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

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Abstract

Reference evapotranspiration (ET0) is important for agricultural production and the hydrological cycle. Knowledge of ET0 can aid the appropriate allocation of irrigation water in arid regions. This study analyzed the trends in ET0 over different timescales in the Tarim River basin (TRB), Central Asia. ET0 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 ET0 variation. The results showed that the mean ET0 decreased at a rate of 0.49 mm·10 a−1 on an annual timescale. The mean ET0 exhibited a decreasing trend in summer and increasing trends in other seasons. The effects of climatic factors on ET0 were assessed by sensitivity analysis and contribution rate analysis. Maximum temperature (Tmax), relative humidity (RH) and wind speed (WS) showed important effects on ET0. However, WS, which decreased, was the key element that induced changes in ET0 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 (ET0) is a key indicator in this approach [5]. ET0 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 ET0 and is widely used [6–8].
ET₀ 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, ET₀ has decreased. This combination of global temperature increases and ET₀ 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, ET₀ showed a decreasing trend under changing precipitation [13]. In humid and desert regions in India, ET₀ 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, ET₀ 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 ET₀ will alter the amount of available water resources in this region.

Previous studies of ET₀ have focused on large agricultural regions, with ET₀ calculated as the average over each of these areas [20, 26]. ET₀ trends at different weather stations in the TRB have not been detected. Investigating the influence of climate change on ET₀ 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 ET₀ in the TRB and (2) analyze the key meteorological elements affecting ET₀.

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 1.02×10⁶ km² (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
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 ($T_{\text{max}}$, $T_{\text{min}}$), 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:

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

(1)

where $ET_0$ is the reference evapotranspiration (mm·m⁻²·day⁻¹), $R_n$ is the net radiation (MJ·m⁻²·day⁻¹), $G$ is the soil heat flux (MJ·m⁻²·day⁻¹), $\gamma$ is the psychrometric constant (k·Pa·°C⁻¹), $u_s$ is the wind speed at 2 m height (m·s⁻¹), $e_a$ is the saturation vapor pressure (k·Pa), $e_d$ is the actual vapor pressure (k·Pa), and $T$ is the air temperature (°C).
\( T \) is the air temperature (°C), \( u_2 \) is the wind speed at a height of 2 m (m·s\(^{-1}\)), \( e_a \) is the saturated vapor pressure (kPa), \( e_d \) is the actual vapor pressure (kPa), and \( \Delta \) is the slope of the saturation vapor pressure curve (kPa·°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:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sgn(S_j - S_k) \tag{2}
\]

\[
Sgn(S_j - S_k) = \begin{cases} 
1 & (X_j - X_k) > 0 \\
0 & (X_j - X_k) = 0 \\
-1 & (X_j - X_k) < 0 
\end{cases} \tag{3}
\]

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 | Tieganieke | 87.70          | 40.63         | 846           | 11.66                    |
| 51777 | Ruoqiang   | 88.17          | 39.03         | 887.7         | 12.29                    |
| 51804 | Tashikergan| 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 | Qiemo      | 85.55          | 38.15         | 1247.2        | 11.09                    |
| 51931 | Yutian     | 81.65          | 36.85         | 1422          | 12.33                    |
| 52313 | Honglihe   | 94.67          | 41.53         | 1573.8        | 7.03                     |

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Reference evapotranspiration in the Tarim River Basin

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\[ \text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \]  

\[ Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{Var}(S)}} & S > 0 \\
0 & S = 0 \\
\frac{S + 1}{\sqrt{\text{Var}(S)}} & S < 0 
\end{cases} \]

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 \( \alpha \); otherwise, the null hypothesis of no trend is accepted at the significance level of \( \alpha \).

**Trend-free prewhitening** includes the following steps:

\[ r_1 = \frac{\sum_{i=1}^{n-1} (x_i - \bar{x}_j)(x_{i+1} - x_{i+1}^-)}{\sqrt{\sum_{i=1}^{n-1} (x_i - \bar{x}_j)^2 \sum_{i=1}^{n-1} (x_{i+1} - x_{i+1}^-)^2}} \]

\[ Y_i = x_i - \beta t \]

\[ Y'_i = Y_i - r_1 Y_{i-1} + \beta t \]

where \( x_i \) is the value of year \( t \) of the time series, \( n \) is the length of the data, and \( \bar{x}_j \) is the average value. The original MK test is applied to \( Y_i \) 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.

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

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:

\[ S_{v_i} = \lim_{v_i \to 0} \left( \frac{\Delta ET_0}{\Delta ET_0 / v_i} \right) = \frac{\partial ET_0}{\partial v_i} \cdot \frac{|v_i|}{ET_0} \]

where \( S_{v_i} \) is the sensitivity coefficient of \( v_i \), \( \Delta ET_0 \) is the variation in \( ET_0 \), \( v_i \) is the meteorological factor, and \( \Delta v_i \) 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
the contribution rate of meteorological elements are as follows:
\[ \text{Conv}_i = S_{v_i} \times R_{Cv_i} \quad (11) \]
\[ R_{Cv_i} = \frac{n \times \text{Trend}_{vi}}{|av_i|} \times 100 \quad (12) \]
where \( \text{Conv}_i \) is the contribution rate of \( v_i \), \( R_{Cv_i} \) is the relative change rate in \( v_i \), \( n \) is the number of years, \( av_i \) is the mean value of \( v_i \), and \( \text{Trend}_{vi} \) 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 \( T_{\text{max}} \) and \( T_{\text{min}} \) and an increasing trend in RH. The rates of increase in \( T_{\text{max}} \), \( T_{\text{min}} \) and RH in the TRB were 0.21˚C \( \cdot 10 \text{ a}^{-1} \), 0.45˚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 m \( \cdot \text{s}^{-1} \cdot 10 \text{ a}^{-1} \) and -0.03 h \( \cdot 10 \text{ a}^{-1} \), respectively (Fig 2 and Table 3).

**Temporal and spatial variability of \( \text{ET}_0 \)**

**Temporal variability of annual and seasonal \( \text{ET}_0 \)** The TFPW-MK test showed seasonal differences in the mean \( \text{ET}_0 \) trends. \( \text{ET}_0 \) 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 \( \text{ET}_0 \) in spring, autumn and winter ranged from 0.16 to 0.58 mm \( \cdot 10 \text{ a}^{-1} \). In summer, the rate of decrease in \( \text{ET}_0 \) was 1.41 mm \( \cdot 10 \text{ a}^{-1} \). The annual results of the TFPW-MK test showed that \( \text{ET}_0 \) had a decreasing trend in the TRB, with a rate of decrease of 0.49 mm \( \cdot 10 \text{ a}^{-1} \) (Fig 3).

The trend in \( \text{ET}_0 \) 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 \( \text{ET}_0 \)** In spring and summer, the sites with significant increasing trends were located in the eastern and western parts of the basin, those with significant
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$_{\text{max}}$, followed by RH, WS, SH and T$_{\text{min}}$; the sensitivity coefficients were 0.354, -0.338, 0.264, 0.158 and 0.102, respectively (Table 5). The sensitivity coefficients of T$_{\text{max}}$, RH and WS were high, whereas those of SH and T$_{\text{min}}$ were moderate.

The sensitivity coefficients varied among sites with different microclimate characteristics. The sensitivity coefficients of T$_{\text{max}}$ were high at all sites (Fig 6A). The sensitivity coefficients of T$_{\text{min}}$ 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$_{\text{max}}$, 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$_{\text{max}}$ and T$_{\text{min}}$ 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$_{\text{min}}$ or T$_{\text{max}}$ was the main factor

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

| Test         | T$_{\text{max}}$ | T$_{\text{min}}$ | RH   | WS      | SH     |
|--------------|------------------|------------------|------|---------|--------|
| TFPW-MK      | 4.21*            | 7.76*            | 1.19 | -3.90*  | -2.14* |
| Sen’s slope estimator | 0.21 (˚C·10 a$^{-1}$) | 0.45 (˚C·10 a$^{-1}$) | 0.22 (%·10 a$^{-1}$) | -0.03 (m·s$^{-1}$·10 a$^{-1}$) | -0.03 (h·10 a$^{-1}$) |

*α < 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.

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.

| Trend  | Spring          | Summer          | Autumn          | Winter          | Year          |
|--------|-----------------|-----------------|-----------------|-----------------|---------------|
| 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.
that contributed to changes in ET₀. At two sites, one in the northwest and one in the northeast, RH was the main factor that contributed to changes in ET₀. At other sites near or in the Taklimakan Desert, WS was the main factor that contributed to changes in ET₀ (Fig 7). Overall, WS, which decreased over time, was the main factor that contributed to changes in ET₀ (Table 5).

Discussion

Change in ET₀

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 ET₀ exhibited a decreasing trend at many sites and over the entire area. The changes in annual ET₀ exhibited seasonal variation. Over the entire area, ET₀ increased in spring, autumn and winter but decreased in summer. Annual ET₀ decreased overall because the magnitude of the decrease was larger than that of the increase.

ET₀ 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 ET₀ will generally increase irrigation quotas and irrigation project budgets. In spring and summer, the sites with
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

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**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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sensitivity of $E_T^0$ 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 $T_{\text{max}}$ and $E_T^0$ (Table 5). $T_{\text{max}}$ may be the most sensitive climatic variable influencing $E_T^0$. The absolute values of the sensitivity coefficient of RH and $E_T^0$ and of WS and $E_T^0$ were the second and third largest, respectively. RH and WS may be the second and third most influential factors affecting $E_T^0$. 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 $T_{\text{max}}$ and $T_{\text{min}}$ positively contributed to $E_T^0$, whereas increasing RH and decreasing WS and SH negatively contributed to $E_T^0$ (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 $E_T^0$. 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 $E_T^0$ 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<sub>0</sub> 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<sub>0</sub>. Sensitivity analysis and contribution rate analysis were used to identify the effects of meteorological elements and the key meteorological elements affecting ET<sub>0</sub>. The following main conclusions were drawn from this study.

The TFPW-MK test and Sen’s slope estimator showed seasonal differences in ET<sub>0</sub> trends. The mean ET<sub>0</sub> exhibited an increasing trend in spring, fall and winter and a decreasing trend in summer. On an annual timescale, the mean ET<sub>0</sub> decreased, at a rate of 0.49 mm·10<sup>−1</sup>·a<sup>−1</sup>. Sensitivity analysis showed that T<sub>max</sub>, RH and WS had important effects on ET<sub>0</sub>. Contribution rate analysis showed that WS, which decreased, was the main factor that contributed to changes in ET<sub>0</sub>.

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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