

# Variation characteristics and influencing factors of free water evaporation in recent 58 years in Tai'an area

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**Abstract.** The mutation test and trend analysis of free water evaporation in Tai'an from 1956 to 2013 were carried out with Pettitt detection method, Mann-Kendall method and linear tendency estimation method. The results indicate that: (1) the free water evaporation in Tai'an was distributed unevenly within the year, and the maximum appeared in June, accounting for 14.5% of the whole year; (2) in the last 58 years, the free water evaporation in Tai'an changed significantly in 1985. The evaporation decreased obviously before the change, then fluctuated around the mean value, and gradually became stable; (3) by means of correlation analysis and partial differential decomposition, it was found that free water evaporation in Tai'an before 1985 was positively correlated with air temperature, solar radiation and wind speed, and negatively correlated with actual water vapor pressure. The significant decrease in solar radiation and wind speed are the main reasons for the significant decline in annual evaporation; (4) after 1985, the air temperature played a dominant role, and the rise of air temperature offset the negative influence of decline of wind speed and solar radiation on the free water evaporation.

## 1 Introduction

As an important parameter to assess the extent of climate change, evaporation can help to understand climate conditions and their causes around the world. Therefore, it is of great significance to study the evolution of evaporation under the background of climate change[1-5].

In the context of global warming, Chinese and foreign scholars have done a lot of research on the evolution of evaporation[6-8]. Roderick et al. found that the pan evaporation in Australia declined at a rate of -4 mm/a from 1970 to 2002[9]. Hoffman et al. discovered that there was a downward trend of -9.1 mm/a in pan evaporation in South Africa during 1974-2005[10]. Based on the data from more than 600 meteorological stations in China, it is found that the free water evaporation had a significant downward trend from 1956 to 2000, with east, south and northwest of the country declining the most[11]. As to the influencing factors of evaporation, many scholars have explored in different ways[12, 13], and the conclusions are not the same. Liu et al. divided China into eight climatic sub-regions, and they discovered that the decrease of solar radiation was the driving factor of evaporation decline[14]. Liu et al. found that there was a close relationship between daily temperature range, wind speed and pan evaporation in northern China in recent 45 years[15]. A study on pan evaporation from 1960 to 2005 in China by Qi et al. showed that relative humidity is an important factor affecting the variation of pan evaporation[16], while Hao

et al. hold a view that when the drought index is greater than 1.7[17], the actual evapotranspiration is mainly affected by relative humidity, wind speed and sunshine duration, have little correlation with precipitation. However, most of the previous research were mainly based on large regional scales with relatively low resolutions and there are little local research on small scales. Tai'an is located in both the warm temperate continental climate zone and the semi-humid monsoon climate zone of North China, with a per capita water resources of less than 500 cubic meters. It belongs to an area of extreme water shortage and serves as an important city of Shandong Province and main flow area of Dawen River, an important tributary of the Yellow River. It is of practical significance to study the variation of evaporation for local water resources evaluation and rational allocation, development and utilization of water resources.

Free water evaporation is the loss of water from lakes, reservoirs and other water bodies, and is mainly observed by different types of pans[6, 7]. Based on the observed data of pan evaporation and meteorological factors in Tai'an from 1956 to 2013, the evolution of free water evaporation in recent 58 years is studied in this paper. In order to investigate the main factors affecting free water evaporation, and evaluate the influence of climate change on hydrological cycle and try to provide valuable information for water resources management, we also explored the variation of meteorological factors in different periods and the

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correlations between evaporation and meteorological factors.

## 2 Material and methods

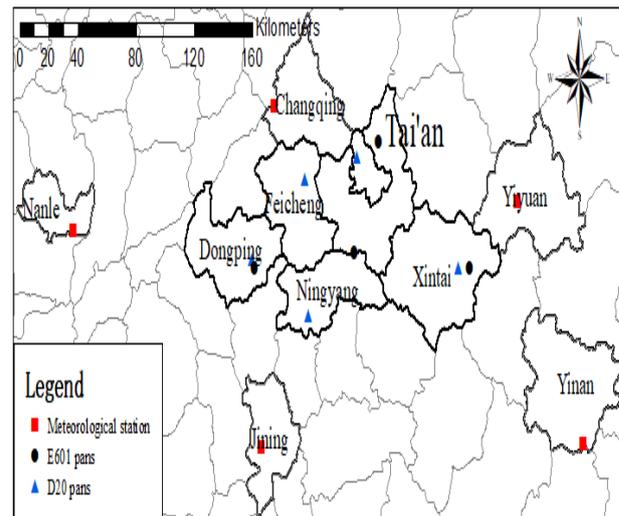
### 2.1 Data

In this paper, the daily pan evaporation data of nine evenly distributed evaporation observation stations in Tai'an City from 1956 to 2013 are selected, and the spatial interpolation method is used to extend the missing data. Five meteorological stations with uniform distribution around Tai'an can approximately reflect the characteristics of climate change in the study area. We use the average seasonal and annual meteorological elements observed by them as time series for regional analysis. The data include daily mean temperature, daily maximum temperature, daily minimum temperature, wind speed, relative humidity and sunshine hours. The length of each station is shown in Table 1. The distribution of stations is shown in Figure 1.

**Table 1.** Data series of meteorological stations.

Types	Stations	Data length
E601 pans	Daicunba	1956-2013
	Huangqian	1963-2013
	Dongzhou	1979-2013
	Dawenkou	1956-1961 、 1978-2013
D20 pans	Taishan	1956-2005
	Dongping	1957-2005
	Xintai	1957-2005
	Feicheng	1958-2005
	Ningyang	1959-2005
Meteorological stations	Jinan	1956-2011
	Shenxian	1957-2011
	Juxian	1956-2013
	Yanzhou	1956-2013
	Yiyuan	1958-2013

The average evaporation of E601 pans from nine observation stations from 1956 to 2013 are used to represent the free water evaporation in Tai'an[18], and the observed values of D20 pans are converted to replace the missing data of individual observation stations.



**Figure 1.** Distribution of meteorological stations.

In order to reflect the seasonal regularity of climate change, according to the characteristics of the temperate continental and semi-humid monsoon climate of Tai'an area, we choose March to May as spring, June to August as summer, September to November as autumn and December to next year's February as winter respectively.

### 2.2 Methods

Pettitt detection method[19] is used to test the turning points of free water evaporation. Mann-Kendall test method[20, 22] and linear tendency estimation method[20] are used to analyse the annual and seasonal trends of free water evaporation. By using the correlation analysis method[15], the modified Penman formula[23] and the partial differential decomposition method[24], we explored the dominant meteorological factors affecting the variation of free water evaporation.

## 3 Variation of free water evaporation

### 3.1 Turning points of free water evaporation

The abrupt change of climate is a phenomenon that the climate changes from one stable state to another. Mutation detection is an important way to help people understand the climate change condition in a region.

Pettitt test of seasonal and annual free water evaporation in Tai'an from 1956 to 2013 is carried out and the results are shown in Table 2. It can be seen from the table that the turning point of the annual free water evaporation in Tai'an during 1956-2013 appears in 1985 and is significant at the significance level of 0.01. The turning points of the four seasons are all around 1985 and the condition of satisfying the significance level of 0.01 was basically the same as that of the annual free water evaporation. Therefore, 1985 is considered as the common turning point of both the year and four seasons. This conclusion is consistent with the corresponding results of the research of Liu et al.[26], Qiu et al.[27], Yang et al.[28], and so on.

From the last column of the table, the seasonal and annual free water evaporation both decrease obviously

after turning points, with spring and summer decreasing the most, decreasing for about 26%.

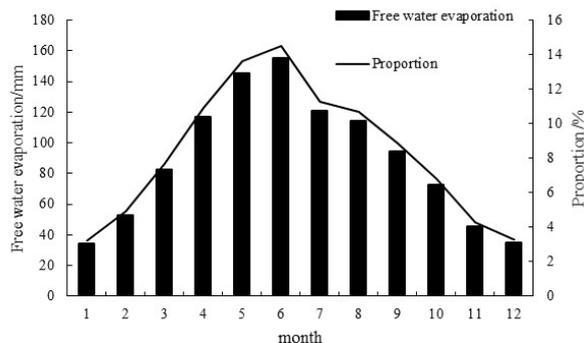
**Table 2.** Pettitt test results of free water evaporation.

Periods	Turning points	Significance level	Mean value before turning points	Mean value after turning points	Mean value ratio
Spring	1991	0.01	400.4	296.4	0.74
Summer	1985	0.01	461.5	341.1	0.74
Autumn	1985	0.01	239.6	191.5	0.80
Winter	1990	0.01	133.8	110.3	0.82
Annual	1985	0.01	1246.3	946.4	0.76

### 3.2 Variation of free water evaporation

#### 3.2.1 Variation within the year

The annual average free water evaporation in Tai'an area is 1070 mm and portrays a single peak curve of the whole year. Figure 2 shows the average monthly free water evaporation in Tai'an. It can be seen that the peak value of evaporation appears in June (155.6 mm), accounting for 14.5% of the annual total which followed by May and July, accounting for 13.6% and 11.3% of the total annual total respectively. The minimum value appears in January (34.2 mm), only accounting for 3.2% of the whole year.

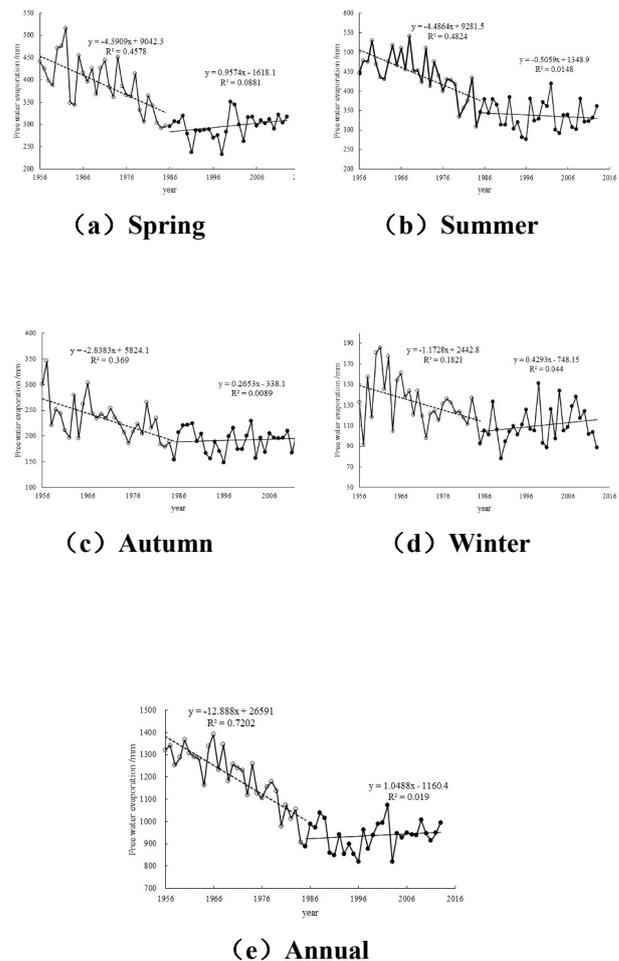


**Figure 2.** The average monthly free water evaporation.

#### 3.2.2 Variation among years

The research period can be divided into two periods: the early period and the later period. According to the turning point of 1985 obtained above, the annual and seasonal free water evaporation can be divided into two sequences: 1956-1985 and 1986-2013. The process lines are shown in Figure 3. From the figure, it can be seen that for the annual free water evaporation, 1957-1966 is the largest decade, with the average value being 1302.0 mm, while 1990-1999 is the lowest decade, with the average value being 885.5 mm. The annual free water evaporation reaches its peak in 1966, then decreases at the rate of 128.9mm per decade until reaching its trough in about 1985, and fluctuates up and down around the mean value from 1986 to 2013, and then gradually levels off. It is shown that the free water evaporation in Tai'an has changed from a relatively strong period to a normal

one in recent 58 years, and the variation of the four seasons is basically consistent with that of the year.



**Figure 3.** Seasonal and annual evaporation process lines.

The tendency of annual and seasonal free water evaporation in Tai'an are analysed by using the method of linear tendency estimation. The results are shown in Table 3 and Table 4. Combined with Figure 3 and Table 3, it can be seen that the average seasonal and annual free water evaporation in Tai'an from 1956 to 1985 decrease significantly with a significance level of 0.01. The correlation coefficient between annual evaporation and time is as high as 0.849, so the decreasing trend is especially significant. The decreasing rate of free water evaporation in spring and summer are as large as 43.9 mm/10a and 44.9 mm/10a, respectively, greater than autumn and winter, indicating that the decline of evaporation in spring and summer is an important factor for the significant decrease of the whole year. Table 4 shows that the annual and seasonal free water evaporation from 1986 to 2013 show slight upward or downward trends, which are all not significant.

**Table 3.** Estimation results of linear tendency of evaporation in Tai'an during 1956-1985.

Periods	Conversion functions	Correlation coefficient ( r )	Rate (mm/10a)	Significance level
Spring	$y = -4.39x + 9042.3$	0.677	-43.9	0.01
Summer	$y = -4.49x + 9281.5$	0.695	-44.9	0.01

Autumn	$y = -2.84x + 5824.1$	0.607	-28.4	0.01
Winter	$y = -1.17x + 2442.8$	0.427	-11.7	0.01
Annual	$y = -12.89x + 26591$	0.849	-128.9	0.01

**Table 4.** Estimation results of linear tendency of evaporation in Tai'an during 1986-2013.

Periods	Conversion functions	Correlation coefficient (r)	Rate (mm/10a)	Significance level
Spring	$y = 0.96x - 1618.1$	0.297	9.6	-
Summer	$y = -0.51x + 1348.9$	0.122	-5.1	-
Autumn	$y = 0.27x - 338.1$	0.094	2.7	-
Winter	$y = 0.43x - 748.2$	0.210	4.3	-
Annual	$y = 1.05x - 1160.4$	0.138	10.5	-

In order to verify the rationality of the linear tendency estimation method, Mann-Kendall method is used to retest the trend. The results are shown in Table 5.

**Table 5.** Mann-Kendall trend test results of free water evaporation in Tai'an.

Z value	Before 1985	After 1985
Spring	-2.01*	0.18
Summer	-2.51*	-0.98
Autumn	-2.01*	0.00
Winter	-1.96*	-0.30
Annual	-3.40**	-0.65

Note: "\*" and "\*\*" represent being significant at the significance level of 0.05 and 0.01 respectively.

It can be seen from the table that the annual and seasonal free water evaporation show significant downward trends during 1956-1985, in which the annual evaporation pass the significant test at a level of 0.01, and the decreasing trend is especially significant. According to the absolute value of Z value, the decreasing rates of spring and summer are greater than that of autumn and winter. There are no obvious increasing or decreasing trends of annual and seasonal evaporation after 1985 and none of them pass the significance test, which shows that the continuous downward trend of evaporation has stopped after 1985 and gradually returns to normal. This phenomenon is consistent with the linear tendency estimation results and further explains the reliability of the results.

#### 4 Study on the influence factors of free water evaporation

The free water evaporation in Tai'an in recent 58 years show different laws around 1985, so the study on the influencing factors of it should be carried out in different periods. Free water evaporation is a highly sensitive climatic factor which is mainly affected by energy radiation and aerodynamics. In this paper, four representative meteorological factors namely air temperature, wind speed, solar radiation and actual water vapor pressure are selected. The effects of meteorological elements on evaporation both in

descending and normal sections are analysed respectively.

#### 4.1 Turning points of free water evaporation

In order to fully understand the correlation degree between meteorological factors and evaporation, the correlation coefficient of each meteorological factor and evaporation is obtained by computer fitting line. The results are shown in Table 6. It can be seen from the table that there are good correlations between the four factors and evaporation at different periods. In order to screen out the meteorological factors which have close correlations with time and evaporation, the trend of meteorological factors are tested by linear tendency estimation method. The results are shown in Table 7.

**Table 6.** Correlation coefficients between evaporation and meteorological factors (1956-1985).

Coefficients	Air temperature	Actual vapor pressure	Wind speed	Solar radiation
Spring	0.208	-0.721**	0.592**	0.724**
Summer	0.388**	-0.655**	0.199	0.714**
Autumn	0.257	-0.891**	0.498**	0.827**
Winter	0.394**	-0.762**	0.192	0.701**
Annual	0.134	-0.304*	0.312*	0.597**

**Table 7.** Each meteorological factor and its correlation coefficients with time (1956-1985).

Coefficients	Air temperature	Actual vapor pressure	Wind speed	Solar radiation
Spring	0.149	-0.075	-0.318*	0.006
Summer	-0.143	0.046	-0.219	-0.276*
Autumn	-0.133	0.079	-0.485**	-0.155
Winter	0.243	-0.079	-0.005	-0.394**
Annual	-0.010	0.156	-0.683**	-0.585**

Table 6 shows that the actual water vapor pressure, wind speed and solar radiation in spring have passed the significance test of 0.01, which shows that the evaporation in spring is significantly positively correlated with wind speed and solar radiation, and negatively correlated with the actual water vapor pressure. From Table 7, only wind speed has passed the linear decline test with the falling rate of 0.13 m/(s·10a), which indicates that the wind speed changes significantly with time. This is consistent with the variation of free water evaporation during 1956-1995. Therefore, it is concluded that the wind speed is the key factor to evaporation decrease in spring, and the significant decrease of wind speed leads to an obvious downward trend of evaporation in spring, decreasing at a rate of 27.66 mm per decade.

Similarly, there are significant positive correlations between evaporation and solar radiation in summer and winter, which indicates the main influence factor of evaporation in summer and winter is solar radiation. There is significant positive correlation between evaporation and wind speed in autumn, which shows that wind speed is the key factor affecting evaporation in

autumn. According to results of the four seasons, the annual free water evaporation is significantly positive correlated with wind speed and solar radiation, so the wind speed and solar radiation are the important influencing factors of evaporation decline. This is consistent with the conclusion of Guo et al.[29] and Liu et al.[6].

#### 4.2 Study on the influencing factors during normal period

It can be seen from Section 3.2 that the decreasing trend of free water evaporation in Tai'an has gradually stopped after 1985 and return to normal condition, in which annual evaporation fluctuates around the mean value 946.4 mm. In fact, it is equally important to explore the influence factors of evaporation from the reduction model to the normal model. Because of the insignificant trend of evaporation, the correlation analysis is not applicable at this period.

The modified Penman formula[20] recommended by FAO provides an effective way to calculate the reference evapotranspiration accurately. The reference evapotranspiration can be obtained directly by inputting the required meteorological factors, and the free water evaporation and the reference evapotranspiration can be transformed to each other by regression equations[30]. In this paper, partial differential equation decomposition is used to quantify the contribution of each meteorological factor to the trend of free water evaporation. The formula can be expressed as follows:

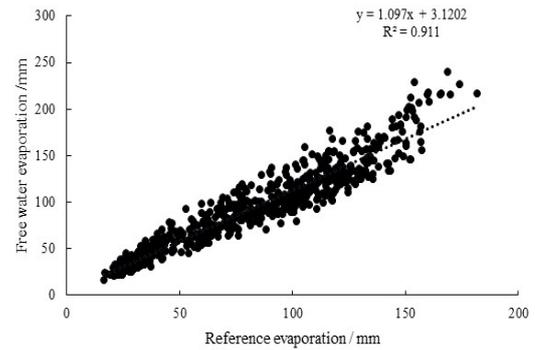
$$\frac{dE_{ref}}{dt} = \frac{\partial E_{ref}}{\partial R_s} \frac{dR_s}{dt} + \frac{\partial E_{ref}}{\partial T_{mean}} \frac{dT_{mean}}{dt} + \frac{\partial E_{ref}}{\partial U_2} \frac{dU_2}{dt} + \frac{\partial E_{ref}}{\partial VP} \frac{dVP}{dt} + \delta \quad (1)$$

$$E_0 = K_p \cdot E_{ref} + K_c \quad (2)$$

$$\frac{dE_0}{dt} = K_p C(R_s) + K_p C(T_{mean}) + K_p C(U_2) + K_p C(VP) + \mathcal{E} \quad (3)$$

Where  $E_0$  represents the free water evaporation,  $E_{ref}$  represents reference evapotranspiration,  $R_s$ ,  $T_{mean}$ ,  $U_2$ ,  $VP$  are solar radiation, air temperature, wind speed at 2m height, saturated vapor pressure, respectively.  $K_p$ ,  $K_c$  are regression coefficients,  $\delta$ ,  $\mathcal{E}$  represent errors.

Figure 4 shows the relationship between the two types of evaporation. It can be seen from the figure that the correlation between the two is good with the correlation coefficient is as high as 0.95. It shows that the reference evapotranspiration can estimate the free water evaporation well when the regression coefficient is known.

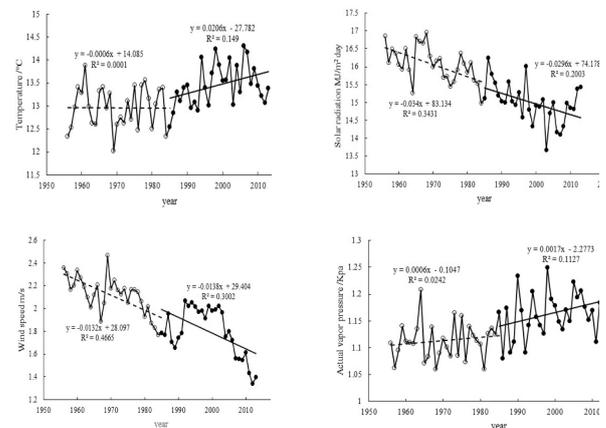


**Figure 4.** Relationship between free water evaporation and reference evaporation.

The partial differential analysis results of free water evaporation from 1986 to 2013 are given in Table 8. It can be seen from the table that the contribution of air temperature to evaporation is much greater than that of other factors. The positive contribution of rising air temperature to evaporation offsets the negative contribution caused by the decrease of solar radiation and wind speed, while the effect of actual vapor pressure on evaporation is so relatively small that the contribution is negligible, so evaporation shows a slight upward trend during this period. This indicates that the influence of air temperature after 1980s is becoming more and more important under the background of climate change. According to twelve global climate models (GCMs) under two greenhouse gas emission scenarios, namely RCP4.5 and RCP8.5[31], the "evaporation paradox" will no longer exist in the future.

**Table 8.** Contributions of meteorological factors to free water evaporation (1986-2013).

Periods	Air temperature	Solar radiation	Wind speed	Actual vapor pressure	Evaporation rate		Absolute error	Relative error/%
					Calculated value	Measured value		
Spring	1.981	-0.412	-0.560	-0.006	1.003	0.957	-0.046	-4.807
Summer	0.977	-0.956	-0.559	-0.010	-0.548	-0.506	0.042	-8.300
Autumn	1.512	-0.630	-0.588	-0.009	0.285	0.265	-0.020	-7.547
Winter	0.976	-0.246	-0.390	0.019	0.359	0.429	0.070	16.317
Annual	1.969	-0.501	-0.580	-0.005	0.883	1.049	0.166	15.809



**Figure 5.** Process lines of meteorological factors.

Figure 5 is the trend map of meteorological factors. The change rate of wind speed remains basically unchanged around 1985, and the change rate of solar

radiation is slightly weakened. In contrast, there are significant changes in air temperature and actual vapor pressure. The results show that the meteorological factors also have the characteristics of periodic variation, which makes the free water evaporation change from decreasing to normal.

## 5 Conclusions

Taking Tai'an area as the research background, this paper reveals the evolution law of free water evaporation in recent 58 years, and analyses the main influencing factors of the decreasing and normal section of free water evaporation with the turning point as the boundary. The main conclusions are as follows:

(1) The distribution of free water evaporation in Tai'an was uneven within the year, and the maximum successive four-month evaporation accounted for more than 50% of the whole year. The turning points of annual and seasonal evaporation were all around 1985, and there were obvious decreasing trends of the annual free water evaporation during 1956-1985, which represents that there existed "evaporation paradox" in Tai'an. The decline of annual free water evaporation was mainly due to the contribution of spring and summer, and the downward trend stopped after 1985 and gradually returned to normal. The air temperature and the actual vapor pressure, which were closely related to evaporation, also showed different periodic variation characteristics.

(2) During 1956-1985, the annual free water evaporation was positively correlated with air temperature, solar radiation and wind speed, and was negatively correlated with the actual water vapor pressure. The solar radiation and wind speed were the key factors affecting the annual free water evaporation and the significant decrease of them were the main factor leading to the decrease of annual free water evaporation in Tai'an.

(3) During 1986-2013, the significant increase of air temperature was the main reason for the stop of the downward trend of free water evaporation, which counteracted the decreasing effect of wind speed and solar radiation on evaporation. Under the background of global warming, evaporation paradox will no longer exist in Tai'an region.

## Acknowledgments

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