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Agricultural drought characteristics identification and analysis of Henan Province in China

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ABSTRACT

In Henan Province the impact of drought on agricultural production is severe, and agricultural drought has become a seriousproblem, restricting economic development. Agricultural drought characteristics were studiedusing run theory followed by intensive analysis of precipitation data across the province. The data analysis focused on 18 sites in Henan Province from which data (1951-2010) was selected and the Mann-Kendallmethod was appliedin the analysisof trends in precipitation, percentageof precipitation anomalies, total frequency of drought, and occurrence frequencies of four drought levels. The average annual rainfall in Henan Province showed a trend of increasing precipitation, but the trend was weak and basically stable. Meanwhile, the annual rainfall fluctuation wasgreater. For precipitation and precipitation anomaly percentage, there was an increasing trend in the southern region and a decreasing trend in northern region, which indicated that northern Henan Province has suffered more drought thanthe southern region. Further investigation using multi-scale wavelet analysis for years with distinct precipitation anomaly percentagesrevealed two main cycles of 10 and 22 years for agricultural drought in Henan province.

KEYWORDS

Run theory; Agricultural drought; Precipitation anomaly Percentage; Mann-kendall method; Wavelet analysis.

INTRODUCTION

Drought is one of the costliest and most widespread naturaldisasters[1] that may have devastatingimpacts on agriculture, water resources, environment andhuman lives. Droughts occur over most parts of the world, bothin wet and humid regions[2]. The spatial and temporal variationof drought ranging from regional to national scale hasbecome a research hot topic in Chinafor the past few years. The previous studies ofdrought during the past decades using SPI showed that the easternpart of China being far more hazardous than the western part, severe drought increased graduallyover China, while rapidly increased in southwest China, north Xinjiang had a decreasing trend of droughtseverity[15].

Henan Provinceis located in the middle and lower Yellow River regions of central China (Figure 1). Its geographic range extends from 31°23′ to 36°22′N and from 110°21′ to 116°39′E. Theprovince is surrounded by mountains, withhigh topography in the west and low topography in the east. Most areas of Henan Province are located in the warm zone, with parts of the southextending into the subtropical zone. Its climatetransitions froma plains regime in the east to a mountain regimein the west. Henan Province is impacted by the continental monsoon climate, which is generally characterized by:1) four distinct seasons, 2) a combination ofrain and heat in the same period, 3) complex and diverse climate patterns, and 4) frequentmeteorological disasters[4]. Itstotal land area is 165500 km^2, accounting for nearly 1.73% of the entire landarea in China. It extends into four major river basins, including theHuaihe River, the Yangtze River, theYellow River and the Haihe River. Itsmean total water volumeis40.356 billion m^3, ranking 19thamong Chinese provinces. It is one of the more water deficientareas in China, with only about 20% of the amount of water resources per arable land areain comparison to that of the entire country.

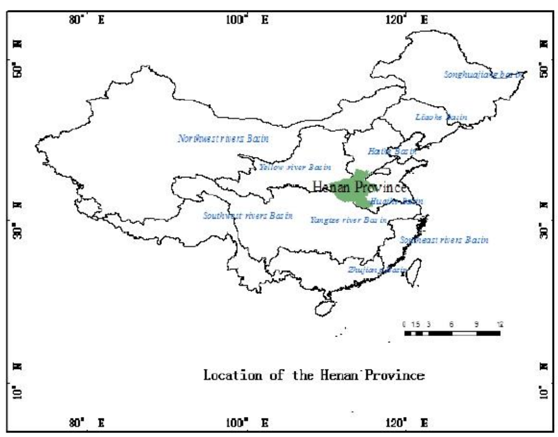

Figure 1: Location of the study region

Of all the disasters in Henan Province, the impact of drought on agricultural production is especially important. According to statistics from 1990 and 2007, the province's annual area subject to droughtis2.62×10^6ha, withan affected area of 8.39×10^5ha, an inundated area of5.75×10^5ha, and a severely affected area of 1.98×10^5ha. The resulting average annuallossof grain output is 27.86×10^5kg. Drought impactsinclude average annual drinking water shortages to a ruralpopulationof 1.05million, a large livestockpopulation of 380thousands, and an urban population of11.07million. Since the1990s, droughthas increased infrequency, scale, andduration, withincreaseddisaster lossesand other undesirable impacts. Agricultural drought has become an increasingly important factor severelyrestricting economic development.

The present study focusses on agricultural droughtidentification and characterizationin Henan Province using Run theory, Kriging, Mann-Kendall (M-K for abbreviation), and wavelet analysis approach, and thesepatterns should increase our understandingthe agriculturaleffects of drought. It can provide an effective theoreticalfoundation for regional drought prevention plans and for sustainable development of ecological agriculture in Henan Province. The remaining parts of this paper are organized as follows. Section 2 describes the agricultural drought featureusing Run theory. Section 3discussesagriculturaldrought trend and spatial distribution. Section 4 discussesagricultural drought period using wavelet analysis approach. Finally, someconclusions are given in Section 5.

AGRICULTURAL DROUGHT FEATURE RECOGNITION

Run theory

Run theory wasused to identify droughtcharacteristicswitha drought index. The threshold values of droughtindicators are set as R0, R1 andR2. When thedrought indexis less thanR1, we preliminarily judgethis periodto be in drought. On this basis, for droughts lasting only one period, if the drought index valueis less than R2, thenthis time period was classified as one droughtcourse, the converse was notcounted asdrought. Fortwoadjacentdroughtsin one timeinterval, if the drought indexvalue of the intervalis less thanR0, then thesetwoadjacentdrought processeswere considered asone, otherwise as two independentdrought events. Droughtseverityrefers to thecumulativedifference between thethresholdvalue andthe actual value of the droughtindicators (Figure 2). Drought intensityis defined as the ratio of drought severityoverdrought duration. Drought durationand droughtseverityare the twomost importantcharacteristic variablesof drought. In this study, onlythe drought severity variable is used for analysis.

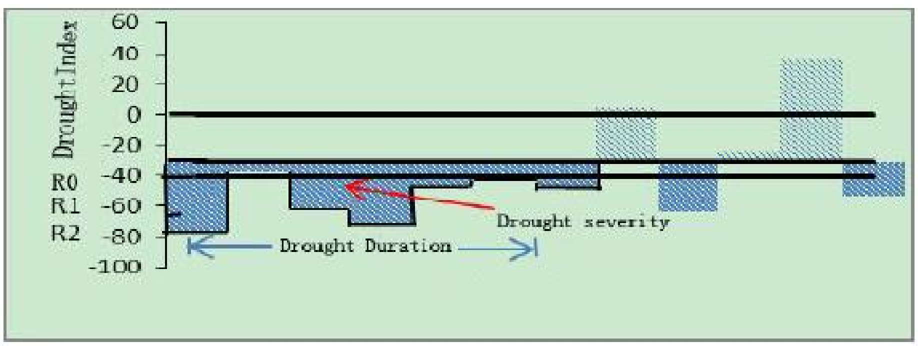

Figure 2: The identification of drought and the determination of drought variables

Characteristics for identification of agricultural drought

(a) Drought index determination

There are many kinds of evaluation indices of agricultural drought. Commonly usedindices include theanomaly percentage, PDSI[8], and SPI[7]. Different indicatorsare applicable to different types of drought. The SPI is relatively simple, spatially consistent, and can be calculated on any desired time scale. However, the SPI does not considersnow/frozen ground, soil conditions, distribution of rainfall withinthe time scale evaluated, or temperature data[6]. Also, zeroprecipitation valuesmayskew the SPI towards positive numbers in arid regions and atshort time scales[13].

The precipitation anomaly percentageindex reflects the value of hydrological factors deviating from the average level of the same period over many years. It is the simplestindicator to understand, the easiest to use, and the most widely applicable.

In this paper, precipitation anomaly percentage is adopted as a drought index. It is calculated as follows:

$$D_P = \frac{P - \overline{P}}{\overline{P}} \times 100\% \tag{1}$$

where$D_P$is the precipitation anomaly percentage (%);P is the rainfall over thecalculation period (mm); and$\overline{P}$ is the average annual rainfall for many years over the same period (mm).

(b) Analysis of drought characteristic variables

The precipitation anomaly percentage is calculated from monthly rainfall precipitation data cover ingnearly 60 years from 1951-2010. It is used as an indicator of agricultural drought. Based on run theory, according to agricultural drought classification guidelines and historical analysis of drought in Henan Province, taking the R0, R1, and R2 values, respectively, 0, -30, and -40, monthly time periods of drought severity and drought duration valuesforalmost 60 years in Henan Province are obtained (TABLE 1). The corresponding statistical unit of drought severity is -100%, and the statistical unit of drought duration is1 month. The P-III distribution function and the exponential function are selected to fit the data, and to draw the distribution curves (Figures 3& 4).

TABLE 1: Drought severity（*DS*, -100%）and drought duration (*DD*, month) statistics

DS	*DD*	*DS*	*DD*	*DS*	*DD*	*DS*	*DD*	*DS*	*DD*
152	2	171	3	72	2	49	1	210	3
98	2	118	2	85	1	86	1	143	2
98	1	161	3	96	1	54	1	87	1
56	1	49	1	73	1	83	1	53	1
56	1	143	2	79	2	98	1	232	5
131	2	138	2	335	6	117	2	116	2
146	2	59	1	43	1	124	2	71	1
108	2	176	3	76	2	54	1	151	3
69	1	350	8	75	1	150	2	129	2
50	1	41	1	102	2	130	2	80	1
170	3	57	1	133	2	116	4	45	1
160	2	158	2	53	1	91	2	81	1
89	1	54	1	171	2	165	4	96	1
321	4	51	1	87	1	207	4	60	1
91	2	74	1	40	1	54	1	176	3
154	2	309	4	183	2	66	1	115	2
84	1	45	1	124	2	277	5	43	1
46	1	126	2	107	2	77	1	277	4
50	1	45	1	119	3	352	7	52	1
144	3	85	3	41	1	98	1	89	1
47	1	62	1	226	3	308	7	48	1
72	2	57	1	389	6	43	1	344	4
54	1	50	1	42	1	448	6	229	5
187	3	215	3	94	2	120	3		
88	2	96	2	431	10	148	2		
105	2	174	3	73	1	261	4		

The optimal drought severityP-III distribution curve is drawnusing the curve-fitting method. The parametervalues are as follows: expectation*Ex* =124.92, deviation coefficient *Cs* = 2.15, and the coefficient of variation *Cv* = 0.72.

According to the Henan drought severity P-III distribution curve, thefrequency of various agricultural droughtseverityvalues can be determined readily.

When the exponential distribution is selected as the distribution function of agricultural drought duration, afrequency histogram of agricultural drought duration in Henan Province is drawn. The optimal distribution curve of drought durationis obtained throughthecurve fittingmethod. Its distribution function is: $F(x) = 79.163e^{-0.534x}$. The frequency of occurrence of drought events lasting 1-4 months is relatively high, whereasthe frequency of occurrence of drought events lasting more than four months is relatively low. The Pearson correlation coefficient for drought severity and drought duration is 0.91, indicatinga large degree of correlation.

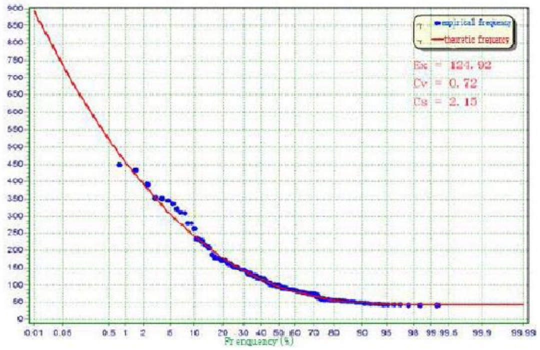

Figure 3: Drought severity frequency curve

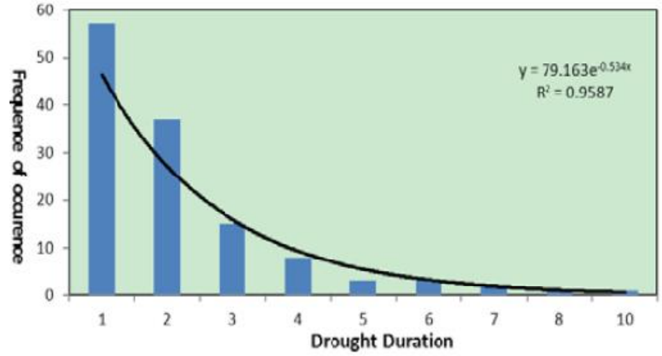

Figure 4: Drought duration frequency curve

AGRICULTURALDROUGHT TREND ANALYSIS AND SPATIAL DISTRIBUTION

Rainfall distribution and trend analysis

The data from18 sites from1951 to 2010 areused to characterize agricultural drought in Henan Province. The sitesselectedare shown in TABLE 2.

TABLE 2: The selected study sites

Sites	Anyang, Xinxiang, Sanmenxia, Lushi, Mengjin, Luoyang, Luanchuan, Zhengzhou, Xuchang, Kaifeng, Xixia, Nanyang, Baofeng, Xihua, Tongbai, Zhumadian, Xinyang, Yongcheng

Based on statistical analysis of the average annual rainfall of nearly 60years (1951-2010) in Henan Province, the inter-annual rainfall increased overall but the trend is not obvious (Figure 5). The inter-annual rainfall had relatively large fluctuations and a certain period. The maximum annual rainfall was 1115.90mm and the minimumwas only 80.30mm. Henan Province underwent varying degrees ofdrought in 1960,1968,1986,1999 and in several subsequent years. Extraordinarydroughtstook place in1960, 1986 and 1990.

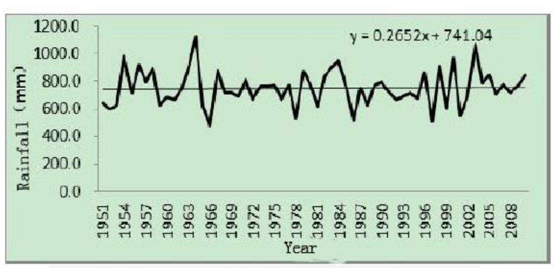

Figure 5: Henanrainfall distributionover the years 1951 to 2010

Rainfall differences (Figure 6A) and rainfalltrends (Figure 6B) in the Henan region were analyzed forthe 18 sites with the M - K test. The average annual rainfall in Henan showed a gradual decrease from south to north. In the northern region of Henan, the multi-year average precipitation of Xinxiangwas 574.10mm, and the multi-year average precipitation of Anyang was 575.30mm. In the center region of Henan, the multi-year average precipitation of Zhengzhou was 645.90mm, and the multi-year average precipitation of Xuchang was 726mm. The multi-year average precipitation of Xinyang in the southern region of Henan was 1104.30 mm. Rainfall in the northern region showed a decreasing trend, while rainfall in central region showed an increasing trend.

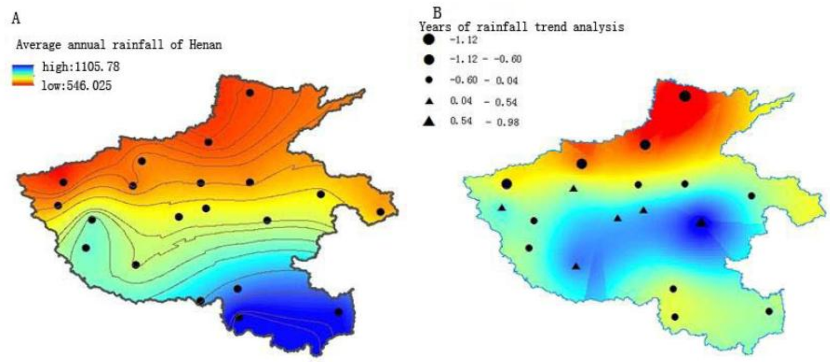

Figure 6: Henan rainfall shown as (A) multi-year average rainfall, and (B) the multi-year average annual rainfall trend

Distribution and trend analysisof agricultural drought factors

The spatial precipitation anomaly percentage was evaluated with the M-K trend test. The test results are shown in TABLE 3, where*Z*statistics andtrend coefficientsindicate the variation in trendfactor, with $Z>0$indicatinganincreasingtrend, and $Z<0$ indicatinga decreasing trend.

The variation trendin spatial precipitation anomaly percentage in Henanwas obtained with spatial interpolation (Figure7). Using the precipitation anomaly percentage as a drought indicator, the droughttrend in thenorthern regionof Henanincreased significantlywith the *Z*statisticrea ching 3.54; southwesternHenanalsoshowed a drying trend, but the trend was not obvious as the*Z*statisticwas0.5-1; the centralandmid-east regionsof Henan showed a trendofincreasing moisturein recent years, with the *Z*statisticreaching-1.24.

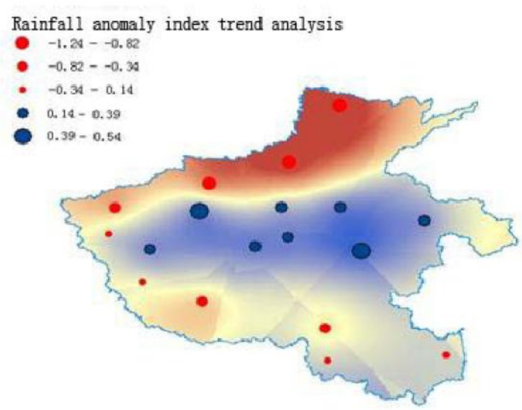

Figure 7: The distribution of precipitationanomaly percentage trendover the years in Henan province

TABLE 3: The M-K trend analysis of precipitation anomaly percentage

Site	Mean value	*Z*statistics	Trend coefficient	Site	Mean value	*Z*statistics	Trend coefficient
Anyang	3.65	-1.24	-0.28	Luanchuan	5.02	0.36	0.06
Xinxiang	3.79	-1.15	-0.24	Zhengzhou	1.59	0.27	0.06
Sanmenxia	-0.75	-0.59	-0.13	Xuchang	3.54	3.54	0.04
Lushi	3.53	0.14	0.04	Kaifeng	-0.48	0.39	0.07
Mengjin	-0.12	-0.82	-0.21	Xixia	1.71	-0.14	0.00
Luoyang	0.40	0.54	0.15	Nanyang	2.47	-0.35	-0.07
Baofeng	1.15	0.38	0.09	Zhumadian	-0.41	0.03	0.00
Xihua	-0.19	0.50	0.10	Xinyang	3.86	0.32	0.06
Tongbai	-0.94	-0.34	-0.11	Yongcheng	0.02	-0.01	0.00

Trend analysis of agricultural drought

According to the classification of different grades of agricultural drought with the index of precipitation anomaly percentage (TABLE 4), drought seasons and drought sites in the past 60 years at18 sitesare shown bytime-scale and spatial scale (Figure 8).

TABLE 4: Drought grade classification with precipitation anomaly percentages

Drought grade	Precipitationanomaly percentageD_p （%）		
	Monthly scale	Seasonal scale	Year scale
Light drought	$-60 < D_p \leq -40$	$-50 < D_p \leq -25$	$-30 < D_p \leq -15$
Moderate drought	$-80 < D_p \leq -40$	$-70 < D_p \leq -50$	$-40 < D_p \leq -30$
Severe drought	$-95 < D_p \leq -80$	$-80 < D_p \leq -70$	$-45 < D_p \leq -40$
Extraordinary drought	$D_p \leq -95$	$D_p \leq -80$	$D_p \leq -45$

At a time scale of months, according to yearly statistics, every year had areasof lightdrought within the province. There were accumulated levels of 80 to 160 site times oflight drought each month in the 60 year period. These events took place from April to July more than in other months. There were accumulated levels of 50 to 100 site times of moderate drought each month. Moderate drought occurring from October to January was significantly higher than in other months. Severe drought fluctuated widely, and occurred mainly from September to March. Extraordinary drought occurred mainly from December to February.

As for spatial scale, the spatial interpolation analysis demonstrated that drought occurred more frequently in the southern region of Henan Province, followed by the northern region. Drought occurred less frequently in the central, midwestern and central-eastern areas of Henan Province (Figure 9).

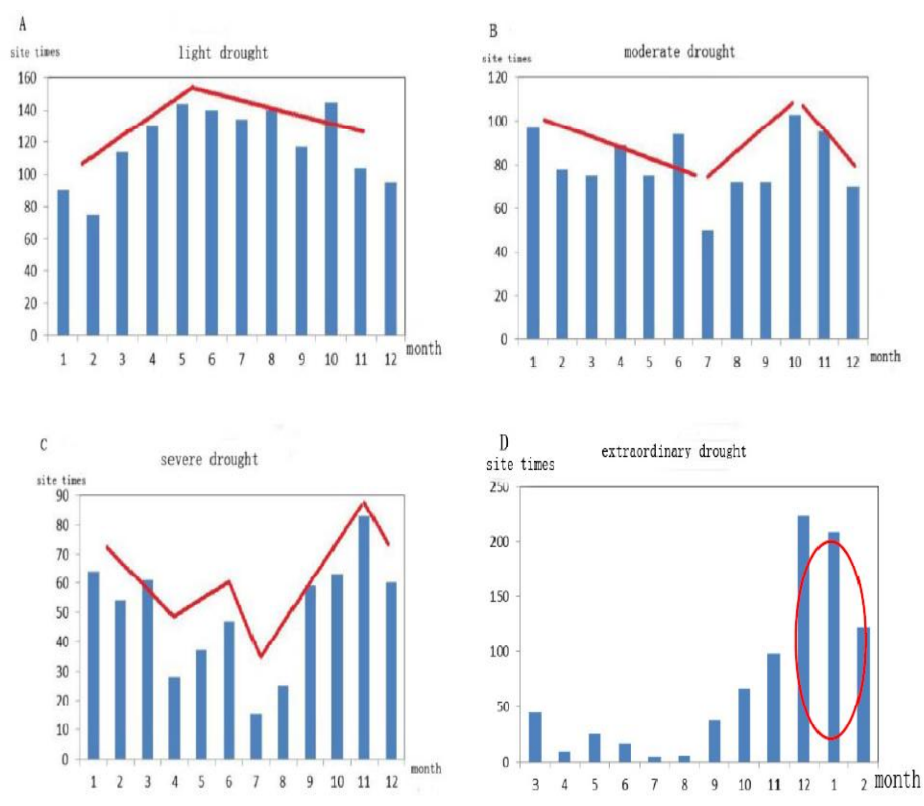

Figure 8: Sites times of drought occurrence by grade (A light drought; B moderate drought; C severe drought; D extraordinary drought)

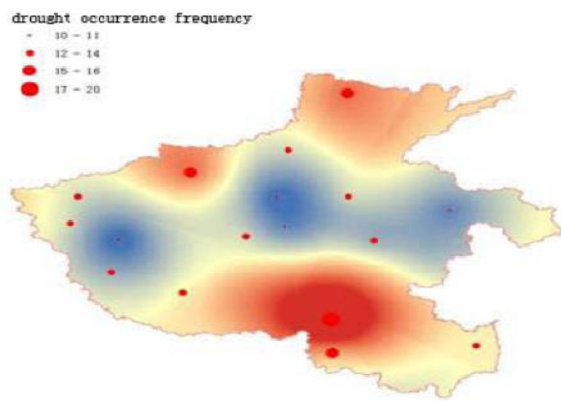

Figure 9: The geographical distribution of drought occurrence frequency

The geographical distribution of drought by severity was analyzed by drought grade classification based on precipitationanomaly percentage (Figure 10). Light drought occurred mainly in western and southwestern Henan Province. Moderate drought was concentrated in the central and northeastern regions of Henan Province. Severe droughtoccurred in various regions over the past 60 years. Extraordinary droughtoccurredan average of 1 to 3 times in the eastern region of Henan Province.

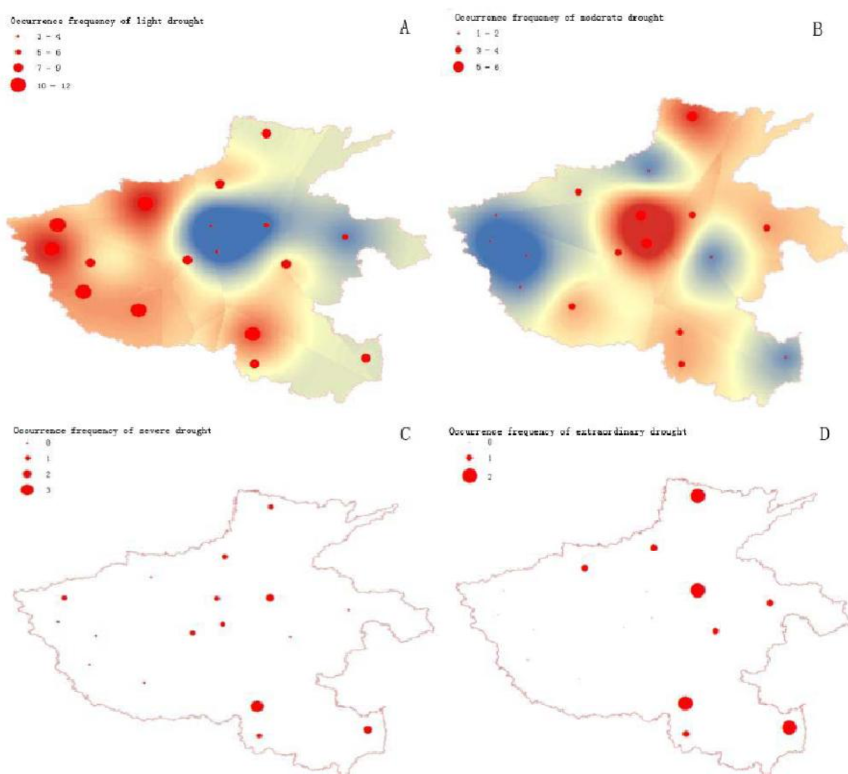

Figure 10: Occurrence frequency distribution of drought by grade (A light drought; B moderate drought; C severe drought; D extraordinarydrought)

WAVELET ANALYSIS OF AGRICULTURAL DROUGHT

Wavelet analysis theory

(a) Wavelet theory

Wavelet analysis evolved from an insufficient form of the Fourier transform. A wavelet is a "wave with small wave form," which has characteristics of volatility and attenuation. Its mathematical definition is shown in Equation (2). It has the following three characteristics: (1) small size and energy, (2) volatility, and (3) self-similarity[12].

$$\int_{-\infty}^{+\infty} \varphi(t)dt = 0 \quad (2)$$

Currently, the widely used wavelet function has six main classes. Namely, the Haar wavelet, the Mexican hat wavelet, the Meyer wavelet, the Daubechies wavelet, the Wave wavelet, and the Morlet wavelet. The Morlet wavelet has good locality in space and frequency domains, and its function is defined in Equation (3)[10].

$$\varphi(t) = e^{-t^2/2}e^{iwt} \quad (3)$$

Based on the multi-time scale analysis of hydrological sequences with the Morlet wavelet analysis method, variation in characteristics of hydrological system can be described. The wavelet coefficients contour map and curves of wavelet variance are key graphical features of wavelet analysis. The cycle variation rulesof hydrological sequences at multiple scales can be obtained by analyzing and identifying changesin these two graphics.

(b) Wavelettransform coefficients

Currently, there are numerous wavelet coefficient transform functions, such as the Morlet wavelet function, and the Mexican hat wavelet function. For a given wavelet function ψ *(t)*, the continuous wavelet transform functionof hydrologic time series$f(t)\epsilon L^2(R)$ is shown inEquation (4) (Sun and Cheng, 2000).

$$W_f(a,b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t)\bar{\psi}(\frac{t-b}{a})dt \quad (4)$$

Where $W_f(a,b)$ is the wavelet transform coefficient; a is the scale factor, reflecting the cycle length of wavelets;and b is the time factor, reflecting the translational movement of waveletson the timeline. However, in practice, the observed signal sequence is often intermittent and discontinuous, such as the sequence $f(k\Delta t)$, where k = 1 to N, andΔt is the sampling interval of observation. After the analysis above, the continuous wavelet transform can be approximated as discrete wavelet transforms using the integral, as shown in Equation (5).

$$W_f(a,b) = |a|^{-1/2}\Delta t \sum_{k=1}^{n} f(k\Delta t)\, \bar{\psi}(\frac{k\Delta t-b}{a} \quad (5)$$

Wavelet coefficients $W_f(a,b)$ can reflect characteristics of the time domain and frequency domain parameters. The wavelet coefficient is the response output of the time series f(t)or $f(k\Delta t)$ to the unit impulse. When parameter a is large, indicating that the frequency domain resolution of wavelet coefficients is high, while the time domain resolution is relatively low, and *vice versa*. Accordingly, the wavelet transform serves to localize the frequency domain and time domain in a fixed window size through adjustment of the parameters. The diagram of wavelet transform coefficients consists ofa two-dimensional contour map using the frequency-domain parameters as the vertical axis, and the time domain parameters as the abscissa. From the diagram of wavelet transform coefficients, variation characteristics of the wavelet transform with the time series change can be determined. Through observation and analysis of the diagram of wavelet transform coefficients, evolution characteristics and mutation scales of the hydrological system under multiple time scales can be obtained (Wanet al., 2002).

(c) Wavelet variance

Wavelet variance is calculated as shown in Equation (6) asthe integral of the square of the modulus of wavelet coefficients obtained by the wavelet transform.

$$Var(a) = \int_{-\infty}^{+\infty} \left| W_f(a,b) \right|^2 db \quad \textbf{(6)}$$

The wavelet variance diagram refers to the changing process of wavelet variance with changes in the time domain scale, which reflects the distribution of energy fluctuations at various time domain scales. The periodic fluctuation and amount of energy in hydrologic time series can be clearly observed at variousscales using the wavelet variance diagram.

Wavelet analysis of agricultural drought in Henan

The precipitationanomaly percentagewas calculated with monthly rainfall precipitation of nearly 60 years from 1951 to 2010. Wavelet coefficients were obtained using wavelet transform analysis. Wavelet variance of the precipitationanomaly percentage of Henan was calculated by the wavelet variance formula. Thediagram of wavelet transform coefficients (A) and the wavelet elevation diagram (B) are shown in Figure 11; and thewavelet variance graph is shown in Figure 12. These were obtained from the changing process of wavelet variance presented in energy fluctuations over the 60-year period.

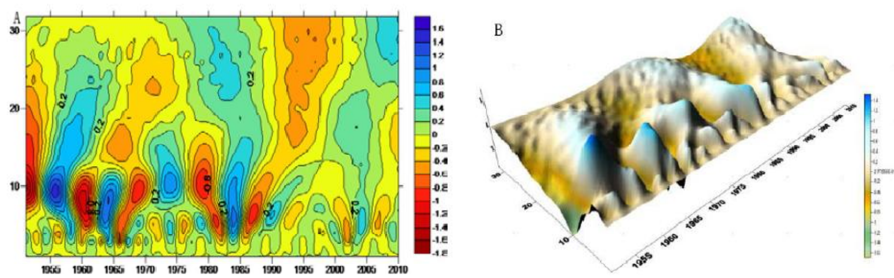

Figure 11: The wavelet transform of precipitationanomaly percentage inHenan (Awavelet transform coefficients diagram，and Bwavelet elevation diagram)

In Figure 11, years of precipitation anomaly percentage in Henan showed a certain period, in which the primary cycles of 10years and 22yearsare obvious, indicatingthat the primary cycles of agricultural drought are 10 years and 22 years. The same pattern can be found in the wavelet elevation diagram of precipitation anomaly percentage in Henan, with a tendency cycle of 35-50 years.

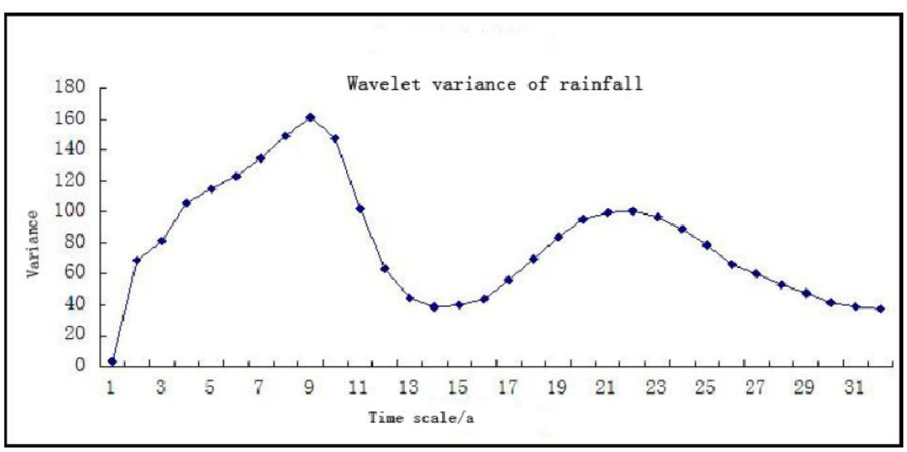

Figure 12: Wavelet variance of precipitationanomaly percentage in Henan

In Figure 12, there are severe concussions on the primary cycle of 10 years and 22 years. There may be a 60-year period which can be seen from the unclosed curve. Agricultural drought in Henan Province may have the same change rule for precipitation anomaly percentage as the index of drought.

DISCUSSION AND CONCLUSIONS

(1) According to the distribution rule of drought severity, the drought severity frequency curve and the drought duration frequency curvefor the period from1951 to 2010 in Henanweredrawnaccording torun theory using P-III-type curve fitting. The distribution function of drought duration was: $F(x) = 79.163e^{-0.534x}$. The frequency of occurrence of droughts lasting 1-4 monthswas relatively high, whereas the frequency of occurrence of droughts lasting more than 4 months was relatively low.

(2) Analysis of data for nearly 60years (1951-2010) at 18 sites in Henan Province, revealedtrendsinrainfall, precipitationanomaly percentage, the total occurrence frequency of drought, and the occurrence frequency of drought in four grades of severity. Theinter-annualrainfall in Henan increased overall, but the trendwas not obvious. Inter-annual rainfall had a relatively large fluctuation and a certain period. The average annual rainfall and the precipitationanomaly percentage showeddecreasing trends in northern Henan, while showing increasing trends in southern Henan. This indicated a trend of more severe drought in northern Henan than in the south.

(3) Years of precipitationanomaly percentage in Henan were analyzed at multiple scales using wavelet analysis theory. The wavelet transform and wavelet variance diagrams of precipitationanomaly percentage in Henan indicated that agricultural drought in Henan Province has two primary cycles of 10years and 22years.

(4) Under the background of global warming, the inter-annual rainfall in Henan increased overallduringthe period from 1951 to 2010. The average annual rainfall showed decreasing trends in northern Henan, while showing increasing trends in southern Henan. These findings were similar to thesimulation results of Liu et al. (2010), namely that the annual precipitation trendin northeastern China and North China decreased overthe period from 1951 to 2000. The simulationalso indicated an obvious warming of0.92□/50a in the Chinese mainlandduring the same period. In future work, it should be useful to combine the precipitation and temperature data to study the variety of agricultural drought in Henan Province.

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