Mann, H.B., 1945. Non-Parametric Test Against Trend. Econometrica. 13: 245-259.975

Onyutha, C., 2016. Statistical analyses of potential evapotranspiration changes over the period 1930–2012 in the Nile River riparian countries. Agricultural & Forest Meteorology, 226-227:80-95.

Roderick, M.L., Farquhar, G.D., 2002. The Cause of Decreased Pan Evaporation over the Past 50 Years. Science, 298(5597):1410-1411.

Roderick, M.L., Farquhar, G.D., 2004. Changes in Australian pan evaporation from 1970 to 2002. International Journal of Climatology, 24(9):1077-1090.

Rana, G., Katerji, N., 1998. A Measurement Based Sensitivity Analysis of the Penman-Monteith Actual Evapotranspiration Model for Crops of Different Height and in Contrasting Water Status. Theoretical & Applied Climatology, 60(1-4):141-149.

Su, X.L., Song, Y., Niu, J.P., Ji, F., 2015. Sensitivity and attribution of potential evapotranspiration in Jinghuiqu irrigation district. Journal of Natural Resources, (1):115-123.

Wang, Y., Jiang, T., Bothe, O., Fraedrich, k., 2007. Changes of pan evaporation and reference evapotranspiration in the Yangtze River basin. Theoretical & Applied Climatology, 90(1-2):13-23.

Yin, Y.H., Wu, S.H., Chen, G., Dai, E.F., 2010. Attribution analyses of potential evapotranspiration changes in China since the 1960s. Theoretical & Applied Climatology, 101(1):19-28.

Yang, X.N., 2019. Effects of landscape pattern on runoff andsediment in the Loess Plateau: A multi-scale study. Shanxi, Yangling: Dissertation Submitted to Northwest A & F University.

Zhou J., 2019. Spatial and temporal variation of droughts over China based on various potential evapotranspiration formulas. Nanjing, Jiangsu: Nanjing University of Information Science and Technology.

Zhang, Y.Q., Liu, C.M., Tang, Y.H., Yang, Y.H., 2007. Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan Plateau. Journal of Geophysical Research Atmospheres, 112(D12).

Zhang, X.L., Xiong, L.H., Lin, L., Long, H.F., 2012. Application of five potential evapotranspiration equations in Hanjiang Basin. Arid Land Geography, 35(02): 229-237.

TABLES

Table 1 Temporal characteristics of ET0 and meteorological factors in Yanhe River Basin.

Table 2 Temporal characteristics of sensitivity coefficient of ET0 to meteorological factors.

Table 3 MK statistics of Sensitivity coefficient of ET0 to meteorological factors of Yanhe River Basin.

Table 4 Temporal characteristic of contribution rate of meteorological factors to ET0 in Yanhe River Basin.

Table 5 Contribution rate of meteorological factors to ET0 of stations in Yanhe River Basin.

FIGURE LEGENDS

Figure 1 Location of the Yanhe River Basin and the meteorological stations used in this study (black dots).

Figure 2 Spatial distribution of contribution rate of each meteorological factor.

Figure 3 Characteristics of average daily sensitivity coefficient of ET0 to meteorological factors.

Figure 4 Spatial distribution of sensitivity coefficients of ET0 to meteorological factors.

Figure 5 Spatial distribution of contribution rate of each meteorological factor.