



available at www.sciencedirect.com



journal homepage: www.elsevier.com/locate/jhydrol



Spatial and temporal variability of annual precipitation during 1961–2006 in Yellow River Basin, China

Qiang Liu, Zhifeng Yang *, Baoshan Cui

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Xijiekouwai Street, Beijing 100875, China

Received 22 September 2007; received in revised form 22 July 2008; accepted 7 August 2008

KEYWORDS

Yellow River Basin;
Annual total
precipitation;
Trend analysis;
Spatial distribution

Summary The Shannon Entropy method, Mann–Kendall method (M–K method) and linear fitted model were applied in this study to investigate the spatial and temporal patterns of trends of the precipitation in the Yellow River Basin (YRB) during 1960–2006. Results indicated that the precipitation possessed longitude zonality and had no clearly linear relationship with the latitude, it showed a decreasing trend in most of the precipitation stations, only two meteorological stations displayed upward trend in the YRB. The abrupt changes revealed by the M–K method mainly occurred to the south of 38°N in the middle-lower reaches of the YRB. Furthermore, the abrupt changes occurred in the period ranged from 1963 to 1998 and the abrupt changes in the lower reaches appeared earlier than those in the middle and upper reaches of the YRB.

© 2008 Elsevier B.V. All rights reserved.

Introduction

Most water resources projects are designed and operated based on the historical pattern of water availability, quality and demand, assuming constantly climatic behaviour (Westmacott and Burn, 1997; Abdul Aziz and Burn, 2006). According to decision making theory, elimination of threats and increase of chances were two fundamental conditions of successful strategic action to assess and manage the water resources and to accelerate the implementation of an idea

relating to sustainable development (Zalewski, 2000). Therefore, to investigate present and probable future climate change pattern and their impacts on water resources, appropriate adaptation strategies may be implemented. Precipitation and evapotranspiration are the most important variables to diagnose the climate change, and are important variables to reveal the eco-environment response to the climate change in regional scale as well (Cannarozzo et al., 2006). The temporal-spatial patterns of the precipitation and evapotranspiration influence the eco-hydrological processes, which controlled the evolution of the surface ecosystem (Oguntunde et al., 2006; Cannarozzo et al., 2006; McVicar et al., 2007a). This type of inquiry is

* Corresponding author. Tel.: +86 10 58807951.

E-mail address: zfyang@bnu.edu.cn (Z.F. Yang).

fundamental to understand the coupling existing between ecosystem dynamics and the water cycle, in particular as precipitation usually but not always larger than actual evapotranspiration in arid and semiarid environments, where water is an important limiting resource not only for its scarcity but also for its intermittency and unpredictable presence (Porporato and Rodriguez-Iturbe, 2002; Rodriguez-Iturbe and Porporato, 2005). The temporal and spatial patterns of the precipitation and its impacts on the surface ecosystem have become one of the key issues in the hydrology and ecology (Delitala et al., 2000). daSilva (2004) used the M–K method to test the climate variability in Northeast of Brazil. Andreo et al. (2006) studied the climate and hydrological variations during the last 117–166 years in the south of the Iberian Peninsula, by spectral and correlation analyses and continuous wavelet analyses. Coulibaly (2006) used the wavelet and cross-wavelet to identify and describe spatial and temporal variability in Canadian seasonal precipitation, and gained further insights into the dynamical relationship between the seasonal precipitation and the dominant modes of climate variability in the Northern hemisphere. However, only little research has been conducted on the spatial distribution of the trends in time series, especially in a basin scale. Assessing temporal trends and their spatial distribution pattern of precipitation remains a difficult task owing to their complex and nonlinear nature in different regions.

The objectives of this study are (i) to reveal the spatial pattern of the precipitation series using the Shannon entropy method; (ii) to explore the trends and its spatial distribution of the trends by virtue of the M–K method; (iii) and to compare the trends applying the M–K method and the linear fitted model. All of the tests are based on the precipitation series collected from 81 meteorological stations in the Yellow River from 1961 to 2006.

Study area of the Yellow River Basin and data processing

Description of the Yellow River Basin

The Yellow River Basin ($7.95 \times 10^5 \text{ km}^2$) is one of the most important basins in China, directly supporting a population of 107 million people (McVicar et al., 2007a). As the river flowing through arid, semi-arid and semi-humid regions, the eco-environment is fragile in part of the basin. For example, the average annual erosion rate of 2480 t km^{-2} of the entire YRB, which is the highest of any major river system worldwide (Shi and Shao, 2000). Furthermore affected by climatic change and human activities in recent years, the eco-hydrological processes have changed, accompanying with the mass and energy transport (Wang et al., 2008). For example in the past 40 years (1960–2000), 11 large reservoirs have been built in the main channel of the Yellow River in the upper and middle reaches (Yu, 2006). All of these have contributed to the eco-environmental change. A greater number of zero-flow days happened at the mouth of the Yellow River in recent years (Liu and Cheng, 2000; Liu, 2004). McVicar et al. (2002) presented that the decreases of precipitation and increases of agricultural and industrial water use being the main causes to the

decrease of the runoff and drying-up in the YRB. In order to solve the environmental issues, several programs have been conducted in the YRB to save water and restore the plant (Pereira et al., 2007), e.g., there is a hydrological impact of the sloping lands conversion program that has been enthusiastically implemented in the Loess Plateau (McVicar et al., 2007b; Chen et al., 2005). Furthermore, many studies also have been performed to explore the interaction between the climatic change and eco-hydrological processes in the YRB (Fu et al., 2004; Huang et al., 2007; Wang et al., 2006). As precipitation is the exclusive source of Yellow River, its distribution and trend affect the water resources in this basin in a large extent. In the past studies, the temporal and spatial pattern of the precipitation has been tested in the upper reach of the Yellow River (Yang and Li, 2004a; Yang and Li, 2004b; Shao et al., 2006). The trend of the precipitation has showed a downward trend in recent 50 years (Xu and Zhang, 2006). However, to our knowledge there is rarely studies had been done to test the spatial distribution of trends in precipitation series, and to explore the interaction between climate change and its regional response. In this paper, the temporal trends of the precipitation in last 46 years and their spatial distribution have been analyzed in YRB, China.

Data processing

The time series of annual precipitation records at 81 meteorological stations were collected for this study from 1961 to 2006, and the stations in and around the YRB were shown in Fig. 1. According to Chinese bureau of meteorology standards, annual data were integrated from daily data. The precipitation data were provided by the National climatic centre (NCC) of China meteorological administration (CMA).

Considering data continuity and integrity, the missing data in 11 of 81 series were interpolated by linear regression based on series from the adjacent meteorological stations. Linear regression equations of 30-year data were established separately with complete series of 1 or 4 adjacent stations as independent variables and incomplete series as dependent variable. Relative error for evaluating interpolation was obtained by averaging 5 relative errors calculated from 5 observed and predicted values near missing data. The linear regression equation with the least relative error was the sole equation for predicting missing data. The detailed interpolation was showed in Table 1. With all relative errors lower than 14.0% and those obtained by inverse distance weighting (IDW) method, the interpolation was relatively satisfying. This common period is long enough to allow reliable climatic conclusions and reveal the rule of the precipitation temporal change in the YRB.

Methodology

In order to reveal the trend of the annual total precipitation and its spatial distribution of the temporal trends in the YRB, three different approaches were applied as described in the following sections. Firstly, the Shannon Entropy method was used to verify the overall spatial structure of the precipitation. Secondly, the spatial distribution of the trend was analyzed by the M–K method and spatial analysis

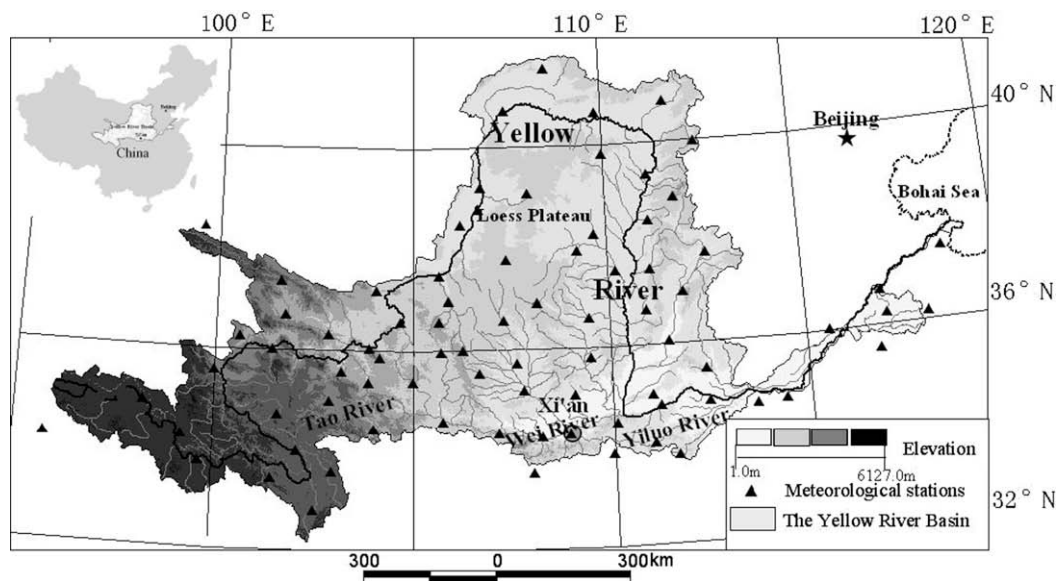


Figure 1 The inset map shows the location of the Yellow River Basin (white shading) in the China. The main map shows the location of the $7.95 \times 10^5 \text{ km}^2$ Yellow River Basin where the dark grey line represents the boundary of the Yellow River Basin. The locations of the Meteorological stations are shown by the black triangle. The location of the Bohai Sea also shows in the map to the east of the Yellow River Basin with dot line.

Table 1 Interpolation of series with missing data by linear regression and IDW method

Series with missing data	Qinghai	Lanzhou	Wuqi	Lishi	Tongchuan	Yangjiaogou	Zhongxinshan	Jiuzhi	Maqu	Tianshui	Baoji
Amount of missing data	1	3	1	1	7	1	9	1	6	3	2
Series for regression	Gonghe	Minhe	Yamchi	Suide	Xi'an	Taishan	Maduo	Dari	Henan	Minxian	Wugong
R square of regression	0.240	0.343	0.382	0.588	0.456	0.275	0.471	0.145	0.435	0.529	0.707
Relative error of regression (%)	13.1	5.1	11.5	13.6	13.4	5.2	13.3	5.6	8.2	1.4	8.5
Relative error of IDW (%)	14.1	21.5	15.7	17.0	15.1	14.1	24.1	33.2	19.2	25.6	22.0

R square, relative errors of regression and relative errors of IDW are showed in the table.

method. Finally, the trend explored by the linear fitted model compared with those revealed by the M–K method.

As the randomness and regularity are the basic characteristics of the precipitation in a basin scale. How to get the spatial structure of the precipitation is important to interact between the hydrological processes and the ecosystem. The Shannon Entropy method could eliminate the randomness and establish the regularity of the time series in the basin scale, so it has been widely used to test the spatial structure of the precipitation (Chapman, 1986; Zhang and Liu, 2000; Luo et al., 2002). In order to obtain the entropy of the precipitation, the time series of the precipitation at the 81 meteorological stations were regarded as a single

observed event separately. To a finite series of the random variable X ,

$P\{X = x_i\} = p_i (i = 1, 2, \dots, n), p_i \geq 0, \sum_{i=1}^n p_i = 1$, where the $H(X)$ is:

$$H(X) = H(p_1, p_2, \dots, p_n) = - \sum_{i=1}^n p_n \log p_n \quad (1)$$

Shannon named the $H(X)$ as information entropy. And the Shannon entropy could be regarded as a function to reveal the randomness of the variable. To continuous variables, the Shannon entropy could be calculated by the function as follows:

$$H(X) = H(x, \Delta x) \approx - \sum_{n=1}^N f(x_n) \log f(x_n) \Delta x - \log \Delta x$$

$$\approx - \int_{-\infty}^{+\infty} f(x) dx \log f(x) dx - \log \Delta x \quad (2)$$

Where Δx is the length of average X divided by the N . The Shannon entropy could be classified into time series entropy and frequency series entropy. In this study, we obtained the entropy from the frequency series, and then got the spatial distribution of the entropy in the YRB.

The non-parametric Mann–Kendall method was used to detect the abrupt climate change against trend, and originated from Mann (1945) and rephrased by Kendall (1948). This test has the advantage of no assuming any special form for the distribution function of the data, while having predictive power nearly as high as their parametric competitors. Especially, it, when applied to annual total precipitation series, could result in more significant trends (Serrano et al., 1999). Thus, it was highly recommended for general use by the World Meteorological Organization (Mitchell et al., 1966). Now, the M–K method has been widely used and tested as an effective method to evaluate a presence of a statistically significant trend in hydrological and climatological time series (Douglas et al., 2000; Yue et al., 2002; Birsan et al., 2005).

Mann–Kendall method presumed that the time series is steady. The element in the series is random and independent to each other, the probability of the element in the series is equal to each other. Under the null hypothesis of no trend the time series of variable has no change, the time series could be regarded as x_1, x_2, \dots, x_n . For each term, m_i is computed as the number of later terms in the series whose values exceeded x_i . The test statistic is calculated as follows:

$$d_k = \sum_{i=1}^k m_i \quad (2 \leq k \leq N). \quad (3)$$

Presuming that the series is random and independent, the expected value $E(d_k)$ and variance of d_k could be shown as follows:

$$\begin{cases} E[d_k] = k(k-1)/4 \dots \\ \text{var}[d_k] = k(k-1)(2k+5)/72 \dots (2 \leq k \leq N) \end{cases} \quad (4)$$

We define

$$u(d_k) = (d_k - E[d_k]) / \sqrt{\text{var}[d_k]}. \quad (5)$$

The terms of the $u(d_k)$ ($1 \leq k \leq n$) constitute curve C_1 .

The null hypothesis of no trend will be rejected at a confidence level of α if the standard normal probability $\Pr(|u| < |u(d_k)|) > \alpha$. A typical confidence level of 95% was used with annual total precipitation series.

Applying the method to the inverse series, we could obtain the series of $\bar{u}(d_k)$ as follows:

$$\begin{cases} \bar{u}(d_i) = -u(d_i) \\ \dots (i, i' = 1, 2 \dots n) \\ i' = n + 1 - i \end{cases} \quad (6)$$

The terms of the $\bar{u}(d_k)$ ($1 \leq k \leq n$) constitute another curve C_2 .

If C_1 exceeds the confidence line, it means that there is a significant upward or downward trend in series. And if the intersection point of the C_1 and C_2 is between the two confidence lines, we can consider that abrupt climate change took place at that point (Fu and Wang, 1992).

Results and discussion

The spatial structure of the precipitation

The relationship between the entropy and longitude, latitude used to reveal the spatial structure of the precipitation, which was shown in Fig. 2. The results presented that the entropy was linear positively related to the longitude, but it was not the linear relation with the latitude. It was suggested that the precipitation possesses the longitude zonality, which implied that precipitation might increase with the longitude from the west to the east, in other words precipitation might increase with getting close to the sea. The reasons for these mainly lie in two aspects. Firstly, the variation and complex terrain of the terrain has led various regional climatic conditions, and also led to the spatial differentiation of the precipitation in the Yellow River Basin. The Yellow River wanders 5400 km in this vast region, after running through the Tibetan Plateau, the Loess Plateau and North China Plain, and then running into Bohai Sea at last (Jia et al., 2006). The average elevation in the Tibetan is above 4200 m, and even in the Loess Plateau

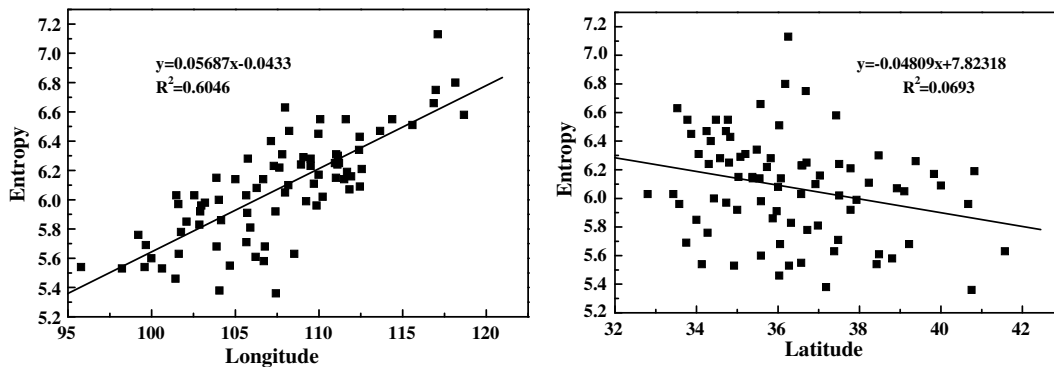


Figure 2 Relationship between entropy and longitude (left), entropy and latitude (right) in Yellow River Basin; and linear fitted model was used to fit the trend between the entropy and longitude, latitude, the linear models and R^2 also gave in the figure.

the elevation ranges from 1000 to 1600 m (Cui et al., 2006; Lu et al., 2004). The fluctuant topography comprised one of the main causes to form the various regional climates in the YRB. Secondly, the monsoon and Tibetan Plateau, which influenced the climatic situation, effect on the precipitation processes in the YRB (Ye and Gao, 1979; Cui et al., 2006). Especially, as its height (average elevation of 4200 m) and size (about $1 \times 10^6 \text{ km}^2$), the Tibetan Plateau plays an important role in forming and inducing variations of regional weather and climate in eastern and southern Asia (Liu and Yin, 2002). Recently, the changes of the land use in the Tibetan Plateau impacted on local to regional, and to a lesser extent global climate, has been explored (Cui et al., 2006). The monsoon, terrain and landscape com-

posed a complex condition to influence the precipitation processes in the YRB.

Trend analysis

The M–K method with a nominal rejection rate of 5% was applied to 81 annual total precipitation series. The Yulin station ($109^\circ 42' \text{E}$, $38^\circ 14' \text{N}$) was selected as an example to demonstrate the abrupt change happening in the time series of annual precipitation. It revealed that the abrupt change occurred in 1970 (Fig. 3). By this method the abrupt changes were detected for 81 time series of annual precipitation in the YRB and significant trends for different stations were shown in Fig. 4.

Although the test could be liberal because of the presence of serial correlation in these series, only 35 among 81 stations showed a significant trend ($P=0.05$), the remaining 46 stations showed no significant trend. Among the 35 stations with significant trend ($P=0.05$), two stations (Yeniugou and Xining) showed an upward trend, 33 stations displayed a downward trend. The distribution of the trend for the annual precipitation exhibited that no trend and upward trend abrupt changes were mainly in the north portion of the upward-middle reaches of the YRB, and climate change in these region had no significant change; Adversely, in the south-east portion of the YRB the downward trend abrupt change had been detected in most of the stations. Furthermore, the distribution of the trend for annual precipitation in the YRB showed that the abrupt changes in precipitation time series most occurred in lower reaches, then middle and upper reaches. The results also indicated that the precipitation possesses the longitude zonality, and the precipitation changed obviously from southeast to upper reach of the Yellow River. The southeast portion of the YRB is close to sea and with low elevation. Influenced by the monsoon, the precipitation was sensitive to the climatic change and showed negative trend in most of the stations in

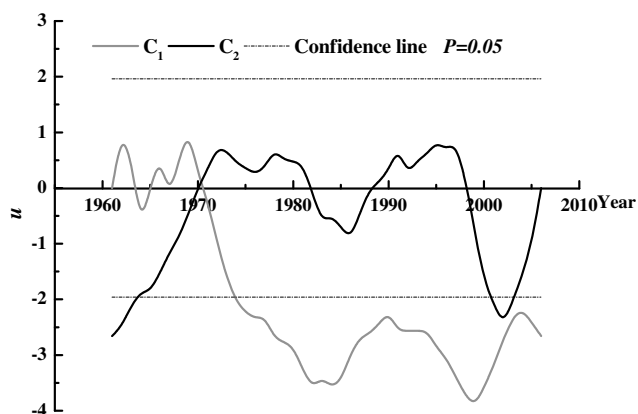


Figure 3 The abrupt change tested by the Mann–Kendall method for annual total precipitation series in Yulin station from 1961 to 2006. In here, as the line C_1 is over the confidence line ($P=0.05$), the cross point of C_1 and C_2 is the start point of abrupt change in this series.

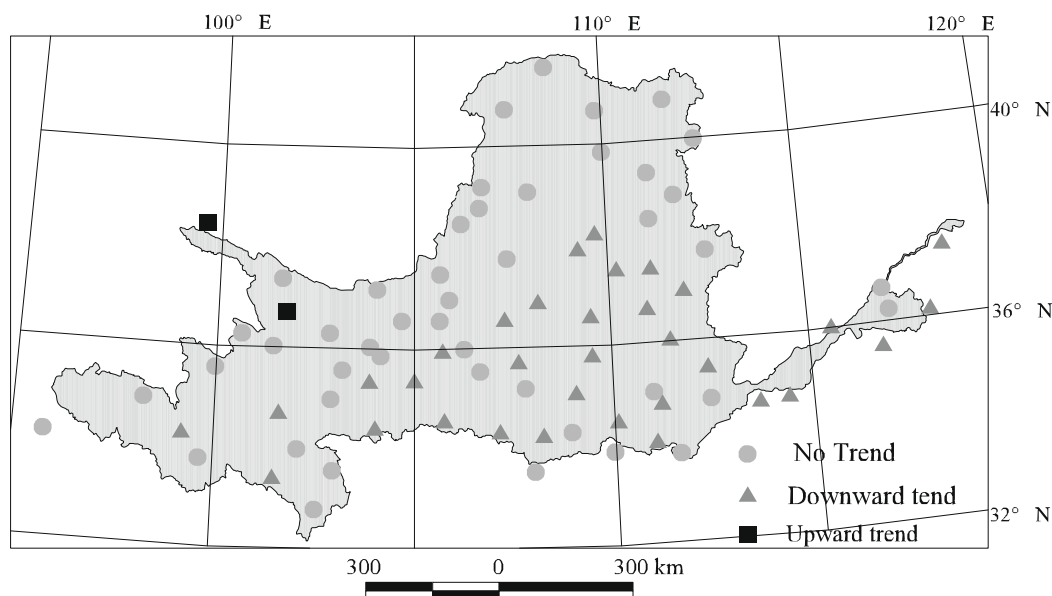


Figure 4 The upward trends (■), downward trends (▲), and no trends (●) in annual total precipitation during 1961–2006 detected by the Mann–Kendall method in the Yellow River basin.

this region. Further, the changes of land use/cover influenced by the population explosion and human activities would alter the albedo, hydrothermal status, wind speed, humidity, and radiation to some extent, yielding sensitive negative or positive feedbacks with monsoon precipitation in the southeast portion of the YRB. The impacts of climate changes and human activities on precipitation need to be understood in context of current and proposed landuse changes. On the other hand, bearing relatively slight effect by the Monsoon and human activities, the precipitation

showed no significant trend ($P = 0.05$) in most of the stations in this region.

The time and frequency of the abrupt changes tested by the M–K method showed in Fig. 5. The results presented that the year of abrupt change ranged from 1963 to 1998 in recent 46 years. There were 40 abrupt changes happening in 35 meteorological stations. Two or three abrupt changes took place in the following four stations, Yeniugou (1973-increasing change, 1995-decreasing change), Xiji (1968-decreasing change, 1982-increasing change and 1992-

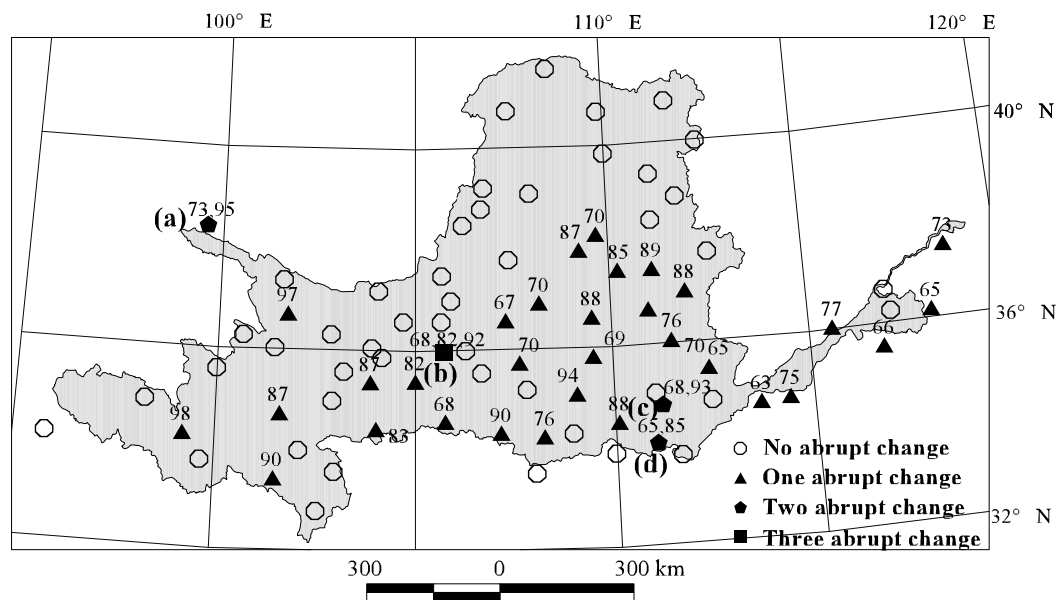


Figure 5 The time and frequency of the abrupt change detected by the Mann–Kendall method in the meteorological stations of YRB; the year the abrupt change happened has been simplified in two figures, e.g., 89 for 1989; (a), (b), (d) and (d) are meteorological stations which happen two or three abrupt change ((a)-Yeniugou, (b)-Xiji, (c)-Sanmenxia and (d)-Lushi).

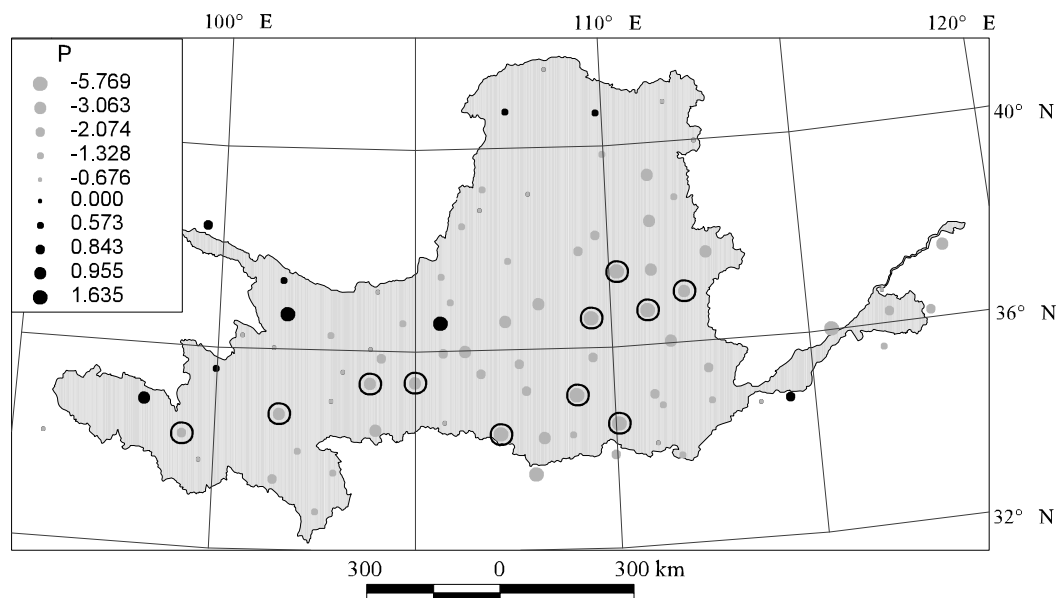


Figure 6 Annual trends (mm a^{-2}) for the annual total precipitation. If the trend is significant at the 95% confidence level then a ring is placed around the circle. The 46-year study site average for annual total precipitation is 485 mm a^{-1} .

decreasing change), Sanmenxia (1968-increasing change, 1993-decreasing change) and Lushi (1965-increasing change, 1985-decreasing change). Three of them locate in the south of the YRB, which indicated that this region was sensitive to the climate change. Furthermore, there were 14 abrupt changes happened from 1961 to 1970, 6 ones from 1971 to 1980, 14 ones from 1981 to 1990 and 6 ones from 1991 to 2000. The stations occurring abrupt changes from 1961 to 1970 mainly was in the southeast of the YRB, and only one station in those happened abrupt changes from 1971 to 1980 lay in the west of the YRB; but the stations happened abrupt changes from 1981 to 1990 and 1991 to 2000 mainly lie in the middle of the YRB and then expand to the west in the upper reaches of YRB.

From 1961 to 2006, the years that abrupt changes happened in the south-east portion of the YRB were relatively

earlier than those in the upper reaches of the YRB. Abrupt changes occurred early in lower reaches, then middle and upper reaches. Furthermore, three of the four stations with two or three abrupt changes were located in the south-east portion YRB, which were Xiji, Sanmenxia and Lushi except Yeniugou lies in the upper reaches of the YRB. It indicated that the middle-lower reaches of the YRB to the south of 38 °N was a sensitive region to the climate change during recent 46 years. In this region, vegetation cover has changed considerably due to human activities. Li and Yang, 2004 study indicated that the NDVI has changed a lot in the Tao River, Yiluo River and Wei River Basins, and the relation between precipitation and NDVI was positive (Fig. 1), which indicated that the land cover changed by human activities interact with the precipitation. The reasons for the change of the precipitation in the YRB need to further study on the

Table 2 Slope, standard error of the slope, and percentage of variance explained by the linear model for those precipitation series showing a significant trend

	Stations	Slope (mm a ⁻²)	Stand.error (mm a ⁻²)	Variance (%)
Significant trend both in M–K and linear model test	Huashan	–5.77	1.7	21.1
	Suide	–3.33	1.0	20.0
	Henan	–2.60	1.0	13.5
	Tongchuan	–3.41	1.4	12.4
	Xixian	–3.22	1.3	12.0
	Jiexiu	–2.94	1.2	11.8
	Yanan	–3.06	1.3	11.3
	Lintao	–2.65	1.2	9.9
	Huajialing	–2.60	1.2	9.7
	Zhongxinshan	–1.76	0.8	9.4
	Baoji	–3.32	1.6	9.3
Average		–3.2	1.2	12.8
Significant trend only in M–K test	Wuqi	–2.33	1.17	8.30
	Minxian	–2.09	1.05	8.20
	Lishi	–2.26	1.34	8.00
	Chaocheng	–3.28	1.75	7.40
	Xiji	–1.80	0.97	7.30
	Xining	1.57	0.85	7.20
	Linfen	–2.07	1.22	6.20
	Hengshan	–1.74	1.05	5.80
	Huanxian	–2.14	1.34	5.40
	Jiuzhi	–1.69	1.10	5.10
	Yangjiaogou	–2.84	1.91	4.80
	Xifengzhen	–1.83	1.34	4.00
	Wugong	–2.26	1.72	3.80
	Yulin	–1.57	1.20	3.70
	Yangcheng	–1.89	1.51	3.50
	Luochuan	–1.71	1.43	3.20
	Yeniugou	0.81	0.68	3.10
	Sanmenxia	–1.06	1.40	1.30
	Yiyuan	–1.38	2.44	0.70
	Yanzhou	–1.08	2.13	0.60
	Kaifeng	0.84	1.90	0.40
	Tianshui	–0.61	1.44	0.40
	Zhengzhou	–0.13	1.75	0.00
	Lushi	–0.08	1.50	0.00
Average		–1.36	1.42	4.10

interaction between the climate change, landuse, and human activities.

Fitting data to linear model

The least-squares linear model is the most common method used for detecting precipitation trends (Hameed et al., 1997; daSilva, 2004), and is the most common technology of statistical diagnosis and forecast in modern climate (Wei, 1999). The linear trend was chosen because of being the simplest model for an unknown trend. The level of adequacy of the model fitted was measured by the percentage of variance explained by it. Linear trends for the series of annual total precipitation were calculated by the least-squares regression. The estimated slopes were tested against the hypothesis of null slope by means of a 2-tailed *T*-test at a confidence level of 95% (Serrano et al., 1999).

The least-squares slopes were shown in Fig. 6. Only 9 stations possessed a positive trend of precipitation with the average annual increase of 0.848 mm a^{-2} while the other 72 stations showed a negative trend of precipitation with the average annual increase of -1.548 mm a^{-2} . Furthermore, the 14% of the stations (or 11 of 81) showed significant trend at $P = 0.05$, which all exhibited negative trend and located in the southern portion of the YRB. The results for precipitation were in agreement with the study conducted in the Loess Plateau (McVicar et al., 2007b). It could be reduced that the precipitation decreased from 1961 to 2006 in most area of the YRB. The climate variation and anthropogenic, such as decrease of precipitation and increase of irrigation water use, are both contributed to the water scarcity in YRB in recent years (Wang et al., 2006).

Table 2 showed the least-squares slope estimation and its standard error for 35 series of annual total precipitation tested by the Mann–Kendall method. The estimated slopes ranged from -5.769 mm a^{-2} for Huashan to 1.573 mm a^{-2} for Xining. Two slopes (Xining and Yeniugou) among the 35 precipitation series were positive, and the other slopes were all negative. The percentage of variance explained by the model was a measure of the adequacy of regression line fitted. Since the percentage of the variance explained by the linear model was high enough for most series, the linear model was adequate for the trend. Especially, the values of the percentage of variance explained by the linear model for the 11 precipitation series with a significant trend were relatively high, ranging from 9.3% to 21.1%.

Conclusions

In this Paper, the Shannon entropy and M–K method were used to reveal the precipitation trends from 1961 to 2006. The results presented as follows:

- (1) The precipitation possesses longitude zonality, which increased from the west to the east with the longitude increasing. The relationship between entropy and latitude was complex because there was no clearly linear relationship between them according to the Shannon entropy.
- (2) The results of M–K analysis indicated that 35 stations experienced abrupt precipitation change, 2 with upward trends and 33 with downward trends, the

other 46 stations have no abrupt change during recent 46 years however. The trends of precipitation tested by linear model showed the similar tendency to those detected by M–K method, but only trends in 11 stations past the *T*-test (at 95% significant level).

- (3) The portion to south of 38°N in the middle-lower reaches of the YRB was sensitive to climate change, because most of the abrupt changes occurred at here during the period of 1961–2006. In this region, the land cover has been changed a lot owing to the human activity, so further studies should be performed on the relations between the land use and cover and the climate change.

Acknowledgments

This research was supported by the Major State Basic Research Development Program of China (973 Program) (No. 2006CB403303), National Science Foundation for Distinguished Young Scholars of China (No. 50625926) and the National Natural Science Foundation of China (No. 40701189). The authors are also grateful for the National Meteorological Information Center, China Meteorological Administration for offer the precipitation data.

References

- Abdul Aziz, O.I., Burn, D.H., 2006. Trends and variability in the hydrological regime of the Mackenzie River Basin. *J. Hydrol.* 319, 282–294.
- Andreo, B., Jiménez, P., Durán, J.J., Carrasco, F., Vadillo, I., Mangin, A., 2006. Climatic and hydrological variations during the last 117–166 years in the south of the Iberian Peninsula, from spectral and correlation analyses and continuous wavelet analyses. *J. Hydrol.* 324, 24–39.
- Birsan, M.V., Molnar, P., Burlando, P., Pfaundler, M., 2005. Streamflow trends in Switzerland. *J. Hydrol.* 314, 312–329.
- Cannarozzo, M., Noto, L.V., Viola, F., 2006. Spatial distribution of rainfall trends in Sicily (1921–2000). *Phys. Chem. Earth* 31, 1201–1211.
- Chapman, T.G., 1986. Entropy as a measure of hydrologic data uncertainty and model performance. *J. Hydrol.* 85, 111–126.
- Chen, H., Zhou, J.X., Cai, Q.G., Yue, Z.Q., Lu, Z.C., Liang, G.L., Huang, J.G., 2005. The impact of vegetation restoration on erosion-induced sediment yield in the middle Yellow River and management prospect. *Sci. China Ser. D* 48 (6), 724–741.
- Coulibaly, P., 2006. Spatial and temporal variability of Canadian seasonal precipitation (1900–2000). *Adv. Water Resour.* 29, 1846–1865.
- Cui, X.F., Graf, H.F., Langmann, B., Chen, W., Huang, R.H., 2006. Climate impacts of anthropogenic land use changes on the Tibetan Plateau. *Global Planet. Change* 54, 33–56.
- daSilva, V.P.R., 2004. On climate variability in Northeast of Brazil. *J. Arid. Environ.* 58, 575–596.
- Delitala, A.M.S., Cesari, D., Chessa, P.A., Ward, M.N., 2000. Precipitation over Sardinia (Italy) during the 1946–1993 rainy seasons and associated large scale climate variations. *Int. J. Climat.* 20, 519–541.
- Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *J. Hydrol.* 240, 90–105.
- Fu, C.B., Wang, Q., 1992. The definition and detection of the abrupt climatic change (In Chinese). *Scientia Atmos. Sinica* 16 (4), 482–493.

- Fu, G.B., Chen, S.L., Liu, C.M., Shepard, D., 2004. Hydro-climatic trends of the Yellow River Basin for the last 50 years. *Climatic Change* 65, 149–178.
- Hameed, T., Mariño, M.A., DeVries, J.J., Tracy, J.C., 1997. Method for trend detection in climatological variables. *J. Hydrol. Eng.* 2, 154–160.
- Huang, C.C., Pang, J.L., Zha, X.C., Su, H.X., Jia, Y.F., Zhu, Y.Z., 2007. Impact of monsoonal climatic change on Holocene overbank flooding along Sushui River, middle reach of the Yellow River, China. *Quater. Sci. Review* 26, 2247–2264.
- Jia, Y.W., Wang, H., Zhou, Z.H., Qiu, Y.Q., Luo, X.Y., Wang, J.H., Yan, D.H., Qin, D.Y., 2006. Development of the WEP-L distributed hydrological model and dynamic assessment of water resources in the Yellow River Basin. *J. Hydrol.* 331, 606–629.
- Kendall, M.G., 1948. *Rank Correlation Methods*. Hafner, New York, 1948.
- Li, C.H., Yang, Z.F., 2004. Spatial-temporal changes of NDVI and their relations with precipitation and runoff in the Yellow River Basin (In Chinese). *Geographic. Res.* 23 (6), 753–759.
- Liu, C.M., Cheng, L., 2000. Analysis on runoff series with special reference to drying up courses of lower Huanghe river (In Chinese). *Acta Geographic. Sinica* 55 (3), 257–265.
- Liu, C.M., 2004. Study of some problems in water cycle changes of the Yellow River Basin (In Chinese). *Adv. Water. Sci.* 15 (5), 608–614.
- Liu, X.D., Yin, Z.Y., 2002. Sensitivity of East Asia Monsoon Climate to the Uplift of Tibetan Plateau, *Palaeogeogr. Palaeoclimatol.* 183, 223–245.
- Lu, C.H., van Ittersum, M.K., Rabbinge, R., 2004. A scenario exploration of strategic land use options for the Loess Plateau in northern China. *Agr. Syst.* 79, 145–170.
- Luo, X.X., Deng, W., He, Y., Luan, Z.Q., 2002. Driving forces for runoff changes for Marshy Rivers in sanjiang Plain (In Chinese). *Acta Geographic. Sinica* 57 (5), 603–610.
- Mann, H.B., 1945. Non-parametric test against trend. *Econometrica* 13, 245–259.
- McVicar, T.R., Zhang, G.L., Bradford, A.S., Wang, H.X., Dawes, W.R., Zhang, L., Li, L.T., 2002. Monitoring regional agricultural water use efficiency for Hebei Province on the North China Plain. *Aust. J. Agr. Res.* 53, 55–76.
- McVicar, T.R., Van Niel, T.G., Li, L.T., Hutchinson, M.F., Mu, X.M., Liu, Z.H., 2007a. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *J. Hydrol.* 338, 196–220.
- McVicar, T.R., Li, L.T., Van Niel, T.G., Zhang, L., Li, R., Yang, Q.K., Zhang, X.P., Mu, X.M., Wen, Z.M., Liu, W.Z., Zhao, Y.A., Liu, Z.H., Gao, P., 2007b. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *Forest Eco. Manage.* 251, 65–81.
- Mitchell, J.M., Dzerdzeevskii, B., Flohn, H., Hofmeyr, W.L., Lamb, H.H., Rao, K.N., Wallén, C.C., 1966. Climatic change. (Report of a working group of the Commission for Climatology). WMO Technical note No. 79. World Meteorological Organization, p. 79.
- Oguntunde, P.G., Friesen, J., van de Giesen, N., Savenije, H.H.G., 2006. Hydroclimatology of Volta River Basin in West Africa: Trends and variability from 1901 to 2002. *Phys. Chem. Earth* 31, 1180–1188.
- Pereira, L.S., Goncalves, J.M., Dong, B., Mao, Z., Fang, S.X., 2007. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the upper Yellow River Basin, China. *Agri. Water Manage.* 93, 109–122.
- Porporato, A., Rodriguez-Iturbe, I., 2002. Ecohydrology - a challenging multidisciplinary research perspective. *Hydrol. Sci. J.* 47 (5), 811–821.
- Rodriguez-Iturbe, I., Porporato, A., 2005. *Ecohydrology of Water-Controlled Ecosystems: Soil Moisture and Plant Dynamics*. Cambridge Univ. Press, Cambridge.
- Serrano, A., Mateos, V.L., García, J.A., 1999. Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. *Phys. Chem. Earth* 24 (B), 85–90.
- Shao, X.M., Yan, C.R., Wei, H.B., 2006. Spatial and temporal structure of precipitation in the Yellow River Basin based on Kriging method (In Chinese). *Chinese J. Agromet.* 27 (2), 65–69.
- Shi, H., Shao, M.A., 2000. Soil and water loss from the Loess Plateau in China. *J. Arid. Environ.* 45, 9–20.
- Wang, H.J., Yang, Z.S., Saito, Y., Liu, J.P., Sun, X.X., 2006. Interannual and seasonal variation of Huanghe (Yellow River) water discharge over the past 50 years: Connections to impacts from ENSO events and dams. *Global Planet. Change* 50, 212–225.
- Wang, S.Y., Liu, J.S., Yang, C.J., 2008. Eco-environmental vulnerability evaluation in the Yellow River Basin, China. *Pedosphere* 18 (2), 171–182.
- Wei, F.Y., 1999. *The Technologies of Statistics Diagnosis and Forecast in Modern Climate* (In Chinese). China Meteorological Press, Beijing.
- Westmacott, J.R., Burn, D.H., 1997. Climate change effects on the hydrologic regime within the Churchill–Nelson River Basin. *J. Hydrol.* 202, 263–279.
- Xu, Z.X., Zhang, N., 2006. Long-term trend of precipitation in the Yellow River Basin during the past 50 years (In Chinese). *Geographic. Res.* 25 (1), 27–34.
- Yang, Z.F., Li, C.H., 2004a. Abrupt and periodic changes of the annual natural runoff in the subregions of the Yellow River (In Chinese). *J. Mount. Sci.* 22, 140–146.
- Yang, Z.F., Li, C.H., 2004b. The spatial and temporal structure of precipitation in the Yellow River Basin (In Chinese). *Prog. Geog.* 23 (2), 27–33.
- Ye, D., Gao, Y., 1979. *The Meteorology of the Qinghai-Xizang (Tibet) Plateau* (in Chinese). Sciences Press, Beijing, 278.
- Yu, L.S., 2006. The Huanghe (Yellow) river: Recent changes and its countermeasures. *Cont. Shelf Res.* 26, 2281–2298.
- Yue, S., Pilon, P., Cavadas, G., 2002. Power of the Mann–Kendall and Searman's rho test for detecting monotonic trend in hydrological series. *J. Hydrol.* 259, 254–271.
- Zalewski, M., 2000. Ecohydrology-the scientific background to use ecosystem properties as management tools toward sustainability of water resources. *Ecologic. Eng.* 16, 1–8.
- Zhang, Z.G., Liu, X.R., 2000. Information entropy analysis on nonuniformity of precipitation distribution in time-space (1): basic concept and data analysis (In Chinese). *Adv. Water. Sci.* 11 (2), 133–137.