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Spatial Differentiation and Influencing Factors Analysis of Drought Characteristics Based on the Standardized Precipitation Index: A Case Study of the Yellow River Basin

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Abstract: It is crucial to identify drought characteristics and determine drought severity in response to climate change. Aiming at the increasingly serious drought situation in the Yellow River Basin, this study firstly selected the standardized precipitation index (SPI) and streamflow drought index (SDI) to analyze the characteristics of drought seasons, then identified the frequency, duration, and intensity of drought based on the run theory, and finally recognized the abrupt changing and driving factors of major drought events in specific years by the Mann–Kendall trend test. The conclusions showed the following: (1) The drought in the downstream of the Yellow River Basin was more severe than that in the upstream. The drought characteristics showed significant regional differentiation and deterioration. (2) The drought intensity and duration had an obvious spatial correlation. Compared with the other seasons, the drought duration and severity in spring and autumn were the most serious, and in winter, they showed an aggravating trend. (3) According to a time series analysis of drought conditions in the Yellow River Basin, the worst drought occurred in 1997–2001 with the least rainfall on record and a sudden rise in temperatures. This study could provide a scientific reference for agricultural drought disaster prevention and mitigation.

Keywords: extreme drought; standardized precipitation index (SPI); run theory; spatial–temporal characteristics

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1. Introduction

Drought is one of the most complex natural disasters, which results in seriously direct economic losses as high as USD 8 billion annually around the world [1–3]. Affected by global climate change, drought will be seriously aggravated in the next few decades, and the frequency of extreme drought will increase significantly, with a longer duration, wider impact, and higher intensity [4–7]. Because of its fragile climate zone and special geographical environment, China is one of the countries with frequent droughts and serious losses [8–11]. The Yellow River Basin is an significant ecological security barrier in China, as well as an important area for economic development and production activities. However, most of the basin is in arid and semi-arid areas. According to the drought disaster data recorded in the Yellow River Basin, major drought events occurred continuously from 1961 to 2012. Since the 1990s, the runoff from the source area and the upper reaches of the Yellow River have decreased significantly, and the affected area has increased year by year [12–14]. In Gansu, Shaanxi, Henan, Shanxi and Shandong Provinces, the drought area reached 75,300 km^2, and the crop area affected by the disaster reached 90,000 km^2, directly causing economic losses of up to CNY 6 billion in 2008 [15]. The frequent occurrence of drought disasters seriously threatens the economic development, agriculture, and water ecological security of the Yellow River Basin. It is of great significance to clarify the characteristics of climate change and drought in the Yellow River Basin.

The formation and evolution of drought is caused by geology, meteorology, and human activities [16–18]. Drought is characterized by a wide range of influence and a large area of disaster. It is of great practical significance to carry out drought risk identification and assessment accurately, for drought prevention and mitigation [19–21]. Scholars at home and abroad have conducted a lot of research on drought hazard identification, risk assessment, and drought evolution characteristics, combined with seasonal trend forecasting, drought indices, and land use and hydrological modeling techniques to assess drought risk [22–25]. Guo et al. evaluated drought dynamic hazard from a macro and micro perspective, to reveal how socioeconomic drought exerts direct negative impacts on the socioeconomic system [26]. Dunne et al. selected drought hazard, exposure, and vulnerability to calculate the drought risk index and produced spatial distribution maps for decision making in drought management strategies [27]. She et al. constructed a two-variable statistical model of drought duration intensity by the Copula function, to identify extreme drought events and evaluate drought risk [28]. Zheng et al. analyzed drought characteristics and compared meteorological and hydrological drought by using the SPI and standardized runoff index (SRI) [29]. With climate change, economic development, and population increase, drought is the most frequent natural disaster in the Yellow River Basin, and the economic losses and ecological problems caused by drought are also increasing [30,31]. The increase in water resource utilization in the middle and lower reaches of the Yellow River has also aggravated the drought situation in the region. An accurate identification and assessment of the intensity, duration, and risk of drought events is critical for drought mitigation [32,33]. Although studies on the spatial and temporal distribution of drought disasters are emerging, drought indices based on a single scale may not be reliable and scientific enough to assess drought risk and make decisions. It is critical to accurately identify drought factors, describe the temporal and spatial characteristics and driving factors of drought, and evaluate regional drought risk.

In this study, the SPI and SDI are combined to characterize the different seasonal changes in site-scale and region-scale drought events. On this basis, the frequency, duration, and intensity of drought are further identified by the run theory to reveal the spatial evolution law of drought factors. Finally, the MK trend test is used to reveal the abrupt characteristics of drought in specific years and analyze the main driving factors leading to the worsening of drought disasters. In conclusion, meteorological drought and hydrological drought were integrated to analyze the trend and influencing factors of drought, avoiding the limitations of considering only one drought index in a single scale. The research results are of great significance for maintaining ecological security and reducing the risk of extreme drought in the Yellow River Basin.

2. Study Area

The Yellow River Basin is significant to China's economic development and high-quality ecological development (Figure 1), and it is located in northern China, between 32° N and 42° N, 96° E and 119° E, involving Qinghai, Shaanxi, Shanxi, the Ningxia Hui Autonomous Region, and other provinces, covering about 790,000 km^2 area. The terrain of the Yellow River Basin fluctuates significantly, from high in the west to low in the east, and rainfall is unevenly distributed due to geographical climatic conditions. With the effect of natural factors and anthropogenic activity, the drought events in most arid and semi-arid areas have become increasingly intensified.

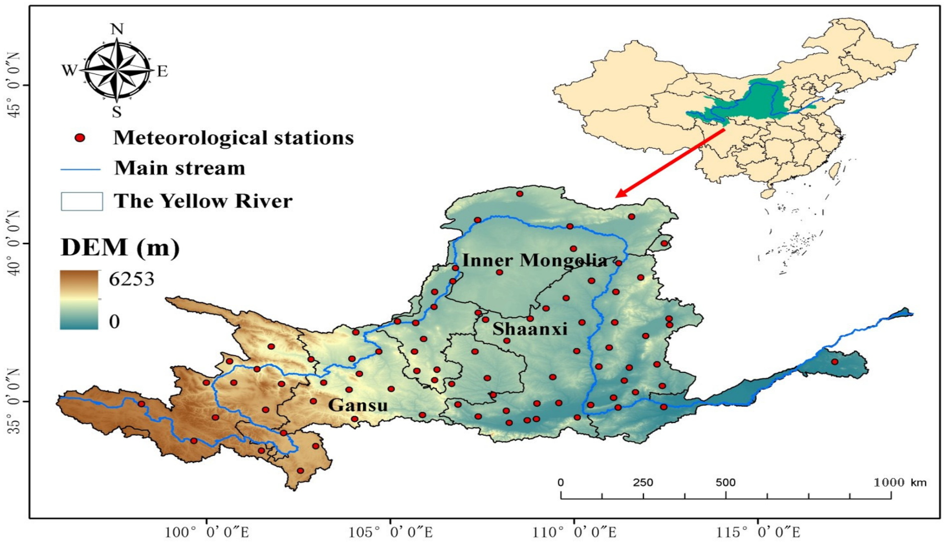

Figure 1. The location of the Yellow River Basin and meteorological stations.

3. Data and Methods

3.1. Data Sources

The daily precipitation from 1991 to 2018 was acquired from the National Meteorological Information Center (NMIC) at the China Meteorological Administration (CMA) (http://data.cma.cn/ (accessed on 28 June 2023)) and processed into a monthly scale. Some of the missing values in this dataset are supplemented by linear interpolation of the contemporaneous data. The streamflow data from 1991 to 2018 named CNRD v1.0 (The China Natural Runoff Dataset version 1.0) are obtained from A Big Earth Data Platform for Three Poles [34]. They have proved that the dataset has a good regionalization performance and can be used for long-term drought reconstruction.

3.2. Methods

3.2.1. Standardized Precipitation Index

The SPI is used to represent the probability of the occurrence of precipitation in a certain period, which is suitable for monitoring and evaluating drought in different regions and different time scales and which meets the needs of various drought studies. The SPI index is simple, and precipitation data are easy to obtain, so it has been widely used to identify the characteristics of drought change in different river basins. With reference to the definition of drought grades issued by the China Meteorological Administration, the distribution of precipitation is a skewed distribution, so in the precipitation analysis, the τ distribution probability is used to describe the change in precipitation, and then the normal normalization is carried out. Finally, the drought grade is classified by the standardized precipitation accumulation frequency distribution.

Assuming that the precipitation in a certain period is a random variable x, then the probability density function of its distribution is:

$$f(x) = \frac{1}{\beta^{\gamma}\tau(\gamma)} x^{\gamma-1} e^{-x/\beta} \quad x > 0 \tag{1}$$

where $\beta > 0$, $\gamma > 0$, and it can be obtained by the maximum likelihood estimation method.

For precipitation x_0 in a certain year, the probability of the event that the random variable x is less than x_0 can be calculated as:

$$F(x < x_0) = \int_0^{x_0} f(x)dx \tag{2}$$

where the τ distribution probability is normalized, and the probability value obtained by Formula (2) is substituted into the normalized normal distribution function:

$$F(x < x_0) = \frac{1}{\sqrt{2\pi}} \int_0^{x_0} e^{-\frac{Z^2}{2}} dx \tag{3}$$

$$Z = S\left[t - \frac{(c_2 t + c_1)t + c_0}{((d_3 t + d_2)t + d_1)t + 1.0}\right] \tag{4}$$

where $t = \sqrt{ln\frac{1}{F^2}}$, F is the probability of formula (2); when $F > 0.5$, $S = 1$, when $F \leq 0.5$, $S = -1$. Z is the standardized precipitation index (c_0 =2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, d_3 = 0.001308).

A higher SPI value means the area is wetter, and the lower the SPI value is, the drier the area will be [35]. SPI1, SPI3, SPI6, and SPI12 were respectively used to detect drought variations at different time scales for 1 month and 3, 6, and 12 months.

3.2.2. Streamflow Drought Index

Based on the observed runoff data, the streamflow drought index (SDI) can calculate hydrological drought conditions at different time scales and reflect the change in drought events due to the lag caused by seasonal changes. The SDI has a similar calculation process and data output to the SPI and can investigate rain and drought periods, as well as the severity of drought disaster events. The calculation method for the SDI can be referenced in the literature [36].

3.2.3. Run Theory

Run theory is used to determine characteristic variables of drought hazards, such as the number, duration and severity of drought events, based on monthly rainfall data [2]. Drought duration refers to the duration from the occurrence of a drought event to its end, and drought severity is the absolute value of accumulated SPI during a drought event. Drought characteristics can be identified by setting a drought threshold and intercepting a time series. If the disaster index is less than the drought threshold and the duration exceeds a certain length, a drought event can be determined. Taking the SPI as an example, a run theory diagram is shown in Figure 2. Here, X0, X1, X2 represent drought threshold, when SPI is less than X0, drought occurs (a); otherwise, no drought occurs (d). The time interval between two adjacent drought events (b, c) is considered as one period, and if the SPI during the period is less than X2, two droughts can be combined into one drought event.

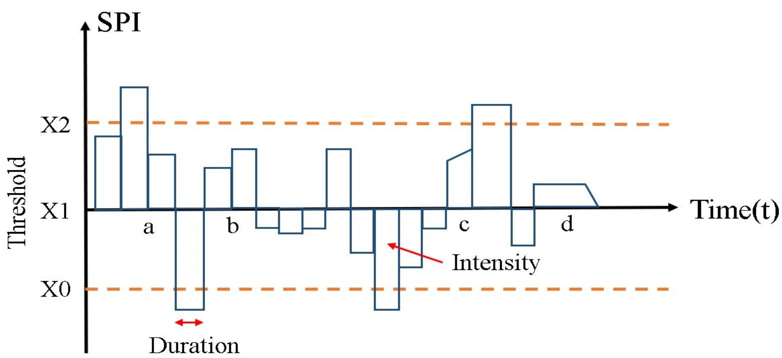

Figure 2. Drought characteristics identification process based on threshold method.

According to the grades of meteorological drought promulgated by the China Meteorological Administration and the actual situation in the Yellow River Basin [37], as shown in Table 1, when the drought index is less than the drought threshold, drought disaster occurred.

Table 1. Drought classification criteria.

Drought Status	Range	Drought Status	Range
Particularly Severe Flooding	SPI > 2.0	Normal	SDI ≥ 0
Severe Flooding	1.5 < SPI ≤ 2.0	Mild Drought	−1.0 ≤ SDI < 0
Moderate Flooding	1.0 < SPI ≤ 1.5	Moderate Drought	−1.5 ≤ SDI < −1.0
Mild Flooding	0.5 < SPI ≤ 1.0	Severe Drought	−2.0 ≤ SDI < −1.5
Normal	−0.5 < SPI ≤ 0.5	Particularly Severe Drought	SDI < −2.0
Mild Drought	−1.0 < SPI ≤ −0.5		
Moderate Drought	−1.5 < SPI ≤ −1.0		
Severe Drought	−2.0 < SPI ≤ −1.5		
Particularly Severe Drought	SPI ≤ −2.0		

3.2.4. Mann–Kendall Trend Test

The Mann–Kendall trend test is suitable for analyzing time series data with a continuous growth or decline trend, and the samples do not have to follow a certain distribution; the absence of some data will not affect the result, and it is not interfered with by a few outliers. This method can reveal the trend change in a whole time series and test abrupt points, and it is widely used in testing the trend change in a long time series of hydrologic meteorological elements.

Supposing that the two subsets of the data series are X_i and X_j, and $i = 1, 2, 3, \ldots, n-1$, $j = i+1, i+2, i+3, \ldots, n$. The Mann–Kendall S Statistic can be shown as follows [38,39]:

$$S = \sum_{i=1}^{n-1} \sum_{j=j+1}^{n} sign\left(X_j - X_i\right) \tag{5}$$

$$Sign\left(T_j - T_i\right) = \begin{cases} 1\ if\ X_j - X_i > 0 \\ 0\ if\ X_j - X_i = 0 \\ -1\ if\ X_j - X_i < 0 \end{cases} \tag{6}$$

The variance (σ^2) for S can be defined as follows:

$$\sigma^2 = \frac{[n(n-1)(2n+5)]}{18} \tag{7}$$

The standard test statistic Z_S is shown by:

$$Z_S = \begin{cases} \frac{S-1}{\sigma}\ for\ S > 0 \\ 0\ for\ S = 0 \\ \frac{S+1}{\sigma}\ for\ S < 0 \end{cases} \tag{8}$$

when $|Z_S| \geq 2.576$, $|Z_S| \geq 1.960$, $|Z_S| \geq 1.645$, the confidence levels of the data series are 0.01, 0.05, and 0.1, respectively. Here, a confidence level of 0.05 was used to analyze the significant change trend of drought in dry years.

4. Results and Analysis

4.1. Seasonal Spatial Evolution of Drought in the Yellow River Basin

To analyze the effects of different seasons on drought evolution in the basin, the study made use of the meteorological stations and monthly rainfall data in 1991–2018 to calculate the multi-year average SPI and SDI, to reveal the spatial change of each grid cell. Figure 3 shows the spatial distribution of seasonal-scale drought trends. It shows that the drought degree of response units in different seasons and different regions were significantly discrepant in space, and the spatial evolution patterns of the SPI and SDI were consistent. The value of majority regions in the Yellow River Basin was between −1 and 0 in the blue and yellow grids. It illustrates that the basin saw a trend of severe drought, and the downstream was much more serious than the midstream and upstream, especially in spring and winter.

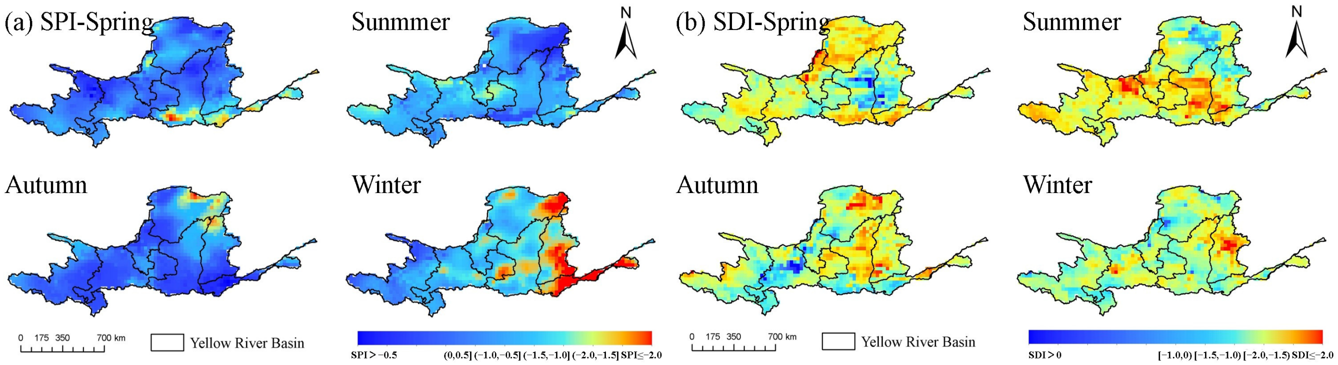

Figure 3. Spatial distribution of seasonal scale drought trend: (**a**) SPI; (**b**) SDI.

From the perspective of meteorological drought, the downstream SPI in spring was less than −0.5, which indicated that the drought in this area was serious. In addition, some cities in the southern Shaanxi Province and nearby areas in Henan Province had regional drought characteristics (Figure 3a). Compared with spring, the drought in the lower reaches was alleviated, the middle reaches were correspondingly humid, and the drought trend in the upper reaches was prominent in summer. Autumn drought was most severe in the eastern part of the middle reaches, followed by the northern part of Shaanxi Province and some areas adjacent to Henan Province. In winter, the upper reaches were mostly humid, while the middle reaches and the lower reaches of Henan and Shandong Provinces showed a severe drought trend.

In addition, the spatial distribution of the SDI indicated that the drought trend in the Yellow River Basin had obvious seasonal characteristics (Figure 3b). The drought in the upper reaches of the basin was most severe in summer, followed by spring. In the middle reaches, the spring drought was most obvious, followed by autumn. The drought characteristics in spring and autumn were more significant in the lower reaches. The spring drought was most severe in the midstream, the summer drought was concentrated in Shaanxi and Gansu, the autumn drought was mainly in northern Shaanxi and the middle reaches of the basin, and the winter drought was mainly in the eastern part of the basin. Through comparison, with the change in seasons (spring to winter), the grid cells of the study area followed a spatial–temporal evolution law from wet to dry and then to wet.

4.2. Spatial Evolution Characteristics of Drought Characteristic Variables Based on Run Theory

Drought is an extreme climate event with multi-variable characteristics, such as drought duration, drought intensity, and the disaster area. This study selected the run theory method, based on threshold recognition, to identify the three characteristic factors of drought frequency, duration, and intensity by a time series analysis, as shown in Figure 4.

Drought characteristic factors identified in different regions in the same season and different seasons in the same region had obvious spatial differences. Drought duration and drought intensity also showed a significant positive correlation. Generally, in spring and winter, the drought frequency was low, while the drought duration was longer and the intensity was also higher. Although the times of drought in summer were greater, the drought duration was shorter and its intensity was less than in other seasons. The spring drought frequency upstream was lower, but the drought duration and intensity were greater. In summer, drought was most frequent in some parts of Gansu Province, but the duration and climate disaster severity caused by drought were low. In autumn, the frequency of midstream drought was lower, while the duration and severity of drought were greater. In winter, especially in some areas of Shandong Province, the lower reaches showed a trend of worsening drought.

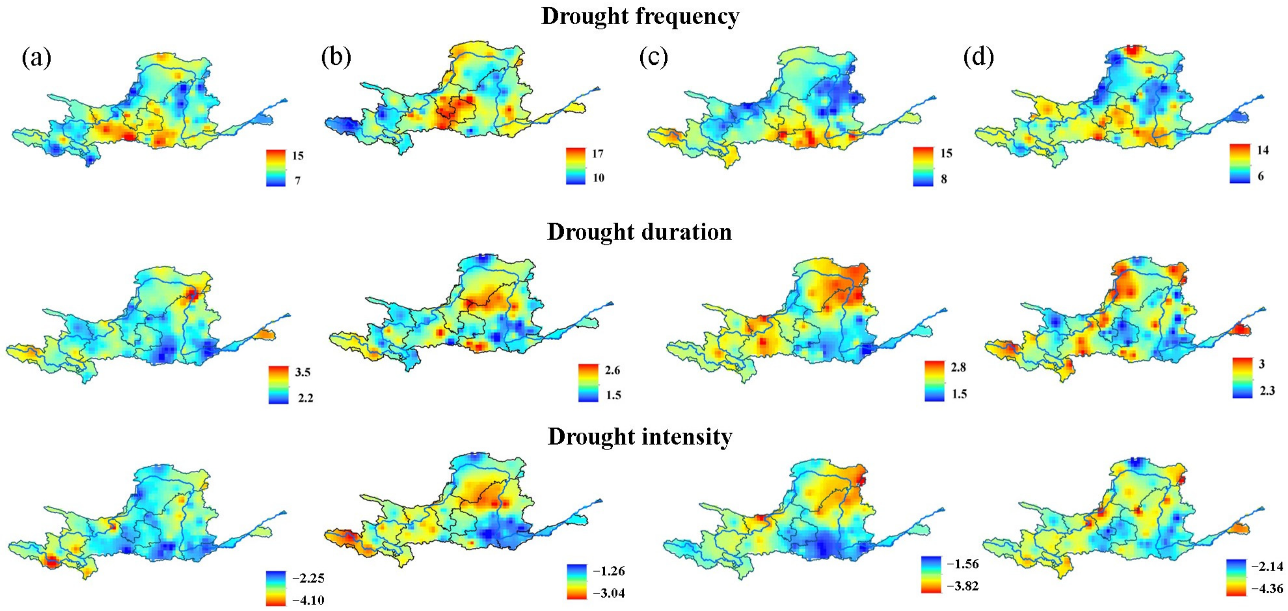

Figure 4. Spatial distribution of drought frequency, drought duration, and drought intensity in the Yellow River Basin: (**a**) spring; (**b**) summer; (**c**) autumn; (**d**) winter.

In conclusion, the spatial distribution of drought characteristic factors in different seasons and regions was various, and drought duration and drought intensity had a certain spatial correlation. Identifying the spatial distribution of drought characteristic factors in study regions at different time scales was very important for the drought events evaluation.

4.3. Spatial Correlation of Drought Characteristic Variables on Seasonal Scale

Figure 5 shows the statistical results for drought frequency, drought duration, and intensity in diverse seasons. Compared to the median of the box chart, the drought frequency in summer and fall was higher than in other seasons. The median frequency in winter and spring was the same, but the drought frequency in spring was significantly higher. It indicated that more drought events occur in most regions of the basin in summer and autumn, and in some areas, droughts occur more than 15 times. However, in spring and winter, the drought frequency was relatively low in some areas. There are more droughts in summer and autumn, and the drought was worsening.

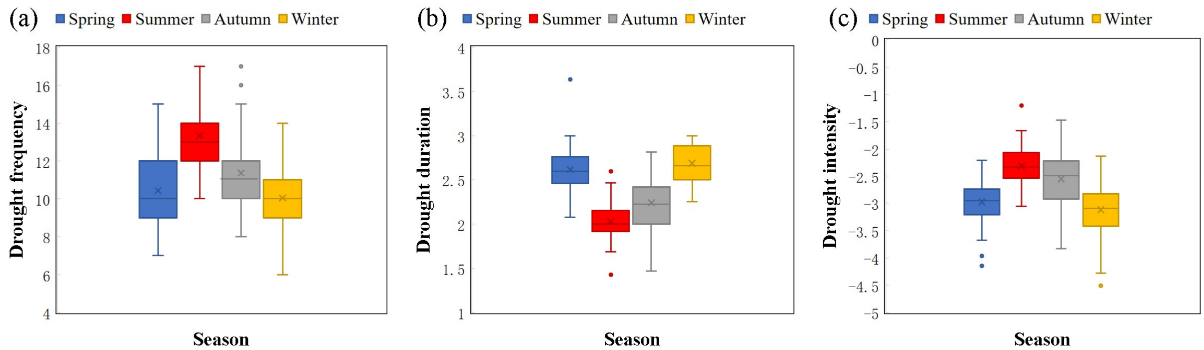

Figure 5. Statistical results of drought frequency, duration, and intensity in different seasons. (**a**) drought frequency; (**b**) drought duration; (**c**) drought intensity.

In the spatial distribution of drought characteristics in Section 4.2, there was a strong positive relevance between drought duration and intensity. Based on the statistical results of 85 meteorological stations in the basin, although the frequency of drought in spring was lower, the drought duration was long and the drought intensity was high. Drought events occurred frequently in spring and autumn, but the duration and intensity of drought were low in general. According to the median of the box chart, the duration and intensity of drought in winter and spring were greater than those in summer and autumn, which indicates that more severe drought events are more likely to occur in spring and winter and cause considerable direct or indirect losses. In addition, droughts that occurred in the basin during the winter tended to extend into the spring of the following year, which meant that droughts in spring were more severe than in other seasons.

4.4. Variation Trend of Drought Characteristics in Yellow River Basin

Figure 6 represented the change sequence of the SPI and SDI; there was an obvious discrepancy in the different time scales. On the monthly scale, the fluctuation frequency indicated that the basin appeared to show a trend of light drought, while on the seasonal and semi-annual scales, it showed a more frequent alternating phenomenon of drought and flood and had an obvious mutation from 1997 to 2000, demonstrating a significant trend towards drought in the basin during this period. In the 1990s, the temperature increase was obvious, while the rainfall decreased year by year significantly, and since 2000, the decline has eased [40,41]. In terms of annual scale, there was no obvious alternation of drought and flood in the fluctuation of time series, and the SPI and SDI were not completely synchronized, which showed that hydrological drought lagged behind meteorological drought. In some years from 1995 to 2003, the SPI value of the basin was less than −1, and the SDI value was also significantly decreased, indicating that relatively serious drought events occurred in the basin during this period.

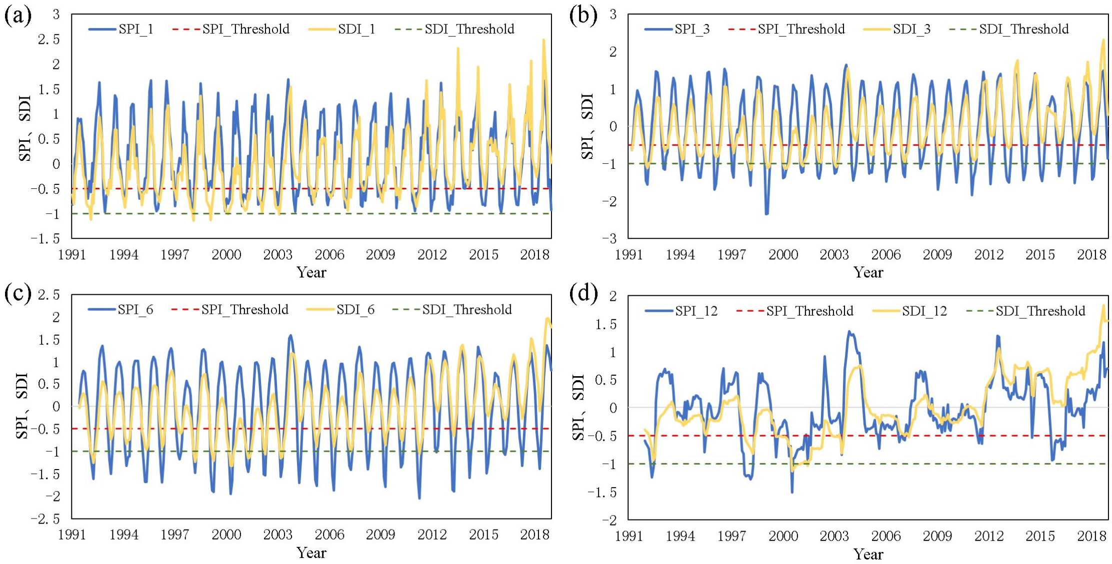

Figure 6. The time series of the Yellow River Basin from 1991 to 2018. (**a**) SPI_1, SDI_1; (**b**) SPI_3, SDI_3; (**c**) SPI_6, SDI_6; (**d**) SPI_12, SDI_12.

4.5. Influencing Factors Analysis of Drought in Yellow River Basin

According to the MK trend test (the pre-established significance level was set at 0.05) for abrupt changes in the SPI time series, the drought trend decreased significantly from 1996 to 2001, and most of the drought events were moderate drought. By analyzing the occurrence process of these drought events, it can be concluded that the first drought event occurred in 1997, which was also the most severe drought year (Figure 7). And the drought continued to intensify from the summer of 1997 until the winter of that year; the average SPI value reached −1.22, the SDI showed an obvious downward trend, and the drought continued until the spring of 1998, the average SPI value reaching −1.28. The drought basically ended in the summer of 1998. The second drought began in the spring of 2000 and was most severe in the summer of 2000, with seasonal changes, with an average SPI of −1.5; the SDI exceeded the critical threshold (−1), before easing in the winter of 2000. The drought event lasted until the spring of 2001, but during this period, most of the events were light droughts, with more frequent droughts but less intense droughts at a seasonal scale. The main reasons for these two droughts were low annual precipitation and continuous high temperature in most areas, which accelerated water evapotranspiration and intensified the drought trend [42,43].

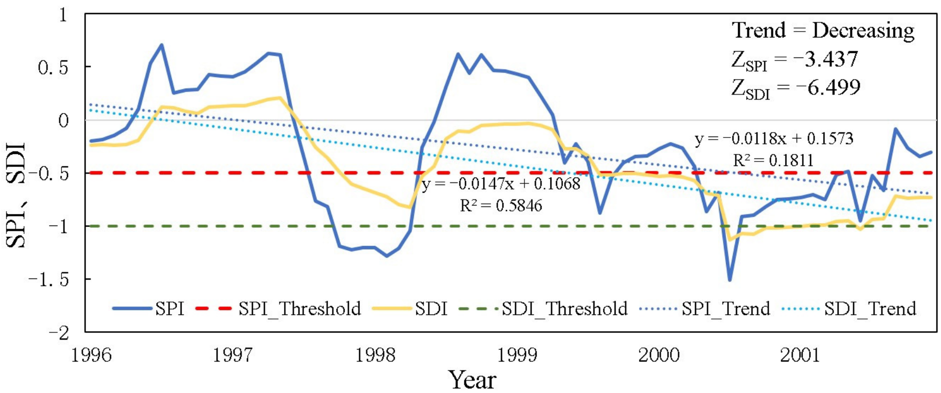

Figure 7. Variation in drought trend of Yellow River Basin from 1996 to 2001.

Figure 8 shows the variation trends for precipitation and temperature from 1991 to 2018 in the Yellow River Basin, and the average annual precipitation is about 473 mm. Most of the precipitation before 2000 was lower than the average, especially in 1997, the drought in the Yellow River Basin was the most serious, and the annual precipitation had the lowest value in many years. After 2000, precipitation showed a fluctuating upward trend, and the annual precipitation in most years was greater than the average.

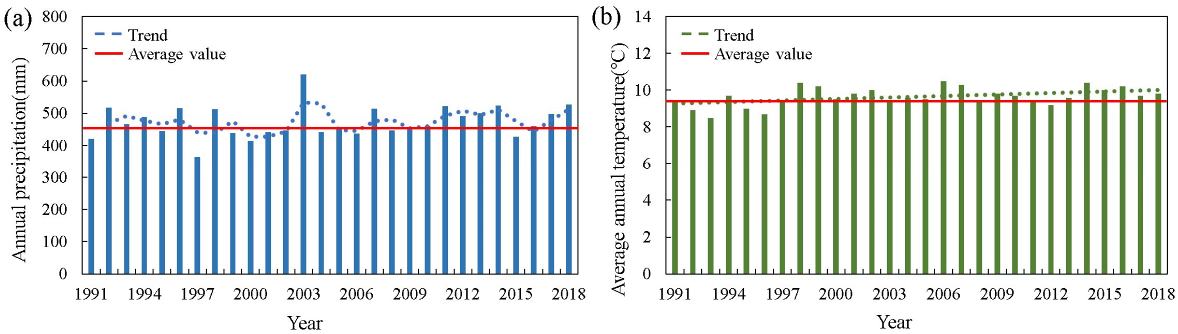

Figure 8. Annual precipitation and average annual temperature of Yellow River Basin from 1991 to 2018. (**a**) annual precipitation; (**b**) average annual temperature.

As shown in Figure 8b, annual precipitation revealed a slight escalating trend from 1991 to 2018, and the average annual temperature increased obviously during this period. The annual average temperature in the Yellow River basin is about 9.6 °C. Before 1997, the average annual temperature was mostly below average temperatures; however since 1997, due to global warming, the temperature in the basin has increased significantly. The range and trend of temperature increase are discrepant in different regions and seasons of the basin. However, with the obvious trend of a temperature rise in the Yellow River Basin, evapotranspiration will also increase, which has a certain impact on the water cycle in the basin. At the same time, temperature is also the other important factor generating drought disaster.

5. Discussion

Drought is one of the most extensive and serious natural disasters in the world. The analysis of drought evolution law and spatial distribution is of great significance for drought relief and ecological security. According to the spatial distribution of the SPI, SDI, and drought characteristic variables in different seasons, there is a phenomenon of changing from wet to dry and then to wet in the same region with seasonal changes. In general, the drought in the basin was severe, and the lower reaches were more arid than the midstream and upstream, especially in spring, summer and winter. In addition, the drought trend of the Yellow River Basin was significantly intensified in winter, mainly concentrated in Shaanxi Province, Henan Province, and the middle and lower reaches of the Yellow River Basin, with serious drought frequency and intensity, and winter drought was more likely to last until the next spring. Spring drought is mainly concentrated in southern Shaanxi Province and the upper reaches of the Yellow River Basin, with a long drought duration and high drought intensity. The drought frequency in summer was mostly concentrated in the midstream and upstream of the basin. The duration of autumn drought was short and concentrated in the upper reaches and the northern area. Zhou and Ren et al. showed that the degree of drought in the upstream is lower than that in the lower reaches, especially Sanmenxia of Henan Province; this is consistent with the results of this study [2,38], but there were distinctions in drought severity and duration in some seasons, which may be due to differences in the time range and specific methods employed by the studies.

In this study, the SPI and SDI were used to describe the drought evolution and drought characteristic factors in the Yellow River Basin on a seasonal scale, and then the influencing factors leading to an abrupt change in drought trend were analyzed. However, this study did not comprehensively analyze the formation and evolution mechanism of drought disaster. In future research, the collection of multi-source data, such as soil moisture continuous monitoring data, to simulate the hydrological cycle process is an important direction to further study the characteristics of drought evolution.

6. Conclusions

Choosing the Yellow River Basin as the research area, the SPI and SDI were adopted to reveal the temporal and spatial evolution of drought events on a seasonal scale, and threshold-based run theory was adopted to identify drought characteristic factors and further explain drought evolution in different seasons. The M-K trend test was used to analyze the time series and the inducing factors of major drought events. The results were as follows:

(1) There was spatial heterogeneity in the drought characteristics of the Yellow River Basin. The response to drought in the same area on different time scales and different areas on the same time scale was inconsistent.
(2) In general, there was a prominent positive correlation between drought duration and intensity. Compared with other seasons, the drought frequency in summer was higher, the drought duration and severity in spring and autumn were the most serious, and the drought in winter showed an aggravating trend.
(3) By comparing the annual precipitation and average annual temperature of the basin from 1991 to 2018 and analyzing typical severe drought events in 1997, it can be concluded that the key factors affecting the change of drought severity were precipitation and temperature.

This study demonstrated the spatial and temporal evolution of drought on different scales in the Yellow River Basin from 1997 to 2018, and it analyzed the driving factors inducing drought in special years and months, which can provide references for drought prevention and reduction.

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