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Drought analysis using multi-scale standardized precipitation index in the Han River Basin, China*

Yue-ping XU[1], Sheng-ji LIN[1,2], Yan HUANG[3], Qin-qing ZHANG[1], Qi-hua RAN[†1]

(*[1]Institute of Hydrology and Water Resources, Civil Engineering, Zhejiang University, Hangzhou 310058, China*)

(*[2]Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China*)

(*[3]Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan 430010, China*)

[†]E-mail: ranqihua@zju.edu.cn

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Abstract: Regional drought analysis provides useful information for sustainable water resources management. In this paper, a standardized precipitation index (SPI) at multiple time scales was used to investigate the spatial patterns and trends of drought in the Han River Basin, one of the largest tributaries of Yangtze River, China. It was found that, in terms of drought severity, the upper basin of the Han River is the least, while the growing trend is the most conspicuous; a less conspicuous growing trend can be observed in the middle basin; and there is an insignificant decreasing trend in the lower basin. Meanwhile, the impact of drought on the Middle Route of the South-to-North Water Transfer Project was investigated, and it is suggested that water intake must be reduced in times of drought, particularly when successive or simultaneous droughts in the upper and middle basins of the Han River Basin occur. The results can provide substantial information for future water allocation schemes of the South-to-North Water Transfer Project.

Key words: Multi-scale standardized precipitation index (SPI), South-to-North Water Transfer Project, Spatial patterns, Mann-Kendal, Han River Basin

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1 Introduction

In recent years, an increasing frequency of floods and droughts, accompanied with evidence of global warming, has caused an increased awareness of potential climate change. Weather and climatic extremes (typhoon, droughts, floods, damaging high winds, extreme heat, and cold, etc.) can exert severe and disastrous effects on infrastructures, facilities, ecosystems, and humanity (Meehl *et al.*, 2000). The impact induced by potential changes in extreme climatic disasters on human activities and the natural environment, however, tends to be greater (Kunkel *et al.*, 1999). Extremes in temperature and precipitation have significant effects on crucial aspects of society, such as crop yield, power consumption, production, and human health (Easterling *et al.*, 2000; Walther *et al.*, 2002). Drought is one of the most significant climatic disasters, and its occurrence is aggravated by global climate changes. Past decades have witnessed the surge of population and rapid economic development, and a trend to increasing drought.

The definition of drought has been important for drought monitoring and analysis. Drought has been categorized into meteorological (lack of precipitation), hydrological (drying of surface water storage), agricultural (lack of root zone soil moisture), and socio-economic (lack of water supply for socio-economic purposes) ones (Wilhite and Glantz, 1985). However, all definitions concur in terms of identifying a condition of insufficient moisture caused by a

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deficit in precipitation over a certain time period. In this paper, the meteorological drought is defined on the basis of the degree of dryness (in comparison to some normal or average amount) and the duration of the dry period.

The most commonly used drought indices include the precipitation anomaly, the Palmer drought severity index, *Z*-index, and the standardized precipitation index (SPI) (Heim, 2002). The SPI was developed for different time scales (McKee *et al.*, 1993), although the majority of drought indices have a fixed time scale. SPI is calculated by fitting a gamma distribution to observed values of total precipitation amount at different time steps (e.g., 1, 2, ..., 48 months), and then transforming back to the normal distribution. The applicability of SPI varies with the time scale for the following reasons: the one-month SPI reflects short-term conditions and its application is related closely to soil moisture; the three-month SPI offers a seasonal estimation of precipitation; and the six- and nine-month SPIs show medium term trends in precipitation patterns (Ji and Peters, 2003). A positive SPI indicates the precipitation is greater than the average, and negative values indicate that it is less than the average. Seiler *et al.* (2002) has already analyzed the potential and the possibility of the SPI as a tool to monitor the flood risk in Southern Cordoba Province in Argentina. Bonaccorso *et al.* (2003) applied the SPI to study long-term drought variability. Wu *et al.* (2005) illustrated the usefulness of SPI by comparing SPI values derived from different lengths of record in severe drought and flood, and drought intensities based on SPI values temporally and spatially. Manatsa *et al.* (2010) analyzed the frequency and spatiotemporal characteristics of agricultural droughts in Zimbabwe through SPI.

With the enormous potential of SPI to detect and characterize drought episodes acknowledged worldwide, this paper focuses on investigating the usefulness of the SPI in characterizing the spatial patterns and trends of the drought events in Han River Basin, China.

2 Study region and materials

Han River, the largest tributary in middle and lower Yangtze River, stretches 1577 km from Shaanxi to Hubei Provinces, returning in the Yangtze River in Wuhan City (Fig. 1). The river passes through Gansu, Sichuan, Henan, and Chongqing. Han River is located at 106°15′–114°20′ east longitude, and 30°10′–34°20′ north latitude, with its basin area of 159 000 km^2. It is 820 km long from northwest to southeast, 320 km at the widest, and 180 km at the narrowest. The climate is monsoon and the average annual precipitation is about 700–1200 mm.

In this study, monthly precipitation data from 15 hydrologic stations are employed, including seven stations in the upper basin (Foping, Hanzhong, Shiquan, Ankang, Yunxi, Xixia, and Yunxian), four stations in the middle basin (Nanyang, Laohekou, Zaoyang, and Fangxian), and three in the lower basin (Zhongxiang, Wuhan, and Tianmen). An extra station Sanmenxia located outside the Han River Basin is used for increasing spatial interpolation accuracy. Data are mainly provided by the National Climate Center of China Meteorological Administration. On the basis of these data, SPI at multiple time scales are calculated to analyze the spatial patterns as well as trend characteristics of drought in the Han River Basin. The statistical properties of precipitation series of 15 stations along with their geographic locations are presented in Table 1.

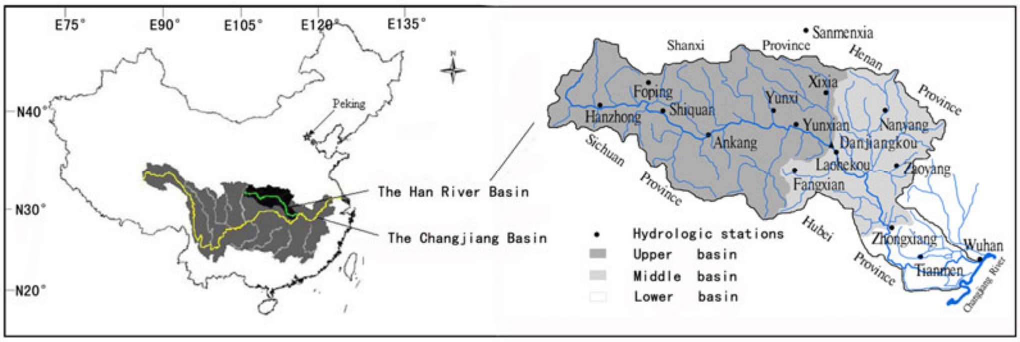

Fig. 1 Location of hydrologic stations used in this study

Table 1 Precipitation properties of hydrologic stations in the Han River Basin

Station	North latitude (°)	East longitude (°)	Period	Mean precipitation (mm)	Max precipitation (mm)	Min precipitation (mm)
Yunxian	32.85	110.82	1952–2008	815.9	1273.1	495.0
Yunxi	33.00	110.42	1989–2008	782.4	566.4	1070.9
Xixia	33.30	111.50	1956–2008	854.7	1463.7	556.6
Wuhan	30.62	114.13	1951–2008	1259.5	2056.9	726.7
Tianmen	30.67	113.17	1954–2008	1109.9	1751.2	737.8
Shiquan	33.05	108.27	1959–2008	873.4	1439.5	574.6
Sanmenxia	34.80	111.20	1957–2008	551.1	332.6	899.4
Nanyang	33.03	112.58	1952–2008	792.9	1356.3	484.0
Laohekou	32.38	111.67	1951–2008	837.3	1243.7	471.5
Hanzhong	33.07	107.03	1951–2008	853.4	1462.8	519.1
Foping	33.53	107.98	1957–2008	912.5	1382.3	603.8
Fangxian	32.05	110.73	1958–2008	831.2	1176.6	523.7
Zhongxiang	31.17	112.57	1952–2008	977.4	1560.1	560.7
Zaoyang	32.15	112.75	1957–2008	855.9	1493.2	473.3
Ankang	32.72	109.03	1952–2008	804.9	1109.2	525.8

3 Methods

3.1 Standardized precipitation index (SPI)

As defined by McKee *et al.* (1993), the time scale of SPI can be flexible. The SPI can be computed for time scales that are important to the water analyst. A time series of long-term monthly precipitation amounts is often prepared for drought analysis. If the water analyst is interested in three- or six-month events, a new time series can be constructed by summarizing the first three or six monthly amounts. For example, six-month SPI (SPI_6) of any month represents the standard deviation in precipitation totals of the month and the previous five months. The six-month SPI is then calculated from this new time series (x).

There are several drought classifications based on SPI values, such as those studied by McKee *et al.* (1993), Agnew (2000), and Patel *et al.* (2007), which have only slight differences. In this study, the classification from GB/T 20481-2006 is used for adaptation to Chinese drought situation (Table 2).

The following states the procedure to compute the SPI value. Assuming that a precipitation series of some time scale (e.g., 1, 2, ..., 48 months) is x, then its probability density function satisfying gamma distribution is

Table 2 Drought classification based on SPI values (GB/T 20481-2006)

Class	SPI value	Drought type
1	SPI>−0.5	No
2	−1.0<SPI≤−0.5	Mild
3	−1.5<SPI≤−1.0	Moderate
4	−2.0<SPI≤−1.5	Severe
5	SPI≤−2.0	Extreme

$$g(x)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}\mathrm{e}^{-x/\beta},\quad x>0, \tag{1}$$

where $\Gamma(\alpha)=\int_0^{\infty}x^{\alpha-1}\mathrm{e}^{-x}\mathrm{d}x$, and α and β stand for shape and scale parameters, respectively.

The shape and scale parameters can be estimated through the maximum likelihood method by using the approximation of Thom (1958) (Edwards and McKee, 1997):

$$\hat{\alpha}=\frac{1+\sqrt{1+4A/3}}{4A}, \tag{2}$$

$$\hat{\beta}=\frac{\overline{x}}{\hat{\alpha}}, \tag{3}$$

where $\hat{\alpha}$ and $\hat{\beta}$ are estimators of α and β, respectively, $A=\ln(\overline{x})-\sum\ln(x)n,$ where n stands for the length of the precipitation time series, and $\bar{x}$ is the mean precipitation.

Due to the fact that gamma function did not include x=0, the actual precipitation, however, can be little as zero. Therefore, assuming that m indicates the number of zeros in the precipitation series, let u=m/n. Consequently, cumulative probability of precipitation for a certain time scale can be calculated as follows:

$$H(x) = u + (1-u)G(x), \tag{4}$$

where $G(x) = \frac{1}{\Gamma(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}\mathrm{e}^{-t}\mathrm{d}t$ and $t = x/\hat{\beta}$.

SPI is then obtained by transforming $H(x)$ to the standard normal random variable with its mean equal to zero and variance equal to one. Following Edwards and McKee (1997), SPI is approximated by

$$\begin{aligned} &\mathrm{SPI} = -\left(k - \frac{c_0 + c_1 k + c_2 k^2}{1 + d_1 k + d_2 k^2 + d_3 k^3}\right), \\ &k = \sqrt{\ln[1/H^2(x)]}, \qquad 0 < H(x) \le 0.5, \end{aligned} \tag{5}$$

$$\begin{aligned} &\mathrm{SPI} = k - \frac{c_0 + c_1 k + c_2 k^2}{1 + d_1 k + d_2 k^2 + d_3 k^3}, \\ &k = \sqrt{\ln\{1/[1-H(x)]^2\}}, \quad 0.5 < H(x) \le 1, \end{aligned} \tag{6}$$

where c_0=2.515517, c_1=0.802853, c_2=0.010328, d_1=1.432788, d_2=0.189269, and d_3=0.001308.

When the value of SPI is continuously negative, a drought event occurs. The event ends when the SPI becomes positive.

3.2 Trend and abrupt point analysis

There are numerous trend analysis methods. The most commonly used methods include linear trend estimation, moving average, cumulative departure curve, quadratic smoothing, and the Mann-Kendall test. In this study, the Mann-Kendall test, put forward by Mann and Kendall (Mann, 1945), was used to testify the change trend of SPI at multiple scales in the Han River Basin, and the inclination rate γ was used to reflect the monotonic trend of SPI time series. Also, the Mann-Kendall test was used to identify the abrupt points of SPI series. This test is a nonparametric one recommended by World Meteorological Organization, and more suitable for non-normal distribution and time series with missing data, due to its nonparametric characteristics and non-disturbance by abnormal values. Therefore, it is widely adopted in hydrometeorology (Hamed and Rao, 1998; Yue *et al.*, 2002).

The statistical variable of the Mann-Kendall test is

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k), \tag{7}$$

where x_i and x_j stand for time series values of the ith and jth years (j>k); n stands for the length of precipitation time series; and sgn(x_i−x_j) stands for the sign function:

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1, & x_j - x_k > 0, \\ 0, & x_j - x_k = 0, \\ -1, & x_j - x_k < 0. \end{cases} \tag{8}$$

The statistics Z_S is

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0, \\ 0, & S = 0, \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0, \end{cases} \tag{9}$$

where Var(S) is the variance of S.

A positive Z_S indicates a rising trend and vice versa. In a two-sided test, given a confidence level of α, if $|Z_S| \le Z_{1-\alpha/2}$, there is no visible trend; if $|Z_S| > Z_{1-\alpha/2}$, there is an obvious increasing or decreasing trend. The inclination rate γ can be used to quantify the monotonic trend:

$$\gamma = \mathrm{Median}\left(\frac{x_i - x_j}{i - j}\right), \ \forall j < i, \tag{10}$$

where Median() indicates the median of data. When β>0, it reflects a rising trend and vice visa.

When the Mann-Kendall test reveals abrupt points, it is necessary to construct a rank series as follows:

$$S_k = \sum_{i=1}^{k}\sum_{j}^{i-1} a_{ij}, \quad k = 2, 3, ..., n,$$
$$a_{ij} = \begin{cases} 1, & x_i > x_j,\ 1 \le i \le j, \\ 0, & x_i > x_j,\ 1 \le i \le j. \end{cases} \tag{11}$$

The formula of statistical variable UF_k is

$$\mathrm{UF}_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{Var}(S_k)}}, \quad k = 1, 2, ..., n, \tag{12}$$

where $E(S_k)=k(k-1)/4$ and $\mathrm{Var}(S_k)=k(k-1)(2k+5)/72$. Another statistical variable UB_k can be defined and calculated in the same way as UF_k by inverting the sequence of time series x_n, x_{n-1}, …, x_1. A $\mathrm{UF}_k>0$ indicates a rising trend and vice versa. Meanwhile, the rising trend is obvious if $|UF_k| > U_{\alpha/2}$, given a significance level of α. When the curves of UF_k and UB_k have intersection points between critical lines, the abrupt change starts.

4 Results

4.1 Historic drought analysis

The drought index at multiple scales could reflect drought severity and duration much more effectively than that at monthly scale (Patel *et al.*, 2007). The regional time series of the SPI value is calculated using the mean areal rainfall over the Han River Basin. The time series of SPI_3, SPI_9, SPI_{12}, and SPI_{24} in upper, and middle and lower basins are calculated and shown in Fig. 2.

Fig. 2 shows that, in the Han River Basin, numerous droughts occurred from the year of 1951 to 2008. The droughts of different severities even occurred several times in one year, and the droughts and floods took place alternately.

The droughts of the Han River Basin are classified mainly as summer, autumn, spring, summer-autumn, and winter droughts (Wen and Pang, 2005; Zhai and Wen, 2005; Wen and Jiang, 2007). Table 3 shows the extreme drought frequency for different drought types (with the SPI value smaller than −2.0 at multiple timescales) in the whole river basin. It can be observed that most of the droughts are characterized as winter and spring droughts when the precipitation was low. The amounts of summer and summer-autumn droughts are fewer compared to spring, autumn, and winter droughts. The years of drought covering the whole basin include 1966, 1978, and 2001.

Among these droughts, SPI_1 identified most of the extreme droughts (20 times in the upper basin, 22

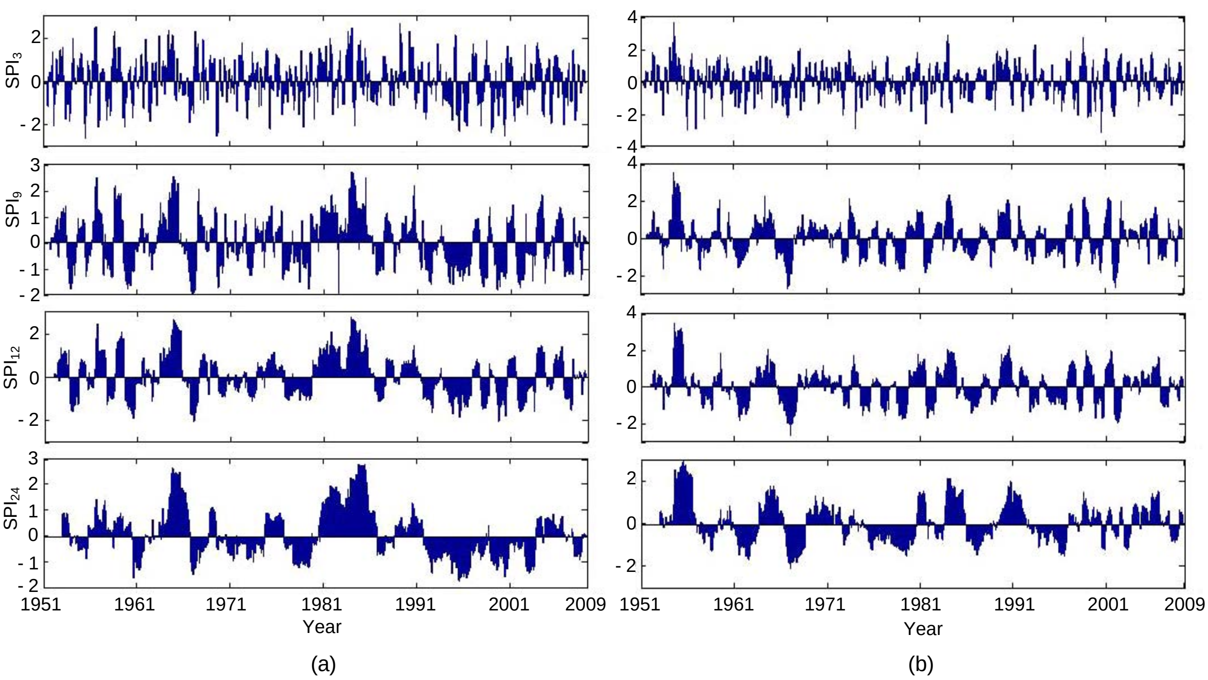

Fig. 2 SPI time series in upper (a) and middle and lower (b) basins of Han River

Table 3 Extreme drought frequency for different drought types

Types	Upper basin	Middle basin	Lower basin
Spring	11	9	11
Summer	7	8	8
Summer-autumn	2	3	5
Autumn	9	8	10
Winter	10	10	8
Total	39[a]	38[b]	42[c]

[a] SPI_1: 20; SPI_3: 15; SPI_6: 6; SPI_9: 0; SPI_{12}: 2; SPI_{24}: 0 with overlaps; [b] SPI_1: 22; SPI_3: 11; SPI_6: 6; SPI_9: 2; SPI_{12}:2; SPI_{24}: 0 with overlaps; [c] SPI_1: 21; SPI_3: 12; SPI_6: 4; SPI_9: 2; SPI_{12}: 1; SPI_{24}: 1 with overlaps

times in the middle basin, and 21 times in the lower basin), followed by SPI_3. SPI at scales larger than nine months identified most of the extreme summer and summer-autumn droughts. SPI_{24} identified the fewest droughts, except those large successive droughts like the one in 1966. However, the numbers of summer and summer-autumn droughts in the middle and lower basins are to some extent underestimated since, historically, numerous droughts occurred in July and September (Wen and Jiang, 2007). The most serious actual droughts occurred in summer when crops needed more water. If the drought continued to September and October, the disaster was much more severe. This is the so-called midsummer-autumn drought (Wen and Jiang, 2007). Typical midsummer-autumn drought years in the middle and lower basins were 1959, 1966, 1972, and 1978. For instance, in June to September, 1978, the water level of Han River dropped to the lowest in history (HLCCC, 1992). These facts imply that the SPI sometimes fails to estimate the actual extreme droughts.

Table 4 shows the calculated SPI values and other data (Wen and Jiang, 2007) for Laohekou and Zhongxiang stations from the middle and lower basins for the four midsummer-autumn drought years. Except at Laohekou in 1972, when the summer was the rainy season in Western Hubei Province and a reasonable amount of precipitation took place, all the SPI values reveal that there were different levels of drought. Particularly, SPIs of different scales at Zhongxiang in 1966 reveal extreme droughts in the middle basin (SPI<−2.0). However, drought severity is occasionally underestimated, as stated before. For example, according to Wen and Jiang (2007), terrible plummeting harvests occurred in 1959 (in the middle basin) while the SPI_1 value of −1.91, shown in Table 4, only indicates severe drought.

The reason why the SPI occasionally fails to identify the summer and summer-autumn droughts lies in the fact that the SPI only reveals the impact of precipitation, while the actual drought can be caused by a combination of factors, including precipitation, human water intake, evaporation, and water pollution, etc.

4.2 Spatial patterns of drought in Han River Basin

Fig. 3 shows that the average annual precipitation in the Han River Basin has a large geographic variation. At the upper basin, more precipitation can

Table 4 Midsummer-autumn drought analysis for Laohekou and Zhongxiang stations

Year	Station	Precipitation (mm)	Time span	SPI_1	SPI_3	SPI_6	SPI_9	SPI_{12}	Days*
1959	Laohekou	4.5	July 2–July 31	−3.02	−0.42	−0.21	−0.01	−0.03	30
	Zhongxiang	99.7	June 30–Sep. 20	−1.91	−2.18	−1.21	−0.95	−1.02	83
1966	Laohekou	126.6	June 6–June 27; July 2–July 31	−0.71	−0.76	−1.33	−1.47	−1.09	52
	Zhongxiang	73.6	June 2–June 23; July 26–Oct. 8	−2.13	−1.57	−2.11	−2.25	−1.77	97
1972	Laohekou	141.9	June 2–June 20; Aug. 6–Sep. 10	−0.05	−0.57	−0.03	0.23	0.43	46
	Zhongxiang	64.3	June 2–Sep. 10	−1.89	−3.27	−1.68	−1.63	−1.18	101
1978	Laohekou	123.8	July 18–Aug. 9; Aug. 12–Oct. 21	−1.26	−1.60	−1.60	−1.64	−1.36	94
	Zhongxiang	158.4	July 17–Aug. 10; Sep. 10–Oct. 25	−0.25	−1.09	−0.61	−0.92	−0.92	71

* Days of drought

be observed in the south than the north, in the west than the east. When it comes to the middle and lower basins, the precipitation increases. The highest amounts of precipitation occur in Tianmen and Wuhan cities at the lower basin, with 1110 and1260 mm per year. Then it decreases toward the northwest to Xixia and Danfeng areas, with the lowest amount of 703 mm, and increases westward to the area around Foping city, with about 912 mm per year. It is noted that precipitation at mountainous region is much more than that at hillock areas and the plain.

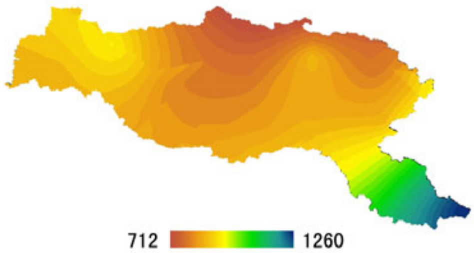

Fig. 3 Average annual precipitation distributions in the Han River Basin

In the Han River Basin, the frequency of drought due to large evaporation, little precipitation, and intense water demand is high. As mentioned before, the years of drought covering the whole basin are 1966, 1978, and 2001. In Fig. 4, spatial analysis for SPI_1 of August, September, and December, which are the typical months for mid-summer drought, autumn drought, and winter drought, respectively, is implemented for the drought years mentioned above.

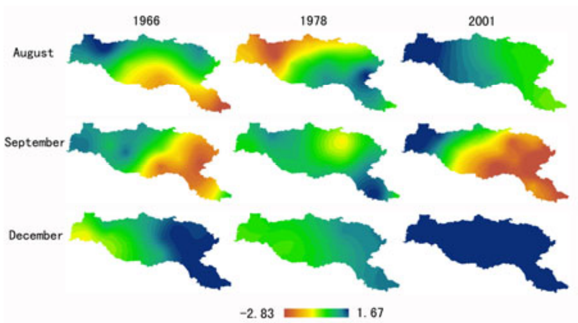

Fig. 4 Spatial interpolation of SPI_1 for severe drought years in the Han River Basin

Drought classifications based on SPI values (Table 2) imply that a smaller SPI means a drier situation. Therefore, Fig. 4 indicates clearly that the most severe drought situation lies in the middle and lower basins, which is in accordance with the precipitation patterns shown in Fig. 3. For 1966 and 1978, the drought in the upper basin is the most severe. If only based on Fig. 4, the summer or autumn drought is the most serious during these three years. The winter droughts in the upper and middle basins are more severe than those in the lower basin, and vice versa for the summer drought.

4.3 Trend analysis and abrupt change

In the following, the Mann-Kendall test for annual SPI_1 is adopted to identify the drought trend among 15 stations along the Han River Basin. The statistical value Z is interpolated by the co-kriging approach to analyze the drought trend in the Han River Basin (Fig. 5).

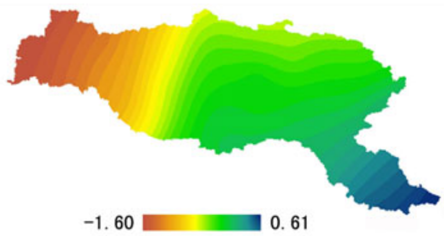

Fig. 5 Long-term trend of annual SPI_1 in the Han River Basin (*Z* value)

In the nearly 60 years, for a significance level of α=0.05, each station satisfies $|Z|\leq Z_{1-\alpha/2}$=1.96, which means there is no remarkable change trend. As a smaller SPI indicates a drier situation, the positive and negative values of Z_s indicate the decreasing and increasing trends of drought, respectively. Fig. 5 shows that in the upper basin and part of the middle basin there is an increasing trend, particularly in Hanzhong and Foping areas, while in the lower basin, a decreasing trend can be observed. These results show that there are existing trends, however, being drier in dry areas, and wetter in humid areas.

According to Figs. 4 and 5, the main conclusions are: in terms of the drought severity, the upper basin of Han River is the least, while the growing trend is the most conspicuous, especially in Foping and Hanzhong areas; a less conspicuous growing trend can be observed in the middle basin, and there is a decreasing trend in the lower basin.

Table 5 shows the Z and β values of SPI_3 at the end month of four seasons at 15 stations, for the significance level of α=0.05. The results show

Table 5 Analysis of the Mann-Kendall changing trend of the SPI_3 in the Han River Basin

Station	Spring		Summer		Autumn		Winter	
	Z	β	Z	β	Z	β	Z	β
Foping	−1.7755	−0.0162	−0.5839	−0.0055	−0.0947	−0.0010	1.1534	0.0089
Hanzhong	−1.4087	−0.0126	−1.4221	−0.0117	−0.5970	−0.0055	0.9500	0.0075
Shiquan	−1.9308	−0.0209	1.5430	0.0173	−1.4999	−0.0155	1.2621	0.0132
Ankang	−1.8941	−0.0168	1.6891	0.0154	−0.8269	−0.0070	0.9002	0.0090
Yunxian	0.8710	0.0153	−0.1210	−0.0023	0.6532	0.0089	0.1634	0.0026
Xixia	−2.5094	−0.0219	0.2210	0.0017	−1.0337	−0.0092	0.7391	0.0066
Nanyang	−0.5442	−0.0045	−0.0919	−0.0009	−0.7562	−0.0061	0.5009	0.0032
Laohekou	−0.1073	−0.0010	1.1739	0.0098	−0.8989	−0.0077	−0.0482	−0.0003
Zaoyang	−2.0280	−0.0163	1.3178	0.0134	−0.8838	−0.0090	1.0396	0.0096
Fangxian	−0.8203	−0.0082	0.7635	0.0070	−1.0559	−0.0117	0.6525	0.0065
Zhongxiang	−1.0248	−0.0086	1.2934	0.0093	−0.5725	−0.0043	0.5372	0.0045
Wuhan	−0.4964	−0.0037	0.6238	0.0053	−0.5635	−0.0044	1.6865	0.0158
Tianmen	−1.5027	−0.0127	0.3848	0.0042	−0.8494	−0.0070	1.2160	0.0113
Sanmenxia	−1.1126	−0.0138	−0.9233	−0.0099	−0.4971	−0.0045	0.0812	0.0016
Yunxi	1.3302	−0.0343	−0.6813	−0.0296	1.2004	0.0437	1.0496	0.0464

insignificant tends in all seasons and all stations with exceptions for Xixia and Zaoyang in spring where $|Z|>Z_{1-\alpha/2}$. This means that there is an obvious growing trend. Most of the β values in spring and autumn, except Yunxian are below 0, indicating growing trends in these two seasons, whereas in summer and winter decreasing trends can be observed in most stations. The highest declining rate in spring occurs in Yunxi with a value of −0.0343, while the highest declining rate in autumn occurs in Shiquan with a value of −0.0155. The highest increasing rate in summer is Shiquan with an average rate of 0.0173, and the highest increase in winter is Yunxi with an average rate of 0.0464. Only a slightly growing trend of drought is observed in Laohekou Station in winter.

Fig. 6 shows the interpolated Z values for SPI_3 in all seasons of the Han River Basin. It shows that there are growing trends in both spring and autumn, while decreasing trends can be observed in summer and winter, except that there is a slight growing trend in part of the upper basin in summer. This indicates more frequent spring and autumn droughts in the future, from a meteorological point of view.

The change point was tested by the Mann-Kendall method with a significance level of α=0.05. The critical value 1.96 is obtained by normal distribution table. Fig. 7 shows the values of UF and UB for different time-scale SPIs in the upper, middle, and lower basins of Han River. It is known that most SPI satisfies −1.96<UF<1.96. Due to $|\text{UF}|<1.96$, the trend is therefore inconspicuous. Although the trend does not meet the conspicuous level, a UF>0 means that SPI increases continuously, and the drought weakens.

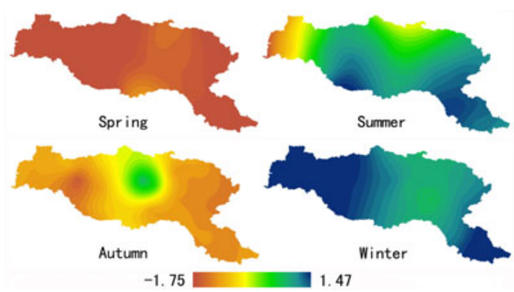

Fig. 6 Spatial interpolation of Z for SPI_3

From Fig. 7, it is observed that when time scale increases, the trend becomes more obvious. The UF value in the upper basin fluctuated from 1950 to 1990 indicating irregular aggravation and weakening. From 1990, a growing trend of drought in the upper and middle basins can be observed while in the lower basin, a decreasing trend can be observed. The change trend of SPI values at different time scales tends to be consistent.

Fig. 7 also shows that numerous change points can be identified, and some are desultory which failed to show any actual change. This is the shortcoming

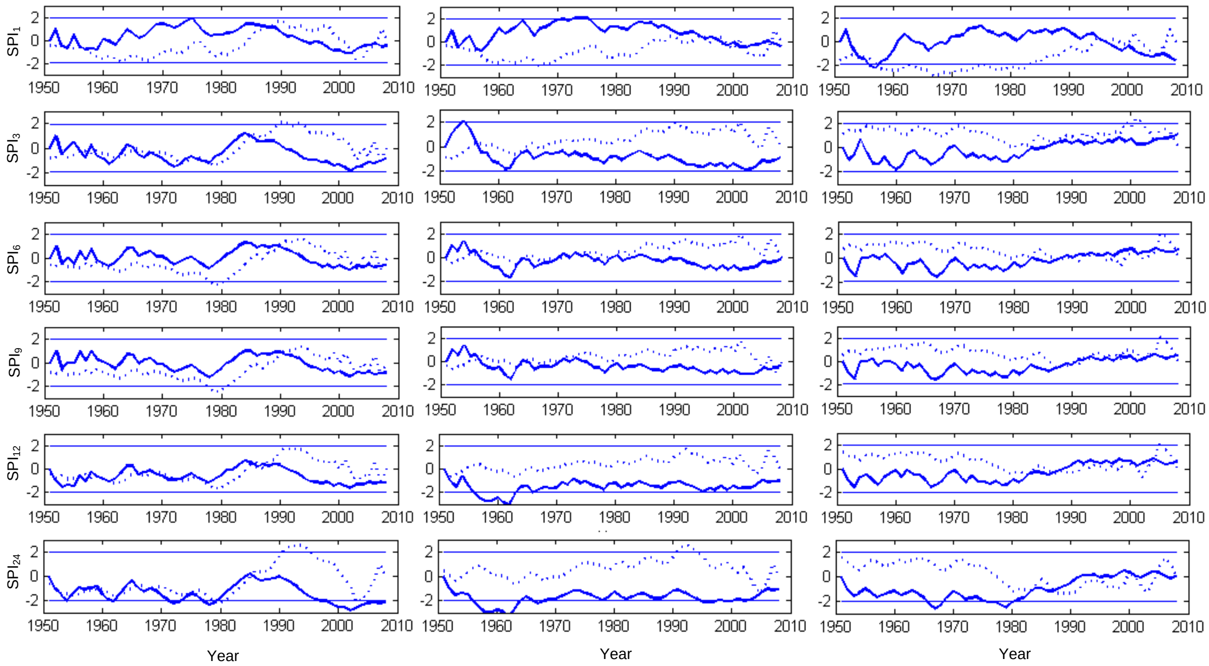

Fig. 7 Abrupt change point test results for multi-scale SPIs in upper (a), middle (b), and lower (c) basins of Han River (the sold line indicates UF, and the dotted line indicates UB)

of detecting change points by the Mann-Kendall test. With the increase in time scale of SPI, desultory points become less or disappear. For the whole basin, two obvious change points can be identified. The first occurred in the 1950s, indicating the transfer from dry period to humid period, and the second occurred after 2000, indicating the transfer from humid period to dry period. For the upper basin, an extra change point at the end of 1980s can be observed, while for the upper and lower basins, an extra change point between 1980 and 1990 can be identified.

4.4 Impact of drought on South-to-North Water Transfer Project (SNWTP)

The Middle Route of SNWTP will take water from Danjiangkou Reservoir and transfer water to Henan, Hebei, Beijing, and Tianjin (Wei *et al.*, 2010). Its main purpose is to alleviate the water shortage situation in more than 20 cities, including Beijing, Tianjin, and Shijiazhuang, with the annual water transfer amount reaching 13 billion cubic meters. Danjiangkou Reservoir, the water intake source for the Middle Route of SNWTP, is located at the intersection point of the upper and lower basins. This reservoir is the largest artificial lake with an area of 400 km^2 as well as 92 500 km^2 of drainage areas. It is noted that the amount of water in the Danjiangkou Reservoir will drop dramatically in drought years, especially with massive drought in successive years, which would consequently impact the water supply to the north. For instance, during 1965 and 1966, there was moderate, but massive, drought in Hanjiang and Nanyang areas when the amount of water into Danjiangkou Reservoir dropped by 78%, less than 50% of the annual average amount. During 1976 to 1978, drought occurred in Hanzhong and Yunxian areas in the upper basin and the water in the reservoir in these three years was below the average. During 1991 to 1995, Ankang and Hanzhong areas in the upper basin experienced three or five droughts for three to five years successively, and the amount of water in the reservoir was less than the average for four years. Up to 1995, the amount was less than 60% of the average (Zhang *et al.*, 2000). Under these circumstances, the water available for the middle line of SNWTP is very limited.

As SPI_{12} and SPI_{24} serve as the effective signals to reflect the water storage capacity of reservoir (Yuan and Zhou, 2004), it is sensible to adopt them to analyze the drought taking place in the watershed of

Danjiangkou Reservoir. Table 6 summarizes the drought occurrence frequency of different levels at the upper basin of the Han River. On the basis of SPI_{12}, it can be observed that in more than fifty years, 12 mild droughts, 16 moderate droughts, 11 severe droughts, and two extreme droughts occurred in the upper basin (yearly based, without overlaps). This indicates a frequent occurrence of droughts in the upper basin. The six extreme droughts occurred around 1959, 1965, 1966, 1994, 1998, and 1999, which is very consistent with the historic drought records (Zhai and Wen, 2005).

Table 6 Drought occurrence frequency in upper and middle basins of Han River

Drought type	Upper basin		Middle basin		Simultaneous times	
	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}
Mild	12	18	13	12	4	3
Moderate	16	11	18	16	9	6
Severe	11	4	9	4	5	1
Extreme	2	0	2	0	2	0
Total	41	33	42	32	20	10

Since the drought in the upper basin affects the inflow to the reservoir and corresponding outflow to the middle basin, it is important to investigate the possibility of simultaneous droughts in the upper and middle basins. Table 6 compares the simultaneous occurrences of droughts in the upper and middle basins of the Han River. Based on SPI_{12}, the occurrence times of extreme droughts in the upper and middle basins are both two and the simultaneous extreme droughts occur two times as well. The simultaneous severe droughts occur five times. In general, the frequency of simultaneous droughts is around 32%. This means the occurrence of simultaneous droughts in the upper and middle basins is rather high.

Fig. 8 shows the drought situation of Danjiangkou Reservoir by analyzing the SPI values from Laohekou Station near the reservoir. Table 7 lists the drought frequency in the Hanjiang source area.

Both Fig. 8 and Table 7 show that most of the droughts which occurred in the Hanjiang source area were moderate and severe, and in total 16 severe and extreme droughts occurred, as determined by SPI_{12}. Extreme droughts occurred less often, and almost all of them were in 1960s. Based on Table 7, the frequency of severe and extreme droughts in Hanjiang areas of the middle line of SNWTP is about 40% in terms of SPI_{12}. When large-scale successive droughts occur, the water storage of Danjiangkou Reservoir would be affected dramatically.

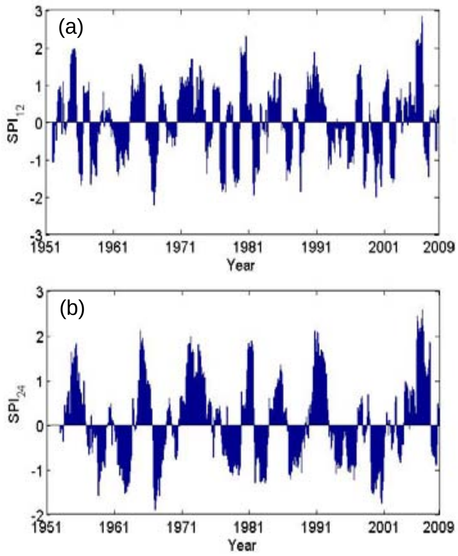

Fig. 8 Drought situations of Danjiangkou Reservoir
(a) SPI_{12}; (b) SPI_{24}

In the following section, the impact of successive droughts on SNWTP is analyzed. Select years when most droughts occurred are chosen for analysis. Fig. 9 shows the SPI_{24} values for the successive drought years 1965–1967, 1976–1979, and 1991–1996. From 1965 to 1967, drought covered the whole

Table 7 Drought frequency in Hanjiang source area of SNWTP (Danjiangkou Reservoir)

Drought type	1951–1960		1961–1970		1971–1980		1981–1990		1991–2000		2001–2008	
	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}	SPI_{12}	SPI_{24}
Mild	0	1	3	3	1	2	1	0	2	2	2	5
Moderate	4	1	3	2	1	3	2	6	3	3	2	0
Severe	2	1	1	3	4	0	3	0	4	3	1	1
Extreme	0	0	1	0	0	0	0	0	0	0	0	0
Total	6	3	8	8	6	5	6	6	9	8	5	6

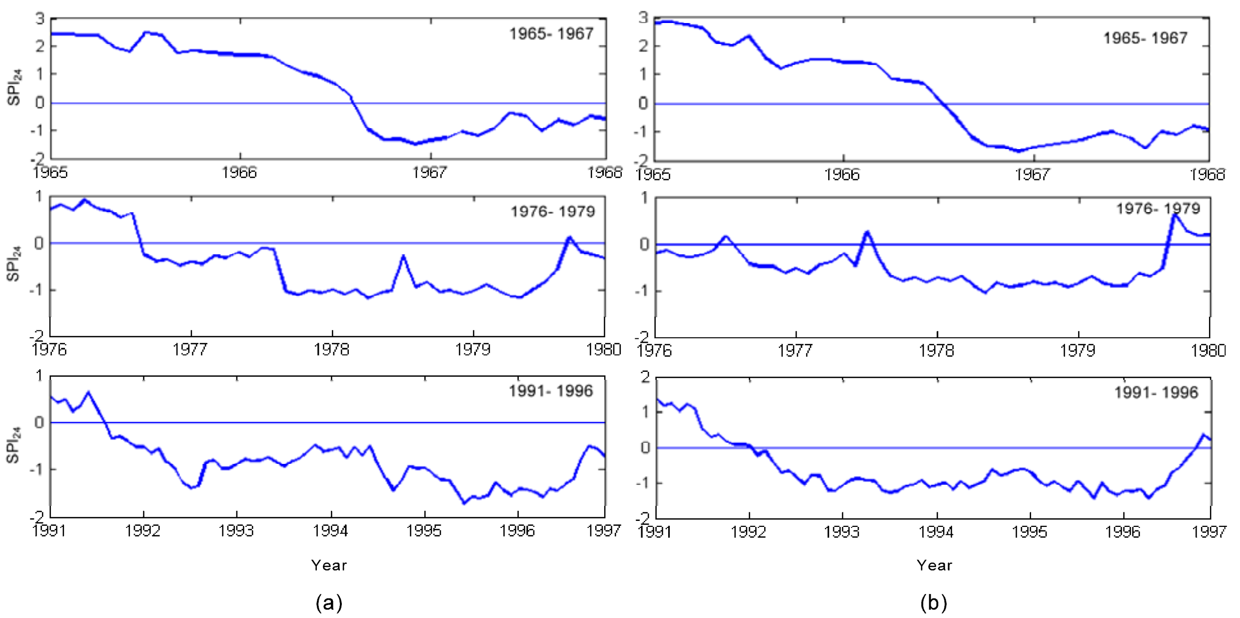

Fig. 9 SPI_{24} values for the upper (a) and middle (b) basins of Han River in three periods

Han River Basin, and the values of SPI_{24} below −1.5, indicated that severe drought occurred. Especially in the middle basin, the SPI_{24} value almost approaches −2.0, indicating severe drought occurred. From 1976 to 1979, the upper and middle basins both experienced droughts with SPI<0.5 for a very long time. From 1991 to 1996, both the upper and middle basins had severe droughts which lasted for almost five years with SPI<1.5. In these years, the inflow into the reservoir was dramatically affected.

5 Conclusions

In this paper, the standardized precipitation index (SPI) is used to quantitatively evaluate the drought situation based on monthly precipitation dataset of 15 hydrologic stations in the Han River Basin. The main conclusions based on this study are:

1. The SPI_1 was found to be effective in revealing most droughts over space and time in the Han River Basin whereas SPI of the larger scales (more than nine months) identified most summer and summer-autumn droughts.

2. In terms of the drought severity, the upper basin of the Han River is the least, while the growing trend is the most conspicuous, especially in Foping and Hanzhong areas; a less conspicuous growing trend can be observed in the middle basin and there is a decreasing trend in the lower basin.

3. The drought trend in all stations and all seasons is not so significant, except at Xixia and Zaoyang stations. In the Han River Basin, an insignificant rising trend of drought can be identified in spring and autumn, whereas in summer and winter, a decreasing trend can be observed in most stations. Furthermore, two change points can be identified. The first occurred in 1950s, indicating the transfer from dry period to humid period, and the second occurred after 2000, indicating the transfer from humid period to dry period.

4. A high frequency of drought occurrences can be observed in the whole Han River Basin, which may affect the inflow to Danjiangkou Reservoir significantly. Particularly, when simultaneous droughts occur in both the upper and middle basins, the water intake from Danjiangkou must be reduced.

The study in this paper provides valuable information to regional water resource management and support to the future water allocation decision making of SNWTP.

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