Trend Analysis of Potential Evapotranspiration and Surface Moisture Conditions in the Xilin River Basin over the Past 59 Years: Postprint

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Abstract

Using daily meteorological data from 13 weather stations around the Xilin River Basin from 1960 to 2018, the Penman-Monteith formula recommended by the Food and Agriculture Organization of the United Nations (FAO) was employed to calculate multi-year potential evapotranspiration and relative moisture index for each station. Through principal component analysis, correlation analysis, and partial correlation analysis, this study investigated the multi-year variation patterns of potential evapotranspiration and surface moisture conditions in the Xilin River Basin; analyzed the main meteorological factors affecting potential evapotranspiration and the interactions among various meteorological elements; and focused on discussing the periodic variation of potential evapotranspiration and its interactions with the relative moisture index and various meteorological elements. The results show that: potential evapotranspiration in the basin over the past 59 years exhibits an overall increasing trend, with the upward trend being statistically significant, characterized by multi-scale time-frequency variation features with alternating significant increase-decrease patterns and multiple dominant periodic variation patterns; among the meteorological elements, potential evapotranspiration shows a greater response to temperature, followed by average wind speed; average relative humidity is more significantly influenced by potential evapotranspiration, followed by precipitation. The entire basin environment shows a non-significant trend toward becoming more humid.

Full Text

Trends of Potential Evapotranspiration and Surface Wet-Dry Conditions in the Xilin River Basin over the Past 59 Years

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Abstract

Using daily meteorological data from 1960 to 2018 obtained from 13 meteorological stations surrounding the Xilin River Basin, the Penman-Monteith formula recommended by the Food and Agriculture Organization of the United Nations (FAO) was employed to calculate multi-year potential evapotranspiration and relative humidity index values. Principal component analysis, correlation analysis, and partial correlation analysis were applied to explore the long-term variation patterns of potential evapotranspiration and surface wet-dry conditions in the basin. The main meteorological factors influencing potential evapotranspiration and their interactions were analyzed, with particular focus on the periodic variations of potential evapotranspiration and its interactions with the relative humidity index and various meteorological elements. The results show that potential evapotranspiration in the basin exhibited a significant increasing trend over the past 59 years, characterized by alternating multi-scale temporal-frequency variations of increase-decrease and multiple dominant periodic patterns. Among meteorological elements, potential evapotranspiration showed the strongest response to temperature, followed by average wind speed. Conversely, average relative humidity was most significantly affected by potential evapotranspiration, followed by precipitation. The overall basin environment showed an insignificant trend toward becoming more humid.

Keywords: Xilin River Basin; potential evapotranspiration; surface wet-dry conditions

Introduction

The arid and semi-arid regions of northern China represent primary areas for building a beautiful northern ecological barrier and constitute ecologically fragile zones. Against the backdrop of global warming and drying, strengthening research on the variation patterns and distribution characteristics of regional climate elements is imperative. Generally, rising temperatures increase water body and surface evaporation, which plays an extremely important role in the hydrological cycle and is closely related to surface water and energy balance. Due to the complexity of natural evaporation phenomena and the lack of measured evaporation data, regional potential evapotranspiration estimation has long been a key focus of hydro-meteorological research. Potential evapotranspiration (also called possible evaporation) is commonly used to estimate actual evaporation. The causes of evaporation variation differ across regions, with solar radiation duration and moisture status generally considered the main influencing factors in arid and semi-arid areas.

Among methods for estimating potential evapotranspiration, this study selected the Penman-Monteith formula because it comprehensively reflects the influence of meteorological elements and demonstrates strong applicability. Using daily observational data from 13 meteorological stations in the Xilin River Basin from 1960 to 2018, this paper analyzes the changing trends of potential evapotranspiration under a changing climate and its response to meteorological factors, and further explores the trend of surface wet-dry conditions over the past 59 years, aiming to provide reference for ecological drought research in semi-arid steppe watersheds.

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1. Study Area and Data Sources

1.1 Study Area Overview

The Xilin River originates in Keshiketeng Banner, Chifeng City, and is an inland river. The river is demarcated by Kunisuman: the upstream section flows through hilly terrain with exceptionally winding channels and occasional marshlands, while the middle and downstream sections turn northward, forming an intermontane basin before finally flowing into Baiyin Nur Lake. The region features a typical temperate arid and semi-arid continental climate with distinct seasonal variations, low precipitation, and dry, windy conditions.

1.2 Data Sources

Meteorological data were obtained from the China Meteorological Data Sharing Service Network (http://data.cma.cn), specifically the daily surface climate dataset, which has undergone quality control. Data from the Xilinhot station and 12 surrounding meteorological stations within the Xilin River Basin were selected, including precipitation, mean temperature, maximum temperature, minimum temperature, mean relative humidity, surface temperature, sunshine duration, mean wind speed, and mean atmospheric pressure (with a missing data rate of less than 1%). To ensure time series completeness, missing data were interpolated and extended using partial least squares regression.

[Figure 1: see original paper] Spatial distribution of study area and annual potential evapotranspiration

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2. Research Methods

2.1 Penman-Monteith Formula

Using data on mean temperature, maximum temperature, minimum temperature, mean relative humidity, sunshine duration, and mean wind speed from 13 meteorological stations in the Xilin River Basin, the Penman-Monteith formula was applied to estimate multi-year daily potential evapotranspiration at each station:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where PET is potential evapotranspiration ($\mathrm{mm \cdot d^{-1}}$), R is net solar radiation ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), T is mean temperature (°C), U_2 is wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$), e is mean saturation vapor pressure (kPa), e is actual vapor pressure (kPa), (e - e) is saturation vapor pressure deficit (kPa), Δ is the slope of the saturation vapor pressure curve ($\mathrm{kPa \cdot °C^{-1}}$), and γ is the psychrometric constant ($\mathrm{kPa \cdot °C^{-1}}$).

2.2 Wavelet Analysis

Wavelet transform can reveal multiple periodic changes hidden in time series. This study employed Morlet wavelet transform to analyze multi-year potential evapotranspiration. The fast wavelet transform method was used without involving specific wavelet and scale functions, offering simple and rapid calculation. MATLAB software was utilized to compute wavelet coefficients and generate wavelet variance diagrams and real-part contour maps.

2.3 Principal Component Analysis

Principal component analysis (PCA) is a mathematical dimensionality reduction technique commonly used in multivariate analysis. Its main principle is to examine correlations among multiple variables and reveal the internal structure of numerous variables through a few principal components. SPSS software was used for PCA, which is particularly suitable for analyzing the dependency between influencing variables and original variables.

2.4 Correlation and Partial Correlation Analysis

Correlation analysis measures the degree of closeness between two variables, while partial correlation analysis examines the relationship between two variables after removing the effect of a third variable when all three are correlated. The correlation coefficient R serves as the judgment criterion. This study combined both methods to analyze correlations among different samples.

2.5 Relative Humidity Index

The national standard "Meteorological Drought Grade" was adopted to quantitatively analyze wet-dry condition variations in the study area. The relative humidity index is calculated as:

$$MI = \frac{P - PE}{PE} \times 100$$

where MI is the relative humidity index, P is total precipitation in a given period (mm), and PE is total potential evapotranspiration in the same period (mm).

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3. Results Analysis

3.1 Temporal Variation of Evapotranspiration

3.1.1 Interannual Variation Characteristics of Potential Evapotranspiration Results show that potential evapotranspiration in the Xilin River Basin from 1960 to 2018 exhibited a significant overall increasing trend, with a linear growth rate of 978.23 mm per decade. The sixth-order polynomial curve revealed regular fluctuation patterns with two distinct peaks. Before 1990, evapotranspiration anomalies were mostly negative, while after 1990 they were primarily positive, with prolonged peak periods. The maximum peak occurred in the 2000s, and the minimum peak appeared around 2010. The minimum annual potential evapotranspiration was 1,105.57 mm (1964), while the maximum was 1,243.51 mm (2017), with a multi-year average of 1,187.63 mm.

[Figure 2: see original paper] Potential evapotranspiration anomalies in the Xilin River Basin from 1960 to 2018

3.1.2 Periodic Variation Analysis of Potential Evapotranspiration Wavelet transform analysis revealed strong periodicity in potential evapotranspiration over the past 59 years, with a primary period of 28–32 years and secondary periods of 14–18 years. The first dominant period emerged around 1989, characterized by strong periodicity and long duration, possibly related to reduced precipitation and multiple precipitation regime shifts during this period. The second and third dominant periods appeared around 1999 and 2007, respectively.

The wavelet real-part time-frequency distribution contour map showed three strong aggregation centers in the first dominant period: the first near 1989 with a time-domain scale of 28–32 years, the second as a dispersed aggregation center near 1999 with a time-domain scale of 14–18 years, and the third near 2007 with a time-domain scale of 7–9 years. The second dominant period showed opposite trends to the first, with a large-scale strong aggregation region from 1975 to

1995, indicating a jump increase in potential evapotranspiration. The third dominant period appeared near 2007 with two centers at 7-9 years and 3-4 years.

[Figure 3: see original paper] Wavelet variance map and real Morlet time-frequency distribution contour map of Morlet wavelet transform in Xilin River Basin

3.2 Impact Factor Analysis

PCA was performed on daily meteorological data from 1960 to 2018. Results showed that the dependency between influencing variables and original variables was approximately 0.9, with the first principal component contributing 50.15% of variance, indicating strong correlation between extracted components and original variables.

As shown in Table 1, the first principal component comprised mean temperature, surface temperature, daily maximum temperature, and daily minimum temperature, with a variance contribution rate of 50.15%. Mean, maximum, and minimum temperatures showed positive loadings on the first component, while mean atmospheric pressure showed negative loading. This indicates that as potential evapotranspiration increases, temperatures and surface temperature rise while atmospheric pressure decreases, confirming that global warming is the primary factor driving increasing potential evapotranspiration in the Xilin River Basin.

The second principal component integrated mean relative humidity, precipitation, and sunshine duration, reflecting moisture effects on potential evapotranspiration. The third principal component was mean wind speed, which transports and exchanges moisture and heat in the air, promoting evaporation and positively affecting potential evapotranspiration, second only to temperature.

Principal component analysis of meteorological factors

3.3 Comparative Analysis of Correlation and Partial Correlation

To further investigate meteorological factors' influence on potential evapotranspiration, correlation and partial correlation analyses were conducted controlling for potential evapotranspiration. Table 2 shows partial correlation coefficients in the upper right and correlation coefficients in the lower left. Except for precipitation and mean wind speed, all correlations between meteorological factors and potential evapotranspiration passed significance tests at the 0.001 level, validating PCA results.

Partial correlation coefficients better revealed interactions among meteorological factors after removing potential evapotranspiration effects. After controlling for potential evapotranspiration, the correlation between mean wind speed and precipitation became insignificant. Maximum, mean, and minimum temperatures and surface temperature showed positive correlations with relative humidity and precipitation, with the strongest correlations among temperature variables. Mean atmospheric pressure and sunshine duration were positively correlated but negatively correlated with other meteorological factors. Mean wind speed was negatively correlated with all other meteorological factors.

Comparative analysis revealed that mean relative humidity was most significantly affected by potential evapotranspiration, followed by precipitation.

Principal component analysis component load matrix

3.4 Surface Wet-Dry Condition Analysis

Annual precipitation in the Xilin River Basin showed a weak increasing trend from 1980 to 2018, with a linear trend rate of 276.33 mm per decade. Maximum annual precipitation was 511.72 mm (1998), minimum was 121.14 mm (1980), with a multi-year average of 276.33 mm. Precipitation anomaly values showed periodic positive-negative variations, with negative anomalies persisting for longer durations.

[Figure 4: see original paper] Variations in precipitation anomalies in the Xilin River Basin from 1980 to 2018

The relative humidity index characterizes surface wet-dry conditions, with smaller values indicating drier surfaces. Figure 5 shows that the relative humidity index exhibited an insignificant increasing trend from 1980 to 2018, suggesting a weak shift toward wetter conditions. The multi-year average relative humidity index was -0.65, with a maximum of -0.35 (1980) and minimum of -0.84 (2000). The anomaly curve showed three peaks and two troughs, with larger peaks in the 1990s and smaller peaks around 2010, and larger troughs in the 1980s and 2000s.

[Figure 5: see original paper] Variation trend of relative humidity index anomalies in Xilin River Basin from 1980 to 2018

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4. Conclusions

1) Overall potential evapotranspiration in the Xilin River Basin showed a significant increasing trend over the past 59 years, with alternating multi-scale temporal-frequency characteristics of increase-decrease and multiple dominant periodic patterns. The main periods were 28–32 years, 14–18 years, and 7–9 years, with varying importance. This indicates that potential evapotranspiration follows a complex multi-period pattern of increase-decrease alternation, with small-scale variations nested within larger-scale structures.

2) Changes in potential evapotranspiration result from comprehensive effects of meteorological elements. Surface temperature, daily maximum temperature, daily minimum temperature, mean temperature, sunshine duration,

mean relative humidity, precipitation, and mean wind speed are positive influencing factors, while mean atmospheric pressure is a negative factor. Among these, potential evapotranspiration showed the strongest response to temperature, followed by wind speed. Conversely, potential evapotranspiration significantly affected mean relative humidity, followed by precipitation.

3) Annual precipitation from 1980 to 2018 showed an insignificant fluctuating upward trend, while potential evapotranspiration showed a more obvious fluctuating upward trend, and the relative humidity index showed a weak increasing trend. These results indicate that while precipitation and potential evapotranspiration have both increased in recent 59 years, surface wet-dry conditions in the basin have slightly trended toward wetter conditions.

The Penman-Monteith formula has rigorous theoretical derivation but remains semi-empirical, requiring further optimization to improve accuracy. Research on long-term daily-scale potential evapotranspiration and relative humidity in the Xilin River Basin has been limited. This study analyzed meteorological observation data from 1960 to 2018 and found an increasing trend in the relative humidity index. Wang Haimei (2009) identified the 1990s as a relatively humid period in the basin, supporting our findings. However, this study only considered single meteorological factors and cannot directly indicate drought conditions. Incorporating topographic factors, vegetation changes, soil moisture, and human activities would provide more accurate and comprehensive understanding of surface wet-dry condition variations.

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Note: Figure translations are in progress. See original paper for figures.