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Research Paper

Variations in evaporation from water surfaces along the margins of the Badain Jaran Desert over nearly 60 years and influencing factors

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Abstract: Based on meteorological data collected over nearly 60 years (1960–2017) from four national meteorological stations along the margins of the Badain Jaran Desert, this study analyzed the spatiotemporal variations in evaporation from water surfaces and identified the dominant controlling factors. Methods used included linear trend analysis, linear tendency estimation, the departure method, the rank correlation coefficient-based method, and Multiple Linear Regression (MLR). Results indicate notable spatiotemporal differences in evaporation distribution and evolution. Spatially, average annual evaporation exhibited a pronounced altitude effect, decreasing at a rate of about 8.23 mm/m from east to west with increasing altitude. Temporally, annual evaporation showed significant upward trends after 1996 at the northeastern (Guaizi Lake) and western (Dingxin) margins, with rates of 132 mm/10a and 105 mm/10a, respectively. Conversely, along the northwestern (Ejina Banner) and southern (Alxa Right Banner) margins of the desert, an evaporation paradox was observed, with annual evaporation trending downward at rates of 162 mm/10a and 187 mm/10a, respectively, especially after 1987. The dominant factors controlling evaporation varied spatially: Average annual temperature and relative humidity influended the western margin (Dingxin), average annual temperature was the key factor for the northeastern margin (Guaizi Lake), and average wind speed was crucial for the northern (Ejina Banner) and southern (Alxa Right Banner) margins.

Keywords: Evaporation from water surface; Evaporation paradox; Dominant controlling factor; Variation trend

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Introduction

The Badain Jaran Desert, situated at the heart of the Alxa Plateau, covers an area exceeding 50,000 km^2, making it the second largest desert in China after the Taklamakan Desert. Characterized by a temperate continental climate, the Badain Jaran Desert experiences scarce precipitation, averaging only 80 mm annually, and intense evaporation, with mean annual potential evaporation reaching 3,000 mm (Hu et al. 2015). These conditions result in a simple vegetation structure and a fragile ecosystem.

Global warming has intensified the water cycle, exacerbating water shortage in this arid region of northwest China. This leads to decreased vegetation coverage, accelerated desertification, and further ecosystem degradation. Consequently, there is an urgent need to investigate the water cycle evolution in the Badain Jaran Desert (Cao et al. 2021; Wang et al. 2024). Such research can offer a scientific basis for the rational extraction and utilization of water resources in the desert and provide technical support for ecological management.

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Evaporation, the process of transformation from a liquid or solid state to a gaseous state, is a critical component of the natural water cycle and essential for maintaining water balance. In deserts, where precipitation is scarce and evaporation is intense, evaporation is a primary means of water resource consumption. Therefore, understanding the spatiotemporal dynamics and driving factors of evaporation is essential for advancing research on the water cycle evolution in desert environments.

The Badain Jaran Desert is renowned for its unique geomorphologic landscape, characterized by the coexistence of megadunes and lakes. This distinctive feature has drawn significant attention from researchers both domestically and internationally, resulting in numerous scientific studies in various fields. These include Quaternary geology (Li et al. 2018; Li et al. 2019; Fan et al. 2021; Jiang et al. 2021; Jiang et al. 2017; Zhang et al. 2023), desert ecology (Liu et al. 2016; Liu et al. 2021; Qin et al. 2021; Jiang et al.2023; Liu et al. 2022; Mao et al. 2022), desert hydrology (Chen et al. 2006; Wang et al. 2016; Zhang et al. 2020), and tourism (Wu et al. 2015; Sarina et al. 2021). Despite these advancements, there is a notable lack of comprehensive studies on evaporation in the Badain Jaran Desert. Furthermore, most existing research primarily focuses on evaporation from surfaces of lakes within the desert, and the results vary significantly (Hu et al. 2015; Yang et al. 2010; Ke, 2014; Gates et al. 2008; Wang et al. 2014). For instance, Yang et al. (2010) estimated annual evaporation from water surfaces at 1,040 mm, while Chen et al. (2004) suggested it could reach up to 4,000 mm. Ma (2012) calculated the evaporation at about 1,400 mm for the year 2012, Chen et al. (2019) reported annual evaporation of 1,500 mm, and Wang et al. (2014) observed evaporation between 1,200–1,550 mm using an E601 evaporation pan. Additionally, these studies predominantly assess annual evaporation from lake surfaces, but there is a scarcity of research on the spatiotemporal evolutionary characteristics and driving factors of evaporation from water surfaces in the desert. Addressing this gap is crucial for a better understanding of the water cycle in the Badain Jaran Desert, which is essential for managing water resources and mitigating the impacts of desertification.

Based on nearly 60 years of meteorological data (1960–2017) from four national meteorological stations located at the periphery of the Badain Jaran Desert, this study systematically analyzes the spatiotemporal variations in evaporation from water surfaces along the desert margins and their driving factors. The purpose of this analysis is to provide a scientific reference for understanding the evolution of water circulation, promoting the rational exploitation and utilization of water resources, and supporting ecological management within the Badain Jaran Desert.

1 Data and methods

1.1 Overview of the Badain Jaran Desert

The Badain Jaran Desert is located within Alxa League of Inner Mongolia Autonomous Region, with geographical coordinates of 99°30 ′E–104°00′E and 39°30′N–42°00′N. This desert is bounded by the Beida, Yabulai, and Zongnai mountains to the south, southeast, and east, respectively, and lies adjacent to the China-Mongolia border in the north. The terrain generally slopes gently from south to north, exhibiting mild undulations and an average altitude of approximately 1,300 m. The landscape of the Badain Jaran Desert is predominantly characterized by shifting sand dunes. The climate is a temperate continental desert type, marked by scant precipitation and high aridity. The average multi-year rainfall ranges from 30 mm to 120 mm, decreasing gradually from southeast to northwest. Evaporation is extremely intense, 40–80 times the amount of rainfall, and increases from south to north. The average annual temperatures range between 8°C and 9°C, and the region experience high winds, predominantly from the northwest and west, with average wind speeds exceeding 3.5 m/s. Vegetation is sparse, and the desert is dotted with numerous lakes, mostly saline, creating a unique landscape where small inland lakes are next to the megadunes.

1.2 Data sources and processing

Meteorological data from the periphery of the Badain Jaran Desert were obtained from four national meteorological stations operated by the China Meteorological Administration: Ejina Banner, Guaizi Lake, Dingxin, and Alxa Right Banner, arranged from north to south with a decreasing altitudinal gradient (Table 1). These data included φ20 pan evaporation (hereafter referred to as evaporation), average annual temperature, relative humidity, sunshine duration, and wind speeds (measured 10 m above the ground surface). To ensure data accuracy, completeness, and representativeness, all data were preprocessed to eliminate apparent errors

Table 1 Basic information about the national meteorological stations at the periphery of the Badain Jaran Desert

Station	Elevation/m	Mean annual temperature/°C	Annual precipitation/mm	Mean annual evaporation/mm
Ejina Banner	941.3	9.1	35.3	3,352.3
Guaizi Lake	960.0	9.2	45.2	4,308.4
Dingxin	1,178.6	8.6	57.3	2,508.6
Alxa Right Banner	1,511.5	8.9	120	3,486.2

and fill in missing data. Specifically, this included the 2013–2017 evaporation data for Guaizi Lake and the 1962–1965 evaporation data for Alxa Right Banner. Therefore, to guarantee effective and accurate analytical results, the study utilized meteorological data from 1960–2017 that were recorded continuously and completely, without geographical migration of the stations, for statistical analyses. Fig. 1 and Table 1 illustrate the distribution and specific details of the four national meteorological stations, respectively.

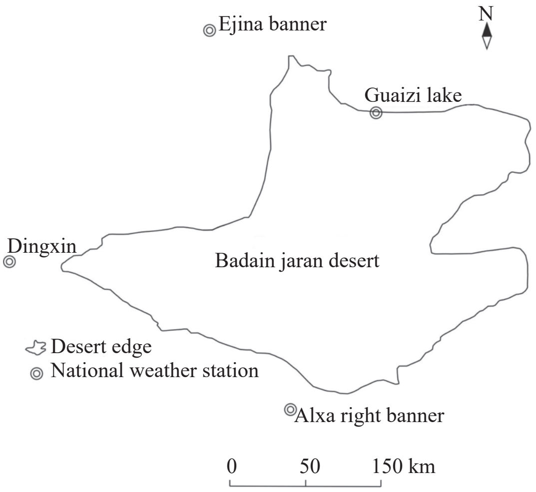

Fig. 1 Distribution of meteorological stations in the Badain Jaran Desert

1.3 Methods

This study analyzed the evolutionary trends and abrupt change characteristics of the meteorological elements in the Badain Jaran Desert using several methods: Linear trend analysis, linear tendency estimation, and the departure method. Additionally, the dominant factors controlling evaporation evolution in the desert were identified using the Spearman correlation coefficient method, combined with the multiple linear regression (MLR) method. Finally, the study summarized the overall climatic trend in the desert.

2 Variations in evaporation and climatic factors

2.1 Variations in evaporation

2.1.1 Interannual variations in evaporation

Significant spatiotemporal differences were observed in the evaporation patterns along the margins of the Badain Jaran Desert. Spatially, the average annual evaporation varied from 4,308.4 mm to 2,508.6 mm, with the maximum values at the northeastern (Guaizi Lake) and minimum at western (Dingxin) margins. The northern (Ejina Banner) and southern (Alxa Right Banner) margins, which have slightly different altitudes, exhibited relatively close average annual evaporation of 3,352.3 mm and 3,486.2 mm, respectively. Furthermore, as altitude increases from east to west, the average annual evaporation decreases at a rate of about 8.23 mm/m, consistent with Li et al. (2022) who found that evaporation in the Shiyang River basin decreases with altitude (Table 1). In terms of temporal evolution, the annual evaporation in the desert exhibited distinct interannual variation trends. At Ejina Banner and Alxa Right Banner, the annual evaporation showed similar

Table 2 Interannual variation trends in primary meteorological elements of four national meteorological stations in the Badain Jaran Desert (1960–2017)

Meteorological element	Trend check	Ejina Banner	Guaizi Lake	Dingxin	Alxa Right Banner
Temperature (°C)	Changing rate/10a	0.49	0.41	0.32	0.34
Precipitation (mm)	Changing rate/10a	−0.18	−0.53	1.98	2.99
φ20 pan evaporation (mm)	Changing rate/10a	−162.42	131.72	104.97	−187.36
Relative humidity (%)	Changing rate/10a	−0.90	−0.79	−0.99	−0.50
Mean wind speed (m/s)	Changing rate/10a	−0.26	0.10	−0.07	−0.31
Sunshine duration (h)	Changing rate/10a	−34.48	20.28	−7.65	106.00

*Confidence level: α=0.05;

patterns, with a general declining trend at rates of 162 mm/10a and 187 mm/10a, respectively (Table 2). The cumulative departure curves (current value minus the average) for both stations indicated abrupt changes in 1987. Positive departures (annual evaporation higher than average) were mainly observed before 1987, while negative departures (annual evaporation lower than average) were predominated after 1987 (Fig. 3). Conversely, the annual evaporation curves of Guaizi Lake and Dingxin exhibited slightly different fluctuations but generally showed a significant upward trend, with rates of 131.72 mm/10a and 104.97 mm/10a, respectively. The cumulative departure curves for these stations indicated abrupt changes in 1996, with negative departures (annual evaporation lower than average) before 1996, and positive departures (annual evaporation higher than average) after 1996.

Overall, the evaporation along the margins of the Badain Jaran Desert demonstrated significantly different spatiotemporal variation trends. Beyond the influence of altitude, these variation trends are attributed to differing dominant controlling factors and evolutionary patterns arising from the diverse geographic and climatic conditions at the desert margins.

2.1.2 Interdecadal variations of evaporation

The interdecadal variation trends in evaporation at the four national meteorological stations are shown in Fig. 4. The annual evaporation at Ejina Banner increased from the 1960s to the 1970s, decreased from the late 1970s to the 1990s, increased from 1999 to 2009, and decreased from 2009 to 2017, showing an overall downward trend. At Alxa Right Banner, annual evaporation decreased from the 1960s to the 1990s, increased from 1999 to 2009, and decreased from 2009 to 2017, also exhibiting a general downward trend. The annual evaporation at Guaizi Lake increased from the 1960s to the 1980s, decreased from the late 1980s to the 1990s, increased from 1999 to 2009, and slightly dec-

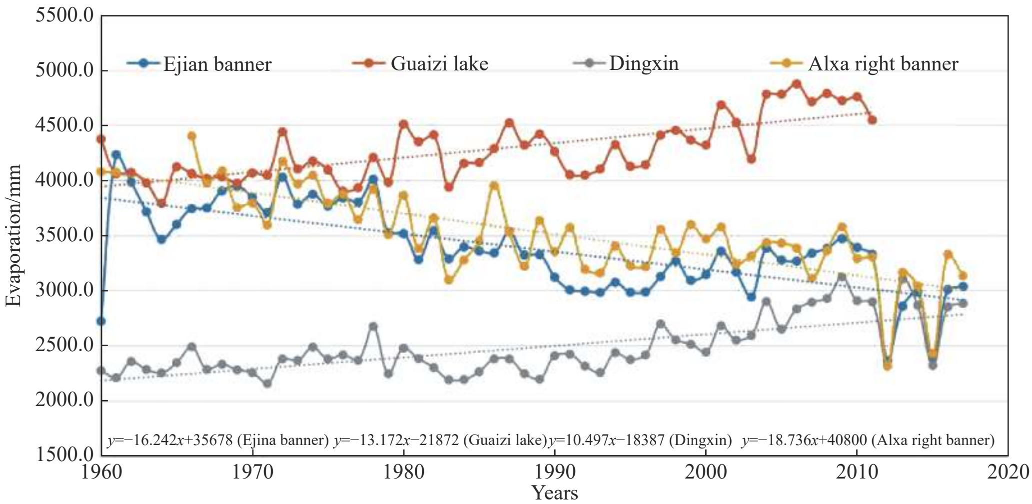

Fig. 2 Interannual variation trends in evaporation

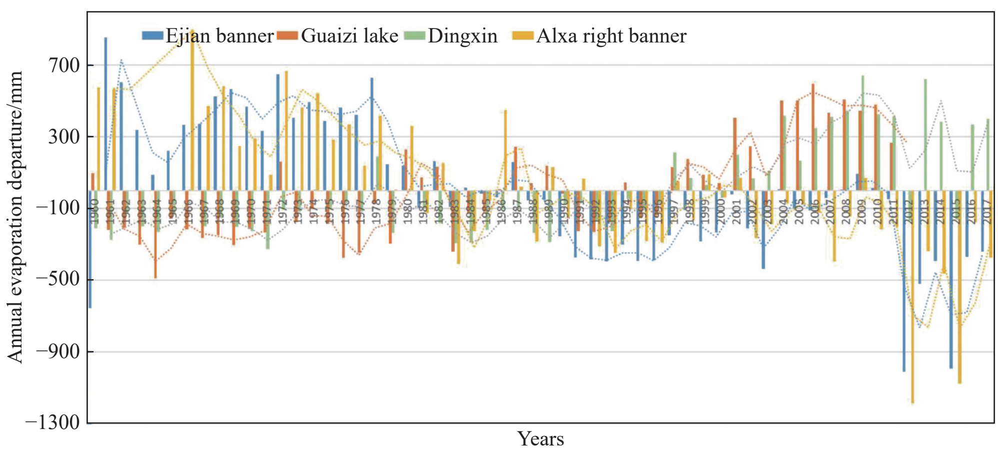

Fig. 3 Annual evaporation departure and variation curves

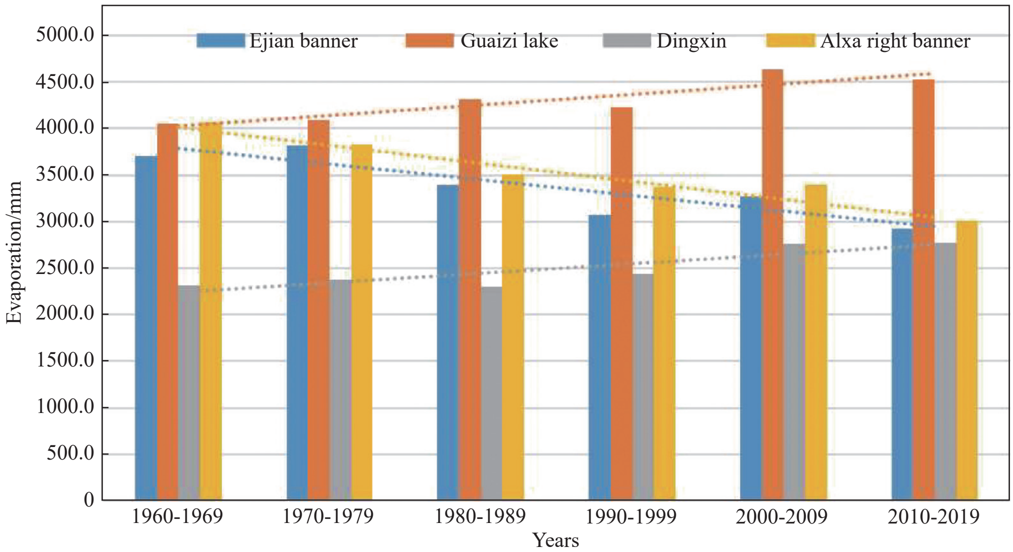

Fig. 4 Interdecadal variation trends of evaporation

reased from 2009 to 2017, overall showing an upward trend. At Dingxin, annual evaporation increased from the 1960s to the 1970s, slightly decreased from the late 1970s to the 1980s, increased again from the late 1980s to the 1990s, continued to increase from 1999 to 2009, and slightly decreased from 2009 to 2017, generally exhibiting an upward trend. In summary, during the 20th century, the annual evaporation at the four stations showed significant fluctuations and notable differences in variation trends. Generally, annual evaporation showed an upward and then a downward trend, except at Alxa Right Banner. Since the beginning of the 21st century, the annual evaporation at all four stations exhibited roughly consistent variation trends, increasing in the early years and decreasing in the later years.

2.2 Variations in meteorological elements

Evaporation in nature is a complex process. Researchers both domestically and internationally have conducted extensive studies on the primary factors influencing evaporation evolution, generally identifying average wind speed, relative humidity, temperature, and sunshine duration as key factors (He et al. 2015; Liu et al. 2019; Qi et al. 2015; Chen et al. 2016). Therefore, this study selected average annual temperature, average wind speed (10 m above the ground surface), relative humidity, sunshine duration, and rainfall from 1960–2017 as the primary meteorological elements influencing evaporation evolution in the Badain Jaran Desert. Additionally, this study explored the evolutionary trends of these meteorological elements and assessed the degrees of their influence on evaporation evolution.

Figs. 5–9 and Table 2 depict the trends in average annual temperature, annual rainfall, average wind speed, sunshine duration, and relative humidity along the margins of the Badain Jaran Desert over nearly 60 years. The average annual temperature exhibited a significant upward trend, with rising rates of 0.49°C/10a, 0.41°C/10a, 0.32°C/10a, and 0.34°C/10a, respectively, at Ejina Banner, Guaizi Lake, Dingxin, and Alxa Right Banner from north to south. The average annual temperature of the desert increased by about 2.5°C over nearly 60 years. The annual rainfall demonstrated significantly different evolutionary trends at the four stations. Ejina Banner and Guaizi Lake displayed an insignificant downward trend, with decreasing rates of 0.18 mm/10a and 0.53 mm/10a, respectively. Conversely, Dingxin and Alxa Right Banner exhibited an insignificant upward trend, with increasing rates of 1.98 mm/10a and 2.99 mm/10a, respectively. Additionally, the annual rainfall generally decreased from the southwestern to northeastern margins. The average wind speed exhibited a significant downward trend, with decreasing rates ranging from 0.07 m/s/10a to 0.31 m/s/10a at the four stations, except for Guaizi Lake, where the average wind speed trended slightly upward. The downward trends in average wind speed are associated with the continuously weakened Southeast Asian monsoon in the mid-1960s. Sunshine duration trended downward at Ejina Banner and Dingxin and upward at Alxa Right Banner and Guaizi Lake, especially at Alxa Right Banner, which exhibited an increasing rate

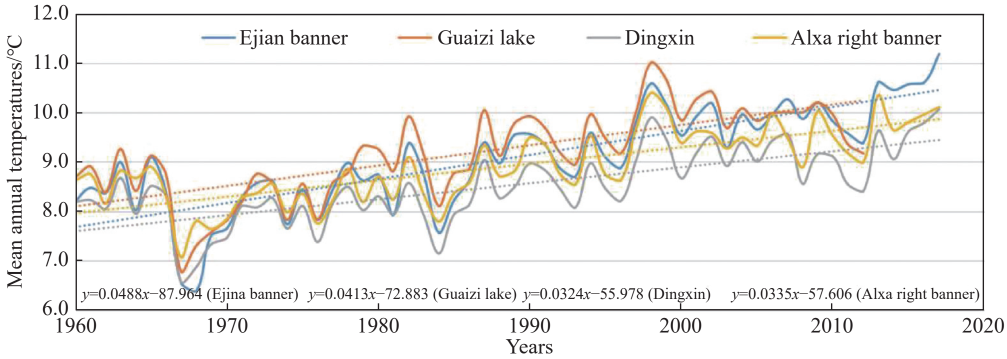

Fig. 5 Variation trends in the average annual temperatures in the Badain Jaran Desert during 1960–2017

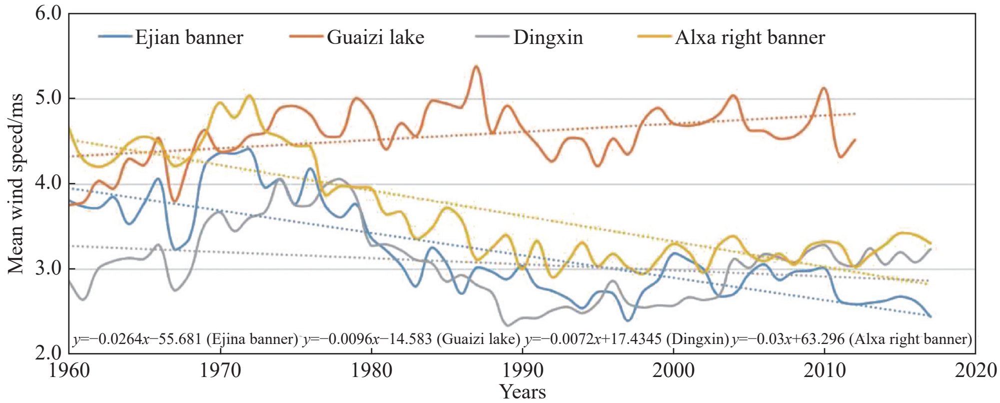

Fig. 6 Variation trends in the average wind speeds in the Badain Jaran Desert during 1960–2017

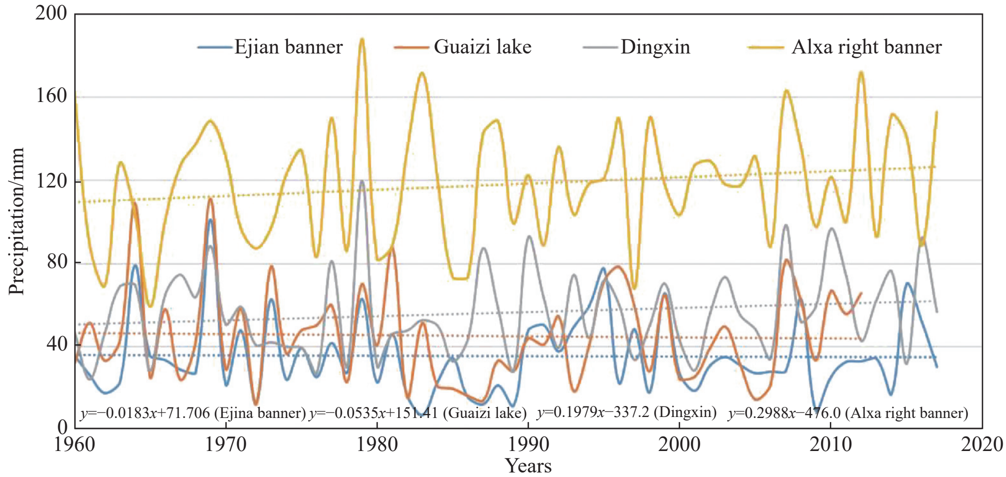

Fig. 7 Variation trends in the annual rainfall in the Badain Jaran Desert during 1960–2017

of 106 h/10a. Relative humidity demonstrated a downward trend throughout the desert.

3 Analysis and discussion

3.1 Correlations between evaporation and climatic factors

The annual evaporation along the desert margins exhibited significant correlations with the average annual temperature, average wind speed, and relative humidity. However, the correlation between annual evaporation and average annual temperature varied across stations. It showed a significant negative correlation at Ejina Banner and Alxa Right Banner, with correlation coefficients of 0.574 and 0.437, respectively, but a significant positive correlation at Dingxin and Guaizi Lake, with correlation coefficients of up to 0.717 and

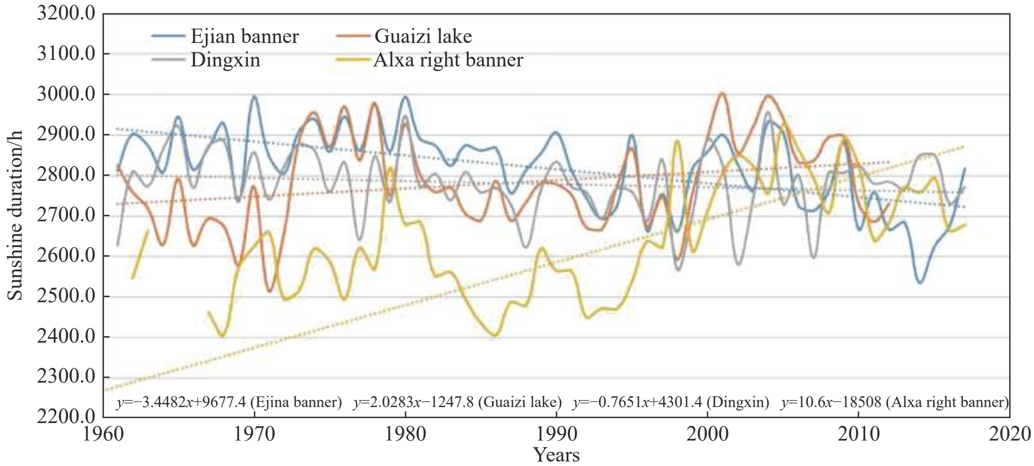

Fig. 8 Variation trends in the sunshine duration in the Badain Jaran Desert during 1960–2017

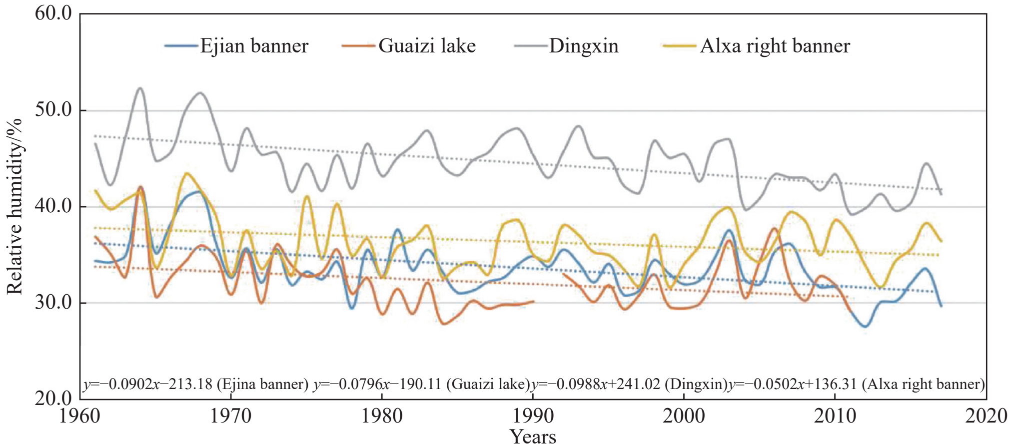

Fig. 9 Variation trends in the relative humidity in the Badain Jaran Desert during 1960–2017

0.677, respectively. Annual evaporation was significantly positively correlated with average wind speed, with a correlation coefficient of 0.786, but significantly negatively correlated with relative humidity, with a correlation coefficient reaching up to 0.652. Additionally, there was a weakly significant or no correlation between annual evaporation and annual rainfall and sunshine duration (Table 3). Overall, annual evaporation showed significant correlations with climatic factors such as average annual temperature, average wind speed, and relative humidity along the desert margins, with the degrees of correlations varying across stations. Specifically, the degrees of correlations decreased in the order of average wind speed, mean temperature, and relative humidity at Ejina Banner, in the order of mean temperature, relative humidity, and average wind speed at Dingxin, in the order of mean temperature, relative humidity, and average wind speed at Guaizi Lake, and in the order of average wind speed, relative humidity, and mean temperature at Alxa Right Banner. In

Table 3 Coefficients of correlations (*re*) between meteorological elements and evaporation in the Badain Jaran Desert during 1960–2017

	Coefficients of correlations between meteorological elements and pan evaporation				
	Temperature	**Wind speed**	**Rainfall**	**Relative humidity**	**Sunshine duration**
Right Banner	−.574**	.786**	−.266*	−.431**	.298*
Dingxin	.677**	.467**	−.115	−.621**	.197
Guaizi Lake	.717**	.368**	−.312*	−.419**	.343*
Ejina Banner	−.437**	.703**	−.304*	−.476**	.171

* and ** denote the significance levels of 0.05 and 0.01, respectively in statistics.

contrast, annual evaporation exhibited weak correlations with sunshine duration and annual rainfall along the desert margins.

3.2 MLR analysis of the evaporation and meteorological elements

Based on the correlation analysis results mentioned earlier, this study utilized average annual temperature, average wind speed, and relative humidity as independent variables, and evaporation as the dependent variable to establish a Multiple Linear Regression (MLR) model using the Statistical Product and Service Solutions (SPSS) software.

The same independent variable exhibits varying explanatory power for the variation in the dependent variable, with a higher goodness of fit (R^2) corresponding to higher explanatory power. Table 4 indicates the multiple regression models for Dingxin, Ejina Banner, Guaizi Lake, and Alxa Right Banner yielded R^2 values of 0.535, 0.646, 0.48, and 0.468, respectively. These R^2 values suggest that the impacts of independent variables at the four stations decreased in the order of Ejina Banner, Dingxin, Guaizi Lake, and Alxa Right Banner. Therefore, the same independent variable demonstrates varying explanatory power for the variation in the dependent variable (evaporation) at different locations in the desert.

Table 4 Multiple correlation coefficients between evaporation and three independent variables for the Badain Jaran Desert during 1960–2017

	R	***R***^{2}	**Adjusted *R***^{2}
Dingxin	0.748	0.56	0.535
Ejina Banner	0.815	0.665	0.646
Guaizi Lake	0.708	0.501	0.482
Alxa Right Banner	0.706	0.498	0.468

The MLR equations resulting from Equations (1)–(4), where X1 denotes the average annual temperature, X2 represents the wind speed, X3 denotes the relative humidity and y is the pan evaporation in the multiple regression equation. The MLR equation for different locations are as follows:

For Dingxin, the *p*-values associated with the average annual temperature, relative humidity, and constant were all below 0.05, indicating statistically significant regression analysis results for the three variables. Consequently, the MLR equation for Dingxin is

$$y = 183.685X1 - 28.906X3 + 1951.433 \quad (1)$$

For Ejina Banner, the *p*-values related to the average wind speed and constant were both below 0.05, indicating statistically significant regression analysis results for them. The resulting MLR equation for this location is

$$y = 450.80X2 + 2325.353 \quad (2)$$

For Guaizi Lake, the *p*-values related to the average annual temperature and constant were both below 0.05, signaling statistically significant regression analysis results for them. The resulting MLR equation for this site is

$$y = 189.746X1 + 2326.376 \quad (3)$$

Regarding Alxa Right Banner, the *p*-value connected with the average wind speed was below 0.05, indicating statistically significant regression analysis results for this variable. The resulting MLR equation is

$$y = 475.506X2 \quad (4)$$

These equations, combined with Table 3, indicate that at Dingxin and Guaizi Lake, the dominant factor controlling the variation in evaporation is average annual temperature. Additionally, relative humidity is also a dominant controlling factor at Dingxin. At Ejina Banner and Alxa Right Banner, the dominant factor controlling the variation in the evaporation is average wind speed.

3.3 Discussion

The evaporation mechanism is affected by many

Table 5 Partial regression coefficients between evaporation and three independent variables of the Badain Jaran Desert during 1960–2017 and their t-tests

	Dingxin			**Ejina Banner**			**Guaizi Lake**			**Alxa right banner**		
	Coefficient	***p***	**VIF**	**Coefficient**	***p***	**VIF**	**Coefficient**	***p***	**VIF**	**Coefficient**	***p***	**VIF**
Constant	1951.433	**0.011**		2325.353	**0.005**		2326.376	**0.003**		1431.275	0.197	
Temperature	183.685	**0.000**	1.478	378.623	0.736	1.659	189.746	**0.000**	1.198	338.132	0.652	1.937
Wind speed	84.535	0.153	1.275	450.80	**0.000**	2.037	104.134	0.305	1.255	475.506	**0.000**	1.851
Relative humidity	−28.906	**0.003**	1.406	2.487	0.844	1.356	−8.177	0.477	1.239	3.751	0.797	1.072

climatic factors, including temperature, pressure, wind speed, surface temperature, vapor pressure, and relative humidity. An analysis of evaporation in the Badain Jaran Desert over nearly 60 years reveals significant spatial differences. Specifically, evaporation decreased at Ejina Banner and Alxa Right Banner, while it increased at Guaizi Lake and Dingxin. However, abrupt changes in evaporation occurred in the late 1980s and early 1990s at all four stations, possibly due to the intensified impacts of human activities on evaporation amidst accelerated economic reform and opening-up in China. The dominant factors controlling evaporation varied across stations, identified as average annual temperature and relative humidity at Dingxin, average annual temperature at Guaizi Lake, and average wind speed at Ejina Banner and Alxa Right Banner, suggesting the complexity of factors influencing evaporation in the inland arid region.

In the broader context of global warming and humidification, analyses of temperature and precipitation along the margins of the Badain Jaran Desert over nearly 60 years reveal noteworthy trends. The temperature in the desert has shown an upward trend, while precipitation has exhibited varying patterns. There was a negligible downward trend in precipitation along the northeastern margin, contrasted by a significant upward trend along the southwestern margin. These findings suggest dramatic climate changes over the years, characterized by a warming and drying trend along the northeastern margin and a warming and wetting trend along the northwestern margin. These different climate evolutions may be attributed to altitude effects.

Despite the rising temperature trend in the desert, evaporation showed a downward trend at Ejina Banner and Alxa Right Banner, indicating an evaporation paradox (Roderick et al. 2002). Roderick et al. (2007) suggested that increased cloud cover and aerosols have reduced evaporation in many regions worldwide. However, this study proposes different dominant factors controlling evaporation at different stations, providing novel insights into the analysis of factors influencing evaporation evolution.

4 Conclusions

(1) Evaporation along the margins of the Badain Jaran Desert exhibits significant spatiotemporal variations. Spatially, evaporation decreases with increasing altitude from east to west, with the maximum and minimum values observed at the northeastern (Guaizi Lake) and western (Dingxin) margins, respectively. Over nearly 60 years (1960–2017), evaporation declines along the northern (Ejina Banner) and southern (Alxa Right Banner) margins, with abrupt changes occurring in 1987. Conversely, significant upward trends in evaporation are observed at the northeastern (Guaizi Lake) and western (Dingxin) margins, with abrupt changes in 1996.

(2) An evaporation paradox is evident along the northern (Ejina Banner) and southern (Alxa Right Banner) margins of the desert. Despite the warming and drying trend along the northeastern margin and the warming and wetting trend along the northwestern margin, evaporation does not generally increase with temperature in these areas.

(3) Dominant factors controlling evaporation vary across different regions of the desert. Average annual temperature and relative humidity are identified as controlling factors along the western margin (Dingxin), while average annual temperature predominates along the northeastern margin (Guaizi Lake), and average wind speed influences evaporation along the northern (Ejina Banner) and southern (Alxa Right Banner) margins.

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