Investigating the effects of precipitation on drought in the Hanjiang River Basin using SPI

Hai Liu, Jing Wu and Yanqing Xu

ABSTRACT

The Hanjiang River Basin serves as the water source for the Middle Route South-to-North Water Delivery Project. Droughts are not uncommon in this region and have affected the water supply directly. This study is designed to gain more in-depth knowledge of spatial and temporal drought variations in the Hanjiang River Basin, and the synchronization of drought variations in upstream and downstream regions of the Danjiangkou Dam. Compared with drought analysis in the upstream or the downstream, respectively, research shows the spatial difference between the upstream and the downstream clearly. The following conclusions can be drawn: Standardized Precipitation Indexes in the Hanjiang River Basin did not significantly decrease; droughts considered moderate or worse occurred most frequently in autumn and winter, but most rarely in summer; the cumulative probability of moderate to severe droughts was highest in October and December. Drought conditions in the upstream region varied in a fluctuating way. The upstream region has become increasingly wet since the turn of the 21st century, while the downstream region has become increasingly dry since the 1990s. The probability of synchronous droughts both upstream and downstream was only 9.8%.

Key words | drought, Hanjiang River Basin, rainfall, SPI

INTRODUCTION

Drought is an agricultural disaster characterized by decreased precipitation over a long period of time. Drought can lead to dry air and a deficiency in soil moisture, which can and has severely affected the growth and development of crops. They also generally have wide damage areas, long durations and significantly delayed effects (Ye et al. 2007; Dai 2011). In addition to the deterioration of the ecological environment, droughts can trigger secondary disasters and even affect social and economic activities in drought zones Standardized Precipitation Index (SPI) < −0.5. For all of these reasons, droughts are considered a negative factor that restricts substantial development in affected regions (Zhang et al. 2016). Sheffield et al. (2012) pointed out that there has been little change in global droughts over the past 60 years; however, the intensity and frequency of future droughts are expected to increase as global warming causes less precipitation and more evaporation. Therefore, it is of great significance to study the characteristics of drought evolution and strengthen management strategy of drought disaster and risk under the background of climatic warming.

Since the 20th century, many methods of quantitative study on droughts have been put forward. These methods can be divided into two categories: one of them being based on the drought mechanism. This method improves the accuracy of drought intensity and the duration by reflecting the physical processes involved in the drought, such as soil moisture evaporation, surface runoff and surface water recharge, and is represented by the Palmer Drought Index (PDSI) (Palmer 1965). The other category is based on the meteorological indicators that lead to drought. This method reflects
drought intensity and duration by studying the distribution of precipitation, such as SPI (McKee et al. 1993), Z-index (Kite 1977) and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010).

PDSI is based on the drought mechanism, which mainly reflects the condition of soil drought. It can monitor the change of soil moisture and runoff. However, the calculation of this index is hard to ascertain, and the process parameters are only taken from small areas. The calculation of the Z-index is not only related to precipitation, but also to the temporal and spatial distribution of precipitation, and the calculation of the Z-index involved in the parameters such as skewness coefficient and standard variable complicated the calculation process. Therefore, the difference in precipitation between different regions or different seasons leads to the difference in the use of the Z-index (Yuan & Zhou 2004). SPEI is based on the differences between precipitation and evapotranspiration. This method not only has the characteristics of being sensitive to temperatures, but also has the advantages of being multi-scale. However, this method is not mature, and different evapotranspiration models have different or even reverse effects on the trend of SPEI (Li et al. 2017).

SPI represents the probability of precipitation in a certain period and can show the severity of the drought degree and its duration in a given region. Currently, SPI is widely applied in the areas of drought monitoring and evaluation. SPI has two main advantages in the evaluation of drought conditions (Shah et al. 2015). First, the calculation can be performed using only precipitation data, and SPI is dimensionless and standardized; therefore, SPI-based evaluations are relatively simple to perform. Second, SPI covers multi-time scales. In other words, in addition to reflecting the precipitation variation over a short period of time, SPI can also reflect the evolution of water resources over a long time period. Compared with Z-index, in the calculation process of SPI, the parameters related to the temporal and spatial distribution of precipitation were not involved, which reduced the temporal and spatial variation of index values. Compared with SPEI, SPI is more mature. Therefore, SPI is more widely used among the methods of drought analysis.

The Hanjiang River Basin plays a pivotal role in China’s middle-west economic exchange and its south–north communication and transportation networks. In terms of economic impact, this region occupies an important position in the Yangtze River Basin, and the agricultural production in this region represents a major contribution to the whole nation of China. Due to climatic and topographic effects, the Hanjiang River Basin shows obvious sensitivity to the climatic environment, and thus is characterized by complex spatial and temporal precipitation distributions and frequently-occurring droughts (Pan et al. 2012; Ren et al. 2014). Additionally, the Hanjiang River serves as the water source for the Middle Route South-to-North Water Diversion Project, which is a strategic project for alleviating the severe water shortage in northern China. Since the 1990s, as climate change has worsened, the precipitation in this region has been abnormal (IPCC 2007) and droughts have frequently occurred along the middle and lower reaches of the Hanjiang River. In particular, nearly the entire Hanjiang River Basin has suffered from successive years of great drought, which have had enormous impacts on this region’s ecological environment, rational water resource allocation and water supply. This has, therefore, directly affected the river water supply as well as the system of water transfer and distribution in the Hanjiang River Basin (Kirby et al. 2014). Drought has become one of the most important factors that leads to hydrological risks in the middle-line water source areas.

In consideration of the climatic diversity in the Hanjiang River Basin and the importance of this region to China, many scholars have conducted a great deal of research regarding hydrological conditions, water resources and sustainable development in this region (Huang 1999; Gao & Gao 2010; Zeng et al. 2013). Researchers generally agree that precipitation has continually decreased along the north section of the Hanjiang River and droughts have become increasingly severe. As a result of these changes, the ecological environment surrounding Hanjiang River has experienced continuous deterioration. Recently, researchers have emphasized climatic changes in the Hanjiang River Basin and carried out a series of studies on the analysis and prediction of precipitation and temperature variation characteristics (Li et al. 2015), runoff variation and the related simulations (Chen et al. 2006) and the distribution of extreme hydrological events (Xia et al. 2009); however, the variation of spatial and temporal drought distribution has not yet been adequately examined (Yang et al. 2015).
With a view to provide a theoretical basis and technical support for the drought monitoring and evaluation in the Hanjiang River Basin, this paper will aim to analyze the spatial and temporal characteristics of droughts using SPI based on meteorological data in this region. At the same time, considering the spatial differences in the Hanjiang River Basin, drought variation synchronization in the upstream and downstream regions of the Danjiangkou Dam is analyzed. Compared with drought analysis in the upstream and the downstream, respectively, research shows the spatial differences between the upstream and the downstream clearly. These analyses can provide a reference for how water is diverted and when water is transferred. They are also beneficial to provide comparative data for the dispatch and operation of the water diversion project, and to provide a reference for the coordinated development of the upstream and downstream, as well as the suggestion for scientific water transfer.

MATERIAL AND METHODS

Study area

Originating from the southern foothills of the Qinling Mountain, the Hanjiang River is the largest tributary of the Yangtze River. The river flows through complex landforms that generally have high elevations in the west and low elevations in the east. The river basin is surrounded by highlands on three sides and adjoins the Jianghan Plain to the southeast. The river basin features a northern subtropical monsoon climate characterized by a warm and humid climate with a multi-year average precipitation of 873 mm. Precipitation tends to be high in the downstream area of the river, and in the upper reaches the precipitation decreases gradually from south to north. The rainfall mostly occurs in summer, and the precipitation from June to September comprises approximately 60–65% of the annual precipitation. According to the natural conditions of the basin and the existing research results, the Hanjiang River Basin is divided into two regions, upstream and downstream, with the Danjiangkou Dam as the dividing point. Characterized by abundant water resources, the upstream region occupies 59% of the whole river, with an area of 95,200 km². The downstream region covers an area of 63,800 km² (www.geodata.cn).

Research data

The precipitation data comes from the China Meteorological Data Service Center (CMDC). The CMDC is an authoritative and unified shared service platform for the China Meteorological Administration to open its meteorological data resources to domestic and global users. The precipitation time series data from 1960 to 2010 in the national ground station were offered by CDMC. In this study, five meteorological stations in the Hanjiang River Basin were used. Table 1 lists the details of these five stations, and Figure 1 shows their spatial distribution. The Lushi Station and the Hanzhong Station are located in the upstream region of the Danjiangkou Dam, while the other three stations, namely Xinyang Station, Laohekou Station and Wuhan Station, are located in the downstream region of the dam. Based on the rainfall runoff characteristics of the basin, this study will consider that a hydrological year runs from December to November of the next year.

Method

Introduction of SPI

SPI with a short time scale (for example, one month or three months) can clearly reflect the drought variation characteristics in a short time, but it is susceptible to abnormal short-time rainfalls. With a time scale of three months, SPI can be used to characterize seasonal drought conditions, while on the other hand, SPI with a longer time scale (for example, six or 12 months) shows weak responses to short-time

<table>
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<th>Station name</th>
<th>Longitude</th>
<th>Latitude</th>
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rainfalls. Because the drought-flood alternation weakens and the period becomes more obvious, SPI can clearly reflect drought-flood variation tendencies over a long period of time. SPI with a time scale of 12 months can be used to characterize the annual drought variation characteristics (Wang et al. 2014b).

SPI follows a Gamma (Γ) probability distribution to describe precipitation variation. In this study, normalized processing was conducted on the precipitation data with a skewed distribution. The drought degrees were then classified using the standardized cumulative frequency distribution of precipitation. SPI can be calculated by (McKee et al. 1993):

\[ SPI = S \frac{t - (c_2 t + c_1) t + c_0}{(d_5 t + d_2) t + d_1} t + 1 \]  

where \( t = \sqrt{\ln(1/G(x)^2)} \), \( G(x) \) denotes the cumulative probability distribution of precipitation, \( x \) denotes the annual or seasonal precipitation samples, \( S \) denotes the positive-negative coefficient of the probability density, and \( c_0, c_1, c_2, d_1, d_2 \) and \( d_3 \) are the parameters in the simplified approximation conversion of the Γ distribution function into cumulative frequency. Specifically, \( c_0 = 2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269 \) and \( d_3 = 0.001308 \). These values are used in the calculation of SPI, and these values are constants that do not vary with the region.

When \( G(x) > 0.5, S = 1; \) when \( G(x) \leq 0.5, S = -1 \). \( G(x) \) can be calculated by the integration of the probability density of the Γ distribution function:

\[ G(x) = \frac{1}{\beta \Gamma(\gamma)} \int_0^x y^{\gamma-1} e^{-\gamma y} dx, \ x > 0 \]  

\[ \Gamma(\gamma) = \int_0^\infty y^{\gamma-1} e^{-\gamma y} dy \]  

where \( \alpha, \gamma \) and \( \beta \) are the shape and scale parameters of the Γ distribution function. Specifically, \( \alpha, \gamma \) and \( \beta \) can be...
written as:

\[
\alpha = \frac{1 + \sqrt{1 + 4A/3}}{4A}; \quad \beta = \frac{\bar{x}}{\alpha}; \quad \gamma = \ln(\bar{x}) - \frac{\sum_{i=1}^{n} \ln(x_i)}{m} \tag{4}
\]

When the annual and seasonal SPIs have been calculated, the drought-flood grades can be classified according to Classification of Meteorological Drought (GB/T 20481-2006) (Table 2).

**Drought evaluation index**

Two indexes were introduced to better characterize the drought degree, occurrence probability of drought and climate tendency rate.

(1) Drought probability, denoted as \(P_i\), was used to evaluate how often droughts occurred in the data-recording years (Shah et al. 2013). \(P_i\) can be calculated by:

\[
P_i = \left(\frac{n_i}{N}\right) \times 100\% \tag{5}
\]

where \(N\) denotes the total number of months with meteorological data recording, \(n\) denotes the number of months with drought, and the subscript \(i\) was used to distinguish different stations. The probability of droughts of different degrees was then calculated by the number of drought-occurring years.

(2) The climate tendency rate, also known as the variation tendency rate, generally refers to the slope of the fitted line that describes the variation process of a climatic element over the years. The climate tendency rate can be used to characterize the variation tendency degree of long-term meteorological data (Yang 1985). If the climate tendency rate is positive, the climatic element increases with time; if the climate tendency rate is negative, the element decreases.

Assuming that \(x_i\) denotes a certain climatic variable including \(n\) samples and \(t_i\) denotes the corresponding recording time, a linear regression equation between \(x_i\) and \(t_i\) was then constructed as follows:

\[
x_i = a + bt_i (i = 1, 2, \ldots n) \tag{6}
\]

where \(a\) and \(b\) are two regression coefficients. Coefficients \(a\) and \(b\) can be estimated using the least square method. Coefficient \(b\) is then referred to as the tendency ratio of this climatic element.

**RESULTS AND DISCUSSION**

**Variation of precipitation**

The precipitation in the entire Hanjiang River Basin was estimated based on the month-to-month and year-to-year precipitation data collected for the above five meteorological stations (Hanzhong, Lushi, Xinyang, Wuhan and Laohekou) from 1960 to 2010. The mean annual precipitation over the past 50 years was 1,055 mm. Figure 2 shows the variation of annual precipitation in the Hanjiang River Basin from 1960 to 2010. From this figure, it is clear that the annual precipitation has greatly fluctuated over the past 50 years. The maximum and minimum annual precipitations were 1,370 mm in 1983 and 663.1 mm in 2001, respectively. This gives a range of approximately 707 mm. In 1983, abnormally rainy weather had occurred in the Hanjiang River Basin from late spring to early summer, and the torrential rains started rather early in May compared with most years. This was caused by the anomalous warming in the Pacific and changes in the El Nino and the subtropical anticyclone of the Northwest Pacific. Since July, a series of heavy rainfalls with huge impact have emerged one after another, leading to a drastic increase of annual rainfall in the Hanjiang River Basin (Zhang & Li 1985). However, in 2001, due to the abnormal atmospheric circulation, rainfall intensity in the Hanjiang river basin was lower during the Meiyu period, and the precipitation was about 20–40% less than in previous years.
The emergence of extreme weather has led to the greater rainfall in the Hanjiang River Basin. Figure 3 shows the monthly variation of the average precipitation within each year. It is clear that the months with average precipitation over 120 mm were mainly concentrated from April to September, suggesting that in this region most of the rainfall is concentrated in the summer. The two months with the highest average precipitation were July and August.

Temporal variation characteristics of drought

SPI variations at different time scales

In order to analyze the SPI variation of the entire Hanjiang River Basin, the SPI values were calculated at time scales of two, three, six and 12 months in this study. These time scales were named SPI1, SPI3, SPI6 and SPI12, respectively. To examine the overall SPI variation in this region, the calculated SPIs of these five meteorological stations were averaged for further analysis (Wang et al. 2014b).

Figure 4 shows the calculated results of the SPI variation at different time scales. Overall, the SPI variation at different time scales showed different degrees of sensitivity to the precipitation. SPI1 reflects the monthly drought-flood variation, and thus is quite sensitive to any monthly precipitation variation. The SPI1 series fluctuated in a wide range and varied quickly between drought and flood, suggesting that the SPI1 series can accurately describe monthly precipitation variation and thus reflect rapid changes between drought and flood. For example, in 1962, there was very little rainfall in March (SPI1 = 2.28); however, the precipitation increased to 844 mm in April (SPI1 = 0.264). Thus, the SPI was able to accurately show this fluctuation in rainfall.

Of the drought classifications, moderate drought (SPI < –1) was the most common, with 0.8 occurrences per year. Severe droughts (SPI < –1.5), however, occurred on average once every three years with a short duration. These severe droughts began to occur more frequently after 1990, increasing to an average frequency of 2.5 years.

SPI3 reflects the variation of drought characteristics over a short period of time. Compared with SPI1, SPI3 is less affected by precipitation variation and focuses more on the drought-flood variations over the course of a given year. SPI3 can accurately represent water surplus and deficit conditions over a short period of time, and therefore it is well suited for agricultural drought research (Wang et al. 2014b). Using SPI3, it can be observed that moderate droughts (SPI < –1) occurred approximately once every 0.9 years, with most of these occurrences happening in winter and autumn, and severe droughts (SPI < –1.5) occurring at an average frequency of approximately 3.5 years. By contrast with the results of SPI1, more severe droughts began to occur more frequently after 1990, and from 1990 to 2010 they occurred nearly once every year.

From the temporal distribution chart, it can be observed that SPI6 is only slightly affected by any one rainfall event and would only fluctuate after continuous precipitation. Compared with the SPI1 and SPI3 results, the SPI6 variation results demonstrate less frequently-occurring but longer-lasting droughts; severe droughts (SPI < –1.5) occurred once every three years (the same as in SPI1...
variation results). Compared with SPI1 results, the SPI6 variation results demonstrate more droughts after the 1990s. In particular, the situation of droughts had obviously increased since 2001. There was less precipitation in the middle and lower reaches of the Yangtze River during this time period due to the abnormal sea surface temperature (sst) temperature field, along with the circulation of the Eurasian westerly winds that showed a west–east low distribution in the pressure field, resulting in little or no rainfall in the Hanjiang River Basin (Cheng et al. 2013). In addition, the number of typhoon landings significantly increased around 2001. Due to the frequent typhoon activity, the subtropical high is caused to be northward, which is not conducive to the water vapor transport within the basin. Therefore, typhoon activity is also an important factor contributing to the frequent droughts in the Hanjiang River Basin during this period.

SPI12 can successfully reflect the effects of rainfall on soil moisture and underground water (Ye 2014). Using this metric, severe droughts can be observed to have effects that continue for multiple years. For example, the severe drought that occurred in August 1966 had effects that lasted even into January 1967. This indicates that SPIs at large time scales play an important role in revealing the long-term effects of regional droughts or floods. According to the variation tendency of SPI12, typical drought years were identified: 1966, 1978, 1998, 1999, 2001 and 2002. These drought years came at an average frequency of approximately 10 years. More specifically, the climate was more humid in the 1980s, and drought years occurred more frequently after 1990. Droughts in the Hanjiang River Basin had a more concentrated distribution in the late 1990s and early 2000s, when drought years occurred four times in total between 1990 and 2010.

SPIs at different time scales all exhibited a complex variation tendency of decrease-increase-decrease-increase, but all of them showed a slight overall decrease. The probability of no-drought exceeds 60%; the probability of light drought ranges between 12.7 and 17.6%. The probability of moderate drought or above ranges between 4.5 and 10.9%. Between 1960 and 1990, droughts that were moderate or worse occurred once every 10 years. However, after 1990 this occurrence frequency significantly increased. Six continuous droughts in total were observed in the Hanjiang River

![SPI1](image1.png)
![SPI3](image2.png)
![SPI6](image3.png)

**Figure 4 | Variations of SPIs at different time scales.**

Abnormal atmospheric circulation is the direct cause of abnormal precipitation and drought (Wang et al. 2014). The East Asian monsoon, the South Asian monsoon, the plateau monsoon and the westerly circulation have a direct effect on the precipitation in China. The East Asian summer monsoon weakened at the end of the 20th century. In addition to this weakening, the temperature increased in this period, resulting in less precipitation in the basin. So the trend of drought in this period was remarkable. During 2003–2005, the East Asian monsoon has changed from weak to strong, which reduced droughts in recent years. In addition, the urban heat effect increased, making the surface temperature rise year by year. The updraft over urban areas is enhanced, so as to increase the ability of cloud lifts (Cui & Shi 2010). In the end, the precipitation decreases in the Hanjiang River Basin have aggravated the occurrence of drought.

**Monthly and seasonal SPI variations**

The monthly and seasonal drought occurrence probabilities from 1960 to 2010 were calculated according to Equations (1)–(5). The statistical results are shown in Figures 5 and 6.

As shown in Figure 5, extremely severe droughts were generally rare and only appeared in January, April and November, with an average occurrence probability of 1.96%. Severe droughts rarely occurred in June–September, but most frequently occurred in October, with an occurrence probability of 5.88%, and occurred in the other months at almost identical probabilities of 2–3.9%. Moderate droughts occurred more frequently in February, September, October and December, with probabilities of 7.8–18.73%, but occurred uniformly in the other months, with probabilities of 2–3.9%. Light droughts show quite different occurrence probabilities, with a range of 9.8–25% among different months. These light droughts most frequently occurred during the months of May, June and July. Overall, in the Hanjiang River Basin, the occurrence probability of moderate droughts and above was highest in October and December but lowest in June and July, with an average occurrence value of approximately 1.96–3.92%.

As shown in Figure 6, extremely severe droughts were generally rare, with an occurrence probability range of 0–0.65%. Severe droughts were least probable in summer (0.65%) but most probable in spring and autumn (3.27%). Moderate droughts occurred the least in the summer, with an occurrence probability of 4.58%, and occurred almost equally in spring, autumn and winter, with a probability range of 7.19–7.84%. Light droughts occurred most frequently in the summer, with occurrence probabilities reaching 22.3%, but the probability of light drought was still high in spring and autumn, in the range of 14–15.3%.
Overall, moderate and above droughts most frequently occurred in autumn and winter in the Hanjiang River Basin, with an occurrence probability range of 11.1–11.76%, but these droughts occurred less frequently in the summer, with an average probability of 5.23%.

Analysis of causes and effects on water transfer

The frequency of droughts in the Hanjiang River Basin can be considered a result of both natural and human factors (Li et al. 2015). Human factors have directly led to the occurrence of drought disasters. During the period from 1960 to 2010, the precipitation in the Hanjiang River basin showed no great variations (Zeng et al. 2016), with a multi-year average value of 930 mm; however, during this period the temperature steadily rose (see Figure 7). Research shows that in the past 45 years the greenhouse effect has increased and the climate has continued to warm; therefore the evaporation of water in this basin is increasing. At the same time, the distribution of precipitation during the year is sporadic and concentrated in the short term, thus making droughts occur frequently in the area. With the evaporation of water increasing, coupled with serious soil erosion in the Hanjiang River Basin, the water retaining capacity of the soil is poor. Once the precipitation is reduced, it is very easy to form a drought. Even when there is heavy rainfall, it still may be hard for the soil to maintain its moisture for a long time (Ren et al. 2013). The combination of these factors eventually led to the occurrence of droughts in the Hanjiang River Basin.

With the development of the social economy in the Hanjiang River Basin, the influence of human factors on the natural environment is increasing. The expansion of urbanization leads to a decrease in woodlands, resulting in the increase of surface reflectance. The decrease of these woodlands also leads to increased evaporation of the soil indirectly and the water retaining ability of the soil is decreased. When the water retaining capacity of the soil is reduced, this aggravates the occurrence of drought disasters. In addition, the urban heat island effect increases, making the surface temperature rise year by year. The updraft over the town is enhanced, so as to increase the ability of cloud lifts (Cui & Shi 2010). In the end, the precipitation decreases in the Hanjiang river basin, which aggravates the occurrence of drought.

According to the results of the SPI calculations at different time scales, the occurrence probability of light drought in the Hanjiang River Basin over the past 50 years ranges from 12.7 to 25%, while the probability of moderate drought and above falls in the range of 4.5–10.9%. The annual SPI results demonstrate that before 1990, severe and extremely severe droughts occurred almost every ten years, but after 1990, severe and extremely severe droughts occurred more frequently. Three severe droughts were observed during the period from 1991 to 2001 (1995, 1997 and 2001). Since the turn of the 21st century, the frequency of these severe droughts decreased, but the SPI values showed no significant decrease. This indicates that the Hanjiang River gradually dried out. In terms of seasonal SPI, the cumulative occurrence probability of moderate drought and above is highest in autumn and winter and lowest in summer. In terms of monthly SPI, moderate droughts and above most frequently occurred in October and February. Therefore, when hydrological safety and runoff conditions are taken into account, water should be appropriately transferred in October and December.

Studies show that government policy plays a very important role in the management of water resources (Shao et al. 2017). Against the background of the extreme climate events caused by global warming, the government should maximize its own positive role in drought monitoring and prevention. For example, the government could establish a monitoring-assessment-prediction-early warning information service system (Li et al. 2011) based on Remote Sensing and GIS.
strengthen the construction and maintenance of the irrigation and water conservancy; organize emergency response projects and water-saving construction; and try to improve water supply capacity and water use efficiency. In the dry areas, the government should build a water diversion project and a rainwater collection and utilization project in regard to local conditions. Because the upstream of the Hanjiang River Basin is the water source area of the middle route project, water resources would be affected after the water diversion. Therefore, the government should speed up the construction of water supply projects and water-saving projects (Liu et al. 2005). The government should try to minimize the increase of drought frequency caused by human factors and realize coordinated development between people and nature in the water source area.

Spatial variation characteristics of drought

SPI variations and tendencies in upstream and downstream regions of the Danjiangkou Dam

In order to analyze the regional differences in the SPI variation, the average values and tendency rates of SPI from 1956 to 2010 were calculated. In this study, the Danjiangkou Dam is used as the dividing point; stations in the upper and middle reaches of the Hanjiang River were referred to as upstream-dam stations, while stations in the lower reaches were referred to as downstream-dam stations.

Intra-annual and inter-annual continuous changes over long periods of time can be most accurately reflected by SPI3 and SPI12. Therefore, this study selected the average values of SPI3 and SPI12 for analysis of the SPI variations both upstream and downstream of the dam.

Table 3 lists the average values of SPI3 and SPI12 both upstream and downstream of the dam. It can be observed that the average values of SPI3 and SPI12 of the upstream region were smaller than those of the downstream region, suggesting that the upstream region was drier in terms of both seasonal and long-term drought variations.

In order to further analyze the SPI variations in the various periods both upstream and downstream of the dam, a tendency rate was introduced, which was defined as the slope of the fitted line of SPI variation with time. Generally, the tendency rate is used to characterize the tendency degree of the variation of a given SPI series. A positive tendency rate suggests that as the SPI increases with time, the region becomes increasingly wetter; a negative tendency rate suggests that as the SPI decreases with time, the region becomes increasingly drier.

Figure 8 shows the spatial distributions of the SPI3 tendency rates in different periods. It can be observed that in the 1960s, the SPI3 tendency rates in most areas of the Hanjiang River basin were positive, while the values in some areas around the Danjiangkou Dam in the northern area of the River basin were negative. However, in the 1970s, the areas with positive SPI3 tendency rates were generally in the north and southeast of the river basin and occupied a smaller ratio of the total areas, while the areas with negative SPI3 tendency rates occupied an overwhelmingly large area. In the 1980s, most areas showed positive SPI3 tendency rates; the areas that originally showed negative tendency rates showed positive values, with the exception of some eastern areas upstream of the dam, while the northern regions of the basin that originally showed positive tendency rates had small negative values. In the 1990s, the SPI3 tendency rates were negative throughout the entire Hanjiang River Basin. At the beginning of the 21st century, positive SPI3 tendency rates appeared upstream of Danjiangkou Dam, but these rates gradually decreased from the northwest to the southeast. Overall, before 1990, the

<table>
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<th>Basin</th>
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<th>Maximum Value</th>
<th>Year</th>
<th>Minimum Value</th>
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Hanjiang River Basin showed alternating variations between wet and dry; after 1990, the upstream region of the Danjiangkou Dam continued to alternate between wet and dry, while the downstream region became increasingly dry.

Figure 9 shows the spatial distributions of the tendency rates of SPI12 in different periods. It can be observed that in the 1960s, negative and positive SPI12 tendency rates occupied nearly the same ratios in the Hanjiang River basin, and
the tendency rate decreased gradually from southeast to northwest. In the 1970s, there were fewer areas with positive SPI12 tendency rates; these areas were concentrated in the eastern areas downstream of the Danjiangkou Dam. In the 1980s, the area with positive SPI12 tendency rates increased and moved from the east to the middle south, but the areas...
upstream of the dam showed negative SPI12 tendency rates. In the 1990s, the areas with positive SPI12 tendency rates further expanded, but the main stream area that is downstream of Danjiangkou Dam showed negative SPI12 tendency rates and deteriorating moisture conditions. From 2000 to 2010, almost all of the areas in the Hanjiang River Basin showed positive SPI12 tendency rates, except some small regions in the southeast. This indicates increased moisture conditions during that time period. Overall, the SPI12 tendency rate in the upstream region of the Danjiangkou Dam underwent a V-shaped variation, i.e. the upstream region became drier before 1990, but the dry conditions were improved after 1990. By contrast, the SPI12 tendency rate of the downstream region alternated between dry and wet.

Taken together, although the average SPI values in the upstream region were lower than the values in the downstream region, the upstream region has become more wet since 2000, while the downstream region has become increasingly dry since the 1990s. As the downstream region becomes drier, many negative effects have resulted, such as a weakened water environmental capacity and damage to the normal water supply in the downstream region. Accordingly, with the implementation of the South-to-North Water Diversion Project, timely measures for environmental protection should be taken in order to eliminate the adverse effects of water transference on the water supply in the lower reaches of the Hanjiang River.

Synchronization of droughts in upstream and downstream regions of the dam

The South-to-North Water Diversion Project has been a very successful water transfer project. However, because the water source is not inexhaustible, it is crucial to monitor and maintain this supply so that the project may be smoothly implemented. The Danjiangkou Reservoir not only takes on the heavy responsibility of water delivery to the north, but it also must ensure the safety of the water supply from the water source and the lower reaches of the Hanjiang River. Thus, analyzing the synchronous drought conditions in the upstream and downstream regions of the Danjiangkou Dam can provide a scientific reference for achieving reasonable dispatching of water at the dam. As shown in Figures 8 and 9, drought does not always simultaneously occur upstream and downstream. Rather, the synchronization probability of drought in the different regions determines the feasibility of the project, and this metric can be used to determine whether the water source has sufficient water for transferring (Yan & Chen 2013). Sufficient water cannot be transferred from the Danjiangkou Reservoir when moderate droughts continuously occur in the water source region or when droughts occur continuously in different upstream and downstream areas (Zhang et al. 2000).

As stated above, the five meteorological stations in the Hanjiang River basin were divided into upstream and downstream stations according to their locations relative to Danjiangkou Dam. Based on the SPI values, the evolution of the monthly drought degrees in both the upstream and downstream regions were investigated. Nine different distributions are possible: wet upstream and normal downstream, wet both upstream and downstream, wet upstream and dry downstream, dry upstream and normal downstream, dry upstream and wet downstream, normal both upstream and downstream, normal upstream and wet downstream, normal upstream and dry downstream, and dry both upstream and downstream. Specifically, ‘dry’ indicates that drought appeared in the region, whether light, moderate, severe, or extremely severe drought. ‘Normal’ indicates that the region is wet according to the drought classification standard. Table 4 lists the occurrence probabilities of these nine conditions.

Among the different distribution patterns of drought degrees, wet upstream and normal downstream; wet upstream and wet downstream; normal upstream and normal downstream; and normal upstream and wet downstream indicate that the Hanjiang River basin, as a water supply district, is wet or normal and has sufficient water for supply, i.e. the benefits of the South-to-North Water Diversion Middle Route Project can be maximized. According to the statistics, these four distribution patterns occupied 56.5% of the time between 1960 and 2010, which suggests that the South-to-North Water Diversion Project yielded benefits on the whole. However, the other two conditions, partial drought in water sources (including wet upstream and dry downstream; dry upstream and normal downstream; dry upstream and wet downstream; and normal upstream and dry downstream) and overall drought (dry both upstream and downstream), still existed, particularly continuous overall drought. These conditions occupied ratios of 33.8 and 9.7%,
respectively. Under these conditions, there is continuous development of drought over a large area, and the project then has a low chance of success; the water source has little or no water to transfer. Accordingly, targeted measures must be taken to remedy the situation of water shortage.

CONCLUSION

This study calculated and analyzed monthly precipitation data collected from five national meteorological stations in the Hanjiang River basin from 1960 to 2010. Using the SPI as the drought index, the temporal and spatial distribution characteristics and their evolution rules were investigated in this region. The following conclusions can be drawn from this research:

Overall, the SPI in the Hanjiang River Basin showed no significant decrease, and the region tended to be increasingly dry. When the time scale of the calculated SPI was increased, the SPI was less affected by any one rainfall event. In fact, SPI at a greater time scale showed less randomness and was more stable.

The cumulative probability of drought in the Hanjiang River basin exceeded 60%. Specifically, the cumulative probability of light drought ranged from 12.7 to 25%, while the probability of moderate drought and above ranged from 4.5 to 10.9%. Between 1960 and 1990, droughts that were moderate or worse occurred approximately every ten years. However, after 1990, these serious droughts became more frequent. In regard to the seasonal differences, moderate and more severe droughts occurred most often in the autumn and winter. In terms of monthly differences, moderate and more severe droughts occurred most frequently in October and February and least in the months of June and July.

Gradual drying in the Hanjiang River Basin can be attributed to the decline in precipitation and the warming climate. Therefore, hydrological safety and drought conditions should be fully considered with respect to water transport, and countermeasures for coping with the adverse effects induced by global warming should be prepared in advance. In addition, the protection of this water source should be strengthened.

Drought conditions in the upstream region of the Danjiangkou Dam fluctuated between 1960 and 2010, showing a remarkable improvement at the beginning of the 21st century. By contrast, the region downstream of the dam has become increasingly dry. Of the nine possible patterns of upstream and downstream drought degrees, synchronous moisture and synchronous normal conditions in these two regions occurred 56% of the time, while synchronous drought occurred 9.8% of the time. With the implementation of the South-to-North Water Delivery Project, measures for the occurrence of synchronous drought should be taken into account to ensure the smooth operation of the Middle Route Project.

There are still some shortcomings in this study; for example, the number of meteorological stations and time span that could be selected is limited, making the data that was selected for analysis not sufficient. However, there are

<table>
<thead>
<tr>
<th>Distribution patterns</th>
<th>Wet upstream and normal downstream</th>
<th>Wet both upstream and downstream</th>
<th>Wet upstream and dry downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurrence number</td>
<td>81</td>
<td>67</td>
<td>18</td>
</tr>
<tr>
<td>Probability</td>
<td>13.5%</td>
<td>11.2%</td>
<td>3%</td>
</tr>
<tr>
<td>Distribution patterns</td>
<td>Dry upstream and normal downstream</td>
<td>Dry upstream and wet downstream</td>
<td>Dry both upstream and downstream</td>
</tr>
<tr>
<td>Occurrence number</td>
<td>100</td>
<td>39</td>
<td>58</td>
</tr>
<tr>
<td>Probability</td>
<td>16.7%</td>
<td>6.5%</td>
<td>9.7%</td>
</tr>
<tr>
<td>Distribution patterns</td>
<td>Normal both upstream and downstream</td>
<td>Normal upstream and wet downstream</td>
<td>Normal upstream and dry downstream</td>
</tr>
<tr>
<td>Occurrence number</td>
<td>174</td>
<td>17</td>
<td>46</td>
</tr>
<tr>
<td>Probability</td>
<td>29%</td>
<td>2.8%</td>
<td>7.6%</td>
</tr>
</tbody>
</table>
improvements that could be made to this study for future research. The drought variation in water-receiving regions will need to be investigated in addition to water supply regions. This will help to achieve rational utilization of water resources and a maximizing of the benefits of the South-to-North Water Delivery Project.

SPI is simple and easy to obtain, and its calculation principle also guarantees the stability and standardization in different regions and time scales, which can effectively reflect the spatial and temporal changes of droughts. However, SPI is established on the basis of long time series, whereas the monthly values reflect the average level in the same period. As a result, SPI values in the dry season may be higher than in the rainy season. In addition, the influence of temperature and evaporation is not considered in the process of SPI calculation. However, under the background of global warming, the influence of these two factors on drought is more and more obvious (Li et al. 2017). Therefore, it is necessary to further study the spatial and temporal change of droughts in the Hanjiang River Basin by combining the factors of temperature and evaporation.

The meteorological stations selected for this study were limited, so it cannot accurately describe the spatial and temporal characteristics of droughts in the Hanjiang River Basin. However, the drought evaluation model combined with meteorological and hydrological drought indicators (Sun et al. 2014), such as the Markov chain model, can analyze the probability, recurrence period and diachronic of the grade of drought. This can be used to predict the probability of droughts, which can help to understand droughts in the region.

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