Quantitative effects of changes in agricultural irrigation on potential evaporation

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Abstract: Evaporation is the key to the basin's water cycle. Agricultural irrigation has resulted in a significant variation of regional potential evaporation (E_{pen}). The spatiotemporal variation of E_{pen} and the influencing factors in the natural, agricultural, and desert areas in different developmental stages of irrigation in the Heihe River Basin (HRB) from 1970 to 2017 are comparatively analyzed in this study. This work focused on the correction effect of irrigation on the variation of E_{pen}. The agricultural water consumption in HRB significantly varied around 1998 due to the agricultural development and water policy. Under the influence of irrigation, the annual variation of E_{pen} in the agricultural, natural, and desert areas was significantly different. From 1970 to 1998, the annual trend slope of E_{pen} in the natural area only reduced by 1 mm decade^{-1}, while that in the agricultural area significantly decreased by 39 mm decade^{-1}. After the implementation of water-saving irrigation, the E_{pen} in the natural and agricultural areas increased by 11 and 54 mm decade^{-1}, respectively, from 1998 to 2017. In contrast with the natural and agricultural areas, E_{pen} in the desert area decreased by 80 mm decade^{-1} from 1970 to 1998 and continuously decreased by 41 mm decade^{-1} from 1998 to 2017. However, the regulatory effect of irrigation on E_{pen} in the desert area started to manifest due to the expansion of the cultivated land area in the desert area from 2010 to 2017. Irrigation has a significant regulatory effect on the variation of E_{pen} in HRB. The regulatory effect is mainly reflected on the aerodynamic term (E_{aero}). The analytical results of the main meteorological factors affecting E_{pen} in different regions indicated that the main meteorological factors influencing the variation of E_{pen} in each region are the wind speed 2 m above the surface (U_2) and the water vapor pressure difference (VPD).

Keywords:

Evaporation, Irrigation, Meteorological factor, Contribution

1. Introduction

Evaporation is an important component of the hydrological cycle. The development of large-scale and water-saving irrigation in nonhumid areas has caused significant changes in evaporation. The effect of irrigation on regional evaporation should be understood to strengthen the regional water management and evaluate crop growth (Niles & Mueller, 2016; Wang et al., 2016; Zipper et al., 2016). The climate system of farmland, regional, and global scales has been affected by irrigation due to the rapid development of irrigation. Many people prefer the regulatory effect of irrigation on regional climate and evaporation (Han et al., 2014a, 2018; Decker et al., 2017). Irrigation changed the division of the regional surface energy (Lei et al., 2015), and irrigation expansion increased the latent heat flux and decreased the sensible heat flux (Zhang et al., 2017). The comparison results of the meteorological factors between the irrigated and the nonirrigated areas indicated that the air humidity (Boucher et al., 2004; Sridhar & Anderson, 2017), rainfall (Wei et al., 2013; Harding et al., 2015; Yang et al., 2017), water vapor pressure (Perkins, 2011), and average dew point temperature (Mahmood et al., 2008) in the irrigated area increased, while the U_2 decreased (Mcvicar et al., 2012; Han et al., 2016; Vautard et al., 2010). The regional "cooling effect" (Nocco et al., 2019; Shi et al., 2014; Xu et al., 2017; Vahmani & Hogue, 2015) increased with the increase in the irrigation area. By contrast, irrigation reduction promoted the reversed transformation of the above-mentioned variations. For example, the "cooling effect" of irrigation began to slow down after the completion of irrigation expansion in California (Bonfils and Lobell, 2007). The "cooling effect" of irrigation slowed down, similar to that in California. The air humidity near the ground decreased, and the reference evaporation increased after the reduction of irrigation diversion in the Awati irrigation area in Xinjiang (Han et al., 2017).

Scholars worldwide have conducted a substantial amount of research to further clarify the main control factors of regional evaporation. Studies have shown that the main reason for the decrease in E_{pen} in the Tarim Basin in Xinjiang is the decrease in wind speed and the increase in relative humidity (Han & Hu, 2012). The increase of E_{pen} in East Asia is mainly caused by the increase in temperature (Hulme et al., 1994). The increase of reference evaporation in the Apulian Tavoliere irrigation district in southern Italy is mainly due to the increase in temperature and the decrease in rainfall (Palumbo et al., 2011). The significant decrease of reference evaporation in the Platte River Basin in Nebraska, USA is caused by the significant increase in rainfall (Irmak et al., 2012). The variation in the relative humidity is the main reason for the increase in reference evaporation in the Canary Islands in Africa (Vicente-Serrano et al., 2016). The reference evaporation in Greece from 1950 to 2001 was mainly affected by the effective sunshine hours (Papaioannou et al., 2011; Kitsara et al., 2017). Ozdogan and Salvucci (2004) qualitatively explained that the increase of actual evaporation caused by irrigation was the reason for the rapid decline of potential evaporation in the irrigation district of southern Turkey. Liu et al. (2016) pointed out that wind speed is the main factor affecting the variation of reference evaporation in Southwest China. Sun et al. (2017) thought that the main factor in the east of Southwest China is net radiation, and that beyond the east of Southwest China is the wind speed or vapor pressure difference (*VPD*), and the factor varies in different months.

In conclusion, the factors driving the variation of regional evaporation are temporal and spatial (Han et al., 2014b; Ozdogan et al., 2006; Han et al., 2012; Zheng & Wang, 2015; Fan et al., 2016). Existing research mainly focuses on the effect of irrigation on evaporation and local climate in the agricultural area. However, existing work lacks the synchronous research about the effect of irrigation expansion and water-saving irrigation on that for different underlying surfaces, such as natural, agricultural, and desert areas.

The HRB is the second largest inland river basin in China, traversing arid and semiarid areas. The irrigation area is concentrated in the middle reaches of the basin. The amount of water in different regions in HRB significantly varied due to agricultural development. The irrigation water per unit area in the agricultural area in HRB has undergone a significant variation of first increasing and then decreasing. In 2015, the effective irrigation area of the oases located in the middle reaches of HRB increased by 38% compared with that in 1980. The surface water diversion increased by 53% compared with that in 1980. However, the amount of water diverted to the middle oasis in 2015 decreased by 24% compared with that in 1998 after the implementation of large-scale agricultural water-saving projects. Studies have shown that E_{pen} decreased with the increase in irrigation diversion and water consumption (Han et al., 2009; Zhang et al., 2017). However, the variation of E_{pen} after the implementation of water-saving irrigation and the influencing mechanism of meteorological factors on E_{pen} for different underlying surfaces are not clear at present.

This work takes HRB as the study area and E_{pen} as the research target and selects three hydrological stations and ten meteorological stations in the basin as the data sources. The study area is divided into natural, agricultural, and desert areas according to the main landscape within 4 km of the meteorological stations (Han & Yang, 2013). This study aims to clarify the following issues: (1) How large-scale irrigation influences the spatiotemporal variation of E_{pen} in HRB; (2) How water-saving irrigation influences the spatiotemporal variation of E_{pen}; and (3) Quantify the contribution of meteorological factors to regional E_{pen}. This study will provide a theoretical basis for the research of irrigation–climate effect in HRB.

2. Materials and methods

2.1 Overview of the study area

The HRB (37°43′N–42°41′N, 97°23′E–102°72′E) ranges with an elevation of 716–5583 m and covers approximately 143,000 km^2. The characteristics of the underlying surface in HRB are significant and can be divided into natural, agricultural, and desert areas from upstream to downstream. The natural area originates from the Qilian Mountains in Qinghai Province. This area is humid and cold all year round and is the main runoff-generation area in the basin. The agricultural area is dry and rainless all year round, and the water requirement of crops is mainly met by irrigation. The irrigation is mainly satisfied by surface water supplemented by groundwater. The irrigation water consumption in HRB accounts for approximately 84% of the total water resources (Ge et al., 2013). The desert area is located in the lower reaches of HRB, and the climate is extremely dry. The water supply for the lower reaches is insufficient due to the excessive water diversion in the agricultural area, thereby resulting in the river cutoff, lake disappearance, and serious desertification (Yi, 2015). The hydrological stations of Yingluo Gorge, Zhengyi Gorge, and Langxin Mountain are distributed along the trunk stream of the Heihe River. These stations are important water conservancy control hubs that regulate and control the water input or output in natural, agricultural, and desert areas. The geographical location and regional characteristics of HRB are shown in Fig. 1 and Table 1, respectively.

---Fig.1---

---Table.1---

2.2 Data acquisition and methods

In this study, 10 meteorological stations in HRB were selected as the research objects, including three stations in the natural area, six stations in the agricultural area, and one station in the desert area. The distribution of the stations is shown in Fig. 1. This study calculated the proportion of cultivated land area within 4 km of the meteorological stations on the basis of the land use with a resolution of 1 km in 2015 provided by the National Platform for Basic Conditions of Science and Technology – National Earth System Science Data Center (http://www.geodata.cn). The results are shown in Table 2. The aforementioned table demonstrates that the proportions of cultivated land area in the natural area is less than 5%, that in the agricultural area is more than 30%, and that in the desert area is about 5%.

---Table 2--

2.3 Data analytical method

(1) Calculation of potential evaporation

In this study, Penman formula is used to calculate E_{pen} of the 10 meteorological stations in HRB from 1970 to 2017. The E_{pen} includes radiation (E_{rad}) and aerodynamic (E_{aero}) terms. The calculation formulas are as follows:

$$E_{pen} = E_{rad} + E_{aero}, \tag{1}$$

$$E_{rad} = \frac{\Delta\left(R_n - G\right)}{\Delta + \gamma}, \tag{2}$$

$$E_{aero} = \frac{\gamma}{\Delta + \gamma} f\left(U_2\right) e^*\left(T_a\right)\left(1 - RH\right), \tag{3}$$

$$f\left(U_2\right) = 0.26(1 + 0.54U_2), \tag{4}$$

where Δ is the slope of the saturation vapor curve at the temperature of the surface that evaporates at a potential rate, kPa C^{-1}; γ is a psychrometric constant, kPa C^{-1}; *Rn* and *G* are the net radiation and ground heat flux, respectively, MJ kg^{-1}; e^* is the saturated air vapor pressure, kPa; *Ta* is the air temperature, ℃; *RH* is the relative humidity, %; and $f(U_2)$ is the function of U_2, m s^{-1} (Penman, 1948).

(2) Variation trend and significance analysis

The trend slopes of the meteorological factors, namely, E_{pen}, E_{rad}, and E_{aero}, are evaluated by the method of Theil–Sen (Thiel, 1950; Sen, 1968) (Eq. [5]). The significance level of the trend slopes is calculated by using the Mann–Kendall method (Mann, 1945; Kendall, 1948) (Eqs. [6–9]). Mann and Kendall pointed out that when n≥8, the test statistic S can be standardized to obtain the standardized statistic Z.

$$\beta = median\left[\frac{\left(X_j - X_i\right)}{\left(j-i\right)}\right], \forall i < j \quad (5)$$

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}\left(X_j - X_i\right) \quad (6)$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & if\ \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & if\ \theta < 0 \end{cases} \quad (7)$$

$$V(S) = \frac{n(n-1)(2n+5)}{18} \quad (8)$$

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases} \quad (9)$$

where X_j and X_i are the time series data, respectively; and β is the trend slope. When β is greater than zero, then the factor shows an increasing trend. Meanwhile, when β is less than zero, the factor shows a decreasing trend.

At a given level of α confidence, if $|Z| > Z_{(1-\alpha/2)}$, then the original assumption is unacceptable. Specifically, the time series data show an obvious upward or downward trend at the level of α confidence.

(3) Water balance analysis

The water balance method was used to analyze the water variation in the natural, agricultural, and desert areas in the HRB.

Natural area $$P + Q_{in} = E + \Delta S + Q_{out} + R_{out}, \tag{10}$$

Agricultural area $$I + P + Q_{in} = E + \Delta S + Q_{out}, \tag{11}$$

Desert area $$R_{in} + P + Q_{in} = E + Q_{out} + \Delta S, \tag{12}$$

where R_{out} is the water flowing out of the area; P is the rainfall; I is the irrigation volume; R_{in} is the water flowing into the area; ΔS is the variation of soil water storage, which can be ignored on annual or multiyear time; Q_{in} is other water supply (such as groundwater recharge); Q_{out} is other water loss (such as deep percolation); and E is the actual evaporation. The agricultural area in the HRB is dry and rainless all year round, thereby resulting in its inability to form an effective runoff, and most rainfall is directly used for evaporation. The side seepage of the river and groundwater has a slight influence on the regional evaporation. The actual evaporation of the agricultural area accounts for 52% of irrigation and effective rainfall; the deep percolation and canal conveyance losses account for 22% and 25%, respectively(Jiang, 2017).

3. Results and discussion

3.1 Variation characteristics of agricultural water diversion in different regions

Heihe River is the main source of water for agriculture, industry, and life in the HRB. The measured runoff of the Yingluo Gorge, Zhengyi Gorge, and Langxin Mountain hydrological stations from 1970 to 2017 is shown in Fig. 2. The agricultural area can be divided into two parts according to the source of water supplied there in HRB: (1) Upstream of the agricultural area. This area is an important grain production base in the HRB, and the water diversion is controlled by the hydrological stations of Yingluo Gorge and Zhengyi Gorge. The variation of water diversion in this region around 1998 is shown in Fig. 2. The cultivated land area accounts for approximately 64% of the total cultivated land area in the agricultural area. The agricultural water diversion is from Heihe River and accounts for approximately 39% of the Mountain Runoff of Heihe River. (2) Downstream of the agricultural area. The agricultural water diversion is mainly from Heihe River, supplemented by water from other river systems in the west and central part of HRB, such as Hongshuiba and Fengle Rivers. The water diversion from Heihe River is regulated by Zhengyi Gorge and Langxin Mountain hydrological stations, thereby accounting for approximately 29% of the Mountain Runoff of Heihe River. The water diversion from Hongshuiba and Fengle Rivers is still obscured due to the lack of data. Thus, this section only analyzes the variations of water supply from Heihe River to different regions.

Fig. 2 demonstrates that the runoff of Yingluo Gorge significantly increases from 1970 to 2017. The total amount of agricultural water diversion increased by approximately 660 million m^3 from 1970 to 1998. The amount of water diversion in the upstream of the agricultural area significantly increased by 610 million m^3. In 1998, the average irrigation quota in the agricultural area reached by 967 mm. The increase of water diversion in the agricultural area led to a significant decrease in the discharge of Langxin Mountain hydrological station. After the implementation of water-saving irrigation, the water diversion, especially in the upstream of the agricultural area, significantly decreased by 250 million m^3 from 1998 to 2017. The average irrigation quota in 2017 decreased by 34% compared with that in 1998. The discharge of Langxin Mountain hydrological station increased by 750 million m^3 in 2017 after the implementation of water-saving irrigation, which provided a water source guarantee for ecological restoration in the downstream.

---Fig.2--

3.2 Spatiotemporal variations of E_{pen}, E_{rad}, and E_{aero}

The annual trend slopes and spatial distributions of E_{pen} in the HRB and its terms are shown in Table 3 and Fig. 3. In the natural area, E_{pen} continuously increased from 1970 to 2017. E_{pen} increased by only 1 mm decade^{-1} from 1970 to 1998 and then significantly increased by 11 mm decade^{-1} from 1998 to 2017 (Table 3). The trend slopes of E_{rad} and E_{aero} are opposite. E_{rad} increased by 7 mm decade^{-1}, and E_{aero} decreased by 7 mm decade^{-1} from 1970 to 1998. Meanwhile, E_{rad} decreased by 2 mm decade^{-1}, and E_{aero} increased by 12 mm decade^{-1} from 1998 to 2017.

In the agricultural area, E_{pen} significantly decreased by 39 mm decade^{-1} from 1970 to 1998 and significantly increased by 54 mm decade^{-1} from 1998 to 2017. The variation trend of E_{rad} is opposite to that of E_{pen} with small trend slopes, while that of E_{aero} and E_{pen} was similar.

In the desert area, E_{pen}, E_{rad}, and E_{aero} continuously decreased from 1970 to 2017. The variation trends of E_{pen} and E_{aero} were significant from 1970 to 1998 and that of E_{pen} and E_{rad} were significant from 1998 to 2017.

Fig. 3 shows that the spatiotemporal variations of E_{pen}, E_{rad}, and E_{aero} in the natural area are relatively small, while that in the agricultural area are significant. The E_{pen}, E_{rad}, and E_{aero} of Shandan are much smaller than those of other stations. In the desert area, the variations of E_{pen}, E_{rad}, and E_{aero} were significant. The comparison result of the trend slopes of E_{pen}, E_{rad} and E_{aero} demonstrates that the trend slopes of E_{pen} are mainly influenced by E_{aero}.

---Table 3---

---Fig.3--

3.2.1 Relationship between the spatiotemporal variation of E_{pen} and irrigation

Fig. 4 (a–c) show the annual variations of the averaged E_{pen}, E_{rad}, and E_{aero} in the natural, agricultural, and desert areas in the HRB. The variations among E_{pen}, E_{rad}, and E_{aero} in different areas and the corresponding regional runoff or water diversion (Section 3.1) are examined. The result showed that E_{pen} and its terms in natural area are almost not affected by irrigation because of its location, which is in the runoff-generating area. Figs. 4 (a) and (c) demonstrate that the variations of E_{pen} and E_{aero} in the agricultural area were negatively correlated with the variation of water diversion. E_{pen} and E_{aero} significantly decreased before 1998 due to the increase in water diversion. After 1998, the water-saving measures promoted the increase of E_{pen} and E_{aero}. The correlation between the annual variation of E_{rad} and the regional water diversion is relatively weak (Fig. 4[b]).

Section 3.1 indicated that E_{pen} and E_{aero} in the desert area significantly decreased from 1970 to 1998 with the decrease in water diverted to the desert area; meanwhile, E_{pen} and E_{aero} began to slowly recover from 1998 to 2009 with the increase in water diversion (Figs. 4 [a] and [c]). Statistics show that the average cultivated land area in the desert area only accounted for 0.33% from 1995 to 2005. However, the area has reached 2.48% since 2010, and the water diversion increased by 225 million m^3. The intensified irrigation activities contributed to the decrease of E_{pen} and E_{aero} from 2009 to 2017 in the desert area.

In conclusion, irrigation has a significant regulatory effect on E_{pen} in the HRB. Specifically, the increase of irrigation can significantly reduce the regional E_{pen}. The regulatory effect is mainly realized through the aerodynamic term.

--Fig.4--

3.2.2 Relationship between the variations of potential and actual evaporation

The annual E, E_{pen}, and E_{rad} in the agricultural area from 1970 to 2017 are compared in Fig. 5. The aforementioned figure demonstrates that the annual variation trend between E_{pen} and E is opposite from 1970 to 2017, while no significant variation of E_{rad} is observed. E_{pen} decreased with the increase in E before 1998; however, the variation trend reversed after 1998. The trend was consistent with the study of Zhang et al. (2020), who simulated the variation of E with rainfall by means of WRF model in the HRB. The complementary relationship of evaporation (Bouchet, 1963) can be used to explain the influence of actual evaporation variation caused by irrigation on E_{pen} on the basis of the interaction between the land and the atmosphere above land. Water-saving irrigation does not necessarily lead to the increase of E_{pen}, only when the agricultural water diversion and actual evaporation decreased with water-saving irrigation (Han et al., 2017). The variation of E_{pen} in the agricultural area in the HRB is consistent with the situation described above.

--Fig.5--

3.3 Analysis of meteorological factors affecting potential evaporation

3.3.1 Relationship between meteorological factor variations and irrigation

Table 4 shows the trend slopes and significance of the main meteorological factors, including T_{mean}, U_2, VPD, and Rn, for the different stations from 1970 to 2017 in the HRB. Table 4 illustrates that T_{mean} at different stations continuously increased, except Yeniugou. The trend slopes of the other meteorological factors are different.

In the natural area, the annual U_2 at different stations first decreased and then increased with trend slopes of −0.24–0.15 m s^{-1} $decade^{-1}$. The trend slopes of the annual *VPD* are almost 0 kPa $decade^{-1}$, except Tuole and Qilian, where the *VPD* increased by 0.01 kPa $decade^{-1}$ and 0.03 kPa $decade^{-1}$, respectively, from 1998 to 2017. The annual *Rn* at the stations increased in varying degrees, except Qilian, where the *Rn* decreased by 131 MJ m^{-2} d^{-1} $decade^{-1}$ from 1998 to 2017.

In the agricultural area, a significantly negative correlation exists between the annual variation of U_2 and the water diversion. The annual variation of U_2 is significant with trend slopes of −0.77–0.5 m s^{-1} $decade^{-1}$. The *VPD* continuously increased from 1970 to 2017 other than Gaotai, where the *VPD* decreased 0.01 kPa $decade^{-1}$ from 1970 to 1998. The trend slopes of *VPD* from 1970 to 1998 are smaller than those from 1998 to 2017, which is related to the decrease of irrigation from 1998 to 2017. The spatiotemporal variation of *Rn* is significant. However, no significant relationship exists between the variation and irrigation.

In the desert area, the annual U_2 continuously decreased. However, the trend slope became weak from 1998 to 2017. Section 3.2.1 illustrates that this phenomenon may be related to the increase in the roughness of the underlying surface caused by the enhancement of irrigation in the region.

In conclusion, the annual variation of T_{mean} and *Rn* in HRB is almost not affected by the agricultural water diversion. The annual variation trend of U_2 between the natural and the agricultural area is the same, but it is affected by irrigation. The variation in the agricultural area is significantly greater than that in the natural area. Statistics show that the average reduction in wind speed in the agricultural area is 3.8 times that in the natural area from 1970 to 1998. The average increase in wind speed in the agricultural area is 2.2 times that in the natural area from 1998 to 2017. This finding indicates that irrigation can change the roughness of the underlying surface and then change the near-ground wind speed (Mcvicar et al., 2012; Han et al., 2016; Vautard et al., 2010).

--Table 4--

3.3.2 Relationship between meteorological factor variations and E_{pen}

The correlation analysis between E_{pen}, E_{rad}, and E_{aero} and T_{mean}, U_2, *VPD*, and *Rn* in different regions in the HRB shows that T_{mean} and *Rn* have a good correlation with E_{rad}. Meanwhile, U_2 and *VPD* have a good correlation with E_{aero}. The increase of T_{mean} and *Rn* will cause the increase of E_{rad}. Meanwhile, the increase of U_2 and *VPD* will cause the increase of E_{aero}. The variations of E_{pen}, E_{rad}, and E_{aero} during different times (Table 5) were compared with the variations of meteorological factors (Table 4), and the results are as follows:

In the natural area, the contributions of T_{mean} and *Rn* to the variation of E_{rad} are spatiotemporally different. The contribution of T_{mean} to the variation of E_{rad} at Tuole from 1970 to 1998 is significant. The contribution of T_{mean} to the variation of E_{rad} at Yeniugou from 1998 to 2017 is significant. Meanwhile, the contribution of *Rn* to the variation of E_{rad} at Qilian from 1998 to 2017 is significant. U_2 significantly contributed to the variation of E_{aero} at Yeniugou and Qilian from 1970 to 1998.

In the agricultural area, T_{mean} greatly contributed to the variation of E_{rad} at Dingxin from 1970 to 1998. Meanwhile, *Rn* greatly contributed to the variation of E_{rad} at Zhangye and Shandan from 1998 to 2017. *VPD* substantially contributed to the variation of E_{aero} at Dingxin from 1970 to 1998. During the same time, U_2 considerably contributed to the variation of E_{aero} at Jinta, Jiuquan, Zhangye and Shandan.

In the desert area, *Rn* greatly contributed to the variation of E_{rad} at Ejina from 1970 to 2017. Meanwhile, U_2 substantially contributed to the variation of E_{aero} during the same time.

--Table 5---

3.3.3 Contribution of the meteorological factors to the variation of E_{pen}

The response of E_{pen} at different stations to T_{mean}, U_2, VPD, and Rn is analyzed by regression method (Han & Hu, 2012), and the regression model is presented as Eq. 13. Statistics show that the regression effects between E_{pen} and the meteorological factors at all stations are good, and the multiple correlation coefficients (R) are all above 0.93.

$$E_{pen} = \alpha_1 T_{mean} + \alpha_2 U_2 + \alpha_3 VPD + \alpha_4 Rn + \varepsilon \tag{13}$$

The partial regression coefficients of the model were used to calculate the variations of E_{pen} at each station (Eq. [14]) (Han & Hu, 2012). The calculated results were compared with the trend slopes calculated by the method of Theil–Sen. The comparison result is shown in Fig. 6. The aforementioned figure demonstrates that the fitting effect of the two methods is good with R^2 both above 0.96. Therefore, the regression method can be used to calculate the contribution of meteorological factors to E_{pen} and predict the influence of meteorological factors on E_{pen} in the HRB.

$$\Delta E_{pen} = \alpha_1 \Delta T_{mean} + \alpha_2 \Delta U_2 + \alpha_3 \Delta VPD + \alpha_4 \Delta Rn \tag{14}$$

--Fig.6---

The contributions of the meteorological factors to ΔE_{pen} in different regions in the HRB are shown in Table 6. The table demonstrates that the contributions of T_{mean} and Rn to ΔE_{pen} are small. However, the contribution of U_2 to ΔE_{pen} is significant. The contribution is significantly larger in the agricultural and desert areas than that in the natural area. The contribution of VPD to ΔE_{pen} in different regions greatly varies. The detailed comparison of the contributions of the meteorological factors to ΔE_{pen} in different regions is analyzed.

In the natural area, the decrease of U_2 from 1970 to 1998 led to the decrease of E_{pen}, and the increase of U_2 led to the increase of E_{pen} from 1998 to 2017. The range of the contribution of U_2 to ΔE_{pen} is −11–13 mm decade^{-1}. The contribution of VPD to ΔE_{pen} is generally 0 mm decade^{-1}, except that at Tuole and Qilian from 1998 to 2017.

In the agricultural area, the contribution rule of U_2 to ΔE_{pen} is the same as that in the natural area. However, the range of the contribution is −63–48 mm decade^{-1} during which the contribution from 1970 to 1998 is generally greater than that from 1998 to 2017. The range of the contribution of VPD to ΔE_{pen} is −6–43 mm decade^{-1} during which the contribution from 1998 to 2017 is generally greater than that from 1970 to 1998.

In the desert area, the contribution of U_2 to ΔE_{pen} is −83 mm decade^{-1} from 1970 to 1998 and −32 mm decade^{-1} from 1998 to 2017. The contribution of VPD to ΔE_{pen} is 12 mm decade^{-1} from 1970 to 1998 and 10 mm decade^{-1} from 1998 to 2017. The contribution of meteorological factors to ΔE_{pen} is uncertain because only one meteorological station is present in the desert area.

---Table 6---

4. Conclusion

(1) The annual variation of E_{pen} for the different underlying surfaces in the HRB exhibits a significant spatiotemporal heterogeneity. Irrigation has a significant regulatory effect on the variation of E_{pen} in the HRB. E_{pen} is significantly reduced with the increase in the agricultural water diversion, and the water-saving irrigation increased E_{pen}. The regulatory effect of irrigation on the E_{pen} is mainly realized through the aerodynamics.

(2) The development of irrigation has a significant effect on the annual variation of U_2 and VPD in the agricultural area. U_2 has a significantly negative correlation with

agricultural water diversion. U_2 in the agricultural area significantly decreased with the increase in the agricultural water diversion. Meanwhile, *VPD* increased with the development of water-saving irrigation. The influence of the meteorological factors on E_{pen} in different regions is quite different, and U_2 and *VPD* are the main factors that affect E_{pen} in the HRB.

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