Pan evaporation trend for the Haihe River basin and its response to climate change

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Abstract The Mann-Kendall trend test technique was used to detect the pan evaporation trend for the Haihe River basin (HRB). The results showed that there was a statistically significant decreasing trend of pan evaporation in the HRB during the last 50 years. An empirical formula (E-THWS formula) for calculating pan evaporation was proposed with temperature, relative humidity, wind speed and sunshine duration, to investigate the possible reasons. The results indicated that the positive impacts of increasing temperature and decreasing relative humidity on pan evaporation were offset by the negative impacts of the decreasing trends of sunshine duration and wind speed, which were the dominant factors resulting in pan evaporation decrease in HRB.

Key words pan evaporation trend; Mann-Kendall test; E-THWS formula; climate change; Haihe River basin, China

1 INTRODUCTION

Evaporation is one of the most important components and active factors of the hydrological cycle. A slight change of evaporation may have a tremendous impact on water resources. Over the past several decades, the rate of evaporation from open pans of water has been steadily decreasing, both in the Northern and the Southern Hemispheres, for instance in India (Chattopadhyay & Hulme, 1997), dry and humid regions of the USA (Lawrimore & Peterson, 2000), the conterminous USA (Hobbins *et al.*, 2004), the Canadian Prairies (Burn & Hesch, 2007), China (Liu *et al.*, 2004), and Australia (Roderick & Farquhar, 2004). However, the global average surface temperature increased tremendously during the last century, due to the increase of greenhouse gases in the atmosphere. This inverse relationship has been recognized as a pan evaporation paradox leading to a controversy worldwide (Peterson *et al.*, 1995; Fu *et al.*, 2009).

There are three main explanations for the pan evaporation paradox: (a) decreasing solar radiation or sunlight referred to as global dimming, due to increasing cloud coverage; (b) decreasing vapour pressure deficit due to increasing air humidity, regarded as a complementary relationship between actual evaporation and potential evaporation; and (c) decreasing wind speed (Cong *et al.*, 2009; Fu *et al.*, 2009). The pan evaporation paradox has also been observed in the Haihe River basin (HRB) (Zheng *et al.*, 2009) which is located in a semi-humid and semi-arid region and plays an important part in China's economy and society. Consequently, the trend analysis of pan evaporation, quantification of the cause of pan evaporation reduction, and the explanation of the pan evaporation paradox could be very useful for water resources prediction and management especially in future climate change scenarios.

Worldwide, much research has studied the decreasing trend of pan evaporation (E_{pan}). With 150 meteorological stations' data, Xu *et al.* (2006) detected a significant decreasing trend in E_{pan} in the Yangtze River catchment of China during 1960–2000; and it was found that it was mainly caused by a significant decrease in the net total radiation and to a lesser extent by a significant decrease in the wind speed, by using the Penman-Monteith formula. Based on data from 317 meteorological stations in China from 1956 to 2005, Cong *et al.* (2009) used a stepwise regression method to find that E_{pan} reduction was caused by decreasing radiation and decreasing wind speed before 1985, and that after 1986 E_{pan} was increasing due to decreasing vapour pressure deficit and strong warming. However, Liu *et al.* (2010) reported that sunshine duration and maximum air temperature were the most important meteorological variables influencing the changes of E_{pan} in

298 stations of China during 1959–2000. Using a generic physical model based on mass and energy balances, Roderick *et al*. (2007) showed that the observed reductions in E_{pan} of 41 Australian sites from 1975 to 2004, were mostly due to decreasing wind speed with some regional contributions from decreasing solar irradiance. Using a Penman-style E_{pan} model, Rayner (2007) also showed that the trends in daily average wind speed were an important cause of trends in E_{pan} in Australia during the period 1975–2004.

Without use of radiation data, four climatic variables: mean temperature (*T*), relative humidity (*H*), wind speed (*W*) and sunshine duration (*S*) were selected to analyse the cause of pan evaporation (E_{pan}) decrease in HRB in this study. The primary objectives of this research were: (a) to use the Mann-Kendall test to detect any significant trends of E_{pan} and of the other four climatic variables; (b) construction of an empirical formula for E_{pan} based on the four climatic variables; and (c) quantification of the cause for E_{pan} reduction.

2 DATA AND METHODOLOGY

2.1 Study region and data

The HRB is located in northern China (112°–120°E, 35°–43°N). It has a basin area of 317 800 km^2, representing 3.3% of the national total, and a continental monsoon climate: annual mean temperature is 9.6°C; annual precipitation, annual land surface evaporation, and annual water surface evaporation are 530 mm, 470 mm, 1100 mm, respectively. There were 0.132 billion residents and a 55.92 million ton total grain yield within the watershed in 2005, and the watershed's 2005 GDP (Gross Domestic Product) was about 2140 billion RMB yuan, representing 10%, 12% and 14% of the national totals, respectively. Water shortages and related environmental problems are very severe in HRB, i.e. the amount of water resources per capita is only 305 m^3 representing 1/7 of the average in China and 1/27 of the average in the world (Haihe River Commission, 2010).

There are 28 standard meteorological stations providing daily E_{pan}, *T*, *H*, *W* and *S* data from 1961 to 2006 in HRB. These stations, having high-quality data, are maintained according to the standard methods of the National Meteorological Administration of China, which applies data quality control before releasing the data.

2.2 The Mann-Kendall test

The nonparametric Mann-Kendall test created by H. B. Mann and M. G. Kendall, was used to detect trends on E_{pan}, *T*, *H*, *W* and *S* in HRB (Kendall, 1975). The advantages of this method include: (a) that the sample does not have a fixed probability distribution; and (b) it has a high asymptotic efficiency.

2.3 Modelling and quantification of reduction of pan evaporation

An empirical formula for E_{pan} based on *T*, *H*, *W* and *S* was developed. At first saturated vapour pressure (e_s) was estimated by (Maidment, 1993):

$$e_s = 0.618\exp(\frac{17.27T}{237.3+T}) \tag{1}$$

Based on the relationship between annual E_{pan} and *T*, *H*, *W* and *S* (Fig. 1), a hypothesis was constructed whereby it was assumed that: $E_{pan} \propto e_s$, $E_{pan} \propto 1/H$, $E_{pan} \propto W$, $E_{pan} \propto S$, could be used to build an empirical formula (E-THWS formula) for monthly E_{pan} as:

$$E_{pan} = \frac{a\exp(\frac{17.27T}{237.3+T})}{1+\frac{H}{\overline{\overline{H}}}}(1+\frac{W}{\overline{\overline{W}}})(1+\frac{S}{\overline{\overline{S}}}) \tag{2}$$

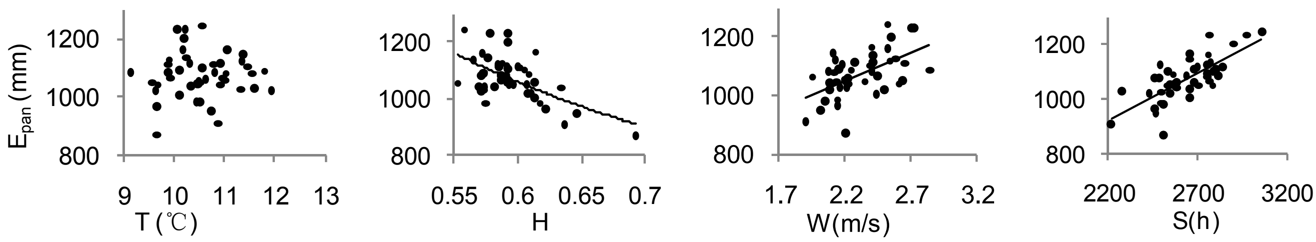

Fig. 1 The relationship between annual pan evaporation (E_{pan}) and mean temperature (T), relative humidity (H), wind speed (W) and sunshine duration (S), respectively.

where $\bar{H}$, $\bar{W}$ and $\bar{S}$ are the mean values of H, W and S, respectively, and a is a parameter needing to be calibrated.

Using the E-THWS formula (1), the impact of climate variables on E_{pan} reduction could be analysed as:

$$\frac{dE}{dt} = \frac{\partial E}{\partial T}\frac{dT}{dt} + \frac{\partial E}{\partial H}\frac{dH}{dt} + \frac{\partial E}{\partial W}\frac{dW}{dt} + \frac{\partial E}{\partial S}\frac{dS}{dt} \tag{3}$$

3 RESULTS AND DISCUSSION

3.1 Trend for pan evaporation

Time series of annual HRB E_{pan} anomalies and the Mann-Kendall (MK) test results of HRB E_{pan}, expressed in percent, from 1961 to 2006, are shown in Fig. 2(a). Although, the lowest annual E_{pan} was in 1964, there was a statistically significant decreasing trend since 1985 ($\alpha = 0.05$ level), and the MK value was lower than –2.58 ($\alpha = 0.01$ level) since 1990. Over the whole time series, the MK value was –2.98, which indicates a very rapid decreasing trend, although a slight rebound has occurred since the 1990s. The E_{pan} trend varied monthly (Fig. 2(b)). Except for February and March, 10 months showed a decreasing trend for monthly E_{pan}, with two of these (May and June) being statistically significant at the $\alpha = 0.01$ level.

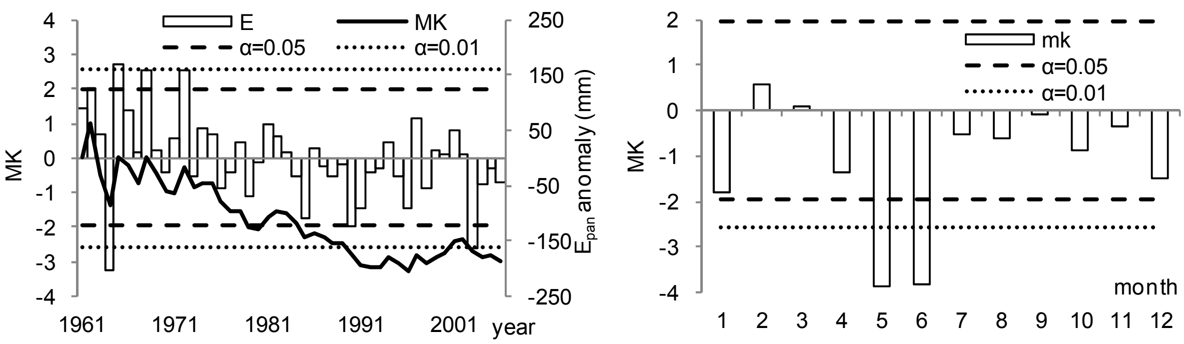

Fig. 2 (a) Mann-Kendall test statistic values and anomalies for annual pan evaporation (E_{pan}) of the HRB. (b) Mann-Kendall test statistic values for monthly pan evaporation (E_{pan}) of the HRB.

The spatial distribution of annual E_{pan} trend is shown in Fig. 4(a). Spatially, 22 out of 28 stations showed a decreasing annual trend, and 14 of them, most of which were located in the southeast of HRB, were statistically significant at the $\alpha = 0.05$ level (Fig. 4(a)). The remaining six stations, five of which were located in the north of HRB, showed an increasing trend, but none of the trends were statistically significant.

3.2 Trend for other climatic variables

The results of the Mann-Kendall test showed a statistically significant increasing trend for annual T (MK value was 5.01) but decreasing trends for annual W (MK value was –5.85) and S (MK value was –6.1) at the $\alpha = 0.01$ level, and a statistically insignificant decreasing trend for annual H (MK value was –1.955) in HRB from 1961 to 2006 (Fig. 3). Meanwhile, the decreasing trends of W and S were higher than the increasing trend of T.

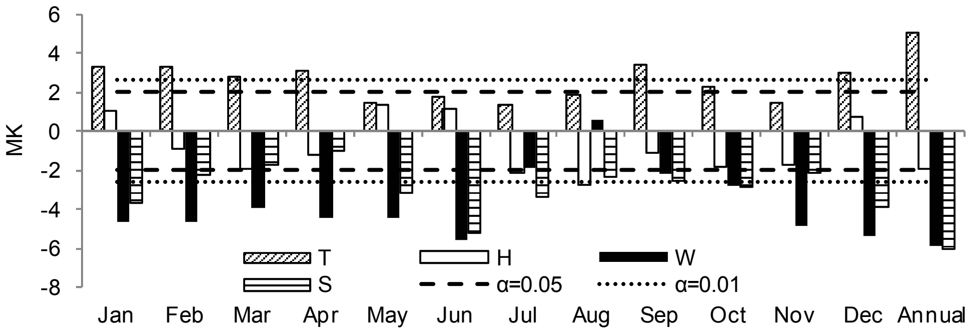

Fig. 3 Mann-Kendall test statistic values for monthly and annual mean temperature (T), relative humidity (H), wind speed (W) and sunshine duration (S) of the HRB.

The trends varied monthly for the four climatic variables (Fig. 3). All months showed an increasing (decreasing) trend for monthly mean T (S), 7 (10) of these were statistically significant at the $\alpha = 0.05$ level, and 6 (6) of these were statistically significant at the $\alpha = 0.01$ level. Winter months usually had a greater increasing trend for mean T than summer months. In contrast, the highest decreasing trend for S was in June, but the lowest was in April. For W, there were 11 months (except August) with decreasing trends, with 10 of these being statistically significant at $\alpha = 0.05$ level, and 9 of these were statistically significant at $\alpha = 0.01$. An overall trend for H was not manifest, i.e. 4 months had statistically insignificant increasing trends, and 8 months showed decreasing trends which were statistically significant in March, July and August.

The spatial distribution of trend for the four climatic variables is shown in Fig. 4. For annual T, 27 out of the 28 stations (except one located in the northeast of HRB) showed increasing trends which were statistically insignificant for only one station located in the southeast (Fig. 4(b)). By contrast, the distribution of H trends was not very clear. Generally, fewer stations located in the east showed increasing trends, only two of which were statistically significant (Fig. 4(c)). Except for one station located in the southwest which had statistically significant increasing trends of W, the other 27 stations showed decreasing trend with statistical significance for 25 stations (Fig. 4(d)). All 28 stations showed decreasing trends for S, while only one station had a statistically insignificant decreasing trend (Fig. 4(e)).

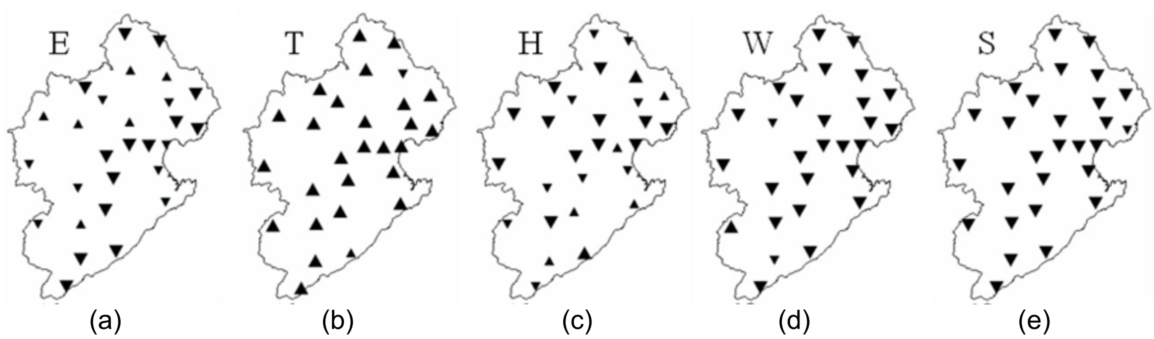

Fig. 4 Annual trends for: (a) pan evaporation (E_{pan}), (b) mean temperature (T), (c) relative humidity (H), (d) wind speed (W) and (e) sunshine duration (S) for each station in HRB. ▲: increasing trend; ▼: decreasing trend. Large symbols indicate that the trends are statistically significant at the $\alpha = 0.05$ level.

3.3 Simulation of monthly pan evaporation

Table 1 summarizes the model accuracy of the E-THWS monthly E_{pan} formula applied for the HRB. The Re (relative error) was as low as -1.63×10^{-7}% and 0.44% for the calibration and verification period, respectively. Meanwhile, the *Nse* (Nash-Sutcliffe efficiency coefficient) was as high as 0.948 in both the calibration and verification periods. Figure 5 shows the simulated and observed E_{pan} in the verification period. The results rendered good performance of the E-THWS monthly E_{pan} formula, although, there were some differences between simulated and observed peak E_{pan}.

Table 1 The performance of E-THWS formula in calibration and verification periods.

	Time (year)	Re (%)	*Nse*
Calibration period	1961–1996	-1.63×10^{-7}	0.948
Verification period	1997–2006	0.44	0.948

Notes: (1) $R_e = (V_{sim} - V_{obs}) / V_{obs} \times 100\%$ was the relative error, in which V_{sim} and V_{obs} were the simulated and observed total E_{pan} in the whole calibration and verification periods, respectively.
(2) $Nse = 1 - \sum (E_{sim} - E_{obs})^2 \big/ \sum (E_{obs} - \bar{E}_{obs})^2$ is the Nash-Sutcliffe efficiency coefficient, in which E_{sim} and E_{obs} were simulated and observed E_{pan}, and $\bar{E}_{obs}$ was the mean value of the observed E_{pan}.

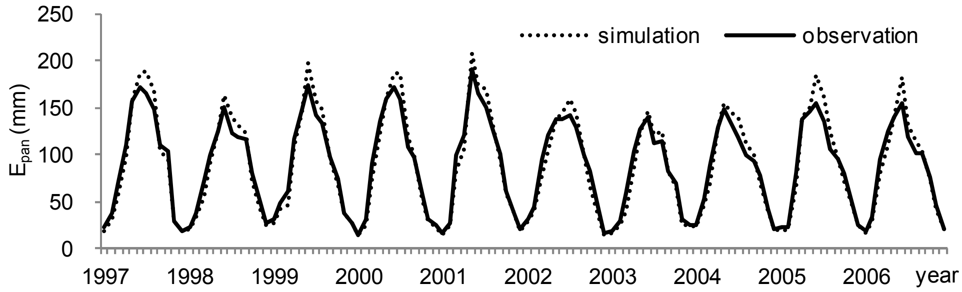

Fig. 5 Simulated and observed monthly pan evaporation (E_{pan}) in the verification period.

3.4 Quantification of the cause for pan evaporation reduction

The trends and relationships between E_{pan} and the other four climatic variables detected in this study lead to investigation of the attribution of *T*, *H*, *W* and *S* to E_{pan} reduction. The simulated annual E_{pan} shows the same decreasing trend as the observations (Fig. 6(a)). The increasing *T* and decreasing *H* lead to an increasing vapour pressure deficit in the HRB. This meant that decreasing

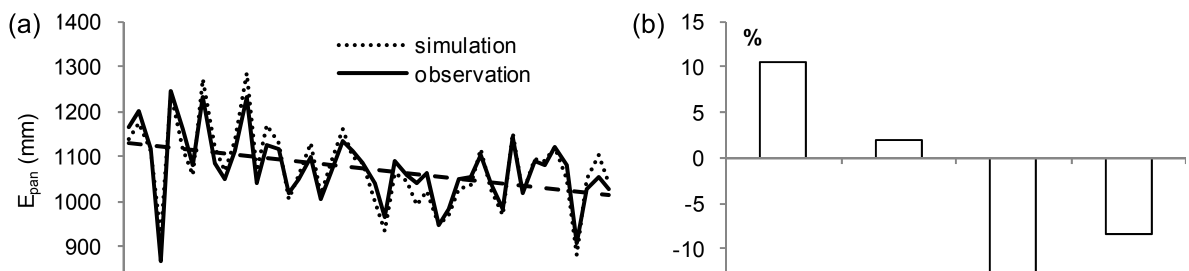

Fig. 6 (a) Simulated and observed annual pan evaporation (E_{pan}) in the study period. (b) Attribution of the four climatic variables (*T*, *H*, *W* and *S*) for pan evaporation reduction.

vapour pressure deficit due to increasing air humidity was not present in the HRB. Hence, a complementary relationship between actual evaporation and potential evaporation could not be used to explain the evaporation paradox in HRB. Here, the attribution of climatic variables to E_{pan} reduction was analysed (Fig. 6(b)). The results showed that increasing T and decreasing H caused E_{pan} to increase by 10.5% and 2%, respectively. Meanwhile, the decreasing W and S caused E_{pan} to decrease by 13% and 8%, respectively. That meant that the positive impacts of increasing T and decreasing H on E_{pan} were offset by the effects of decreasing trends of W and S. The decreasing W was the dominant cause for E_{pan} reduction in the HRB. These results correspond to the conclusions of Zheng *et al*. (2009) who used the Penman-Monteith formula which is more complicated than the E-THWS formula that does not need inputs of radiation data.

4 CONCLUSIONS

(a) There was a statistically significant decrease of annual E_{pan} in HRB from 1961 to 2006, with statistically significant reductions in May and June. Meanwhile, the increasing trend for annual T, and decreasing trends for annual W and S were statistically significant, but the decreasing trend for annual H was not significant.
(b) By using an empirical formula (E-THWS formula) which was found to accurately simulate monthly E_{pan}, the causes for E_{pan} reduction have been analysed. The positive impacts of increasing temperature and decreasing humidity on E_{pan} were offset by the effects of decreasing trends of W and S. In general, the decrease of W was the dominant cause for E_{pan} reduction in HRB.

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