Sensitivity analysis of potential evapotranspiration to key climatic factors in the Shiyang River Basin

Xuelei Zhang, Weihua Xiao, Yicheng Wang, Yan Wang, Miaoye Kang, Hejia Wang and Ya Huang

ABSTRACT

This paper focuses on determining the spatial and temporal characteristics of the sensitivity coefficients (SCs) between potential evapotranspiration (ET_0) and key climatic factors across the Shiyang River Basin (SYRB) from 1981 to 2015. Penman–Monteith equation and a sensitivity analysis were used to calculate ET_0 and the SCs for key climatic factors. Sen's slope was used to analyze the observed series. According to the results, the sensitivity significances were in the order of relative humidity (RH) $>$ net solar radiation (NSR) $>$ wind speed (WS) $>$ maximum air temperature (T_{max}) $>$ minimum air temperature (T_{min}). The SCs for the RH and NSR were larger in the upper mountainous region, while the other three coefficients were larger in the middle and lower reaches. All five climatic factors for the ET_0 SCs showed increasing trends in the mountainous region, and the T_{max}, WS and RH SCs increased in the middle and lower reaches. Over the past 35 years, the change in ET_0 was dominated by the air temperature (T), RH and NSR, and the increase in ET_0 during the studied period was mainly due to the increases in T and NSR.

Key words | ET_0 (evapotranspiration), P-M (Penman–Monteith) equation, sensitivity analysis, Shiyang River Basin

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HIGHLIGHTS

- Determined the spatial and temporal characteristics of the sensitivity coefficients between ET0 and key climatic factors across the SYRB.
- Explored the causes of ET_0 changes and their responses to climate change in the SYRB.
- Quantified the contribution rate of each climatic element to ET_0 in the SYRB from 1981 to 2015.

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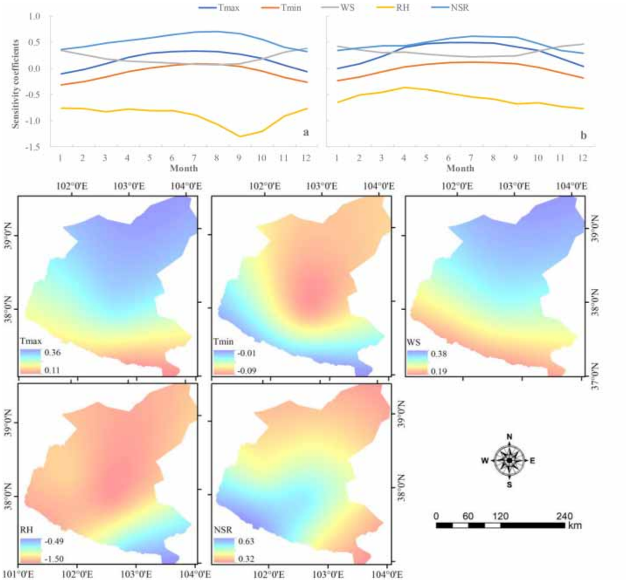
GRAPHICAL ABSTRACT



INTRODUCTION

Potential evapotranspiration (ET_0) refers to the actual evapotranspiration (AET) under full water supply conditions and is an important indicator of regional evaporation potential (Guo *et al.* 2015). As an important part of the hydrological cycle (Horváth *et al.* 2010), ET_0 is related not only to the water balance and water conversion (Darshana *et al.* 2013) but also to the surface energy balance, and it plays a crucial role in the global climate system (Aouissi *et al.* 2016). In the current calculation methods for ET_0 (Lhomme 1997), the Penman–Monteith (P-M) equation recommended by the Food and Agriculture Organization (FAO) is based on the energy balance and diffusion principles for water vapor turbulence; it considers the influences of the aerodynamics and solar radiation terms (Li *et al.* 2015) and is widely used in the field of hydrometeorology (Penman 1948; Hao *et al.* 2013).

Climate change has profoundly affected the ecohydrology models of basins and has caused a series of problems about water resources (Xu *et al.* 2013). In arid and semiarid areas, small changes in climate factors have had significant impacts on hydrological processes (Ti *et al.* 2018). As a key parameter of the hydrological cycle, analyzing the sensitivity of ET_0 to climate variables is an important research topic that has attracted attention in the hydrological field in recent years (Bormann 2010).

Zhao *et al.* (2014) showed that the wind speed (WS) has the greatest impact on ET_0 on the Qinghai-Tibet Plateau. Zhao *et al.* (2015) believed that the influence of relative humidity (RH) on ET_0 is most significant in the Heihe River Basin. Research by Yang *et al.* (2013) on the Huang-Huai-Hai Plain showed that ET_0 is most sensitive to net solar radiation (NSR) in the eastern part of the plain and to T in the southwestern region. Yang *et al.* (2014) believed that NSR is the most sensitive meteorological factor to ET_0 in the Tao River Basin. Studies by Lian & Huang (2016) in an oasis-desert region during a growing season showed that selecting extreme pixels or edges can achieve reasonable estimates of ET_0 and that validation of remote sensing models is necessary. Zheng & Wang (2015) used a global sensitivity analysis method to study the sensitivities of ET_0 to climate variables in China; the results showed that the spatial variation in the sensitivity varied seasonally and that stations at low latitudes were more sensitive to the NSR and less sensitive to T than those at high latitudes.

Studies by Gao *et al.* (2015) in the West Liao River Basin indicated that the T increased significantly, while WS, NSR and RH decreased remarkably. ET_0 is most sensitive to NSR and RH and is least sensitive to the average temperature. Liu *et al.* (2014) selected Beijing as a study area to investigate the effects of climate change on ET_0. The results showed that the T was the most key factor for ET_0 change, followed by RH and WS, and the $T_{\min}$ and $T_{\max}$ were less sensitive factors.

The hydro-geomorphological pattern of the mountain-basin system in the Shiyang River Basin (SYRB) is unique, and the hydro-geomorphological and geo-ecological patterns are quite different. The SYRB is representative of the inland river basins in China. Over the past half century, the hydrological processes of the SYRB have changed dramatically, resulting in several hydrological and ecological problems (Wang *et al.* 2012) that seriously threaten the sustainable development of the ecosystems in the basin. It is urgent and important to analyze the sensitivity of evapotranspiration (ET) to climatic factors under the background of climate change, qualitatively and quantitatively study the mechanism and extent of climate change affecting ET_0, and determine the causes of ET_0 changes and the characteristics of its response to climate change in the SYRB.

Few studies have performed sensitivity analyses of climatic factors and ET_0 in the SYRB, and few time series are available. Based on the hydrometeorological observation series in the SYRB and neighboring stations, the P-M model was used to evaluate ET_0 and combined the results with the Beven (Beven 1979) sensitivity method to perform an analysis of the sensitivities of ET_0 to key climatic factors, including $T_{\max,}$ $T_{\min}$, WS, RH and NSR. Based on the spatial and temporal distributions of the sensitivity coefficients (SCs) and the change characteristics, the relationships between ET_0 and key climate elements determined the causes of ET_0 changes and their responses to climate change in the SYRB during 1981–2015 were explored. This research is of great importance both in theory and practice for thorough comprehension for climate change impacting on the hydrological cycle and providing scientific support for the planning and efficient use of water resources, ecological environment protection and sustainable development.

STUDY AREA

The SYRB is located to the east of the Hexi Corridor in Gansu Province, has a total area of 41,600 km^2 and is geographically located from 101°22′ to 104°14′ E and from 36°57′ to 39°27′ N (Figure 1). The topography is high in the south and low in the north. The Yellow River Basin and Heihe River Basin are located to the southeast and southwest of the SYRB, respectively, while the Tengger Desert lies to the northwest, and the Badan Jaran Desert lies to the northeast. The elevation in the SYRB decreases from upstream to downstream from 5,130 to 1,263 m. The total annual precipitation (P) in the area ranges from 110 to 530 mm, and the annual average temperature ranges from 0 to 9 °C. The northern Qilian Mountains in the upper reaches have a semiarid climate in a cold temperate zone and include the catchment areas of eight major tributaries. The middle and lower reaches of the plain, which mainly include the Wuwei Basin and Yongchang Basin in the middle reaches and the Minqin Basin in the lower reaches, have a warm temperate arid climate, and the terrain is relatively flat.

DATA AND METHODS

Data collection

The hydrometeorological observation sequences from five reference meteorological stations (Minqin, Jinchang, Wuwei, Gulang and Yongchang) in the SYRB from 1981 to 2015 were collected and assembled. The data are from the China Meteorological Data Service Center (http://data.cma.cn/).

Research methods

Evapotranspiration (ET_0)

The P-M equation is extensively used to determine ET_0 due to its accurate representation of the regional energy balance and aerodynamic influence on terrestrial ET (Li *et al.* 2015). It is described as follows:

$$ET_0 = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G) + \rho_\alpha c_p(e_s - e_\alpha)/r_\alpha}{\triangle + \gamma(1 + r_s/r_\alpha)}\right] \tag{1}$$

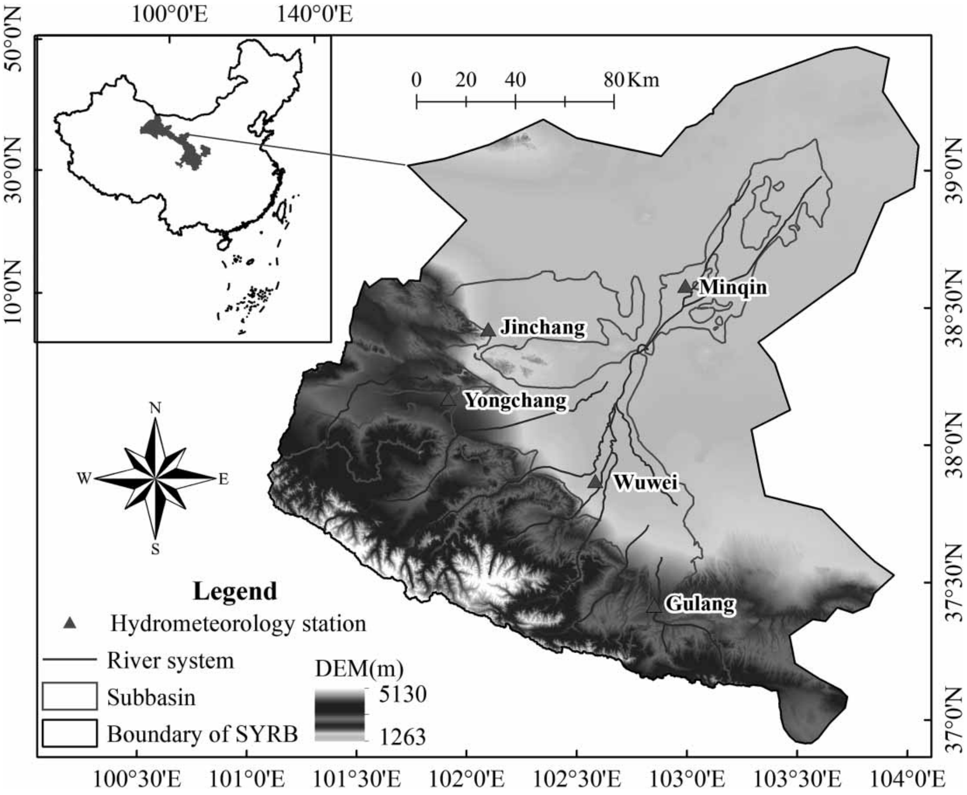


Figure 1 | Location of the study area and the distribution of hydrometeorology stations.

where Δ represents the saturation vapor pressure–temperature relationship slope (kPa/°C); G represents the soil heat flux (MJ/m^2/d); R_n represents the net radiation (MJ/m^2/d); ρ_a represents the air density (kg/m^3); c_p represents the constant pressure ratio; e_s and e_α represent the saturated and actual vapor pressures, respectively (kPa); r_α and r_s represent the aerodynamic and stomatal resistance, respectively (s/m); γ represents the psychrometric constant (kPa/°C); and λ represents the latent heat of vaporization, 2.45 MJ/kg.

Sensitivity coefficient

The sensitivity coefficient (SC) is described as follows:

$$Se_{vi} = \lim_{\Delta vi \to 0}\left(\frac{\Delta ET_0}{ET_0}\Big/\frac{\Delta V_i}{V_i}\right) = \frac{\partial ET_0}{\partial V_i}\cdot\frac{V_i}{ET_0} \tag{2}$$

$$G_{vi} = \frac{\triangle V_{\mathrm{i}}}{\overline{V_i}}\cdot Se_{\mathrm{vi}} \tag{3}$$

where Se_{vi} represents the SC of the ith meteorological factor, and G_{vi} represents the contribution rate of the ith factor to the change in ET$_0$. The SC for a meteorological element is positive or negative, indicating that ET$_0$ increases or decreases as the element increases, respectively (Huo *et al.* 2013). The greater the SC is, the greater the effect of ET$_0$ due to the meteorological factor is (Yang *et al.* 2014).

Sen's slope

Sen's slope (SS) (Sen 1968) is widely used in trend and magnitude analysis by using the median value of the slope series to evaluate the trend. The formula is

$$\mathrm{Sen} = \mathrm{Median}\left[\frac{x_j - x_i}{j - i}\right], \quad \forall\, j > i \tag{4}$$

where Sen represents the value of SS; x_i and x_j represent the values at moments i and j, respectively, $1 \le i < j \le n$; and n is the length of the sequence.

RESULTS AND DISCUSSION

Change characteristics of ET_0 and climatic factors

Figure 2 shows the variations of T_{max}, T_{min}, WS, RH, NSR and ET_0 during 1981–2015. The results show that the values of T_{max}, T_{min}, NSR and ET_0 in the middle and lower reaches were higher than that in the upper mountainous reaches; T_{max} and T_{min} fluctuated significantly in the middle and lower reaches; the oasis areas are greatly affected by human activities, with low vegetation coverage and more sensitive to climate change. Therefore, the fluctuation of temperature is relatively significant. The multiyear average values of T_{max} in mountainous and oasis areas are 0.16 and 9.95 °C, respectively, while the average values of T_{min} are -0.08 and 0.52 °C, respectively. WS fluctuated more significantly in the upper mountainous with the multiyear average value of 4.86 m/s. Temperature may be related to the complex terrain, the diversity of vegetation and the great difference of the vertical zone of the underlying surface of the upper mountain area. NSR and ET_0 fluctuated largely in both two regions. The multiyear average values of ET_0 in the mountainous and oasis areas are 684.46 and 894.71 mm, respectively. Since 2003, the ET_0 in the middle and lower reaches of the river has been rising significantly. The increase of T and WS is the possible reason. In addition, the vegetation state has also improved with the implementation of the regulation plan of Shiyang River, and the enhancement of vegetation dynamics promotes the increase of ET, thus leading to a certain increase in ET.

Temporal and spatial distribution characteristics of ET_0 and climatic factors

The analysis of change magnitude and trend based on SS for ET_0 and the five key climatic factors in the mountainous area and the oasis plains are shown in Table 1. The increasing trends in ET_0 were significant in both regions, with increases of 5.61 and 28.01 mm/10 a in the mountain and plains, respectively. In contrast to the decrease in RH in the middle and lower reaches, all of the other factors showed increasing trends. The increase in NSR in the upper reaches was 3.30 (MJ/m^2/d)/10 a, followed by RH with an increase of 0.33/10 a; T_{max}, T_{min} and WS had small variations of 0.01 °C/10 a, 0.01 °C/10 a and 0.01 (m/s)/10 a, respectively. The NSR in the middle and lower plains increased at a rate of 11.48 (MJ/m^2/d)/10 a, RH decreased at a rate of 0.91/10 a, and T_{max}, T_{min} and

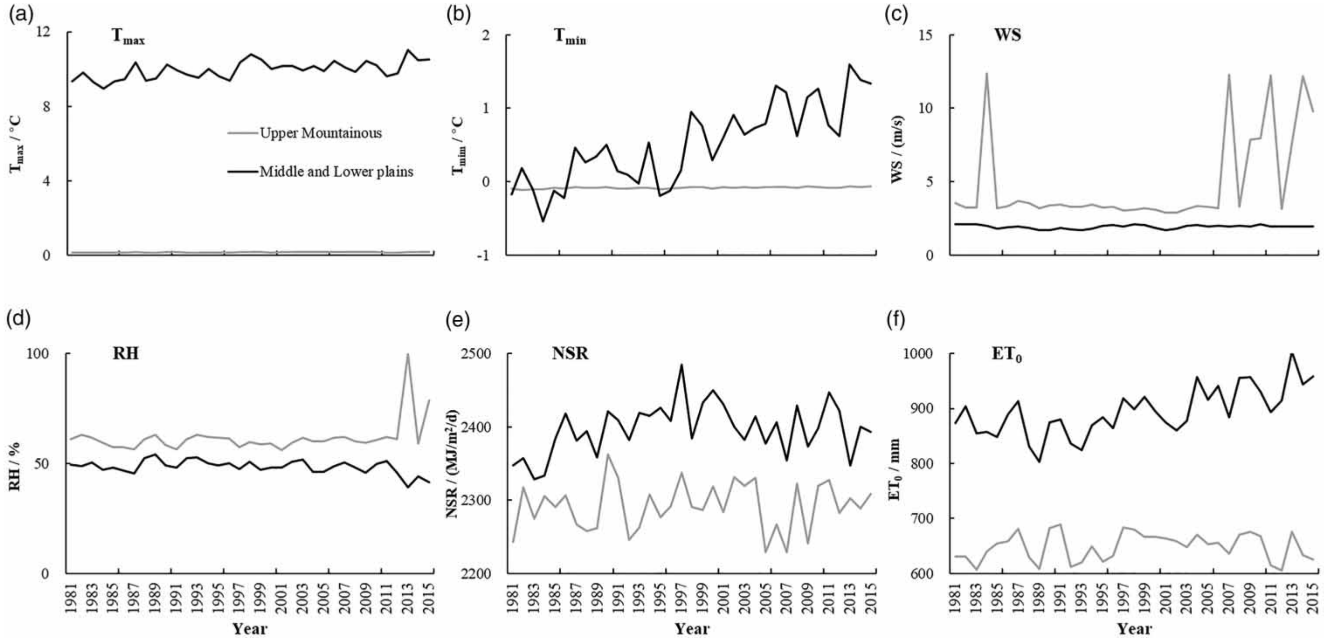


Figure 2 | Variations of five climatic factors and ET_0 from 1981 to 2015 in the two regions of the SYRB.

Table 1 | SS tests of the amplitudes of T_{max}, T_{min}, WS, RH, NSR and ET_0 (/10 a)

Areas	T_{max} (°C)	T_{min} (°C)	WS (m/s)	RH (%)	NSR (MJ/m^2/d)	ET_0 (mm)
Upper mountainous	0.01^b	0.01^b	0.01	0.33	3.30	5.61^a
Middle and lower plains	0.29^b	0.45^b	0.01	-0.91^a	11.48^a	28.01^b

[a]Values are significant at $P \leq 0.05$.
[b]Values are significant at $P \leq 0.01$.

WS increased at rates of 0.29 °C/10 a, 0.45 °C/10 a and 0.01 (m/s)/10 a, respectively. Overall, the variabilities in ET_0 and the meteorological elements were higher in the middle and lower plains, and lower in the upstream area. The climate conditions in the oasis plains had higher variabilities than those in the upstream mountains, and the impacts on ET_0 were also more significant.

Huo *et al.* (2013) showed that *T*, *P* and RH increased, while WS decreased in arid areas of China. The research of Yang *et al.* (2013) on the Huang-Huai-Hai Plain showed that *T* has increased, but NSR, RH and WS have decreased. These results are different from the conclusion of this study. In comparison, all of the regions show increasing *T*, which is consistent with global changes. Other factors have different variation characteristics, which are mainly related to the different climatic zones, underlying surface conditions, elevations, research periods and statistical methods used.

Sensitivity analysis

Annual variation in SCs

The absolute values of the SCs indicate the degree of sensitivity of ET_0 to each meteorological factor, therefore, the analysis of the degrees of sensitivity is based on the absolute value of each sensitivity factor. Figure 3(a) and 3(b) shows the annual distributions of the monthly SCs in the mountainous regions and the middle-lower plains in the SYRB. The statistical results of the seasonal SCs of ET_0 to the climate elements are shown in Table 2. The results show that the SCs of ET_0 to WS and NSR were positive for the entire year, and the SC for RH was negative, indicating that ET_0 increased with increases in WS and NSR and decreased with an increase in RH. The SCs of ET_0 to T_{max}, T_{min} and NSR showed increasing trends first and then decreasing trends, where the maximum occurred in July and August, and the minimum occurred in December and January. The SC for WS first decreased and then increased; the values were the highest in December and the smallest in July and August. The maximum values of RH in the mountainous area and the plains occurred in January and April, respectively, and the minimum values occurred in September and January, respectively. On a seasonal scale, the effects of NSR and RH on ET_0 were dominant throughout the year; T_{min} was the least sensitive in the spring and summer, and T_{max} was the least sensitive in the autumn and winter. The SCs for T_{max} and T_{min} were negative in some months, which is mainly because the actual values of T_{max} and

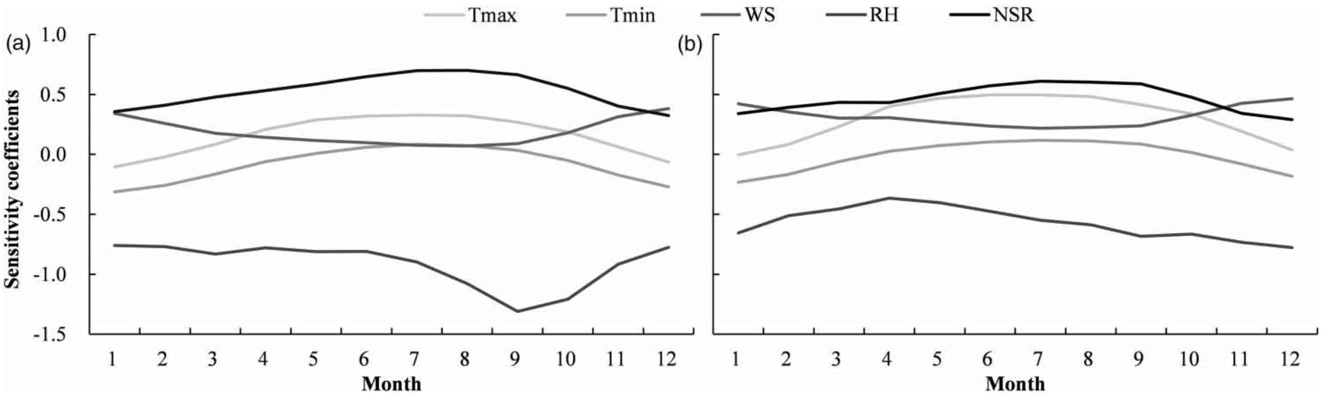


Figure 3 | Interannual distributions of the monthly SCs for climatic factors in the upper mountainous (a) and the middle and lower plains (b) of the SYRB.

Table 2 | Mean seasonal SCs for climatic factors in the two areas of the SYRB

	Upper mountainous					Middle and lower plains				
Season	T_{max}	T_{min}	WS	RH	NSR	T_{max}	T_{min}	WS	RH	NSR
Spring	0.19	−0.07	0.15	−0.81	0.53	0.37	0.01	0.29	−0.41	0.46
Summer	0.32	0.07	0.08	−0.93	0.68	0.49	0.11	0.23	−0.54	0.6
Autumn	0.17	−0.06	0.19	−1.14	0.54	0.32	0.01	0.33	−0.69	0.47
Winter	−0.06	−0.28	0.33	−0.77	0.36	0.04	−0.19	0.41	−0.65	0.34

T_{min} were negative during these months. Therefore, ET_0 still increased as the T increased.

Spatial distributions of the SCs

Figure 4 shows the spatial distributions of the multiyear averaged SCs of ET_0 to each climate factor. The spatial distributions show that the SCs had obvious zonal characteristics. The SCs for T_{max} and WS increased from the upstream to the downstream regions, with the value of T_{max} range from 0.11 to 0.36 and WS range from 0.19 to 0.38 in the study area. The SC for T_{min} was relatively small, and the range was between −0.09 and −0.01. The RH SC ranged from −1.50 to −0.49; the highest absolute values were located in the southeastern mountainous areas, and the lowest values were distributed across the Wuwei Basin in the middle

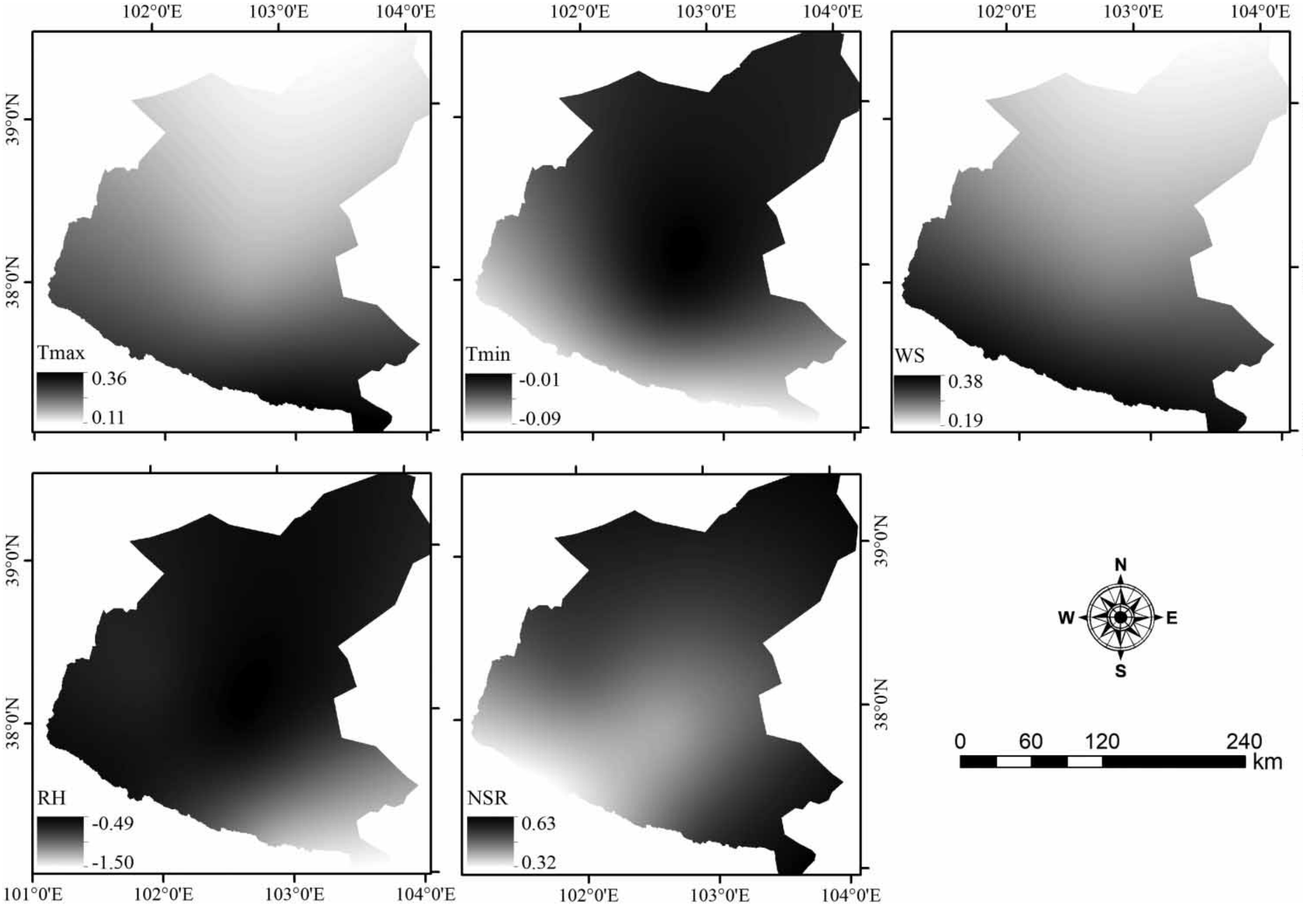


Figure 4 | Distributions of the SCs of the climate factors.

reaches. The SCs for the NSR ranged from 0.32 to 0.63, with the higher values in the upper reaches and the lower values in the northern part of the Minqin Basin. Based on the values of the five SCs, there was a significant difference in the sensitivity of ET_0 to each meteorological factor. The order of the absolute values of the SCs was as follows: RH > NSR > WS > $T_{max} > T_{min}$.

The SCs of the meteorological elements in the upper mountainous regions and the middle-lower plains of the basin were determined separately. The SCs of WS, T_{max} and T_{min} were all higher in the plains than in the mountains, indicating that the sensitivity of ET_0 to those three factors was lower in the upper mountains. These differences may be related to the latitudes, elevations and the underlying surface conditions of the two regions.

The research of Zhao *et al.* (2014) in the Loess Plateau showed that ET_0 was most sensitive to WS, followed by NSR. Huo *et al.* (2013) concluded that ET_0 is more sensitive to WS and RH in arid areas of China. The analysis of ET_0 and various climatic factors in the Heihe River Basin by Zhao *et al.* (2015) showed that ET_0 has the highest SC to RH, followed by WS, and the spatial differences in the degree of sensitivity are significant. The climate factors with the highest ET_0 SCs in the SYRB are WS, NSR and RH, which is consistent with previous results. These results show that ET_0 is more sensitive to changes in WS, NSR and RH in arid and semiarid regions of China and that ET_0 is more prone to significant fluctuations due to changes in these three climatic factors.

Interannual variation in SCs

The sensitivity statistics of the key climatic factors in the two regions based on SS are listed in Table 3. The SCs of T_{max}, T_{min} and WS showed increasing trends; their variation amplitudes were 0.011/10 a, 0.010/10 a and 0.008/10 a, respectively, in the upper region and 0.008/10 a, 0.001/10 a and 0.010/10 a, respectively, in the middle and lower reaches. The RH SC showed decreasing trends with amplitudes of −0.006/10 a and −0.013/10 a in the upper and middle-lower regions, respectively. The SC for the NSR in the upper mountainous reaches increased, and that decreased in the middle and lower reaches; the amplitudes of the changes in the two regions were 0.004/10 a and −0.010/10 a, respectively.

A comparison of the two regions shows that the sensitivities of ET_0 to WS, RH and NSR in the middle-lower reaches of the plain were more significant, indicating that ET_0 fluctuated more in the middle and lower reaches of the plain than in the upstream mountainous region, was more sensitive to climatic factors and responded greatly to climate change.

Table 3 | SS tests for the amplitudes of the SCs for climatic factors of the SYRB (/10 a)

Areas	T_{max}	T_{min}	WS	RH	NSR
Upper mountainous	0.011^b	0.008^b	0.001	−0.006	0.004
Middle and lower plains	0.010^a	0.008^b	0.010^a	−0.013	−0.010

Contributions of meteorological factors to the changes in ET_0

The previous analysis showed that although the T_{min} SC was negative, the change in ET_0 was positively driven and showed an increasing trend during the statistical period. Therefore, for ease of analysis, the absolute value of the T_{min} contribution rate was used. The contribution rates of each meteorological element to the changes in ET_0 in the two regions of the basin were calculated according to Equation (3) and are shown in Table 4. The *T* contributed the most to the change in ET_0, followed by RH and NSR, and the contribution of WS was the smallest. In comparison, the contribution rates of the meteorological factors to the change in ET_0 were higher in the middle and lower plains than in the upstream mountains, which validated that ET_0 in plains is vulnerable to climate change. The contributions of RH in the two regions were opposite and positive upstream. An increase in RH inhibits ET_0 in the upper region to some extent, while the decreasing RH in the middle and lower reaches made ET_0 increase.

Table 4 | Contributions of meteorological factors to the variation in ET0 (%)

Areas	T_{max}	T_{min}	WS	RH	NSR
Upper mountainous	3.84	2.59	0.07	−1.65	0.26
Middle and lower plains	2.97	4.62	0.08	3.65	0.76

In general, the increases in T and NSR were the main reasons for the increase in ET_0 in the SYRB. The increase in RH in the upper reaches weakened the increase in ET_0, while it accelerated the increase in ET_0 in the middle and lower reaches.

Yang *et al.* (2014) believed that NSR and T together resulted in the increase of ET_0 in the Taohe River Basin and that T contributed more than NSR. The increase of ET_0 in the SYRB is mainly attributed to T, RH and NSR, and the increase of T is the main reason. This phenomenon suggests that ET_0 in the two basins is greatly affected by climate warming. The contribution of RH to ET_0 in the SYRB is higher than that in the Taohe River Basin, mainly because of the high SC of ET_0 to RH and the larger range of RH in the SYRB. The change in ET_0 is affected not only by the SCs of the climatic factors but is also closely related to the change of each factor itself. This also indicates that ET_0 in arid regions is more susceptible to the restriction of air humidity conditions.

P is scarce in the middle and lower reaches of the arid inland river basin, and it is difficult to form surface runoff to effectively recharge groundwater. The water system in the upstream mountainous area is well developed, groundwater is discharged, and the surface water is collected near the outlet, which constitutes the total available water resources of the mountain-basin system. Currently, the exploitation and utilization of water resources in oasis areas is high, the circulation and transformation patterns of the surface water and groundwater have changed, and the natural hydrological process has been changed significantly by artificial systems. The current hydrological processes in the SYRB have been affected by human activities. This paper only discussed the impact of climate factors on ET_0 without considering human activities. However, the planting structure, irrigation methods, water conservancy projects and comprehensive management measures in river basins all have impacts on the various elements of the hydrological cycle. The relationship between ET_0 and human activities needs to be explored in future studies.

CONCLUSIONS

ET_0 in the SYRB was estimated by the P-M equation in this paper. The SCs of ET_0 to T_{max}, T_{min}, WS, RH and NSR were calculated based on the Beven sensitivity calculation method. SS was used to analyze the amplitude and spatial–temporal characteristics of the SC for each element in the SYRB during 1981–2015. The following conclusions were obtained:

On the annual scale, the sensitivities of ET_0 to each meteorological factor were in the following order: $RH > NSR > WS > T_{max} > T_{min}$. The effects of NSR and RH on ET_0 were dominant throughout the year on the seasonal scale. T_{min} was the least sensitive in the spring and summer, and T_{max} was the lowest in the autumn and winter.

The SCs of T_{max} and WS increased from upstream to downstream; the highest value of the RH SC was located in the mountainous areas southeast of the basin, and the lowest value was distributed in the Wuwei Basin in the middle reaches. The SC of the NSR in the mountainous region had the highest value, while that in the northern part of the lower Minqin Basin was smaller. In general, the SCs of ET_0 to each climatic factor in the upper mountains showed increasing trends, while those of T_{max}, T_{min}, WS and RH in the middle and lower plains increased and NSR decreased.

ET_0 had an increasing trend during the study period. The contributions of T, RH and NSR to the change in ET_0 were dominant. The increases in T and NSR were the main reasons for the increase in ET_0.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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