Analysis of Meteorological Drought Factors in the Desert Steppe of the Northern Foothills of Yinshan Mountains (Postprint)

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Abstract

Grasslands are a critical component of ecological environment construction in western China, and their ecosystems are highly susceptible to degradation. In recent years, drought disasters have occurred frequently in desert steppes. Taking the Desert Steppe Eco-hydrology National Field Scientific Observation and Research Station at the northern foot of Yinshan Mountain in Inner Mongolia as the experimental area, this study monitored precipitation variations at different slope positions, analyzed the relationships and interactions between meteorological factors and the drought index PA value, and constructed a regression model. The results show: (1) Precipitation at different slope positions in the desert steppe at the northern foot of Yinshan Mountain follows the order: lower slope > middle slope > upper slope, with corresponding drought index PA values: upper slope PA > middle slope PA > lower slope PA. (2) Observations at various temporal scales reveal: monthly-scale analysis found that drought phenomena of varying degrees occurred at all slope positions, with high drought frequency; seasonal-scale analysis found that only slight drought occurred in winter; annual-scale analysis found that the region did not reach the drought threshold in the recent 5 years. This indicates that the region has sufficient mean annual precipitation and has not experienced drought disasters. (3) The multiple regression model constructed based on major meteorological factors such as precipitation, temperature, wind speed, and the drought index PA value is: YPA=78.799+0.255x1-3.395x2-1.831x3, with R2 of 0.994. The model exhibits high goodness of fit and can effectively reflect the drought conditions in this region. This provides a theoretical basis for further research on the relationships between multiple meteorological factors and various drought indicators, as well as for constructing drought assessment systems.

Full Text

Analysis of Meteorological Factors Affecting Drought in a Desert Steppe of the Northern Foot of Yinshan Mountain

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Abstract

Grassland is a key component of ecological environment construction in western China, and its ecosystem is extremely vulnerable to damage. In recent years, drought disasters have occurred frequently in desert steppes. Taking the Yinshanbeilu National Field Research Station of Desert Steppe Eco-Hydrological System in Inner Mongolia as the experimental area, this study monitored precipitation changes at different slope positions, analyzed the relationship and interaction between meteorological factors and the drought index PA value, and constructed a regression model. The results show that: (1) The precipitation at different slope positions of the desert steppe at the northern foot of Yinshan Mountain follows the pattern: downhill > middle slope > uphill, with corresponding drought index PA values: uphill PA > middle slope PA > downhill PA. (2) From observations at various temporal scales: monthly scale analysis revealed different degrees of drought at each slope position with high drought frequency; seasonal scale analysis found light drought only in winter; annual scale analysis found that the region did not reach the drought threshold during 2015–2019. Overall, the average annual precipitation in this area is sufficient and no drought disaster occurred. (3) The multiple regression model constructed based on main meteorological factors such as precipitation, air temperature, and humidity with the drought index PA value is: $Y\_\{PA\} = 78.799 + 0.255x_1 - 3.395x_2 + 1.831x_3$, with $R^2 = 0.994$, indicating high model fit that can well reflect the drought situation in the region. This provides a theoretical basis for further research on the relationship between multiple meteorological factors and various drought indicators, as well as for constructing drought evaluation systems.

Keywords: precipitation; drought index; desert steppe; the northern foot of Yinshan Mountain; multiple linear regression

1 Study Area and Methods

1.1 Study Area Overview

The study area is located in Halawusu Gacha, Xilamuren Town, Damao Banner, Baotou City, Inner Mongolia, with geographical coordinates of 111°12 00 –111°12 50 E, 41°20 40 –41°21 30 N, at an average elevation of 1600 m. It lies in the transition zone from the Yinshan Mountains to the Inner Mongolia Plateau, with flat terrain. The climate is a mid-temperate semi-arid continental monsoon climate with strong cold and heat variations and large diurnal temperature differences. The average annual precipitation is 284 mm, mainly concentrated in June–September. The average annual evaporation is 2305 mm. The annual average temperature is 2.5 ℃, the average annual sunshine hours are 3100 h, and the annual average wind speed is 4.5 $m \cdot s^{-1}$. Northerly and northwesterly winds prevail in winter and spring, with 20–25 days of strong wind annually and occasional dust storms.

The zonal soil in this area is chestnut soil with coarse texture and shallow soil layers. The constructive species is *Stipa krylovii*, with dominant species including *Leymus chinensis*, *Artemisia frigida*, and other plants such as *Cleistogenes squarrosa*, *Agropyron cristatum*, etc.

1.2 Research Methods

1.2.1 Research Design The experiment was established at the Yinshanbeilu National Field Research Station of Desert Steppe Eco-Hydrological System in Inner Mongolia. The study area comprised three different slope positions: uphill, middle slope, and downhill, classified according to elevation differences. Meteorological monitoring instruments were installed at each selected slope position, with three sets of instruments, each equipped with integrated meteorological units for data collection. The meteorological units collected relevant data, monitoring and recording meteorological data every half hour. This study collected daily meteorological data from each slope position for the period 2015–2019, including wind speed, wind direction, and precipitation. Combined with the meteorological drought indicator Percentage of Precipitation Anomaly (PA), a regression prediction model was constructed to analyze drought conditions and test the reliability of the prediction model.

1.2.2 Data Analysis 1) Selection of Drought Indicators

The Percentage of Precipitation Anomaly (PA value) refers to the percentage of the difference between precipitation in a certain period and the average precipitation in the same period over many years, relative to the average precipitation. It has clear meaning, simple calculation, and strong dependence on the average value. In this paper, the drought grades corresponding to PA values are classified according to the *Standard for Meteorological Drought Grades* [].

2) Principal Component Analysis

Principal component analysis is used to determine comprehensive indicators of a phenomenon and provide reasonable interpretation to reveal intrinsic laws more rigorously. Its principle is to linearly combine the original p indicators as new comprehensive indicators for analysis. The principal component model is expressed as:

$F_1 = a_{11}x_{11} + a_{21}x_{21} + \cdots + a\ _1x$
$F_2 = a_{12}x_{12} + a_{22}x_{22} + \cdots + a\ _2x$
...
$F\ = a_1\ x_{11} + a_2\ x_{22} + \cdots + a\ \ x$

where the coefficients are eigenvectors corresponding to eigenvalues of the covariance matrix of x, and x variables are standardized values. However, in practical application, this is only a process to achieve the goal, not the final result, and needs to be combined with other statistical methods for comprehensive consideration [].

3) Multiple Linear Regression Model

The mathematical model of multiple linear regression is expressed as:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta\ x\ +$

where the dependent variable y is a random observation value, β_0 is the constant term, and β (i = 1, 2, ···, p) are called partial regression coefficients, indicating the average change in the dependent variable y caused solely by each unit change in the independent variable x when other independent variables remain fixed.

Assuming the number of independent variables is p, expressed in vector form as (x_1, x_2, ···, x), and the number of observations is n, the ith case (i = 1, 2, ···, n) has a set of observations (y , x $_1$, x $_2$, ···, x), and there exists the following linear relationship between the dependent variable y and independent variables x:

$y\ = \beta_0 + \beta_1 x\ _1 + \beta_2 x\ _2 + \cdots + \beta\ x\ \ +$

where is the residual, the difference between the measured value y of the dependent variable and its estimated value Y . The residual is not determined by independent variables and follows a normal distribution, which is of great significance for judging the fitting degree of the established PA value regression model and the relationship among other meteorological factors [].

2 Results and Analysis

2.1 Comparison of Annual Precipitation at Different Slope Positions

The meteorological drought indicator Percentage of Precipitation Anomaly (PA value) is mainly calculated based on precipitation at different temporal scales. Therefore, we analyzed the annual precipitation at different slope positions in the desert steppe at the northern foot of Yinshan Mountain to study its variation patterns. [Figure 1: see original paper]

The analysis shows that the precipitation variation trends at different slope positions in the desert steppe at the northern foot of Yinshan Mountain were generally similar during 2015–2019, with larger precipitation amounts in June–September. In 2017, precipitation was lowest at all slope positions, while in 2018, precipitation peaked at all slope positions. The average annual precipitation was 249.74 mm for the uphill position, 290.4 mm for the middle slope position, and higher for the downhill position. Precipitation in the same area is significantly affected by slope gradient, following the pattern: downhill > middle slope > uphill.

2.2 Variation Patterns of PA Values at Different Slope Positions Across Different Temporal Scales

At the monthly scale, analysis of PA value variation patterns for the uphill slope (Figure 2) shows that drought thresholds were reached 23 times during 2015–2019, accounting for a high frequency. Light drought occurred 5 times, moderate drought 6 times, severe drought 3 times, and extreme drought 3 times, mainly concentrated in June and September. [Figure 2: see original paper]

For the middle slope (Figure 3), drought thresholds were reached 23 times. Light drought occurred 6 times, moderate drought 6 times, severe drought 3 times, and extreme drought 3 times, mainly concentrated in June and September, with peaks appearing in these months. [Figure 3: see original paper]

For the downhill slope (Figure 4), drought thresholds were reached 18 times. Light drought occurred 3 times, moderate drought 5 times, severe drought 4 times, and extreme drought 1 time, mainly concentrated in June and September, with peaks appearing in these months. [Figure 4: see original paper]

Overall, the monthly PA value variation patterns at different slope positions and in different years were generally similar. The PA values varied significantly in June–September each year, with high frequency of extreme drought during this period. Since precipitation is concentrated in June–September, the PA values during this period accurately reflect drought conditions. At the monthly scale, drought severity from high to low is: uphill > middle slope > downhill.

2.3 Comparison of Drought Intensity at Different Slope Positions at Seasonal and Annual Scales

From the annual seasonal scale PA value variation patterns (Figure 5), PA values differ significantly among slope positions. The downhill PA values are all positive, indicating precipitation exceeds the multi-year average and drought severity is lowest. Middle slope PA values are greater than uphill values, but in winter, middle slope PA values are much lower than uphill values and exceed the drought threshold, indicating light drought. The uphill peak appears in summer, while the middle slope peak appears in autumn. At the seasonal scale, drought severity from high to low is: uphill > middle slope > downhill. Summer shows the lowest drought severity, while winter shows the highest. [Figure 5: see original paper]

Figure 6 shows the average annual PA value variation patterns. The uphill PA value fluctuates, the middle slope PA value shows a decreasing trend year by year, and the downhill PA value increases year by year. The downhill PA value is much higher than uphill and middle slope values. At the annual scale, drought severity from high to low is: uphill > middle slope > downhill. Overall, the average annual PA values at different slope positions in each year did not reach the drought threshold, indicating that from the PA value analysis alone, the desert steppe at the northern foot of Yinshan Mountain did not experience drought during 2015-2019. [Figure 6: see original paper]

2.4 Construction of PA Value Model Combining Meteorological Factors

In addition to precipitation, meteorological factors affecting drought include air temperature, wind speed, solar radiation, and others. Principal component analysis was performed using the average values of measured meteorological data from 2015-2019. The descriptive statistics of each factor are shown in Table 2.

The principal component analysis results are shown in Table 3. The cumulative variance contribution rate of the extracted principal components reached 94.097%, indicating that these comprehensive indicators can fully reflect the differences among the above meteorological factors.

The component loading matrix of meteorological factors is shown in Table 4. Precipitation, air temperature, and relative humidity account for high proportions in the principal component analysis, indicating that these three meteorological factors can reflect drought phenomena in desert steppe.

Table 5 shows the change in the decision coefficient of the PA value fitting model. The adjusted R^2 and standard error of estimate⋯

Table 6 shows the variance analysis and test of the PA value fitting model. The results show that the regression model constructed with PA values has high fitting degree and practical significance for describing drought conditions in the desert steppe at the northern foot of Yinshan Mountain.

In summary, with PA value as the dependent variable for drought monitoring and precipitation (x_1), air temperature (x_2), and air humidity (x_3) as independent variables, the regression equation is:

$$Y_{PA} = 78.799 + 0.255x_1 - 3.395x_2 + 1.831x_3$$

The model shows high fitting degree and can effectively reflect drought conditions in the region.

3 Discussion

Precipitation analysis reveals significant variation in the desert steppe at the northern foot of Yinshan Mountain during 2015–2019, mainly concentrated in June–September. Precipitation follows the pattern downhill > middle slope > uphill, particularly evident in summer and autumn when precipitation is higher and more susceptible to other meteorological factors. Due to different site conditions, water flows more easily to middle and downhill positions during the rainy season, resulting in relatively less precipitation at uphill positions. The average annual relative humidity decreased significantly, showing an overall warming and drying trend, with warm-humid phenomena occurring only in a few years, consistent with recent related research results.

Regarding drought indicators, drought causation is complex and affected by multiple factors, making it difficult to find a universally applicable drought index []. The same drought index produces different monitoring results for different regions or different drought types, indicating that drought indices have significant regional characteristics or temporal scale requirements. Precipitation is the main influencing factor causing drought, while the Percentage of Precipitation Anomaly (PA) is a single-factor discriminant indicator that only considers precipitation. It is less affected by temporal scale and is not significantly influenced by low evaporation and temperature in winter, making it meaningful for analysis across different temporal scales. As basic research on the eco-hydrological system of the desert steppe at the northern foot of Yinshan Mountain, PA value calculation is simple, dependent variable data are easy to collect, batch processing is fast, and calculation results are direct and accurate, facilitating related research on desert steppe eco-hydrology.

Based on the above analysis, precipitation, air temperature, and relative humidity data from the desert steppe were selected to establish a multiple linear regression model with PA values for drought monitoring. Table 6 shows the relevant indicators of the PA value fitting model. The coefficient of determination R^2 is 0.994, indicating high regression contribution. The multiple correlation coefficient R is 0.997. The ANOVA test results show that the meteorological drought fitting model is highly significant ($P < 0.001$).

PA values were calculated for different slope positions in the desert steppe at the northern foot of Yinshan Mountain from 2015-2019. The monthly PA values in June–September fluctuated near the drought threshold. Since precipitation is concentrated in June–September, PA values during this period are most accurate. Comparative analysis across different temporal scales shows significant differences in monthly PA values, with different degrees of drought occurring each year. Precipitation is relatively low in June–September, with high frequency of extreme drought. Seasonal scale PA value analysis shows light drought occurred only in winter at the middle slope, while annual scale analysis shows the region did not reach the drought threshold. Slope position comparison shows precipitation pattern: downhill > middle slope > uphill, and drought severity pattern:

uphill > middle slope > downhill across all temporal scales. Considering only the single factor of precipitation, analysis of PA value variation patterns at different slope positions and annual scales shows that the region did not experience drought during 2015–2019, with sufficient annual precipitation.

Regarding model prediction, principal component analysis of meteorological data from the desert steppe at the northern foot of Yinshan Mountain identified precipitation, air temperature, and relative humidity as factors affecting regional meteorological drought, with a cumulative contribution rate of 94.097%. A multiple regression model was constructed combining these main meteorological factors with the drought index PA value. The modeling process used original monitoring data, with precipitation in different periods weighted against previous stage data, improving prediction accuracy. The coefficient of determination R^2 is 0.994, indicating high model fit. However, the PA value prediction model is mainly affected by seasonal variation, with larger PA value fluctuations in winter and spring and fewer valid data, resulting in relatively larger errors in the modeling process. Therefore, further research on meteorological drought index prediction analysis is needed using different indicators and analytical methods.

4 Conclusions

1. The precipitation at different slope positions of the desert steppe at the northern foot of Yinshan Mountain follows the pattern: downhill > middle slope > uphill, with corresponding drought index PA values: uphill PA > middle slope PA > downhill PA.

2. From observations at various temporal scales: monthly scale analysis revealed different degrees of drought at all slope positions with high frequency; seasonal scale analysis found light drought only in winter; annual scale analysis found that the region did not reach the drought threshold during 2015–2019, indicating sufficient average annual precipitation and no drought disaster.

3. The multiple regression model constructed based on main meteorological factors (precipitation, air temperature, humidity) and drought index PA value is: $Y\_\{PA\} = 78.799 + 0.255x_1 - 3.395x_2 + 1.831x_3$, with $R^2 = 0.994$, showing high model fit that can effectively reflect drought conditions in the region.

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