RESEARCH ARTICLE

Temporal variations in reference evapotranspiration in the Tarim River basin, Central Asia

Hao Wu¹, Min Xu^{2*}, Zhuoyue Peng¹, Xiaoping Chen¹

1 College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou, China, **2** State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China

* xumin@lzb.ac.cn

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Abstract

Reference evapotranspiration (ET_0) is important for agricultural production and the hydrological cycle. Knowledge of ET_0 can aid the appropriate allocation of irrigation water in arid regions. This study analyzed the trends in ET_0 over different timescales in the Tarim River basin (TRB), Central Asia. ET_0 was calculated by the Penman-Monteith method using data from 1960–2017 from 30 meteorological stations located in the TRB. The Mann-Kendall (MK) test with trend-free prewhitening and Sen's slope estimator were applied to detect trends in ET_0 variation. The results showed that the mean ET_0 decreased at a rate of 0.49 mm·10 a⁻¹ on an annual timescale. The mean ET_0 exhibited a decreasing trend in summer and increasing trends in other seasons. The effects of climatic factors on ET_0 were assessed by sensitivity analysis and contribution rate analysis. Maximum temperature (T_{max}), relative humidity (RH) and wind speed (WS) showed important effects on ET_0 . However, WS, which decreased, was the key element that induced changes in ET_0 in the TRB. This work provides an important baseline for the management of agricultural water resources and scientific planning in agriculture.

Introduction

Evapotranspiration (ET) is an important part of the water cycle; it controls energy exchange in ecological systems and has been a focus of studies on water resources, agriculture and ecosystems [1]. ET can be observed by various methods, including eddy covariance systems, large aperture scintillometer analysis, water balance methods, micrometeorological methods and lysimeter analysis [2–4]. However, in actually irrigation and drainage planning, ET is usually calculated by the crop coefficient method, and reference evapotranspiration (ET_0) is a key indicator in this approach [5]. ET_0 is the evapotranspiration from a reference surface that is similar to extensive grasslands of uniform height and vigorous growth that are supplied with well water. The Penman-Monteith formula is a fairly reliable method for estimating ET_0 and is widely used [6–8].

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ET_0 represents the potential evaporation of the atmosphere [9] and is affected by climate factors, such as solar radiation, wind speed (WS), precipitation and air temperature [10]. A previous study has shown that the mean temperature near the surface of the earth increased by 0.74°C in the twentieth century [11]. As air temperature increases, evapotranspiration from land-based ecosystems increases. However, observations have shown that in many areas, ET_0 has decreased. This combination of global temperature increases and ET_0 decreases is called the pan evaporation paradox [12]. This paradox and the key factors responsible have been widely discussed in many studies. For example, in the Platte River Basin, central Nebraska, USA, ET_0 showed a decreasing trend under changing precipitation [13]. In humid and desert regions in India, ET_0 showed a decreasing trend under changing net radiation and WS [14, 15]. In the Yangtze River, Yellow River, Meigong River and Gan-Xin Region of China, ET_0 exhibited a decreasing trend, and the main influencing factors were radiation, sunshine hours (SH) and WS [8, 16–21].

The Tarim River basin (TRB) is situated inland and has a dry climate, low rainfall, strong evaporation, water shortages, and an extremely fragile ecological environment. The upper reaches of the basin are mountainous areas and oases, and the lower reaches are deserts [22]. The water cycle in the basin is characterized by water production in mountainous areas [23] and water consumption in oasis areas. The basin is an important irrigated agricultural area. With the development of agriculture in the oasis regions, the farmland area and irrigation water consumption have increased. An investigation showed that irrigation water consumption accounts for more than 98% of the total water consumption [24]. Increasing irrigation water use and intensive evaporation have caused serious secondary salinization of the soil. Approximately 48% of farmland in the TRB exhibits some degree of soil salinization. In addition, the increase in irrigated agriculture has led to reductions in the discharge of natural rivers and declines in the natural vegetation in desert areas [25]. The TRB is the core area of the Silk Road Economic Belt and plays an important strategic role in the overall opening-up of China. Continued economic development must rely on water resources, and any change in the water cycle will significantly impact agricultural and hydrological processes. Evapotranspiration has an important influence on the amount of available water resources in the TRB. Thus, changes in the spatiotemporal distribution of ET_0 will alter the amount of available water resources in this region.

Previous studies of ET_0 have focused on large agricultural regions, with ET_0 calculated as the average over each of these areas [20, 26]. ET_0 trends at different weather stations in the TRB have not been detected. Investigating the influence of climate change on ET_0 can help guide regional water resource management and the adjustment of cropping structures. The main purposes of this paper are to (1) explore changes in the spatial and temporal distributions of ET_0 in the TRB and (2) analyze the key meteorological elements affecting ET_0 .

Materials and methods

Study area and data

The TRB is located in Central Asia (34° – 45° N; 73° – 97° E) and covers a total area of approximately $1.02 \times 10^6 \text{ km}^2$ (Fig 1). It is surrounded by Tianshan, eastern Pamir, Kunlun, and the Karakorum Mountains, with elevations ranging from -156 m to 8238 m [27]. The precipitation is greater than 300 mm in the mountainous regions and below 50 mm in the lower basin. More than 54% of the precipitation occurs in June, July and August. The temperature ranges from -35°C in winter to 40°C in summer [28]. The water resources of the basin are mainly generated by rainfall and glacier/snow meltwater in the mountainous regions [29]. The oasis is the main social unit in the TRB, and agriculture is an important component of oasis

Fig 1. Locations of the meteorological stations involved in this study.

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sustainable development. The water consumption of agricultural production amounts to 98% of the total water consumption in the TRB.

In this study, climate data for the period of 1960~2017 from 30 meteorological stations distributed all over the TRB were obtained from the China Meteorological Data Service Center (<http://data.cma.cn/>) (Table 1). The data included maximum and minimum temperature ($T_{\max}$, $T_{\min}$), relative humidity (RH), wind speed (WS), and sunshine hour (SH) on a daily timescale. The daily ET_0 values were estimated from these five meteorological elements, and seasonal and annual ET_0 were estimated from daily ET_0 .

Methods

Penman-Monteith method. ET_0 is the evapotranspiration from a reference surface with a height of 0.12 m, an albedo of 0.23 and a surface resistance of 70 s/m [9]. The Penman-Monteith equation has been recommended as the standard method for determining ET_0 by the FAO [30]. The equation is shown below:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is the reference evapotranspiration ($\text{mm} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), R_n is the net radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), G is the soil heat flux ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), γ is the psychrometric constant ($\text{k} \cdot \text{Pa} \cdot \text{C}^{-1}$),

Table 1. Meteorological stations involved in this study.

ID	Station	Longitude (°E)	Latitude (°N)	Elevation (m)	Average temperature (°C)
51467	Baluntai	86.30	42.73	1739	7.39
51477	Dabancheng	88.32	43.35	1103.5	7.14
51495	Qijiaojing	91.73	43.22	721.4	10.71
51526	Kumishi	88.22	42.23	922.4	9.55
51542	Bayinbuluke	84.15	43.03	2458	-3.63
51567	Yanqi	86.57	42.08	1055.3	9.08
51573	Yulufan	89.20	42.93	34.5	15.27
51628	Akesu	80.23	41.17	1103.8	11.12
51633	Baicheng	81.90	41.78	1229.2	8.69
51642	Luntai	84.25	41.78	976.1	11.73
51644	Kuche	82.97	41.72	1081.9	11.63
51656	Kuerle	86.13	41.75	931.5	12.11
51701	Tuergate	75.40	40.52	3504.4	-2.80
51705	Wuqia	75.25	39.72	2175.7	7.82
51709	Kashi	75.98	39.47	1289.4	12.23
51711	Aheqi	78.45	40.93	1984.9	7.35
51716	Bachu	78.57	39.80	1116.5	12.47
51720	Keping	79.05	40.50	1161.8	11.91
51730	Alaer	81.27	40.55	1012.2	11.35
51747	Tazhong	83.67	39.00	1099.3	11.95
51765	Tieganlike	87.70	40.63	846	11.66
51777	Ruoqiang	88.17	39.03	887.7	12.29
51804	Tashikuergan	75.23	37.77	3090.1	3.90
51811	Shache	77.27	38.43	1231.2	12.34
51818	Pishan	78.28	37.62	1375.4	12.72
51828	Hetian	79.93	37.13	1375	13.37
51839	Minfeng	82.72	37.07	1409.5	12.16
51855	Qiemmo	85.55	38.15	1247.2	11.09
51931	Yutian	81.65	36.85	1422	12.33
52313	Hongliuhe	94.67	41.53	1573.8	7.03

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T is the air temperature (°C), u_2 is the wind speed at a height of 2 m ($\text{m}\cdot\text{s}^{-1}$), e_a is the saturated vapor pressure (kPa), e_d is the actual vapor pressure (kPa), and Δ is the slope of the saturation vapor pressure curve ($\text{kPa}\cdot^\circ\text{C}^{-1}$).

Mann-Kendall test with trend-free prewhitening. In the Mann-Kendall (MK) test with trend-free prewhitening (TFPW-MK), the influence of the trend on the autocorrelation coefficient was removed, allowing the MK test to be performed on the data sequence with greater accuracy; this approach has been widely used in studies of hydrological trend detection [31–33]. The equations for the MK test method are given below:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{Sgn}(S_j - S_k) \quad (2)$$

$$\text{Sgn}(S_j - S_k) = \begin{cases} 1 & (X_j - X_k) > 0 \\ 0 & (X_j - X_k) = 0 \\ -1 & (X_j - X_k) < 0 \end{cases} \quad (3)$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (4)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (5)$$

where X_i is the value of year i ; n is the length of the data, and m is the number of groups with tied ranks, each with t_i tied observations. If $|Z| \geq Z_{1-\alpha/2}$, the null hypothesis is rejected, and the alternative hypothesis is accepted at the significance level of α ; otherwise, the null hypothesis of no trend is accepted at the significance level of α .

Trend-free prewhitening includes the following steps:

$$r_1 = \frac{\sum_{t=1}^{n-1} (x_t - \bar{x}_t)(x_{t+1} - \bar{x}_{t+1})}{\sqrt{\sum_{t=1}^{n-1} (x_t - \bar{x}_t)^2 \sum_{t=1}^{n-1} (x_{t+1} - \bar{x}_{t+1})^2}} \quad (6)$$

$$Y_t = x_t - \beta t \quad (7)$$

$$Y'_t = Y_t - r_1 Y_{t-1} + \beta t \quad (8)$$

where x_t is the value of year t of the time series, n is the length of the data, and $\bar{x}_t$ is the average value. The original MK test is applied to Y_t to assess the significance of the trend.

Sen's slope estimator. Sen's slope estimation is a method for estimating the magnitude of time series data [34]. In this study, the magnitudes of the trends in ET_0 were investigated using Sen's slope estimator.

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad j > i \quad (9)$$

If $\beta > 0$, the time series of ET_0 and other climatic factors are increasing; otherwise, the time series are decreasing.

Sensitivity analysis. The sensitivity coefficient is the rate of variation in ET_0 with meteorological elements [35, 36]. The equation is shown below:

$$Sv_i = \lim_{v_i \rightarrow 0} \left(\frac{\Delta ET_0 / ET_0}{\Delta v_i / v_i} \right) = \frac{\partial ET_0}{\partial v_i} \cdot \frac{|v_i|}{ET_0} \quad (10)$$

where Sv_i is the sensitivity coefficient of v_i , ΔET_0 is the variation in ET_0 , v_i is the meteorological factor, and Δv_i is the variation in v_i . To evaluate the influence of a climate factor on ET_0 , the sensitivity coefficient was divided into four levels [37], as shown in Table 2.

Contribution rate analysis. The contribution rate of the meteorological elements is calculated by multiplying the sensitivity coefficient by its relative change rate [36]. The equations of

Table 2. Classification of the sensitivity coefficient.

Sensitivity coefficient	Sensitivity level
$0.00 \leq Sv_i < 0.05$	Negligible
$0.05 \leq Sv_i < 0.20$	Moderate
$0.20 \leq Sv_i < 1.00$	High
$1.00 \leq Sv_i $	Very high

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the contribution rate of meteorological elements are as follows:

$$Conv_i = Sv_i \times RCv_i \quad (11)$$

$$RCv_i = \frac{n \times Trend_{v_i}}{|av_i|} \times 100 \quad (12)$$

where $Conv_i$ is the contribution rate of v_i , RCv_i is the relative change rate in v_i , n is the number of years, av_i is the mean value of v_i , and $Trend_{v_i}$ is the annual trend in v_i .

Results

Temporal variations in meteorological elements

The TFPW-MK test and Sen's slope estimator showed significant increasing trends in $T_{\max}$ and $T_{\min}$ and an increasing trend in RH. The rates of increase in $T_{\max}$, $T_{\min}$ and RH in the TRB were $0.21^\circ\text{C} \cdot 10 \text{ a}^{-1}$, $0.45^\circ\text{C} \cdot 10 \text{ a}^{-1}$ and $0.22\% \cdot 10 \text{ a}^{-1}$, respectively. WS and SH showed significant downward trends in the TRB, with decrease rates of $-0.03 \text{ m} \cdot \text{s}^{-1} \cdot 10 \text{ a}^{-1}$ and $-0.03 \text{ h} \cdot 10 \text{ a}^{-1}$, respectively (Fig 2 and Table 3).

Temporal and spatial variability of ET_0

Temporal variability of annual and seasonal ET_0 . The TFPW-MK test showed seasonal differences in the mean ET_0 trends. ET_0 had increasing trends in spring, autumn, and winter and a decreasing trend in summer. Sen's slope estimator showed that the rate of increase in ET_0 in spring, autumn and winter ranged from 0.16 to $0.58 \text{ mm} \cdot 10 \text{ a}^{-1}$. In summer, the rate of decrease in ET_0 was $1.41 \text{ mm} \cdot 10 \text{ a}^{-1}$. The annual results of the TFPW-MK test showed that ET_0 had a decreasing trend in the TRB, with a rate of decrease of $0.49 \text{ mm} \cdot 10 \text{ a}^{-1}$ (Fig 3).

The trend in ET_0 varied among different sites with different microclimatic characteristics. In spring, summer, and autumn, the number of sites with decreasing trends was larger than that with increasing trends. Among the sites, 53.3%~66.7% showed decreasing trends, of which 75.0~76.5% showed significantly negative trends (Table 4). Increasing trends were observed for 33.3~47.7% of the sites, of which 50.0~60.0% showed significantly positive trends (Table 4). In winter, the number of sites with increasing trends was larger than that with decreasing trends. Among the sites, 56.7% exhibited increasing trends, of which 35.3% exhibited significant increasing trends. Furthermore, 43.3% of the sites exhibited decreasing trends, of which 46.2% exhibited significant decreasing trends (Table 4).

On an annual scale, the number of sites with decreasing trends was larger than that with increasing trends; 40% of the sites exhibited increasing trends, with significant increasing trends observed for 66.7% of those sites. In addition, 60% of the sites showed decreasing annual trends, of which 29.2% exhibited significant decreasing trends (Table 4).

Spatial variations in ET_0 . In spring and summer, the sites with significant increasing trends were located in the eastern and western parts of the basin, those with significant

Fig 2. Change trends in the mean meteorological elements in the Tarim River basin during 1960–2017. (a) $T_{\max}$. (b) $T_{\min}$. (c) RH. (d) WS. (e) SH.

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decreases were localized in the southern and northern parts, and those with nonsignificant changes were spread throughout the basin (Fig 4A and 4B). In autumn, the sites with significant increasing trends or nonsignificant changes were distributed throughout the basin, whereas those with significant decreases were located in the southern and northern regions (Fig 4C). In winter, the sites with significant increasing trends were located in the eastern, northern and western regions of the basin, whereas those with significant decreases were located in the southern and northern parts. The sites with nonsignificant changes were distributed across the basin (Fig 4D).

The sites with significant increasing trends at the annual scale were located in the eastern and western regions of the TRB. Those with significant decreases were located in the southern and northern regions of the basin (Fig 5).

Climate factors that affect ET_0 variability

Sensitivity coefficients of meteorological elements to ET_0 . Meteorological elements represent important input data for calculating ET_0 , and changes in these elements have important impacts on ET_0 . To analyze the effects of climate elements on ET_0 , sensitivity analysis was used.

The results of the sensitivity analysis showed that the average ET_0 over the whole basin was most sensitive to $T_{\max}$, followed by RH, WS, SH and $T_{\min}$; the sensitivity coefficients were 0.354, -0.338, 0.264, 0.158 and 0.102, respectively (Table 5). The sensitivity coefficients of $T_{\max}$, RH and WS were high, whereas those of SH and $T_{\min}$ were moderate.

The sensitivity coefficients varied among sites with different microclimate characteristics. The sensitivity coefficients of $T_{\max}$ were high at all sites (Fig 6A). The sensitivity coefficients of $T_{\min}$ were high at one site in the northern part of the basin and moderate at other sites (Fig 6B). For RH, the sensitivity coefficients were moderate at one site in the northeast and two sites in the south and high elsewhere (Fig 6C). The sensitivity coefficients of WS were moderate at three sites in the northern region and high at the other sites (Fig 6D). For SH, the sensitivity coefficients were high at some sites in the northern, southern, and western regions and moderate elsewhere (Fig 6E). These results showed that $T_{\max}$, RH and WS had important effects on ET_0 .

Contribution rates of meteorological elements to ET_0 . To explore the meteorological elements with key contributions to changes in ET_0 , contribution rate analysis was performed. The results suggested that over the whole basin, the increases in $T_{\max}$ and $T_{\min}$ positively contributed to the increase in ET_0 . In addition, increases in RH and decreases in WS and SH negatively contributed to the increase in ET_0 (Table 5).

The contributions of meteorological elements to ET_0 differed among the different sites. At eight sites, in the northwest, southwest and northern regions, $T_{\min}$ or $T_{\max}$ was the main factor

Table 3. Results of the trend analyses of annual meteorological elements.

Test	$T_{\max}$	$T_{\min}$	RH	WS	SH
TFPW-MK	4.21*	7.76*	1.19	-3.90*	-2.14*
Sen's slope estimator	0.21 ($^{\circ}\text{C} \cdot 10 \text{ a}^{-1}$)	0.45 ($^{\circ}\text{C} \cdot 10 \text{ a}^{-1}$)	0.22 ($\% \cdot 10 \text{ a}^{-1}$)	-0.03 ($\text{m} \cdot \text{s}^{-1} \cdot 10 \text{ a}^{-1}$)	-0.03 ($\text{h} \cdot 10 \text{ a}^{-1}$)

* $\alpha < 0.05$

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Fig 3. Results of the TFPW-MK test and Sen's slope estimator for the average ET_0 in the TRB from 1960 to 2017.

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Table 4. Percent of stations with positive (significant at the 0.05 level) and negative (significant at the 0.05 level) trends in ET_0 from 1960 to 2017 in the TRB.

	Spring	Summer	Autumn	Winter	Year
Trend	U	D	U	U	D
Positive	46.7% (50%)	33.3% (60%)	43.3% (54.8%)	56.7% (35.3%)	40% (66.7%)
Negative	53.3% (75%)	66.7% (75%)	56.7% (76.5%)	43.3% (46.2%)	60% (29.2%)

Note: U indicates that the regional trends are increasing; D indicates that the regional trends are decreasing.

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Fig 4. Trends in ET_0 on seasonal timescales at different sites. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

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that contributed to changes in ET_0 . At two sites, one in the northwest and one in the northeast, RH was the main factor that contributed to changes in ET_0 . At other sites near or in the Taklimakan Desert, WS was the main factor that contributed to changes in ET_0 (Fig 7). Overall, WS, which decreased over time, was the main factor that contributed to changes in ET_0 (Table 5).

Discussion

Change in ET_0

The “evaporation paradox” has been observed in many areas and widely discussed [13–15, 26, 38, 39]. Similarly, in this study, this paradox was observed in many sites in the TRB. The annual ET_0 exhibited a decreasing trend at many sites and over the entire area. The changes in annual ET_0 exhibited seasonal variation. Over the entire area, ET_0 increased in spring, autumn and winter but decreased in summer. Annual ET_0 decreased overall because the magnitude of the decrease was larger than that of the increase.

ET_0 is needed for irrigation planning because it is a basic input for estimating crop water requirements [40]. Under a certain irrigation guarantee rate, increases in ET_0 will generally increase irrigation quotas and irrigation project budgets. In spring and summer, the sites with

Fig 5. Annual trends in ET_0 at different sites.

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significant increasing trends were located in the eastern and western parts of the basin. Increases in ET_0 may contribute to increased use of irrigation water by increasing water loss from farmland, thus posing a threat to crop production. The sites with significant decreases were located in the southern part of the basin. Decreases in ET_0 may contribute to decreases in irrigation water use by reducing water loss from farmland, thus benefitting crop production. In autumn and winter, crops are harvested, and no new crops are planted in those seasons. Thus, changes in ET_0 will have little effect on agricultural production and irrigation water.

Climate factors that affect ET_0

ET_0 represents the evaporation demand of the atmosphere and is mainly affected by climatic factors [41]. Wang, Ye [20] showed that specific humidity plays the predominant role in the

Table 5. Contribution rates of the mean meteorological elements to ET_0 .

	T_{max}	T_{min}	RH	WS	SH
Sensitivity coefficient	0.354	0.102	-0.338	0.264	0.158
Trend	0.021	0.038	0.033	-0.004	-0.002
Relative variation ratio	9.103	98.769	3.302	-18.534	-1.954
Contribution rate	2.828	2.314	-1.400	-4.880	-0.261

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Fig 6. Spatial distributions of the sensitivity coefficients of meteorological elements in the TRB. a) T_{max} . b) T_{min} . c) RH. d) WS. e) SH.

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Fig 7. Spatial distribution of the main key meteorological elements contributing to ET_0 in the TRB.

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sensitivity of ET_0 in Northwest China. In this study, the sensitivity analysis indicated that for the entire TRB, the largest absolute value of the sensitivity coefficient was between T_{max} and ET_0 (Table 5). T_{max} may be the most sensitive climatic variable influencing ET_0 . The absolute values of the sensitivity coefficient of RH and ET_0 and of WS and ET_0 were the second and third largest, respectively. RH and WS may be the second and third most influential factors affecting ET_0 . This result may be due to the small study area, where the main landform is deserts.

The contribution rate analysis suggested that in the TRB, increasing T_{max} and T_{min} positively contributed to ET_0 , whereas increasing RH and decreasing WS and SH negatively contributed to ET_0 (Table 5). The absolute value of the contribution of WS was greater than those of the other meteorological elements, indicating that WS was the main factor that induced changes in ET_0 . Wind plays an important role in the evapotranspiration of ecosystems. The process of vapor removal depends to a large extent on wind [9]. The study area is situated inland and experiences a dry climate and strong evaporation. Under these arid conditions, decreases in WS may result in large variations in evapotranspiration. Thomas [42] and Wang, Xie [26] emphasized that WS plays the predominant role in influencing ET_0 in water-limited areas of Western China. The factors driving decreases in WS are extremely complex. Zhang,

Ren [43] noted that changes in large-scale atmospheric circulation patterns were possible factors driving WS reduction in China. Jiang, Luo [44] found that in China, changes in WS may be driven by the East Asian winter and summer monsoons under the background of global warming. Zheng, Li [45] posited that the influence of human activities cannot be ignored and that these activities are likely the main factors driving decreases in WS in northwestern China. Liu, Dong [46] found that changes in WS in the Taklimakan Desert, Northwest China, were mainly caused by a decreased frequency of strong winds, precipitation, and urban development. However, the relationships among atmospheric circulation patterns, climate warming and human activities are extremely complex and influence each other. Changes in WS may be driven by a combination of changes in atmospheric circulation patterns, climate warming and human activities.

Conclusions

The ET_0 at 30 meteorological stations located in the TRB was calculated by the Penman-Monteith formula. The TFPW-MK test and Sen's slope estimator were used to study changes in ET_0 . Sensitivity analysis and contribution rate analysis were used to identify the effects of meteorological elements and the key meteorological elements affecting ET_0 . The following main conclusions were drawn from this study.

The TFPW-MK test and Sen's slope estimator showed seasonal differences in ET_0 trends. The mean ET_0 exhibited an increasing trend in spring, fall and winter and a decreasing trend in summer. On an annual timescale, the mean ET_0 decreased, at a rate of $0.49 \text{ mm} \cdot 10 \text{ a}^{-1}$. Sensitivity analysis showed that $T_{\max}$, RH and WS had important effects on ET_0 . Contribution rate analysis showed that WS, which decreased, was the main factor that contributed to changes in ET_0 .

Supporting information

S1 Data. The data used in the article.
(XLSX)

S2 Data.
(XLSX)

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Author Contributions

Data curation: Hao Wu.

Software: Min Xu, Zhuoyue Peng, Xiaoping Chen.

Validation: Zhuoyue Peng.

Writing – original draft: Hao Wu.

Writing – review & editing: Hao Wu, Min Xu, Zhuoyue Peng, Xiaoping Chen.

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