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Impact of Meteorological Drought on Streamflow Drought in Jinghe River Basin of China

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Abstract: Under global climate change, drought has become one of the most serious natural hazards, affecting the ecological environment and human life. Drought can be categorized as meteorological, agricultural, hydrological or socio-economic drought. Among the different categories of drought, hydrological drought, especially streamflow drought, has been given more attention by local governments, researchers and the public in recent years. Identifying the occurrence of streamflow drought and issuing early warning can provide timely information for effective water resources management. In this study, streamflow drought is detected by using the Standardized Runoff Index, whereas meteorological drought is detected by the Standardized Precipitation Index. Comparative analyses of frequency, magnitude, onset and duration are conducted to identify the impact of meteorological drought on streamflow drought. This study focuses on the Jinghe River Basin in Northwest China, mainly providing the following findings. 1) Eleven meteorological droughts and six streamflow droughts were indicated during 1970 and 1990 after pooling using Inter-event time and volume Criterion method. 2) Streamflow drought in the Jinghe River Basin lagged meteorological drought for about 127 days. 3) The frequency of streamflow drought in Jinghe River Basin was less than meteorological drought. However, the average duration of streamflow drought is longer. 4) The magnitude of streamflow drought is greater than meteorological drought. These results not only play an important theoretical role in understanding relationships between different drought categories, but also have practical implications for streamflow drought mitigation and regional water resources management.

Keywords: streamflow drought; meteorological drought; Standardized Precipitation Index (SPI); Standardized Runoff Index (SRI); time lag; Jinghe River Basin

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1 Introduction

Drought is a multi-faceted phenomenon that occurs across a range of temporal and spatial scales and is experienced across a range of societal sectors that are dependent on climate and water resources (Wilhite, 2000). It can cause significant damages to natural environment and human activities, such as crop losses (Austin *et al.*, 1998), desertification (Nicholson *et al.*, 1998), urban water supply shortages (De Gaetano, 1999), forest fires (Pausas, 2004),

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and so on. Many heavily populated countries face a growing threat of severe and prolonged drought in coming decades (Dai, 2011). So, it is very important to monitor drought effectively and predict its occurrence.

Coping with droughts requires a deep understanding of different categories of drought, as well as linkages that may exist between the associated categories (Mishra and Cherkauer, 2010; Mishra *et al*., 2010). Wilhite and Glantz (1985) identified four categories of drought: meteorological drought, agricultural drought, hydrological drought, and socio-economic drought. Among these four categories, hydrological drought received great amounts of attention from stakeholders such as researchers, governments, and the public due to its severe direct impacts to surface and underground water resources, along with indirect impacts to ecology, environment, navigation and water power. For instance, the extreme hydrological drought of South China in 2011 caused a great reduction of Honghu Lake′s surface area (Hubei Province), which shrank from 35 300 ha to 26 700 ha, leading one fourth of the lake to dry up. This hydrological drought event seriously affected the local aquaculture and tourism, which attracted great governmental and public concerns (http://www.xinhuanet.com/chinanews). Hydrological drought monitoring, mitigation and prediction would play an important role in effective protection of water resources and sustainable development of the local socio-economy.

Drought is hard to detect. It is difficult for us to find out its exact occurring time and range of influence. In general, the other three categories of drought are directly or indirectly related to meteorological drought. The linking variables including precipitation, overland flow, soil evaporation, soil water, infiltration, through flow, recharge, groundwater storage, groundwater discharge and streamflow are all involved in the hydrological cycle. Therefore, the impact of meteorological drought on hydrological drought is of the utmost importance in identifying associations between meteorological drought and other categories. Moreover, identification of the relationship and possible time lag between hydrological drought and meteorological drought would be helpful for hydrological drought monitoring and early warning.

Over the years, previous studies have developed a variety of indices to assess meteorological drought and hydrological drought. For the former, such as Rainfall Anomaly Index (RAI) (Van-Rooy, 1965), Deciles Index (DI) (Gibbs and Maher, 1967), Drought Area Index (DAI) (Bhalme and Mooley, 1980), Z-index (Yao and Ding, 1990), surface humid index (Ma and Fu, 2001), Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005), and Standardized Precipitation Index (SPI) (McKee *et al*., 1993) have been utilized along the time. The SPI is the most commonly used because of its robustness in flexible timescale, comparability in time and space, and sensitivity to meteorological drought (Hayes *et al*., 1999; Pai *et al*., 2010; Stricevic *et al*., 2011). Research on streamflow drought as a form of hydrological drought has been established on the Runs Approach, which is also known as threshold method and was first applied to analyze drought events by Yevjevich (1967). Using the threshold method, drought occurrence, duration, and severity can be identified. In recent years, some new indices were developed to analyze hydrological drought such as Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982), Drought Severity Index (DSIe) (Pandey *et al*., 2008), and Standardized Runoff Index (SRI) (Shukla and Wood, 2008; Vasiliades *et al*., 2010). SRI has been widely used given its comparability in time and space, simplicity in computation and limited data requirements.

A lot of studies have been focusing on individual drought categories whereas only a few studies have analyzed the relationships between meteorological drought and hydrological drought because of its complexity in underlying conditions such as land cover, vegetation, topography, and other associated hydrologic/climatic variables (Mo, 2008; Mishra and Cherkauer, 2010; Mishra *et al*., 2010). In these limited studies, three aspects of research are identified. The first, a few research efforts simply focused on the comparison of regional characteristics between meteorological drought and hydrological drought (Hisdal and Tallaksen, 2003). The results showed that streamflow droughts (classified in hydrological drought) are less homogeneous over Denmark, less frequent and last for longer time periods than meteorological droughts. The second, some researcher utilized physical models to simulate their relationship of meteorological drought on hydrological drought. Tallaksen and van Lanen (2004) described that the impact of meteorological drought on hydrological drought may take several days or months to several years, which is determined by whether it is a flashy catchment or a groundwater-fed catchment. Based on hypothetical data, Peter *et al.* (2005) have shown that the propagation of meteorological drought to groundwater drought decreases the number of drought events and causes a shift in the drought severity distribution. The third, more studies were devoted to identify the time-lag of hydrological responses to meteorological drought events. Vicente-Serrano and López-Moreno (2005) found that surface flows responded to short time scales of meteorological drought (1–4 months) whereas the reservoir storages responded to longer time scales (7–10 months) in a mountainous Mediterranean basin. Edossa *et al.* (2010) analyzed drought characteristics in the Awash River Basin of Ethiopia based on meteorological and hydrological variables, and main results had shown that occurrence of hydrological drought events at Melka Sedi stream gauging station (downstream) lagged meteorological drought events in the upper Awash on average by 7 months. Tabrizi *et al.* (2010) found that annual time scale of meteorological drought in the upstream of the Doroodzan watershed of Iran can be used to investigate occurrence of streamflow drought in the downstream.

These previous studies have given a good elaboration of linkages between hydrological drought and meteorological drought from theoretical and practical views. More importantly, the lag of occurring time between them is crucial in coping with drought. The time lag will provide strong support in preparing for hydrological drought from point of view of meteorological drought, of which data are much easier to access. This time-lag issue has been addressed in some drought-prone regions in Europe and Africa (Hisdal and Tallaksen, 2003; Vicente-Serrano and López-Moreno, 2005; Edossa *et al.*, 2010). However, it has not been carried out in the northwestern China yet, which is an arid and semi-arid region and also suffers drought a lot. Considering these issues above, the main objective of this research is to investigate associations between streamflow drought and meteorological drought of Jinghe River Basin in the northwestern China. In this study, more efforts will be devoted to compare drought characteristics of these two categories and find out the possible time lag between them.

2 Materials and Methods

2.1 Study area

As one of the top ten drainages in the Huanghe (Yellow) River Basin, the Jinghe River Basin is located in the central part of the Loess Plateau in the northwestern China (Fig. 1). The Jinghe River is 483 km long in total, with a drainage area of 45 412 km^2. This basin is a typical inland river basin in a semi-arid and semi-humid region, together with a vulnerable climate and distinct inter-seasonal variations in climate and vegetation cover (Wei and Lin, 1996; Chen *et al.*, 2007). The streamflow in this basin is mainly charged by groundwater.

Droughts are very frequent in this area, which has encountered 255 drought events in the past 510 years (1470–1979), 103 of them being severe or extreme. Particular sequential years with more drought events than floods can last for 60–90 years (Liang *et al.*, 2005; Guo and Zha, 2009). In addition, agriculture within the Jinghe River Basin plays a significant role in the northwestern China, with 1/3 of the area as cropland mainly producing wheat and maize. This important role of agriculture has raised the importance of regional water resources management in this region, including coping with hydrological droughts that can have a negative effect on soil water storage and agricultural irrigation.

2.2 Data

To carry out our analysis, precipitation and streamflow data were used. The daily precipitation data were obtained from 4 meteorological stations within the basin (Fig. 1), which were provided by the China Meteorological Administration (http://cdc.cma.gov.cn) covering the period between 1960 and 2000. The daily streamflow data were obtained from 12 hydrometric stations, of which Zhangjiashan Station was located at the outlet of this drainage (Fig. 1). It was provided by the Institute of Soil and Water Conservation (http://loess.geodata.cn/), Chinese Academy of Sciences & Ministry of Water Resources, covering the period between 1970 and 1990. Quality test of precipitation data and streamflow data has been conducted before calculation of SPI and SRI.

2.3 Methods

The main procedure is 1) correlating the SRI and SPI to select the most proper timescale of SPI; 2) testing key parameters for pooling dependent drought events; 3) identifying long-term meteorological and streamflow drought events using the SPI and SRI, and 4) analyzing the corresponding relationship and the possible lag of occurrence time between meteorological and streamflow drought events.

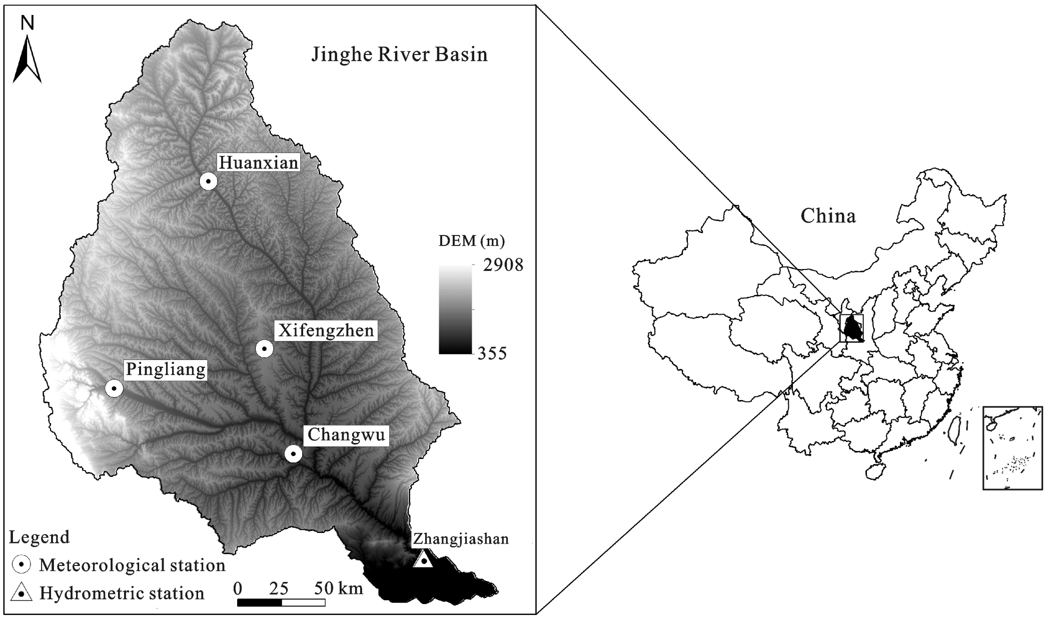

Fig. 1 Map of study area with meteorological stations and hydrometric station

2.3.1 Evaluation of meteorological drought

In this study, meteorological drought events were evaluated based on the SPI developed by McKee *et al.* (1993). Computation of the SPI requires long-term precipitation data, which was arranged to appropriate time scales based on different goals, e.g., 3-month, 6-month, 9-month and 12-month. The different timescale (*i*-month) means the different time length for accumulating precipitation data by backtracking. In this study, *i*-month timescale of SPI was written by SPI_i in abbreviation. The first step for calculating SPI was to determine a probability density function that described the long-term time series of precipitation observations. The second was the computation of the cumulative density function. The last was to transform the cumulative probability into the standard normal values using Gaussian function. More detailed calculation procedures could be found in related references (McKee *et al.*, 1993; Tabrizi *et al.*, 2010).

The classification of meteorological drought based on SPI was given in Table 1 (McKee *et al.*, 1995; Nalbantis and Tsakiris, 2009). Four major drought intensities were classified by the different values of SPI. Input precipitation data for calculating SPI were obtained by averaging the data from four meteorological stations.

2.3.2 Evaluation of streamflow drought

The SRI (Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009) was utilized to identify streamflow drought in this study. To match the monthly timescale of meteorological drought based on the SPI, a 30-day timescale was selected for characterizing streamflow drought based on the SRI. It was calculated in a manner similar to 'normal standardization', which was given as:

Table 1 Classification of Drought intensity

SPI/SRI value	Drought intensity
(–1.00, –0.00]	Mild drought
(–1.50, –1.00]	Moderate drought
(–2.00, –1.50]	Severe drought
(–∞, –2.00]	Extreme drought

$$SRI_{ij} = \left(R_{ij} - \overline{R_j}\right) / \sigma_j \tag{1}$$

where, i and j were the year and day of year, respectively (i = 1970, 1971…, 1990; j = 1, 2, 3…, 365); $\overline{R_j}$ and σ_j were the mean and the standard deviation of R_{ij}, respectively. R_{ij} was the cumulative monthly (30-day) streamflow volume of the *i*-th year and the *j*-th day, which was given as:

$$R_{ij} = \sum_{j-29}^{j} Q_{ij} \tag{2a}$$

or $$R_{ij} = \ln \sum_{j-29}^{j} Q_{ij} \tag{2b}$$

where, Q_{ij} was the average discharge (m^3/s) of the *i*-th year and the j-th day.

The selection of Equation (2a) or (2b) to calculate SRI depended on the histogram of original streamflow data and its natural logarithm. Daily streamflow data from 12 stations were utilized to test the probability density function (PDF) of the original data and its natural logarithm. It was found that the natural logarithm of streamflow data fitted the normal distribution much better than the original data. So, Equation (2b) was selected to calculate SRI.

The classification of streamflow drought based on SRIs was given in Table 1. Four major drought intensities were classified by the different values of SRI.

2.3.3 Pooling drought events

The selection of daily-recorded precipitation and streamflow data may result in the separation of adjacent drought events. During a prolonged dry period it is often observed that the flow exceeds the threshold level for a short period of time and thereby a large drought is divided into a number of minor droughts that are mutually dependent. Thus, a consistent definition of drought events should include some kind of pooling in order to define an independent sequence of droughts (Tallaksen *et al.*, 1997).

As presented by Tallaksen *et al.* (1997), several pooling methods are available, e.g., Moving Average procedure (MA), Sequent Peak Algorithm (SPA) and Inter-event time and volume Criterion (IC). In the study, the IC method was used, which proved to be widely used. At first, it was known as 'inter-event time' criterion and it was introduced by Zelenhasic and Salvai (1987). In a similar way another criterion based on 'inter-event volume' can be also applied. Madsen and Rosbjerg (1995) suggested formulating a combination of the above two as one criterion, resulting in the IC method. In this method, two adjacent drought events (d_i, V_i) and (d_{i+1}, V_{i+1}) can be pooled if the number of days (t_i) between the two droughts was less than the defined critical duration t_c and the ratio (r_i) between the inter-event excess volume (z_i) and the preceding deficit volume (V_i) was less than a critical ratio α (Fig. 2).

r_i was calculated as follows:

$$r_i = \frac{z_i}{V_i} \tag{3}$$

The pooled drought deficit characteristics were calculated as follows:

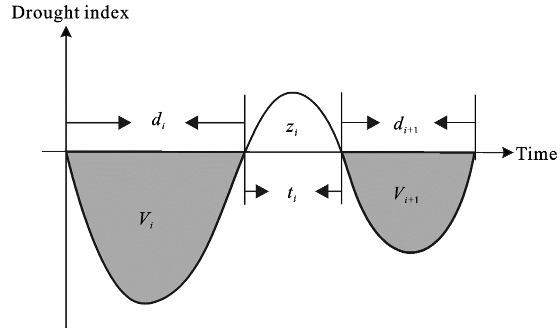

Fig. 2 Schematic diagram of pooling procedure. V_i and V_{i+1} are adjacent drought deficit volumes; z_i is the inter-event excess volume; d_i and d_{i+1} are adjacent drought durations; t_i is the number of days between the two droughts

$$d_p = d_i + d_{i+1} + t_i \tag{4}$$

$$V_p = V_i + V_{i+1} - z_i \tag{5}$$

where, d_p was combined drought duration, d_i and d_{i+1} were adjacent drought durations; V_p was combined drought deficit volume; V_i and V_{i+1} were adjacent drought deficit volumes.

The critical t_c and α were crucial for the pooling approach. In some previous studies, different values were assigned (Tallaksen *et al.*, 1997; Tallaksen and van Lanen, 2004; Tabrizi *et al.*, 2010). In this study, t_c and α were selected respectively following the criteria that the frequency of drought events went to a constant status. The constant status here was defined as when t_c value was changed for the range from 10 to 100 days under a definite α value and α value was changed for the range from 0.1 to 0.9 under a definite t_c, the frequency of drought events between two adjacent combinations of t_c and α did not change much (less than or equal to 1).

3 Results and Analyses

3.1 Identification of meteorological droughts

To select the most suitable time scale of SPI, Pearson correlations between SRI and different timescales of SPI (1–12 months) have been conducted. The result indicates that the increasing of time scales from 1-month to 4-month raises the correlation coefficient significantly. After 4-month, it goes almost steady till 8-month and then decreases. Thus, the 4-month is selected as the most suitable time scale of SPI to identify the meteorological drought regarding of its relation with streamflow drought.

Meteorological drought begins when SPI value first falls below zero and ends when the SPI becomes positive (McKee *et al.*, 1995). Daily time step had identified many minor and dependent droughts. IC method is used to pool these minor meteorological drought events. Different frequencies of meteorological drought events under different parameters combination (t_c and α) are depicted in Fig. 3 and Fig. 4.

From Fig. 3, t_c is assigned as 50 days under the criteria that the curve of meteorological drought frequency goes steady from a critical value. α is accordingly assigned as 0.4 under t_c equals 50 days (Fig. 4). Minor meteorological drought events have been pooled under definite t_c and α (50 days and 0.4). The duration and the average intensity of every drought events identified by SPI_4 (4-month timescale of SPI) are illustrated in Fig. 5.

During 1970 and 1990, by using IC method under t_c = 50 days and α = 0.4, 123 raw meteorological droughts are pooled into 12 new meteorological droughts which are independent with each other. Statistic results of meteorological droughts after pooling are listed in Table 2, except the first one, of which the beginning is not clear within the limited period. In Table 2, magnitude is the sum of SPI_4 between beginning date and ending date. Intensity is the ratio between magnitude and duration.

Eleven meteorological droughts are indicated by SPI_4 after pooling during 1970 and 1990. Its duration is between 76 and 713 days, with the average of 344.5 days. The top three longest meteorological droughts lasted for 713, 522 and 514 days, respectively. Its intensity is between –0.33 and –0.74, with the average of –0.5 which indicates 'mild drought' according to Table 1. However, from the view of raw meteorological droughts in Fig. 5 (left), the intensity of some drought events are on the grade of 'moderate drought', 'severe drought' or 'extreme drought'. This is due to intensity is weakened by averaging the SPI value in pooling procedure. For the magnitude, it retains the information of both duration and intensity. The magnitude of meteorological droughts is between –41.5 and –526.7, with the average of –200.3. Although the magnitude can not indicate the grade of drought events absolutely, it can represent the relative severity of drought events. The top three most severe meteorological droughts happened in 1986-02-10 to 1988-01-23, 1979-01-31 to 1980-06-27 and 1981-12-29 to 1983-04-09.

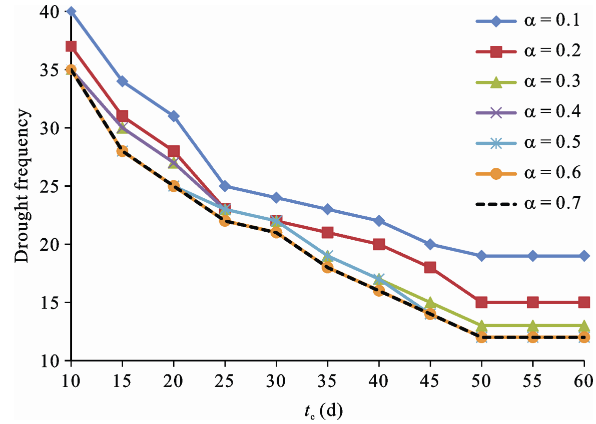

Fig. 3 Meteorological drought frequencies under different pooling parameter combination of critical duration (t_c) and critical ratio (α)

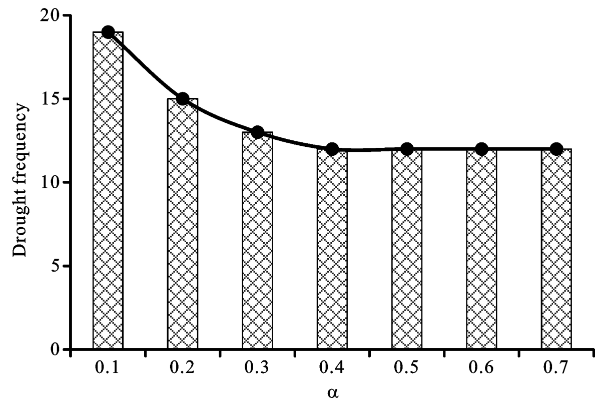

Fig. 4 Meteorological drought frequencies under different α when t_c equals to 50 days

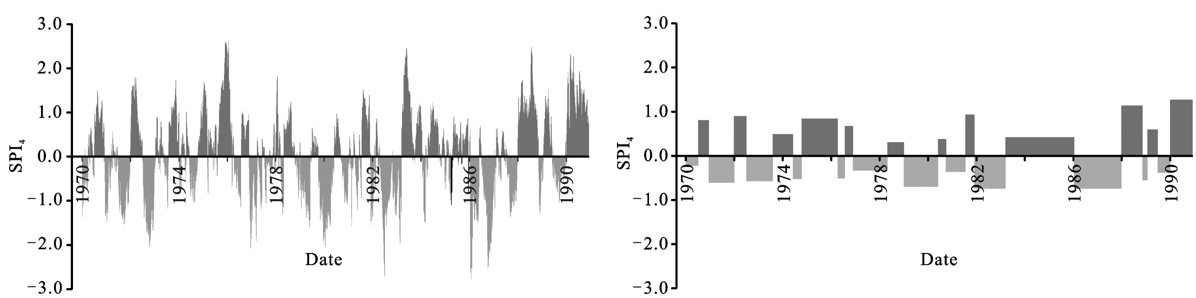

Fig. 5 Meteorological drought events identified by SPI_4 (4-month timescale of SPI) during 1970 and 1990. Left: raw; Right: after pooling under t_c = 50 days and α = 0.4

Table 2 Meteorological drought events indicated by SPI_4

Beginning date	Ending date	Duration (d)	Magnitude	Intensity
1971-01-08	1972-01-25	383	–231.0	–0.60
1972-07-29	1973-08-28	396	–226.6	–0.57
1974-07-04	1974-11-09	129	–66.9	–0.52
1976-05-09	1976-08-23	107	–54.1	–0.51
1976-12-23	1978-05-28	522	–174.7	–0.33
1979-01-31	1980-06-27	**514**	**–358.8**	**–0.70**
1980-10-26	1981-08-17	296	–106.9	–0.36
1981-12-29	1983-04-09	**467**	**–344.5**	**–0.74**
1986-02-10	1988-01-23	**713**	**–526.7**	**–0.74**
1988-12-06	1989-02-19	76	–41.5	–0.55
1989-07-24	1990-01-26	187	–71.4	–0.38

Note: Top three of duration, magnitude and intensity are in bold

3.2 Identification of streamflow droughts

Daily SRI of monthly time scale for the Zhangjiashan hydro-metric station is utilized to indicate streamflow drought events in the Jinghe River Basin. Being similar to meteorological drought, it needs to pool the streamflow drought events by IC method. The selection of proper t_c and α is also needed before pooling. Different frequencies of streamflow drought events under different t_c and α are depicted in Fig. 6 and Fig. 7.

From Fig. 6, it can be seen that the frequency goes steady from t_c equals to 90 days. So, t_c is assigned as 90 days. α is accordingly assigned as 0.5 under t_c = 90 days (Fig. 7). Minor streamflow drought events have been pooled under the definite parameter t_c and α (Fig. 8).

From 1970 to 1990, there were 7 streamflow drought events indicated by SRI. However, the beginning time of the first drought event, which ended in the beginning of February 1970, was not clear. So, only 6 main streamflow drought events were finally detected from Fig. 8. Statistic results of streamflow droughts after pooling are listed in Table 3.

After pooling, the duration of streamflow drought was between 102 and 1406 days with the average of 632.8 days (Table 3). There were three dominant drought spells: January 1971 to November 1974, September 1977 to March 1983 and August 1986 to December 1988. The longest drought event, occurring from the beginning of January 1971 to the middle of November 1974, lasted for 1406 days. This event was also the most severe event with the biggest absolute value of

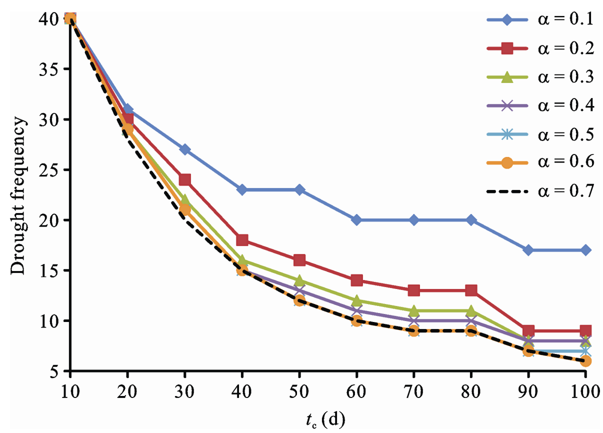

Fig. 6 Streamflow drought frequencies under different pooling parameter combination of t_c and α

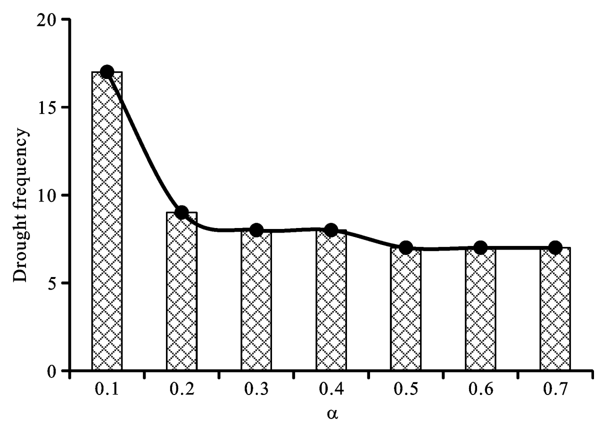

Fig. 7 Streamflow drought frequencies when t_c = 90 days

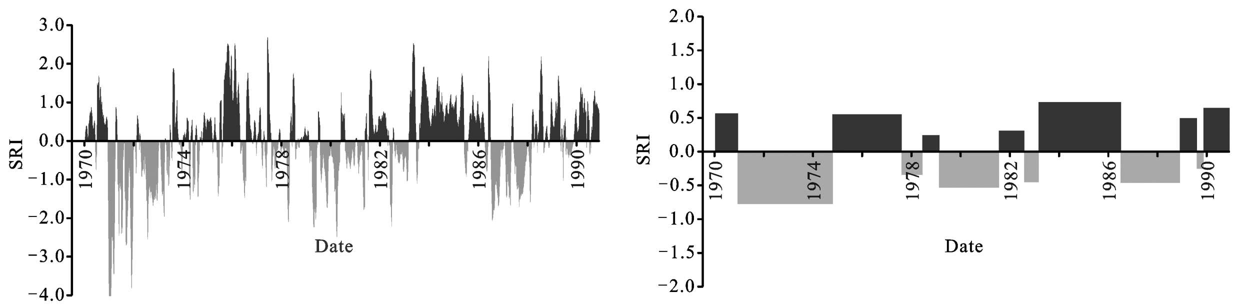

Fig. 8 Streamflow Drought events identified by SRI during 1970 and 1990. Left: raw; Right: after pooling under t_c = 90 days and α = 0.5

Table 3 Streamflow drought events indicated by SRI

Beginning date	Ending date	Duration (d)	Magnitude	Intensity
1971-01-10	1974-11-15	**1406**	**–1089.9**	**–0.78**
1977-09-05	1978-07-10	309	–105.3	–0.34
1979-03-17	1981-08-19	**887**	**–471.4**	**–0.53**
1982-08-30	1983-04-02	216	–97.1	–0.45
1986-08-02	1988-12-25	**877**	**–402.9**	**–0.46**
1989-09-04	1989-12-14	102	–25.7	–0.25

Note: Top three of duration, magnitude and intensity are in bold

magnitude (sum of the SRI is –1089.9) and greatest intensity (average of the SRI is –0.78). The second longest drought event happened from the middle of March 1979 to August 1981, lasting for 887 days with the average SRI of –0.53. The third longest event occurred from the beginning of August 1986 to December 1988, lasting for 877 days with the average SRI of –0.46.

3.3 Response of streamflow drought to meteorological drought

The response of streamflow drought to meteorological drought can be generally found by comparing the respective graphs (Fig. 5 and Fig. 8). They have showed that the dominant meteorological drought events can lead to corresponding streamflow droughts. In this section, quantitative analyses of the responses will be undertaken by comparing drought characteristics in terms of occurring time, duration, magnitude and intensity (Fig. 9).

From Fig. 9, it can be found that streamflow drought in this basin has coupled with meteorological drought quite well. All of the 6 streamflow droughts responded to the corresponding meteorological droughts. Three streamflow droughts were related with the only one meteorological drought. The other three streamflow droughts were related with two or three meteorological droughts. The occurrence of streamflow droughts lagged that of meteorological drought. For a further coupling analysis, the relation between streamflow droughts and meteorological droughts are named 'Drought Event Pair' in this study (Table 4). Time lag of beginning is the lag days between streamflow drought and meteorological drought regarding of occurrence.

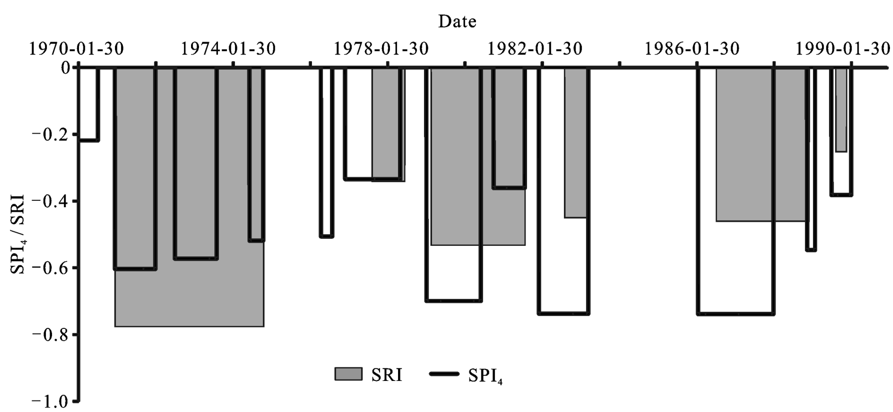

Fig. 9 Comparison of meteorological and streamflow drought events from 1970 to 1990 based on SPI_4 and SRI, respectively

Table 4 Drought Event Pairs in Jinghe River Basin during 1970 and 1990

No.	Streamflow drought		Meteorological drought		Time lag of beginning (d)
	Beginning date	Ending date	Beginning date	Ending date	
1	1971-01-10	1974-11-15	1971-01-08	1972-01-25	2
			1972-07-29	1973-08-28	
			1974-07-04	1974-11-09	
2	1977-09-05	1978-07-10	1976-12-23	1978-05-28	256
3	1979-0317	1981-08-19	1979-01-31	1980-06-27	45
			1980-10-26	1981-08-17	
4	1982-08-30	1983-04-02	1981-12-29	1983-04-09	244
5	1986-08-02	1988-12-25	1986-02-10	1988-01-23	173
			1988-12-06	1989-02-19	
6	1989-09-04	1989-12-14	1989-07-24	1990-01-26	42

All six streamflow drought events corresponded to meteorological drought events. The top-three severe streamflow drought events corresponded to two or three meteorological drought events. It also indicates that consecutive meteorological drought events probably have an essential impact on the lasting of streamflow drought. From Table 4, it can be found that there is an obvious time lag between the beginning of streamflow drought and meteorological drought. Every streamflow drought event happened behind the corresponding meteorological droughts. The beginning time of six streamflow drought events lagged that of meteorological drought by 127 days on average.

This result is in accordance with the field investigation in the basin that when a storm or heavy rainfall lasted, the river level rose quickly, however it dropped down slowly when rainfall ended. In other words, the streamflow drought happened much later, which may be due to the buffering function of the soil layers and groundwater system to the meteorological drought. However, it can end quickly after rainfall has mitigated meteorological drought situation. It also implies that different time scale factors should be considered carefully when making local drought and flood plans.

4 Discussion

As long-term daily streamflow data in this study area is difficult to access, the time period of this study is a little short, resulting in a relatively small data sample of streamflow and meteorological drought events. However, the results can also provide an understanding of the relationship between streamflow drought and meteorological drought quite well. Meanwhile, the timescale of SPI is a very important factor which affected its effectiveness when relating to SRI.

We had tried to identify this relationship between the raw SPI and SRI. But it was hard to find the most proper time scale of SPI to relate with the SRI quite well (Fig. 10). In some cases, the SRI related to short time scale of SPI. However, it was not consistent all the time. SPI_{12} also can match SRI better than SPI_4 in some cases.

However, it was interesting that after pooling the raw SPI and SRI to meteorological and streamflow drought events respectively, consistent results can be achieved. Comparing Fig. 9 and Fig. 11, it was found that SPI_4 performed much better than SPI_{12}. In Fig. 9, it can be seen that all six streamflow droughts can be foretold by corresponding meteorological drought. In Fig. 11, only two severe streamflow droughts happened before meteorological droughts which were indicated by the SPI_{12}. This implies that meteorological drought indicated by SPI_{12} can not monitor the happening of streamflow drought very effectively. Streamflow drought early warning using the SPI_{12} is undependable in this basin.

Furthermore, the pooling procedure has played an essential role in this issue. t_c and α are critical factors in IC method. Different values of t_c and α can result in different findings. From the results of this study, it can be indicated that the selection process of t_c and α is reasonable. However, other methods for pooling drought events or other selection process of t_c and α can be discussed in further work.

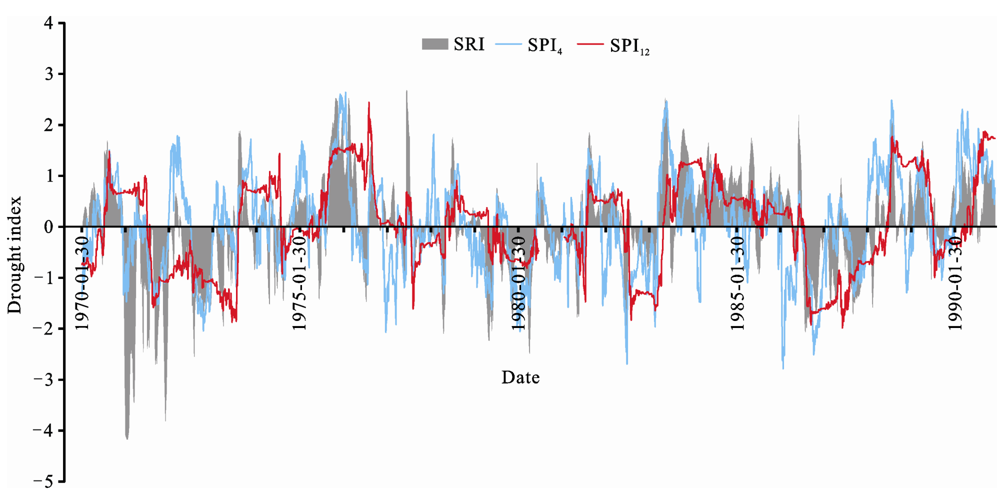

Fig. 10 Time series of SPI_4, SPI_{12} and SRI from 1970 to 1990

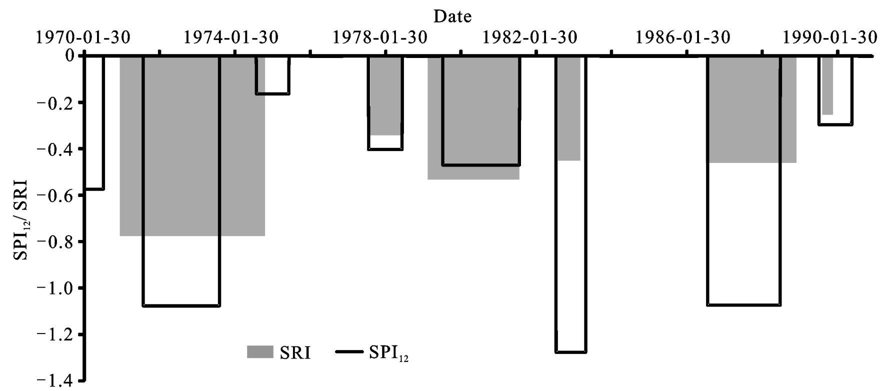

Fig. 11 Comparison of meteorological and streamflow droughts from 1970 to 1990, based on SPI_{12} and SRI

On the other hand, the short time period of data available has potentially limited the results of this study. And longer period of data can improve the relationship by increasing the sample size of drought events. However, the methods and procedures for dealing with this issue are still credible. This study can be regarded as a good reference for other basins, especially those where there are long-term streamflow data available. Better results and applications will be achieved under longer time series of data. Results will be helpful in local streamflow drought monitoring, planning and forecasting.

5 Conclusions

This study used the SPI and SRI to detect meteorological and streamflow drought respectively, and conducted a comparative analysis of frequency, severity, beginning, ending and duration to identify streamflow drought′s response to meteorological drought. The main conclusions from this research are listed below:

(1) IC method was well used in pooling drought events. After pooling under the critical parameter, there were 11 meteorological droughts indicated by SPI_4 and six streamflow droughts indicated by SRI in the Jinghe River Basin during 1970 and 1990. The most severe meteorological drought happened during the end of August 1971 to September 1973, which led to the most severe streamflow drought occurring from January 1971 to November 1974. (2) Streamflow drought indicated by SRI can be well related to meteorological drought indicated by SPI_4. As a comparison, the frequency of streamflow drought was less than meteorological drought. However, it lasted for a longer time on average. Streamflow drought was also more severe in drought magnitude. These findings agreed with the results carried out in the UK (Peters *et al.*, 2005) and Denmark (Hisdal and Tallaksen, 2003). (3) Streamflow drought in the Jinghe River Basin lagged meteorological drought by about 127 days. This conclusion in terms of time lag was consistent with the previous studies in other regions such as Spain (Vicente-Serrano *et al.*, 2005), Africa (Edossa *et al.*, 2010), and Iran (Tabrizi *et al.*, 2010). The time lag in this area was comparatively long, indicating that the Jinghe River Basin was a catchment mainly fed by groundwater. However, there were no obvious differences in the termination time. This may be affected by the buffering role played by the soil layers and groundwater system.

This paper investigated the relationships between streamflow drought and meteorological drought in the Jinghe River Basin. It has mainly identified the corresponding responses in terms of frequency, beginning, ending, magnitude, duration and time lag. Although the short time series of streamflow data had limited up-to-date information, the significant time lag would not only play an important role in understanding of relationships between different drought categories in theory, but also in streamflow drought early warning, prevention and regional water resources management in practice. Furthermore, how is the time lag affected by rainfall intensity, temperature, vegetation cover, underlying surface and anthropogenic activity? What is the spatial pattern of this impact within the basin? These issues should be the next steps for the following research items.

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