



Comparison of drought indices in the analysis of spatial and temporal changes of climatic drought events in a basin

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Abstract

The standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) based on two different methods were calculated using monthly meteorological data from the Yangtze River Basin. According to the completeness and length of dataset, the monthly data of 35 meteorological stations from 1959 to 2017 were applied in this study. The results revealed that the SPEI calculated by the Penman-Monteith (PM) method performed better than the SPI and the SPEI based on the Thornthwaite (TH) method. Since SPEI_{PM} considered more meteorological factors and detailed physical processes, it obtained the most reasonable and accurate results of drought trends. Using the variations of SPEI_{PM} to analyze the decadal changes of drought characteristics in the basin, it could be found that 1980–1989 and 1990–1999 were the most humid periods in the basin, while the drought events became more frequent and severe in the recent decade. The spatial distributions of drought trend, duration and frequency indicated that the stations located in the midstream of the river were most prone to drought events, followed by the upper reaches. Our results provided more information for the regions where severe droughts occurred frequently and last longer, and more attention should be paid to these regions in future catchment management.

Keywords Drought analysis · Standardized precipitation index · Standardized precipitation evapotranspiration index · Yangtze River Basin

Introduction

Drought is considered as a slow-onset natural hazard and a highly complex phenomenon (Dubrovsky et al. 2009; López-Moreno et al. 2009), which is commonly caused by the long periods of low precipitation. As a climate-related disaster, droughts have significant impacts on regional sustainable development by affecting water availability (Tirivarombo et al. 2018). In order to accurately monitor drought events and quantify their duration and magnitude, a series of drought-related indices are proposed. The Palmer drought severity index (PDSI) is the first index to successfully quantify drought severity under various climates (Palmer 1965). However, several shortcomings are revealed during the application process,

including the high effect of calibration period, the problem in spatial comparability and so on (Vicente-Serrano et al. 2010). The subsequent index that has been widely applied in different regions of the world is the standardized precipitation index (SPI) (McKee et al. 1993). The SPI assumes that precipitation is the only dominant factor, while other meteorological factors are considered to be stationary (Du et al. 2013). However, there have been many studies confirming the rise in global temperatures, which leads to the increase in water demand due to evapotranspiration (Heim Jr 2017; Rebetz et al. 2006). Therefore, the standardized precipitation evapotranspiration index (SPEI) is proposed by Vicente-Serrano et al. (Vicente-Serrano et al. 2010) based on precipitation and potential evapotranspiration (PET). The estimation of PET based on the classic Thornthwaite (TH) equation is found to be prone to underestimation in arid and semi-arid regions (Ahmadi and Fooladmand 2008) and overestimation in humid regions (Tabari et al. 2013). Some studies have stated that the application of the Penman-Monteith method (PM) (Allen et al. 1998) for PET estimation can result in more reasonable drought trends globally (Trenberth et al. 2014) and throughout China (Chen and Sun 2015), as this method takes more factors

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and more complex physical processes into account. All of the SPI, SPEI_TH, and SPEI_PM are able to reflect the characteristics of drought events at different time scales, while the differences between them generally occur when the study area is very large. We wonder whether the results of drought analysis based on these indices differ in the relatively small basin scale, which is one of the purposes of this study.

The Yangtze River is the longest river in China and the third longest river in the world. It not only has an important influence on the local economic and ecological sustainable development, but also has a non-negligible effect on Southeast Asia (Sang et al. 2013). However, there have been many incidents caused by extreme weather in the Yangtze River Basin in recent years (Guan et al. 2017), such as the devastating flood in 1998 (Piao et al. 2010), and the increasing shortage of water resources and frequent drought events in the southwestern part of the basin (Shi et al. 2013). The occurrence of severe drought events may have very negative impacts on agriculture, industry, ecosystem, and human life in the basin (Wu et al. 2006; Zhang et al. 2015). Due to the inevitable and recurring features of drought event, the analysis of its temporal and spatial characteristics in the basin is another point of this study. Therefore, the main objectives of this study were (1) to compare the performances of SPI, SPEI_TH, and SPEI_PM in reflecting the drought characteristics of the Yangtze River Basin; (2) to analyze the temporal and spatial changes of climatic drought events in the Yangtze River Basin over the past 60 years.

Study area and data

The Yangtze River (91°–122° E, 25°–35° N) is the longest river in China, with a length of 6300 km. The total area of this basin is approximately 1,800,000 km², some 20% of China's land area. The river originates from the Qinghai-Tibet Plateau, and flows eastward through Shanghai city into the East China Sea finally (Guan et al. 2017). The terrain in the Yangtze River Basin varies greatly, from the high mountains to the fluvial plains, with an elevation drop of more than 6000 m (Yu et al. 2009). Most parts of the basin are affected by the subtropical monsoon climate, and the long-term mean annual precipitation is about 1070 mm, with the majority occurring during June to August (Xu et al. 2018). However, the spatial distribution of precipitation is uneven in the basin, while the range of mean annual precipitation is 500–2500 mm from west to east (Xu et al. 2008).

The monthly precipitation, air temperature, and other meteorological data of 35 principal meteorological stations in the Yangtze River Basin were obtained from the National Climate Center of the China Meteorological Administration (CMA). The selection of stations was primarily based on the completeness and length of dataset (Hui-Mean et al. 2018). The record covered a period of 67 years (1951–2017), but the target

period in this study was from 1959 to 2017 (59 years) due to the missing data of most sites in the 1950s. Before being released, the homogeneity and reliability of these monthly data have been checked and firmly controlled (Yu et al. 2014). The locations of these meteorological stations were shown in Fig. 1. Their geographic information and the mean values of climatic variables were summarized in Table 1.

Methodology

Calculation of the standardized precipitation index (SPI)

The SPI was developed by McKee et al. (McKee et al. 1993) to assess and quantify drought events based on the long-term precipitation data. Due to the few types of required data, the SPI had widely drought-related applications and relatively simple to be calculated as follows:

$$\text{SPI} = \frac{x_i - \bar{x}}{\sigma} \quad (1)$$

where x_i was the monthly precipitation data, \bar{x} and σ were the mean value and standard deviation calculated from the monthly data for the whole selected period.

The calculation of SPI was spatially invariant, so it can be applied to describe and compare drought conditions in different areas (Tirivarombo et al. 2018). It was also able to quantify the precipitation deficit for multiple time scales, which could provide information of drought severity and frequency (Tigkas et al. 2018). However, the lack of parameters expressing air temperature and other meteorological factors may lead to bias in drought assessment results and make the index less adaptable (Zarch et al. 2015).

Calculation of the standardized precipitation evapotranspiration index (SPEI)

The first step in calculating the SPEI was to obtain the potential evapotranspiration (PET), which was obtained using two methods in this study. The simple one was the Thornthwaite method (Thornthwaite 1948), which required only air temperature as the input variable:

$$\text{PET}_{\text{TH}} = 16k \left(\frac{10T}{I} \right)^m \quad (2)$$

where T was the monthly mean air temperature (°C), k was a factor that accounted for the different day length between months, and was estimated based on the latitude of the meteorological station. I represented the annual heat index and m was a coefficient depending on I , both of which were calculated according to empirical formula

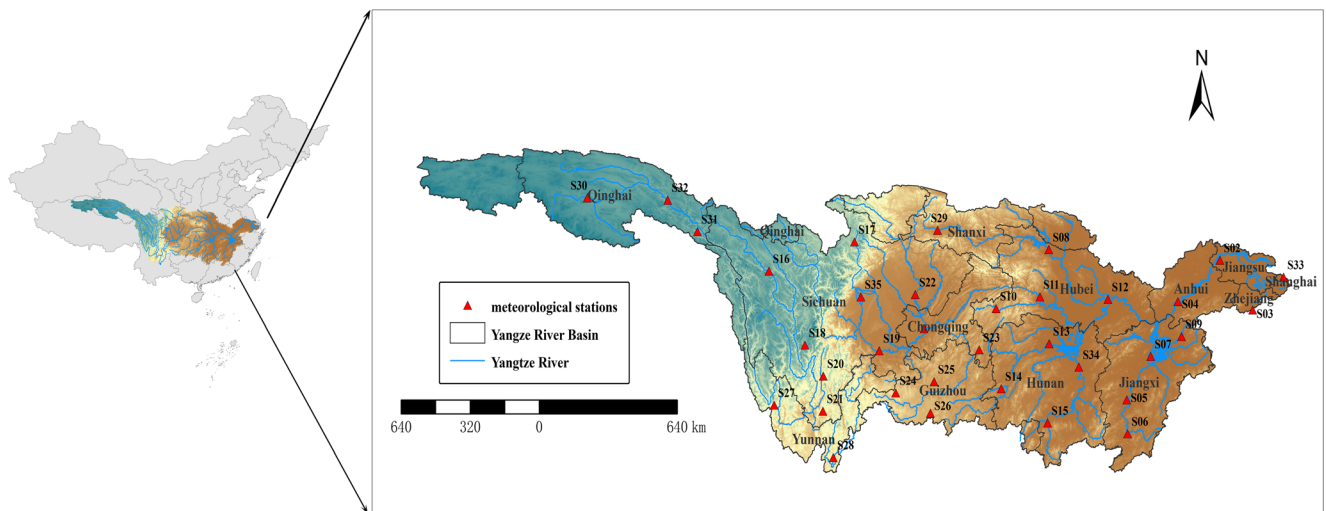


Fig. 1 Locations of the meteorological stations in the Yangtze River Basin

(Tirivarombo et al. 2018; Yu et al. 2014).

The other method was Penman-Monteith method (Allen et al. 1998) as follows:

$$PET_{PM} = \frac{0.408\Delta(R_n - G) + \gamma \left[\frac{900}{(T + 273)} \right] U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

where T was the mean air temperature ($^{\circ}C$), Δ was the slope of the saturated vapor pressure curve ($kPa^{\circ}C^{-1}$), e_s and e_a were the saturation vapor pressure (kPa) and the actual vapor pressure (kPa), respectively; the difference between them ($e_s - e_a$) was the saturation vapor pressure deficit at temperature T . The saturated vapor pressure data were not available from the meteorological stations; thus, they were calculated from the maximum temperature ($^{\circ}C$), the minimum temperature ($^{\circ}C$), and the mean relative humidity data (%) (Sentelhas et al. 2010). U_2 was the averaged wind speed at a height of 2 m, which was converted from the wind speed data obtained at 10 m in this study. R_n was the net radiation ($MJ m^{-2} day^{-1}$), which was determined according to the equations recommended by Allen et al. (1998) based on the observed values of sunshine hours. G was the soil heat flux density ($MJ m^{-2} day^{-1}$), which was considered as 0. γ was the psychrometric constant ($0.0677 kPa^{\circ}C^{-1}$).

The next step of calculating SPEI was to determine the deficit or surplus accumulation of climate water balance (CWB) at different time scales, that is, the difference between the precipitation (P) and PET for the month i : $CWB_i = (P_i - PET_i)$. The classical approximation of Abramowitz and Stegun (Yu et al. 2014) could be expressed as follows:

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}$$

where $W = \sqrt{-2\ln(P)}$ for $P \leq 0.5$, P was the probability of exceeding a determined CWB value. If $P > 0.5$, then P was

replaced by $1 - P$ and the sign of the resultant SPEI was reversed. The values of constants ($C_0, C_1, C_2, d_1, d_2, d_3$) and the remaining calculation steps had been mentioned in many studies (Tirivarombo et al. 2018; Vicente-Serrano et al. 2010), and they were not repeated in this study. Then, the SPEI_TH and SPEI_PM of different time scales were computed for each station.

Drought identification

The categorization of dryness and wetness grade based on the SPI and SPEI values was shown in Table 2. In this study, the focus was on moderate to extreme drought. The time scales of 12 months and 3 months were calculated to analyze the trends, duration, and frequency of drought. The nonparametric Sen’s slop method (Sen 1968) and Mann-Kendall (MK) method (Kendall 1955; Mann 1945) were applied to estimate the linear trend and perform significance test. The values corresponding to the significance levels of 5 and 10% were 1.96 and 1.64 respectively, which would be used to discuss the MK trend statistic in the following parts. The duration of drought was considered as the period of consecutive months for which the severe or extreme drought had occurred. In addition, the drought frequency was explored based on the results of 3-month indices falling in different drought categories.

Results and discussion

Comparison between SPI, SPEI_TH, and SPEI_PM for drought trend analysis

The SPI, as a precipitationbased drought index, relied on an important assumption that the variability of precipitation was much higher than that of other variables, including the air

Table 1 The geographical coordinates of meteorological stations and the mean values of climatic variables used in this study

Station number	Latitude	Longitude	Elevation (m)	Precipitation (mm)	Temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Sunshine hours
S01	29.58	106.47	259.1	92.55	18.46	1.36	0.79	2.93
S02	31.93	118.80	7.1	90.22	15.76	2.49	0.75	5.51
S03	30.23	120.17	41.7	118.31	16.77	2.20	0.76	4.81
S04	30.62	117.05	19.8	118.66	16.90	3.00	0.76	5.07
S05	27.05	114.92	71.2	127.16	18.62	2.06	0.79	4.50
S06	25.87	115.00	137.5	119.94	19.57	1.64	0.75	4.94
S07	28.60	115.92	46.9	132.72	17.92	2.49	0.76	5.07
S08	32.43	111.67	90.0	68.57	15.67	1.48	0.75	4.78
S09	29.30	117.20	61.5	148.65	17.62	1.78	0.77	5.00
S10	30.28	109.47	457.1	120.72	16.36	0.67	0.81	3.40
S11	30.73	111.30	133.1	95.48	16.99	1.29	0.75	4.18
S12	30.60	114.13	23.1	105.14	16.78	1.96	0.77	5.27
S13	29.12	111.68	35.0	111.75	17.08	1.86	0.78	4.44
S14	27.45	109.68	272.2	104.31	16.68	1.50	0.79	3.95
S15	26.23	111.62	172.6	118.08	17.97	2.97	0.77	4.09
S16	31.62	100.00	8393.5	54.04	5.86	1.81	0.56	7.10
S17	32.67	103.57	2850.7	59.86	6.04	1.36	0.63	4.94
S18	29.00	101.50	7987.3	75.99	9.03	2.54	0.61	5.39
S19	28.80	104.60	340.8	89.42	18.05	0.94	0.80	2.78
S20	27.90	102.27	1590.9	83.77	17.10	1.44	0.61	6.42
S21	26.65	102.25	1787.3	95.24	15.29	1.51	0.69	6.68
S22	30.73	106.10	309.7	83.83	17.55	1.12	0.79	3.28
S23	28.82	108.77	664.1	112.25	14.91	0.94	0.79	2.96
S24	27.30	105.28	1510.6	73.94	12.95	0.89	0.81	3.39
S25	27.77	107.47	792.2	92.99	15.13	1.76	0.81	2.95
S26	26.58	106.73	1223.8	92.30	15.09	2.26	0.77	3.17
S27	26.85	100.22	2392.4	79.59	12.91	3.17	0.62	6.76
S28	25.00	102.65	1886.5	82.94	15.18	2.16	0.71	6.17
S29	33.07	107.03	509.5	70.83	14.61	1.07	0.79	4.27
S30	34.22	92.43	4533.1	24.41	-3.79	3.93	0.53	7.92
S31	33.00	97.02	3681.2	40.71	3.41	1.12	0.54	6.77
S32	35.22	93.08	4612.2	24.50	-5.15	4.27	0.56	7.63
S33	31.40	121.45	5.5	93.90	16.35	3.58	0.77	5.39
S34	28.20	113.08	44.9	119.69	17.45	2.29	0.81	4.25
S35	29.57	103.75	424.2	104.90	17.42	1.23	0.79	2.92

temperature. The spatial patterns of the MK trend statistics for the annual precipitation and air temperature in the Yangtze River Basin during 1959–2017 were shown in Fig. 2. The positive and negative values represented upward and downward trends at 5 and 10% confidence level, respectively. From Fig. 2 a, it can be found that there were no significant changes in the annual precipitation of most meteorological stations except S30 and S33. However, nearly one third of the stations in the basin showed upward trends in temperature, especially in the areas with high altitudes and some coastal regions. Since the change of temperature significantly affected the strength of transpiration,

the importance of air temperature should not be ignored. Even at the basin scale, climatic drought events were not controlled by the variability in precipitation alone.

There had been studies proving that no significant difference existed between the SPEI_TH and SPEI_PM from a global perspective (Beguería et al. 2014). However, Chen et al. (Chen and Sun 2015) documented that there were differences between these two indices for monitoring drought throughout China. We wondered if there was difference between these two indices on the basin scale, and would like to address the issue in this study. The spatial distributions of the

Table 2 Categorization of dryness and wetness grade based on the SPI and SPEI values

Category	SPI value	SPEI value
Extremely wet	More than 2.00	More than 2.00
Severely wet	1.50 to 1.99	1.50 to 1.99
Moderately wet	1.00 to 1.49	1.00 to 1.49
Near normal (mildly wet)	0 to 0.99	0 to 0.99
Near normal (mild drought)	−0.99 to 0	−0.99 to 0
Moderate drought	−1.49 to −1.00	−1.49 to −1.00
Severe drought	−1.99 to −1.50	−1.99 to −1.50
Extreme drought	Less than −2.00	Less than −2.00

MK trend statistic of annual SPI, SPEI_TH, and SPEI_PM were shown in Fig. 3. There were apparent differences between the SPI and the SPEI series. The differences were mainly concentrated in the upstream regions, which was consistent with the changes of air temperature. This result indicated that if the influence of temperature on drought conditions was neglected, it may bring a large error to the estimation, even

within the basin. Based on the analysis of Figs. 3 b and c, there were more stations experiencing significant drying trends at the 95% confidence level in the SPEI_TH than the SPEI_PM. Among the stations with trend differences, three of them (S06, S14, S27) were the most significant, showing the opposite trends. They all presented drying trends based on SPEI_TH values, while wetting trends were found based on SPEI_PM values. In order to find out the possible reasons, the trends of wind speed, humidity, and sunshine hours of these three stations were analyzed. The results indicated that wind speed and sunshine hours were shown significant downward trends for S06, S14, and S27. Since the windy days with long-hour sunshine are more likely to increase the amount of water evaporated, the PM algorithm could more accurately reflect the changes in the PET. To further compare the performances of the SPEI_TH and SPEI_PM, the relationships between the streamflow and the two CWB series for S06, S14, and S27 were explored. The monthly streamflow data from three hydrological sites, which were similar in location to S06, S14, and S27 (Table 3), were collected. However, the obtained data were just from 2009 to 2015 due to data limitations and not consistent with the duration of the

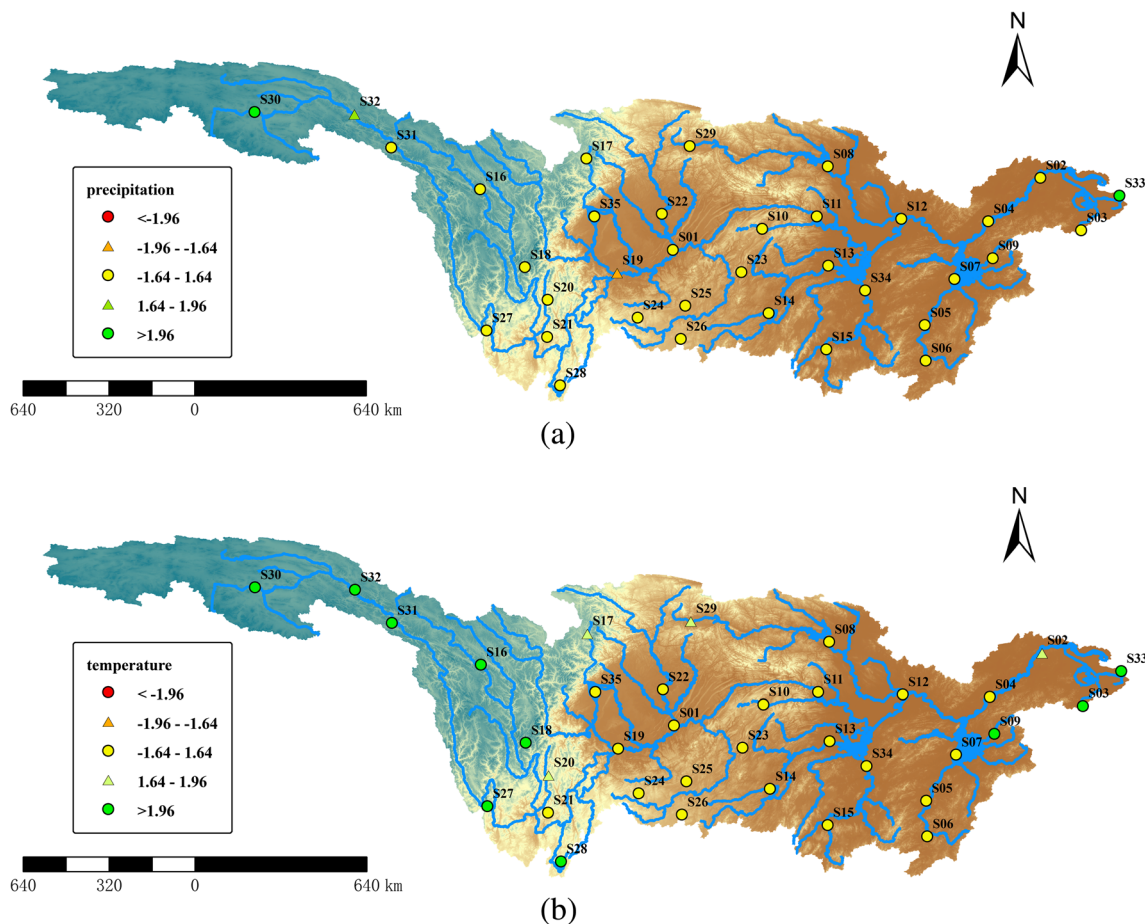
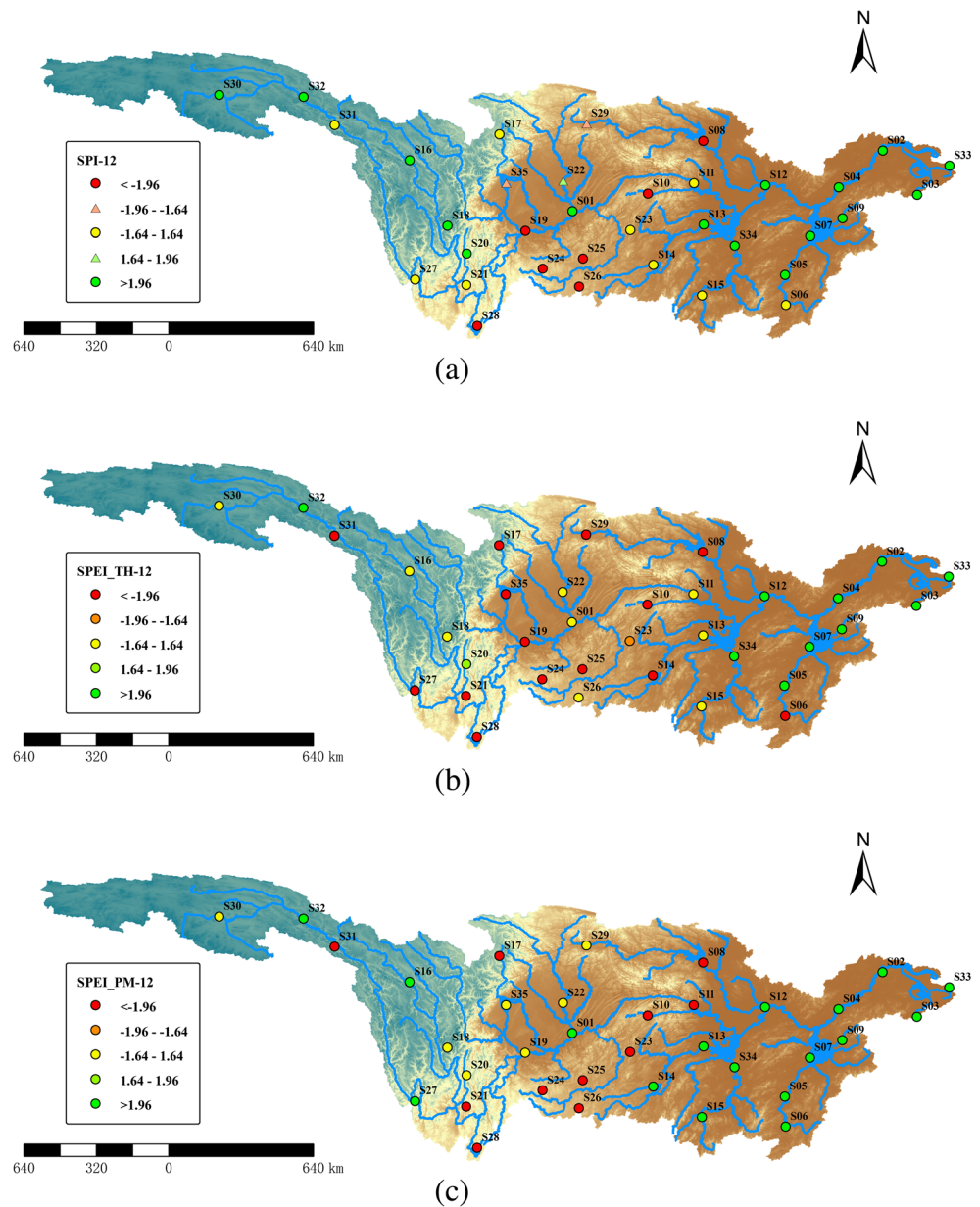


Fig. 2 The spatial distributions of the MK trend statistic for the **a** annual precipitation, **b** annual air temperature from 1959 to 2017

Fig. 3 The spatial distributions of the MK trend statistic for the **a** annual SPI, **b** annual SPEI_TH, and **c** annual SPEI_PM from 1960 to 2017



meteorological data. Although there may be some uncertainties, Spearman correlation tests were performed between monthly streamflow data and CWB series during 2009–2015, and the results were summarized in Table 3. CWB, as the difference between the precipitation and the PET, was an important factor influencing water availability and the surface runoff (Novotny and Stefan 2007). The Mujiaqiao hydrological site, which was close to the S27, was located in an area with little interference from human activities. Therefore, the streamflow has the highest correlation coefficients with the two CWB series at this site. The streamflow data from the other two hydrological sites had weaker correlations with the CWB series, due to the greater impacts of human activities. However, according to

the coefficients shown in Table 3, the correlations between the streamflow and the CWB_PMs were higher than the CWB_THs for all the three stations. Therefore, the CWB_PM can be considered to perform better than the CWB_TH in reflecting streamflow variations. The curves of streamflow and CWB_PM over time for S06, S14, and S27 were shown in Fig. 4; it can be seen that the trends of these two variables were basically the same. In a word, SPEI_PM not only reflected the trend of drought more reasonably but also had better performance in monitoring hydrological variations compared to SPEI_TH in the Yangtze River Basin. Therefore, the spatial and temporal analysis of drought characteristics would be implemented based on the results of SPEI_PM in the following sections.

Table 3 Spearman correlation coefficients between monthly streamflow data and CWB series

Meteorological stations	Corresponding hydrological sites	CWB_TH	CWB_PM
S06	Bashang site (114° 57' E, 25° 49' N)	0.35*	0.61*
S14	Zhijiang site (109° 40' E, 27° 28' N)	0.46*	0.66*
S27	Mujiaqiao site (100°17' E, 26° 48' N)	0.78*	0.80*

*Correlation is significant at the 0.01 level (two-tailed)

Fig. 4 The curves of streamflow and CWB_PM during the period 2009–2015 for **a** S06, **b** S14, **c** S27

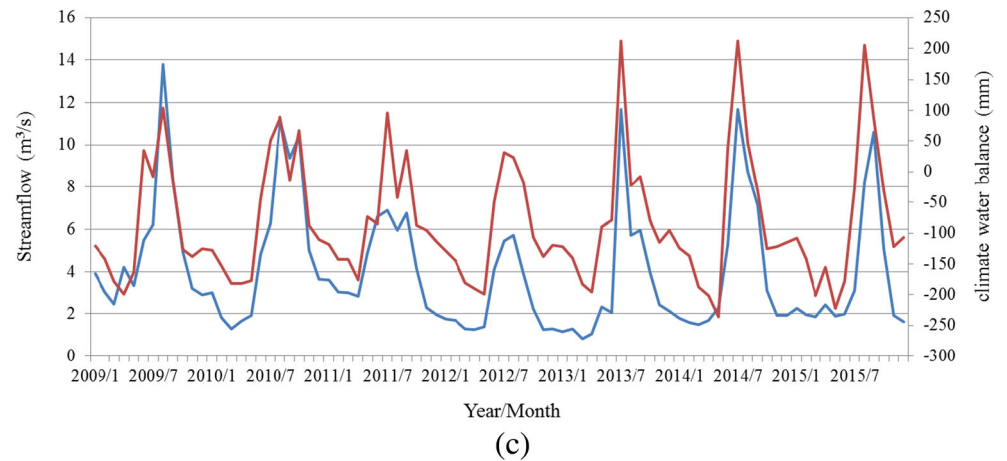
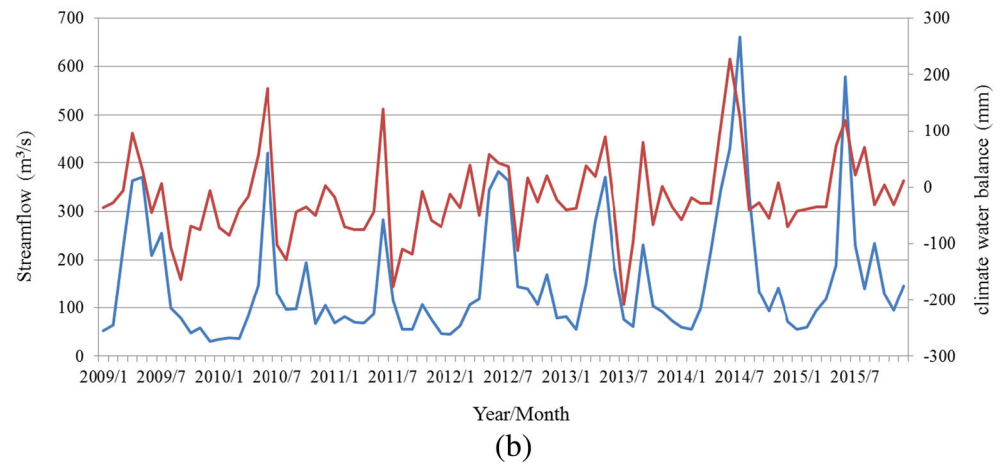
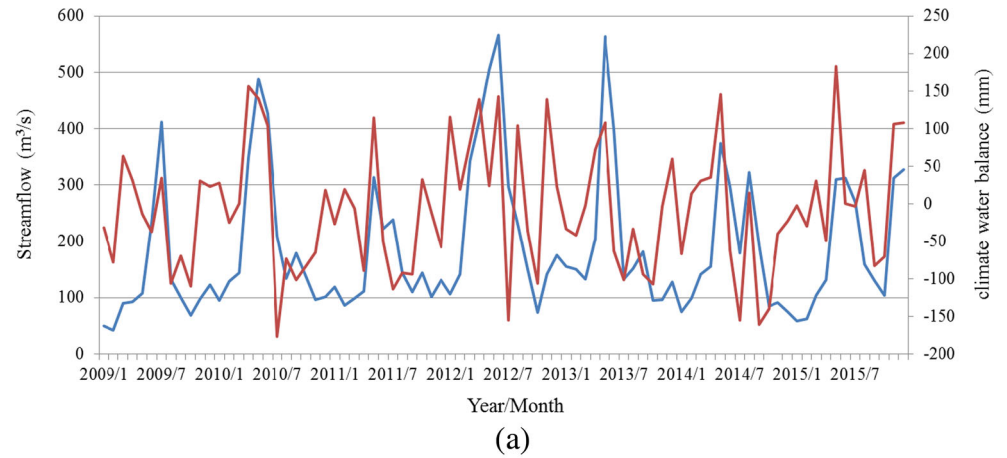


Table 4 The average values of 12-month SPEI_PM during each decade for different provinces

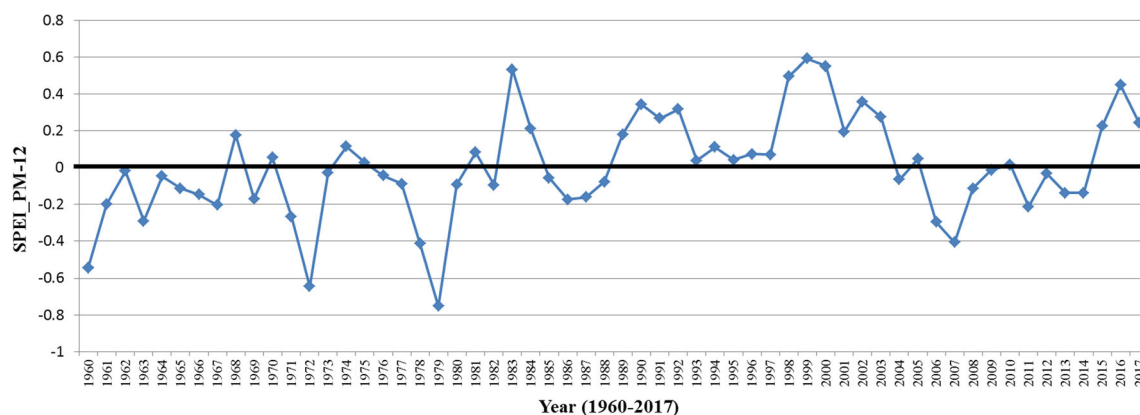
Provinces	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2017
Qinghai	1.39	−1.23	−0.28	−0.55	0.40	0.32
Sichuan	1.48	−2.16	−0.02	1.54	0.38	−1.52
Yunnan	0.42	−0.43	−1.26	1.21	0.83	−0.94
Guizhou	0.09	0.48	−0.01	−0.21	−0.27	−0.11
Hunan	−2.45	−1.61	−0.27	2.55	1.27	0.69
Hubei	0.03	−0.70	1.72	0.60	−0.35	−1.62
Jiangxi	−3.41	−0.92	−0.44	1.85	0.87	2.70
Jiangsu	−0.34	−0.37	−0.15	0.40	0.35	0.16
Zhejiang	−0.14	−0.58	−0.04	0.51	−0.34	0.75
Shanghai	−1.15	−0.65	0.20	0.36	0.38	1.10
Chongqing	−0.21	0.10	0.25	0.61	−0.09	−0.77
Shanxi	−0.38	0.00	1.10	−0.30	−0.61	0.26
Anhui	−0.92	−0.03	0.49	0.07	−0.38	1.01

Spatial variations of drought changing trends

It can be seen from Fig. 3 c that half of the stations showed a significant tendency to become wet, while nearly one third of the stations showed a significant tendency to dry out. According to the spatial distribution characteristics of SPEI_PM changing trends, it could be inferred that this change may be related to the topographical factors in the basin, while mountains occupied 50% of the landscape in the upstream region (Kong et al. 2018), and the middle and lower areas were dominated by plain terrain. In addition, several previous studies had demonstrated that the Yangtze discharge in the middle and lower reaches tends to increase by about 50% over that in the upper reaches (Chen et al. 2001, 2010), which could reflect the more obvious drought trends for the upstream areas than the downstream areas. From the perspective of administrative regions, the Yangtze River Basin involved 13 provinces. The average values of 12-month SPEI_PM during each decade for different provinces were summarized in Table 4. It could be found that Sichuan and

Hubei had drought trends after 2000, while Jiangxi presented a wetting trend. The other provinces had fluctuated in different periods, but there were no obvious change trends.

To further explore the temporal characteristics of drought trends, the annual average values of SPEI_PM for the entire basin were shown in Fig. 5. The results indicated that 1960s, 1970s, and 2000s were relatively dry years in the basin, while 1980s and 1990s were humid periods. In general, the value of SPEI_PM presented a dynamic increase since 1980, that is, the degree of climate drought in the Yangtze River Basin had decreased in recent years. In addition, the spatial distribution of drought trends during each decade was shown in Fig. 6. During the period 1960–1969, although the SPEI values of each station in the basin generally fell in the mild drought moderate drought categories, 49% of the stations showed wetting trends, and only 17% of the stations became more and more dry. However, between 1970 and 1979, only three stations in the basin showed wetting trends, and 34% of the stations presented significant drought trends, which caused this decade to become the driest period of the Yangtze River Basin during

**Fig. 5** The temporal variations of annual SPEI_PM during the period 1960–2017

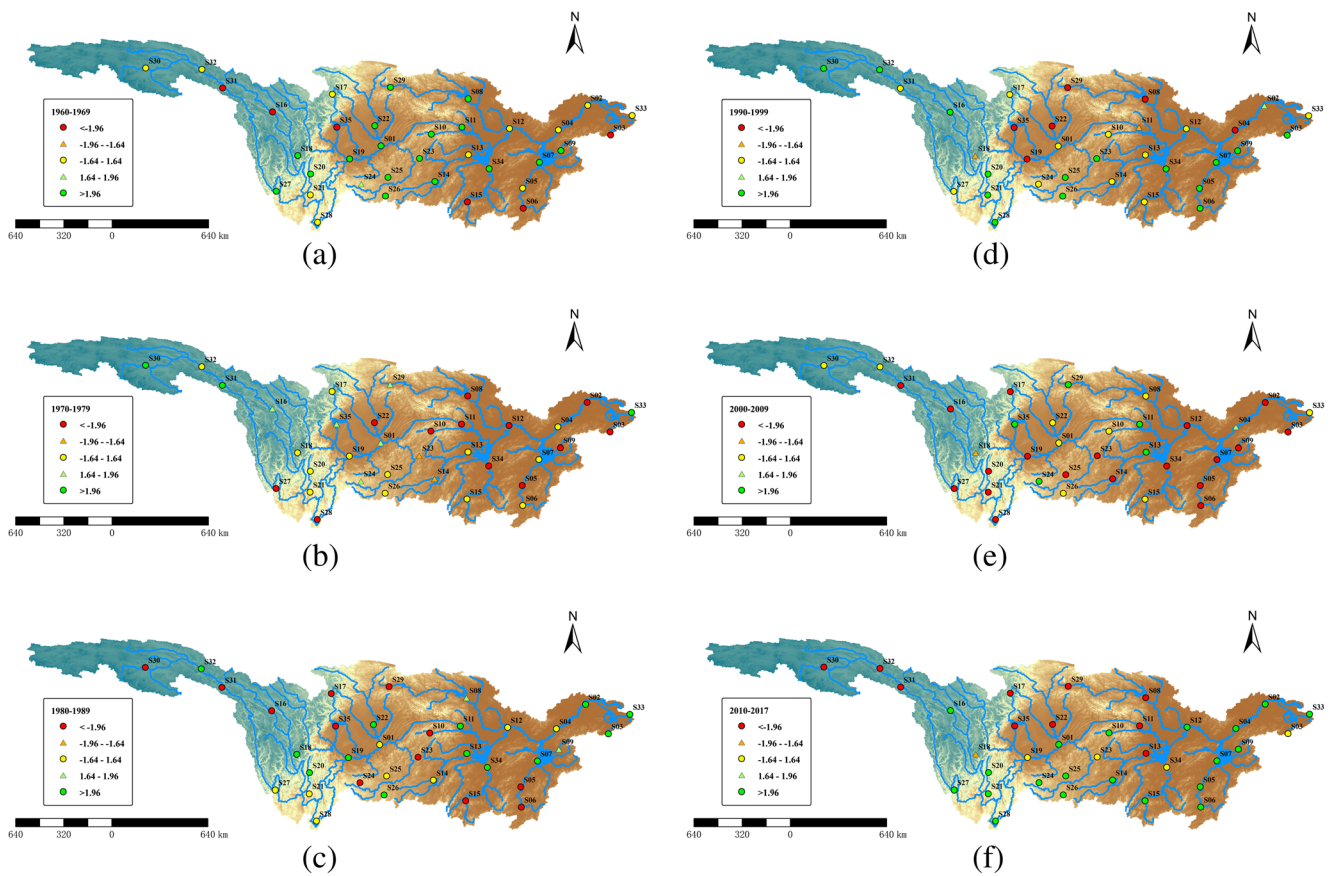


Fig. 6 The spatial distributions of the MK trend statistic for the annual SPEI_{PM} during each decade

60 years. Between 1980 and 1989 and 1990–1999, 37 and 43% of the stations had wetting trends, while the number of drier stations decreased, so the climate drought events in the basin reduced. After 2000, the drought conditions had intensified, and more than half of the stations had a tendency to dry. However, this situation had improved significantly in the past decade, especially in the southwest and southeast regions of the basin.

Variations of drought duration and frequency

The duration of drought in this study was defined as the number of consecutive months in which the value of 3-month SPEI_{PM} was less than -1.5 . Consecutive drought events, especially severe and extreme droughts, may have serious impacts on agriculture and ecosystems (Chen and Sun 2015). In order to

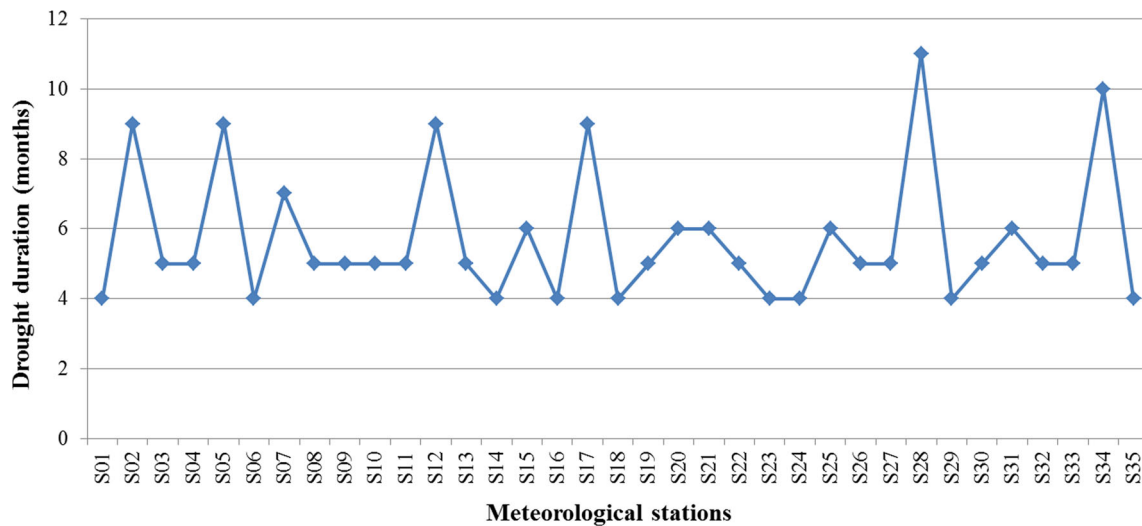


Fig. 7 The longest duration of severe drought events (3-month SPEI_{PM}, < -1.5) at each station

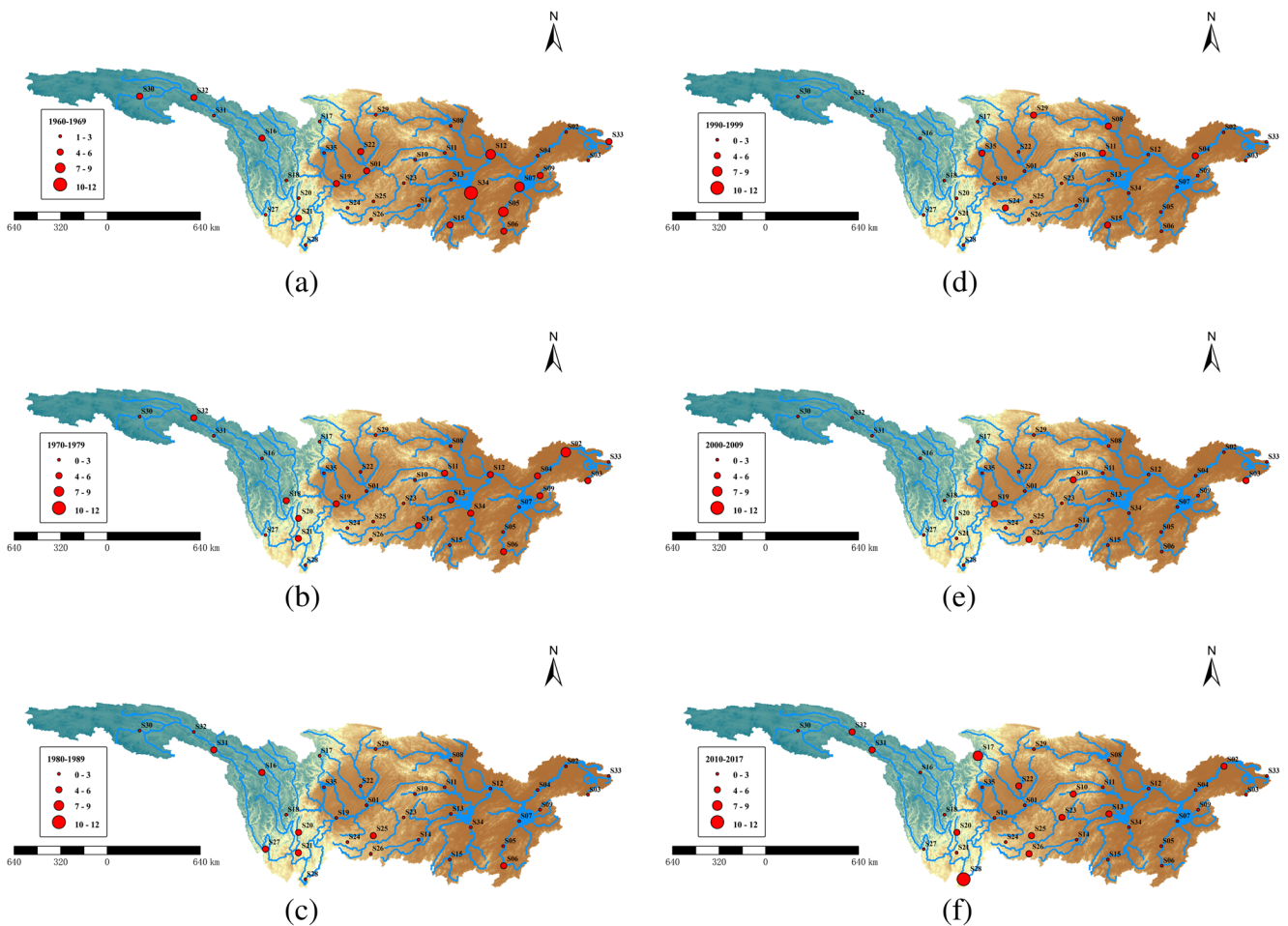


Fig. 8 The spatial distributions of longest drought duration based on 3-month SPEI_{PM} during each decade

determine whether the occurrence of drought events in the basin was affected by natural climate variability, the correlation between 3-month SPEI_{PM} and the Ocean Niño Index was analyzed. The Oceanic Niño index (ONI) was the primary indicator for monitoring El Niño and La Niña proposed by NOAA, which

were opposite phases of the climate pattern called the El Niño-Southern Oscillation (ENSO) (Li et al. 2018). Since ONI was the difference between a 3-month running average of sea surface temperature (Li et al. 2016), which was consistent with 3-month SPEI_{PM} on a time scale, the correlation between them could

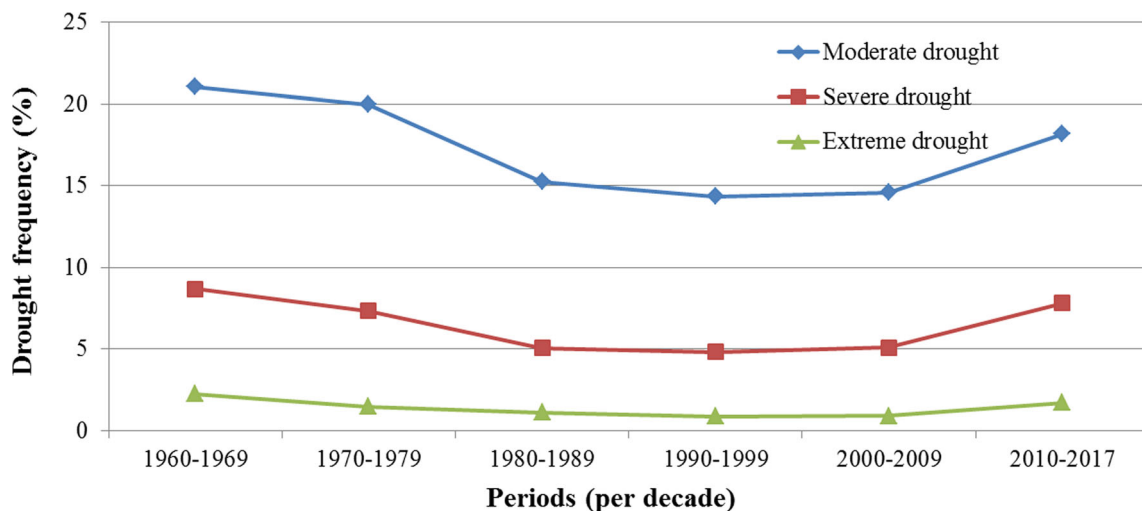


Fig. 9 The frequencies of moderate drought, severe drought, and extreme drought in the basin during each decade

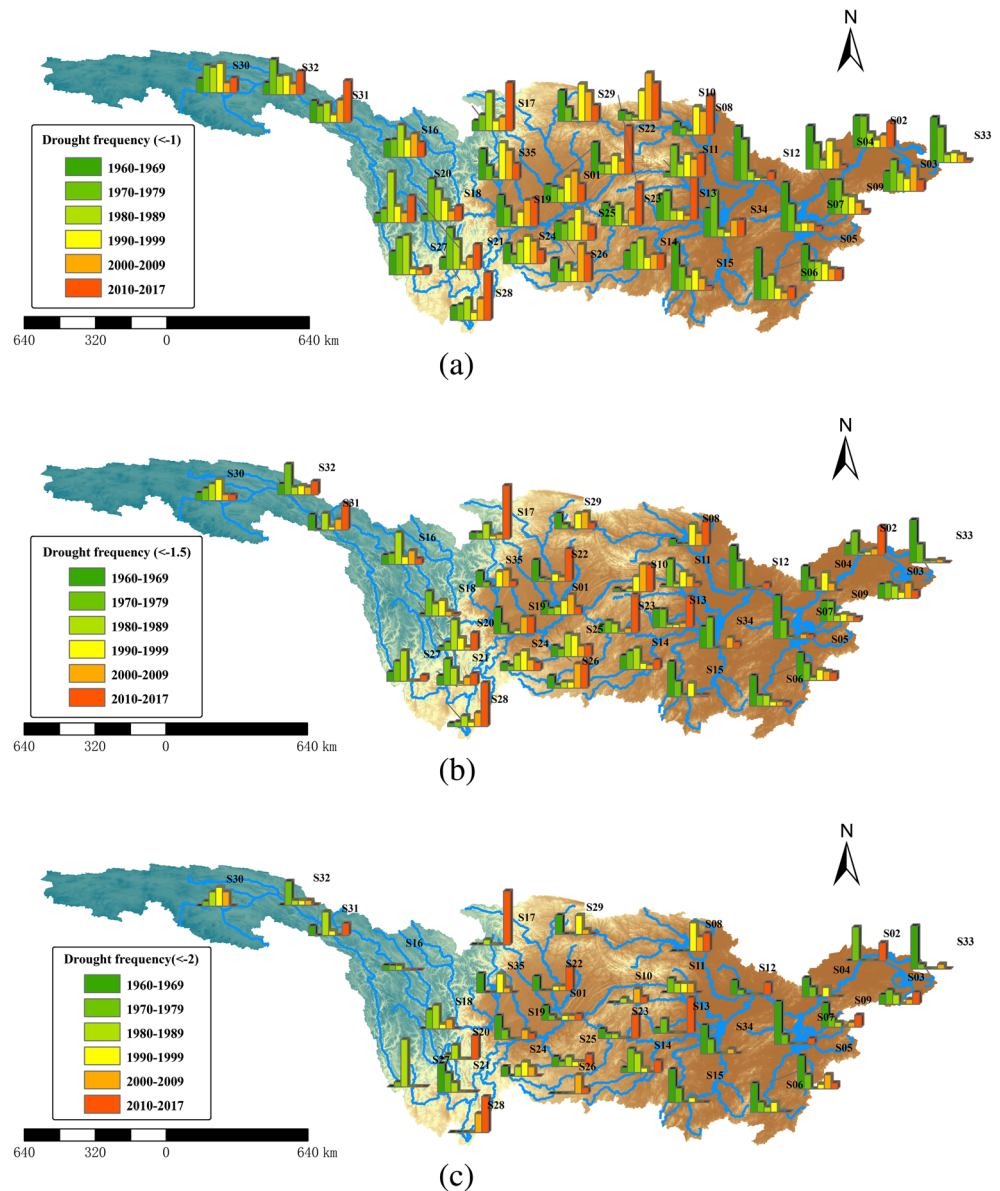
reflect the impacts of natural climate variability on drought events. However, the results of Spearman correlation analysis indicated that there were no strong correlations between the ONI index and the 3-month SPEI_PM of 35 meteorological stations. Therefore, it can be considered that the occurrence of drought events in the basin was not mainly caused by natural climate variability.

According to the longest drought duration during 1960–2017 shown in Fig. 7, 80% of the stations in the basin had drought duration of less than 6 months. The spatial distributions of longest drought duration during each decade were further analyzed, and the results were presented in Fig. 8. The number of stations with a drought duration of less than or equal to 3 months was the highest between 2000 and 2009, followed by 1980–1989 and 1990–1999. In addition, there was no station with a drought

duration of more than 6 months in the 1980–1989, 1990–1999, and 2000–2009 periods, which was consistent with the results of the drought trend analysis obtained above. However, since 2010, the number of stations with a drought duration of about 6 months had increased, which demonstrated that the dry conditions were enhanced in the past decade across most of the basin.

The drought events in the basin were counted according to moderate drought (3-month SPEI_PM, < -1.0); severe drought (3-month SPEI_PM, < -1.5); and extreme drought (3-month SPEI_PM, < -2.0), respectively, and the drought frequency of each category during per decade was shown in Fig. 9. The decadal changes revealed that the drought frequencies of three categories showed a trend of decreasing first and then rising, and the minimum number of drought events occurred in 1990–1999. The drought events falling in different

Fig. 10 The spatial distributions of the decadal changes for **a** moderate drought frequency, **b** severe drought frequency, and **c** extreme drought frequency



categories occurred with similar frequencies during the periods 1970–1989 and 2000–2017, which indicated that the dry condition in the entire basin had been enhanced in the past two decades. Furthermore, the spatial distributions of the decadal changes in moderate, severe, and extreme drought frequencies were presented in Fig. 10. In addition to the S02 station, the moderate drought frequencies at the stations located in the lower reaches of the Yangtze River were generally decreasing in recent years. The S02 station was located in Nanjing City, where the urbanization process was very fast, so there were many factors causing the temporal changes of the drought frequency. In Fig. 10 a, the frequency histograms of the stations in the middle reaches of the Yangtze River showed that the percentage of dry conditions increased apparently after 2010, which indicated that this part of the basin had been experiencing more and more frequent drought events in the past decade. By analyzing the frequencies of severe and extreme drought events, similar results could be obtained, that is, the stations with increased drought frequency in the last decade were mainly concentrated in the middle reaches of the river, and followed by the upper reaches. In particular, the frequent occurrence of extreme climate drought events in several stations (such as S17, S13, and S28) in the past decade may affect the industrial and agricultural development of the surrounding regions, which should be paid attention to by relevant managers.

Conclusions

The primary purpose of this study was to compare the performances of SPI, SPEI_TH, and SPEI_PM in monitoring droughts in the Yangtze River Basin. Although the analysis was based on the basin scale, there were differences in the air temperature from upstream to downstream. The SPI ignored the effect of temperature, which brought great uncertainty to the results. The SPEI index used PET to reflect the effect of temperature, while the values of PET could be estimated based on Thornthwaite method or Penman-Monteith method. There were differences in the estimates of SPEI using these two methods when focusing on the same basin. To validate the performances of these two methods, the correlations between the streamflow data and CWB were compared at three stations with the greatest differences of SPEI_TH and SPEI_PM. The results indicated that the index obtained from the realistic and complicated PM algorithm was considered to be more reliable. Therefore, the SPEI_PM was used to reflect the climate change conditions in the Yangtze River Basin from 1960 to 2017.

The analysis of several characteristics of drought events, including trends, duration, and frequency, found that 1980–1989 and 1990–1999 were the wettest periods in the basin. Furthermore, 1960–1969 was the decade with most severe drought conditions, but the frequency and intensity of climate

drought events had increased significantly since 2010. This result suggested that the dry conditions in the basin had been enhanced in the recent decade. The spatial distribution of drought characteristics indicated that the middle reaches of the river were the regions with the longest duration and highest frequency of climate drought. This study carried out a preliminary analysis of the temporal and spatial changes of climate drought characteristics over the past 60 years in the Yangtze River Basin; however, due to the complexity of climatic events, the mechanism of these changes remained unclear and further studies were needed to address these issues.

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