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Non-linear relationship of hydrological drought responding to meteorological drought and impact of a large reservoir

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ABSTRACT

Exploring the relationship between hydrological and meteorological droughts under influence of large reservoirs is crucial for early warning of hydrological drought. This study took Jinjiang River basin in the southeast coastal region of China as an example, where the Shilong hydrometric station is influenced by a large reservoir (Shanmei), and the Anxi hydrological station is not. Based on monthly data of streamflow with precipitation and historical drought records from 1960 to 2010, the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) series (representing meteorological drought and hydrological drought, respectively) were each calculated with a 3-month timescale. Run theory was then used to identify the characteristics of meteorological and hydrological drought, including duration and magnitude. The relationship with which hydrological drought responds to meteorological drought was established by a non-linear function model at the Anxi station and Shilong station which reflected the periods of natural condition without reservoir and reservoir-influence condition, respectively. The results indicate that (1) there was a clear non-linear relationship of hydrological drought and meteorological drought, and the threshold within which hydrological drought started to respond to meteorological drought was obtained according to the non-linear function model; (2) the operational activities of the Shanmei reservoir during 1983–2010 have significantly reduced the duration and magnitude of hydrological drought at the Shilong station compared to the natural-influence period of 1960–1982, which, in turn, altered the relationship between the hydrological drought and meteorological drought. The propagation process from meteorological to hydrological droughts was shortened because of the changed relationship.

1. Introduction

Droughts are among the most damaging environmental disasters in terms of crop yield reduction, economic costs, and their huge impacts on human society (Dracup et al., 1980; Wilhite, 2000). Droughts are typically divided into meteorological, agricultural, hydrological, and socio-economic droughts, depending on different types of hydrological cycle deficits (American Meteorological Society, 1997; World Meteorological Organization, 2006; Van Loon, 2015). Meteorological droughts are related to shortages of precipitation, and hydrological droughts are associated with deficiencies in streamflow, groundwater, and water storage in natural lakes and artificial reservoirs, which are mainly caused by the continuation of meteorological drought, and also regarded as a thorough drought (Linsley et al., 1982). The Palmer Drought Severity Index (PDSI) (Palmer, 1965), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) and Standardized Precipitation Index (SPI) (Mckee et al., 1993) are the most widely utilized indices to monitor meteorological drought across the world. Among these indices, the main shortcoming of the PDSI is its fixed timescale, which is limited universally because drought is a multi-scalar phenomenon (Mishra and Singh, 2010). The SPEI was used to identify meteorological drought based on precipitation and temperature data, and it has been confirmed that there were different sensitivities to the results calculated in response to different evapotranspiration data (Li et al., 2014, 2016), and that the results needed to be strictly inspected (Stagge et al., 2015, 2016; Vicente-Serrano and Begueria, 2016). Compared with the PDSI and SPEI, the SPI is more widely

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accepted because its calculation is simple, it includes multiple timescales, and it has a lower data demand (requiring only precipitation data) (Mckee et al., 1993; Heim, 2002). Therefore, the SPI has been recommended by WMO (World Meteorological Organization). Previous studies have been carried out using the SPI in different climatic regions around the world, such as the USA, Europe, China, India, Ethiopia and Iran (Bussay et al., 1998; Szalai and Szinell, 2000; Heim, 2002; Mishra and Singh, 2010; Edossa et al., 2010; Raziei et al., 2013; Maccioni et al., 2015; Niu et al., 2015; Wang et al., 2015). In addition, the Standardized Streamflow Index (SSI) (Shukla and Wood, 2008; Vicente-Serrano et al., 2011), whose characteristics are similar to those of the SPI, uses streamflow data to calculate the hydrological drought index and has been widely applied in hydrological research (Lorenzo-Lacruz et al., 2013a; Li et al., 2014; Barker et al., 2016).

A complete consideration of drought structure and characteristics should include the duration (from beginning to end of the drought), severity (accumulated water deficit) and intensity (average water deficit for the duration of the drought) (Mo, 2011; Huang et al., 2015). The physical linkages of water cycle processes lead to the synchronization of the occurrence time and severity of hydrological and meteorological droughts. A meteorological drought may develop quickly, whereas a hydrological drought lags behind meteorological drought, namely, there are close relationships between hydrological drought and meteorological drought (Dracup et al., 1980; Wilhite, 2000). Several methods, such as Pearson and Spearman correlation analysis (Lopez-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013b; Kazemzadeh and Malekian, 2016; Wu et al., 2016a), have been used to study the response of hydrological drought to meteorological drought. In order to find the differences between the droughts' occurrence time, the score of correlation coefficients between the single timescale of the hydrological drought index series and different timescales of the meteorological drought index series should be obtained based on the correlation methods. Obviously, these methods are difficult to use to fully investigate the response of hydrological drought to meteorological drought because these methods only focus on response time and the severities are often overlooked.

Apart from the correlation methods, Edossa et al. (2010) and Li et al. (2016) have studied the relationships between hydrological and meteorological drought with respect to the duration, severity and intensity using a linear model. However, the simple linear relationship between hydrological drought and meteorological drought has not completely considered the complex drought propagation mechanism under the backdrop of the environment, especially not able to accommodate the changes of hydrological processes caused by human perturbations (Van Loon and Laaha, 2015; Wanders and Wada, 2015; Van Loon et al., 2016). Zhang et al. (2015a,b) and Ye et al. (2016) showed that the relationship between different time scales of meteorological and hydrological drought indices were changed under the influences of human activities. Human activities, such as land-use change (Lin et al., 2015), the construction and operation of reservoirs (Knighton and Walter, 2016), water extraction for irrigation (Pique et al., 2016), and so on, intensify or adjust the complicated response of the hydrological process to climatic conditions (Lopez-Moreno et al., 2009; Lorenzo-Lacruz et al., 2013b). In particular, the construction and operation of large reservoirs have been shown to have a significant impact on surface runoff processes and, therefore, modify the propagation process of drought from meteorological to hydrological drought (Mo, 2011; Van Loon et al., 2016). Wen et al. (2011) analyzed the Murrumbidgee River basin in Australia by using long term streamflow records, which showed that the regulation of upstream reservoirs alleviated the extent of hydrological drought in the downstream irrigation regions. Wu et al. (2016a) showed that the construction of upstream reservoir has significantly affected the response where the evolution of hydrological drought responded to meteorological drought, including trend change, decadal frequency change and periodic change. The conclusion that the construction of upstream reservoirs apparently alters downstream hydrological conditions and exacerbates the extent of downstream hydrological drought was highlighted by Al-Faraj and Scholz (2015), who studied the Diyala River basin in central Asia. In studies of the change of hydrological drought conditions upstream and downstream of a drainage basin, Lopez-Moreno et al. (2009), Zhang et al. (2015a,b), and Leitman et al. (2016) showed that the frequency, duration and severity of hydrological drought were closely related to the construction of hydraulic projects. Additionally, with respect to the response of hydrological drought to meteorological drought under the influence of a large reservoir, Lopez-Moreno et al. (2013) and Lorenzo-Lacruz et al. (2013b) indicated that the response time of hydrological drought to meteorological drought was extended by reservoir regulation. However, these previous studies (Lopez-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013b) only revealed how to estimate the response time between hydrological drought and meteorological drought under the influences of large reservoirs, but did not clarify the influence in drought severity and intensity. Therefore, it is necessary to comprehensively investigate the response of hydrological drought to meteorological drought by including the major characteristics such as response time, severity and intensity for assessing the effect of large reservoirs, and the non-linearity in their relationship should be considered.

In order to achieve the above aims, this study took the Jinjiang River basin in the southeastern coast of China as a study area, and used data from the Shilong hydrological station which was affected by a large reservoir, and the Anxi hydrological station which was not. This enabled the relationship between hydrological and meteorological droughts to be analyzed for both regulated and unregulated river basins. Based on monthly streamflow records from 1960 to 2010 and the corresponding precipitation records of three meteorological stations in the study area, the SPI and SSI were calculated, and the relationships of hydrological and meteorological droughts were established with a non-linear model on the basis of identifying the main drought events and their characteristics. The results of this study are expected to assist in monitoring, prediction and management of hydrological droughts.

2. Study area and dataset

2.1. Research area

The study area was the portion of Jinjiang River basin located within Quanzhou City, in the southeast of Fujian Province in China (117°44′–118°47′ E and 24°31′–25°32′ N). The total area of Jinjiang River basin is 5629 km^2 and its length is 302 km. The Jinjiang River basin contains two sub-basins (Fig. 1): Dongxi in the east and Xixi in the west, and Xixi drainage area takes up 3101 km^2. These two rivers merge 2.5 km upstream of the Shilong hydrological station which controls a drainage area of 5024 km^2; thus, the drainage area upstream of Shilong station is chosen as the study watershed. As there is a typical South Asia humid subtropical monsoon climate in this region, rainfall is abundant, with around 1868 mm of annual precipitation. The intra-annual distribution of precipitation is uneven. For example, 83.80% of the annual precipitation occurs between March and September and only 16.20% occurs between October and February of the following year (Lu and Wang, 2012). Due to the high variations in rainfall distribution, severe water shortages and droughts occur frequently in the Jinjiang River basin (Lu and Wang, 2012).

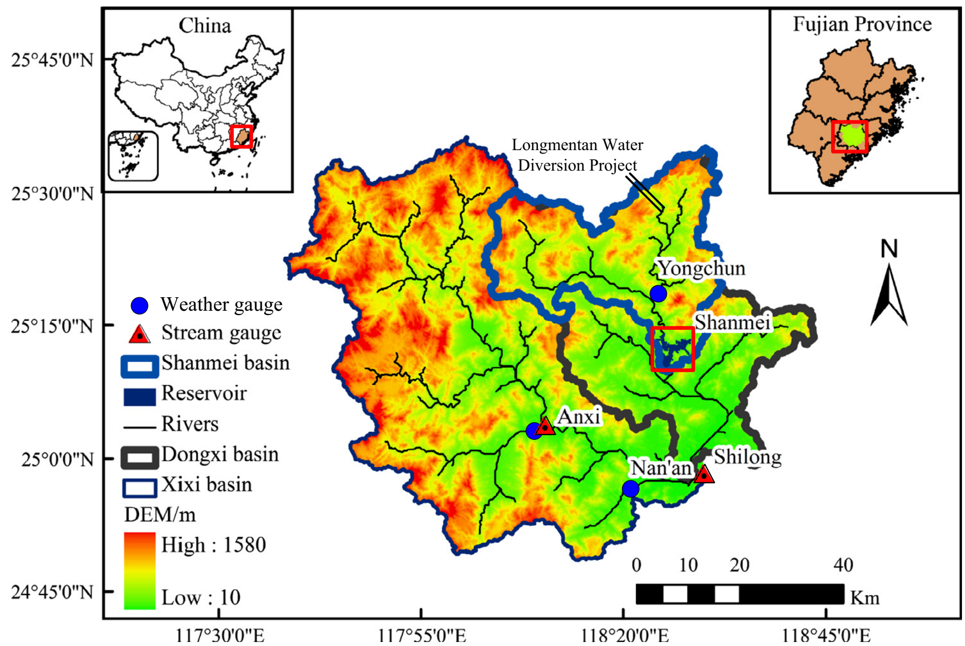

Fig. 1. Location of the research basin and spatial distribution of hydrometric, meteorological stations and Shanmei reservoir.

The Shanmei reservoir with a drainage area of 1023 km^2 and a storage capacity of 6.55×10^8 m^3, as the largest reservoir in Jinjiang River basin, is located in the midstream of the Dongxi sub-basin (Fig. 1), which is one of the two sub-basins that flow through the Shilong station. The filling of the Shanmei dam was completed in 1972, and its expansion and protection projects were constructed from 1979 to 1982. As a multi-annual regulation reservoir associated with water management for downstream flood-control, drinking water supply and irrigation, the downstream hydrological processes in Shilong station have been significantly modified. Additionally, the Longmentan Water Diversion Project was completed in 1989, which is located in the upstream of Dongxi sub-basin and has an annual water diversion of 4.06×108 m^3 entering into the Dongxi sub-basin. This project conveyed the Dazhangxi river streamflow of Min River basin (out of Jingjiang River Basin) to Huyangxi river of Dongxi sub-basin via a transbasin diversion, and then the conveyed water flows into Shanmei Reservoir and was transported to the downstream Shilong station by operation of reservoir.

2.2. Data

The observed monthly precipitation and streamflow data from 1960 to 2010 were obtained from the Meteorology Agency and Water Conservation Agency of Fujian Province, respectively. The information of hydrometric, meteorological gauges are given in Table 1. And all original data of meteorological and hydrometric stations passed a stationarity test (last column in Table 1). In addition, daily inflow and outflow records for the Shanmei reservoir, covering the period from January 2001 to December 2010, were obtained from the Shanmei Reservoir Management Office, Quanzhou City. The basin-average monthly precipitation was obtained by calculating the arithmetic mean of three meteorological stations (Nan'an, Anxi and Yongchun). The streamflow data included two hydrological stations, with the Shilong station located downstream and affected by the Longmentan Water Diversion Project and Shanmei reservoir operation, which were collectively called the impact of Shanmei reservoir. The Anxi station, however, is located upstream (in the Xixi sub-basin) and was not affected by any reservoir. Therefore, the Jinjiang River basin is a suitable area to research the relationship between hydrological drought and meteorological drought with respect to the impact of a large reservoir. The daily inflow and outflow records from 2001 to 2010 were selected from the Shanmei reservoir, as there was no daily flow data available prior to 2001.

3. Methodology

Based on monthly precipitation (basin-average) and streamflow (Shilong and Anxi) data from 1960 to 2010, the SPI and the SSI were calculated. Drought characteristics were extracted using a combination of the threshold of SPI/SSI and the run theory, and the relationship with which hydrological drought responds to meteorological drought was then established by non-linear function model.

3.1. Standardized Precipitation/Streamflow Index (SPI/SSI)

The SPI calculation, which was used to describe the temporal variations of meteorological drought, depended on long-term

Table 1
Information of hydrometric and meteorological stations.

Type	Station	Time series	Length(year)	Latitude	Longitude	Elevation(m)	ADF statistic
Hydrometric	Shilong	1960–2010	51	24°54′	118°27′	47	−5.01*
	Anxi	1960–2010	51	25°30′	118°11′	49	−5.37*
Meteorological	Nan'an	1960–2010	51	24°59′	118°22′	34	−6.27*
	Anxi	1960–2010	51	25°20′	118°11′	49	−5.02*
	Yongchun	1960–2010	51	25°17′	118°23′	125	−5.37*

Note: Stationarity test for monthly streamflow and precipitation series by Augmented Dickey-Fuller. * mean the results reached significant level of 0.01.

monthly precipitation records. The SPI was calculated by fitting a cumulative probability density function (CDF) with the precipitation records, and then was transformed into a standard normal distribution for the actual SPI values using an equal probability transformation (Mckee et al., 1993). Different time scales of SPI can be calculated from one to dozens of months determined by the needs of the research (e.g. a 3-month scale represents seasonal droughts and is related to soil moisture conditions, a 48-month scale represents reservoir storages and is related to long time scales of droughts) (Hayes et al., 1999; Vicente-Serrano et al., 2005). The SSI was used to represent hydrological drought in this study because its advantages are similar to those of SPI (Heim, 2002; Raziei et al., 2013; Barker et al., 2016). Previous studies of Jinjiang River basin showed that the Log-normal function fitted better on multi-timescales (e.g. 1-month, 3-month, 6-month, and 12-month) for streamflow and precipitation, especially streamflow (Wu et al., 2016a). In this paper, three months of precipitation and streamflow records, from 1960 to 2010, were used to calculate the SPI and SSI due to the multi seasonal droughts in this region (Lu and Wang, 2012). The detailed calculation procedures were described in Vicente-Serrano et al. (2011). The SPI/SSI classification of meteorological and hydrological drought levels is shown in Table 2 (Mckee et al., 1993; Wang et al., 2015; Vicente-Serrano et al., 2011).

3.2. Run theory

Run theory is an approach used for the extraction of drought characteristics, including the duration, magnitude and intensity (Chang et al., 2016). Based on the run theory, if drought events over a certain period have a drought index value that remains below a truncation level, the run is considered a negative run (Yevjevich, 1967). The meteorological and hydrological drought characteristics in this study were defined using the SPI/SSI drought levels presented in Table 2 and the run theory as shown in Fig. 2. According to the SPI/SSI drought level classification, three given threshold levels of run theory were set ($SPI/SSI_1 = 1$, $SPI/SSI_2 = 0$, $SPI/SSI_3 = -{-1}$). The period during which droughts appeared with the index SPI/SSI continuously below 0 was defined as the drought duration (D). The accumulated totals of all negative drought index values for the drought duration was used as a measure of drought magnitude (M), and the intensity was usually defined as the average magnitude throughout the duration. When the monthly SPI/SSI values were below 0, the corresponding month was potentially identified as a drought event (e.g. the four drought events shown in Fig. 2, including D_0, D_1, d_0, and d_2). If the duration of a drought event only contained one month where SPI/SSI < −1, this month was regarded as a single drought event (e.g. D_0 with a magnitude M_0). A drought event may contain a few consecutive months with negative SPI/SSI (e.g. duration D_1 and its magnitude M_1). If the duration of a drought event contained two branches, such as d_0 and d_2, and the interruption period d_1 between d_o and d_2 was less than 6 months in which 0 < SPI/SSI < 1, these months were still regarded as a single drought event ($D_2 = d_0 + d_1 + d_2$). The corresponding magnitude was then defined as $M_2 = m_0 + m_1$ (Zhou et al., 2014). Therefore, there were three types of drought events as shown in Fig. 2 (D_0, D_1, and D_2). As drought intensity was the ratio of magnitude to its duration (M/D), only two drought characteristics, the duration D and magnitude M, were needed to represent the characteristics for each drought event in this study.

Table 2
Classification of Standardized Precipitation/Streamflow Index droughts level.

Level	SPI/SSI	Classification
1	SPI/SSI > 0	No drought
2	$-1 \leq$ SPI/SSI < 0	Mild drought
3	$-1.5 \leq$ SPI/SSI < −1	Moderate drought
4	$-2.0 \leq$ SPI/SSI < −1.5	Severe drought
5	SPI/SSI < −2.0	Extreme drought

3.3. Construction of the relationship model

Considering the close relationship between hydrological and meteorological drought, the relationship that hydrological drought responds to meteorological characteristics, including drought duration and magnitude, was constructed. The procedures were given as follows (Fig. 3):

Step 1: Drought characteristics index (basic data): the meteorological and hydrological drought characteristics, which included duration and magnitude, were extracted by run theory (Fig. 2).
Step 2: Construction of model (including linear and non-linear model): the basic form of linear and non-linear function model were given in Fig. 3 (left) (non-linear function model including multiple regression, exponential, power and logarithmic). The cross-validation method was used to construct the relationship between hydrological and meteorological drought characteristics (Shao, 1997; Shao et al., 2011). The main idea of the cross-validation was to divide sample statistics into two sets in which most samples were used for the construction of the model (regarded as a "training set"), and the other samples were used for validation of the model and estimation of the perdition error (regarded as a "test set"). Based on the studies of Shao (1997), the goodness-of-fit for a model was related to the ratio of training and test samples (>2 is optimal). Finally, select a model which has the minimum error between simulated and observed as an excellent model. Therefore, most part of drought characteristics data were used to establish the relationship with which hydrological drought responds to meteorological drought in this paper.

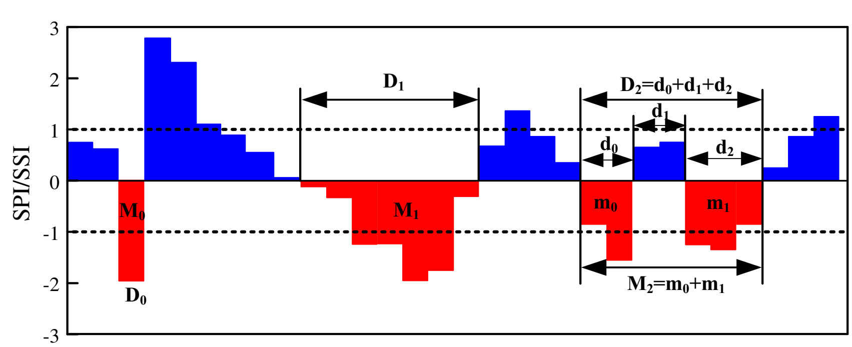

Fig. 2. Definition of drought characteristics including duration and magnitude using the SPI/SSI and run theory.

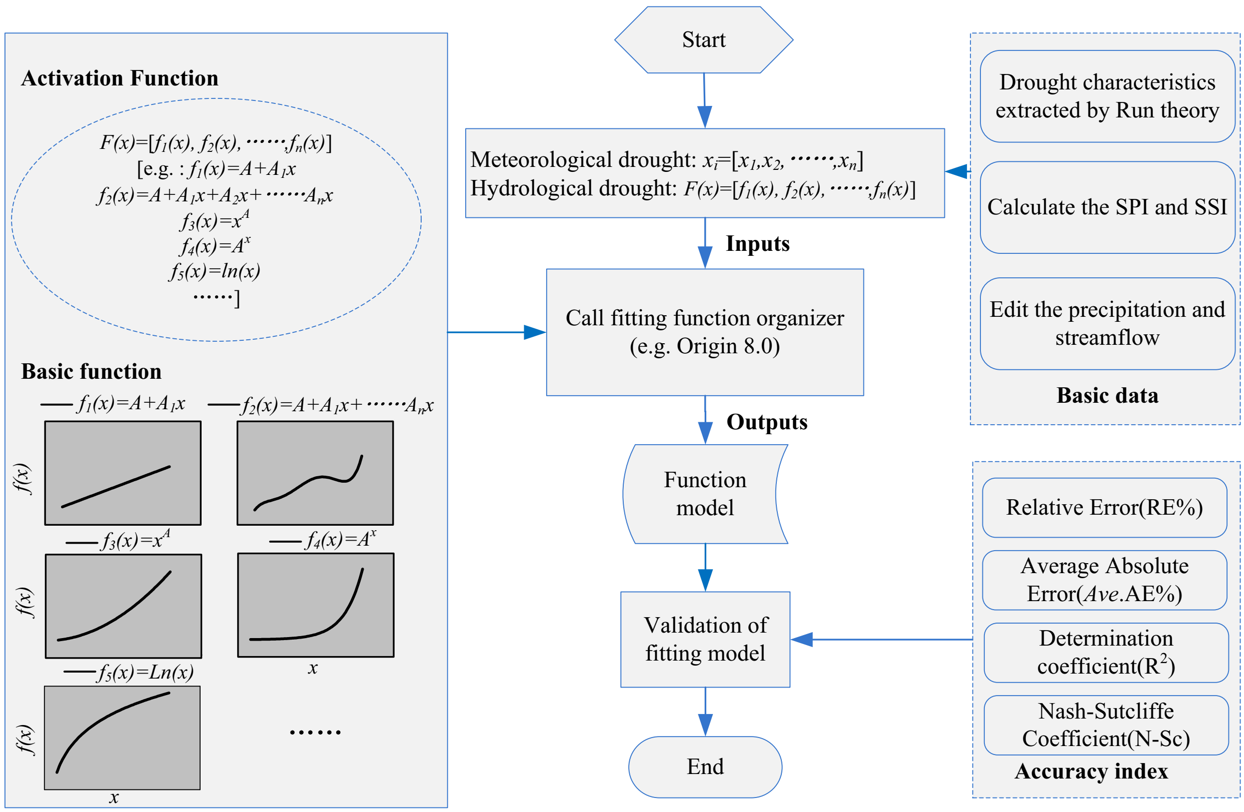

Fig. 3. Procedures of relationship model between hydrological and meteorological droughts characteristics.

Step 3: Model validation: In order to achieve a satisfactory degree of relationship model, the remaining drought characteristics data was used for evaluation. For example, the meteorological drought characteristics (duration and magnitude) were regarded as the input variables, and hydrological drought characteristics, including the duration and magnitude, were the outputted variables (as simulated values). The comparison between the simulated values and the observed values was used to estimate the efficiency of the relationship model. The Relative Error (*RE*), average of absolute error (*Ave.*AE), coefficient of determination (R^2) and Nash-Sutcliffe coefficient (N-Sc) were used to estimate the efficiency of the relationship model. The formulas of *RE*, *Ave.*AE, R^2 and N-Sc are defined in Table 3. We developed the non-linear model between hydrological drought and meteorological drought because a simple linear relationship could not completely consider the complex drought propagation mechanism under the backdrop of the environment.

Table 3
Formulas of the accuracy indices.

Accuracy index	Formula	Optimal value	References
RE(%)	$RE = \left(\frac{S_i - O_i}{O_i}\right) \times 100\%$	0	Legates and McCabe (1999)
Ave. AE(%)	$Ave.\mathrm{AE} = \frac{1}{n} \times \frac{\sum_{i=1}^{n}(\lvert S_i - O_i \rvert)}{\sum_{i=1}^{n} O_i}$	0	Legates and McCabe (1999)
R^2	$R^2 = \frac{\sum_{i=1}^{n}(O_i - \bar{O}) \times \sum_{i=1}^{n}(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2} \times \sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}}$	1	Santhi et al. (2001)
N-Sc	$N - Sc = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$	1	Nash and Sutcliffe (1970)

'O' and 'S' represent observed and simulated values, respectively.

4. Results and discussion

4.1. Identification of meteorological and hydrological drought characteristics

Wu et al. (2016b) have evaluated the relationship between the SSI and historical drought records for the period between 1960 and 2010 and found a strong agreement. The hydrological drought characteristics, both at the Shilong and Anxi stations, and the meteorological characteristics of the whole river basin, including the duration and magnitude, were extracted by the SPI/SSI drought thresholds (Table 2) and run theory (Fig. 2), and were shown in Fig. 4. Table 4 listed the information of hydrological drought and meteorological drought characteristics in details and their comparison with historical drought records ("historical drought records" represent "the drought years in history recorded" and these results come from Fujian Bureau of Statistics (Lu and Wang, 2012)). It was observed that the meteorological drought duration was between 2 and 30 months, and the corresponding magnitudes ranged from 0.62 to 18.89, based on monthly precipitation data at three weather stations. The maximum meteorological drought magnitude and duration were 18.89 and 30 months, respectively. Additionally, the hydrological drought duration was between 1 and 32 months and the magnitude ranged from 0.42 to 23.95 at the Shilong station. The difference between hydrological and meteorological drought characteristics was associated with the watershed condition and human activity. Similarly, the duration of hydrological drought at the Anxi station ranged between 2 and 31 months, with magnitudes from 0.63 to 25.76. The most severe hydrological drought event happened at Shilong station was from September 1966 to May 1968, with a drought duration of 21 months and a magnitude of 23.95. The most severe hydrological drought event happened at Anxi station was from March 2003 to June 2005, with

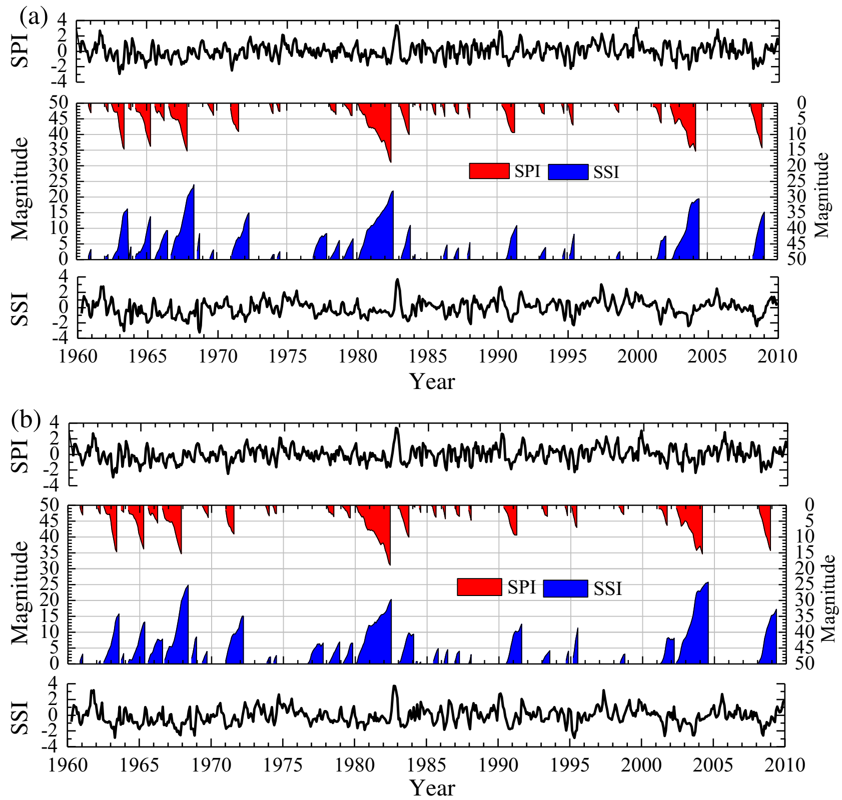

Fig. 4. Characteristics of meteorological drought and hydrological drought during 1960–2010; (a) Shilong station, (b) Anxi station.

Table 4
Identification of meteorological drought and hydrological drought characteristics with run theory and their comparison with historical drought records.

No.	Meteorological drought			Hydrological drought						Historical drought records
				Shilong station			Anxi station			
	Beginning-End	D(month)	M	Beginning-End	D(month)	M	Beginning-End	D(month)	M	
1	1960.11–1961.02	4	3.57	1960.11–1961.01	3	3.23	1960.11–1961.01	3	3.09	√
2	1962.02–1962.04	3	2.72	1962.02–1962.03	2	1.62	1962.03–1962.04	2	0.99	√
3	1962.07–1963.06	12	14.67	1962.08–1963.09	14	16.20	1962.07–1963.08	14	15.77	√
4	1963.10–1963.12	3	2.22	1963.11–1963.12	2	4.06	1963.10–1963.12	3	3.29	×
5	1964.04–1965.05	14	13.77	1964.04–1965.05	14	13.75	1964.04–1965.06	15	13.23	√
6	1965.09–1966.05	9	5.62	1965.09–1966.08	12	9.29	1965.09–1966.09	13	7.83	√
7	1966.09–1968.01	17	15.98	1966.11–1968.07	21	23.95	1966.11–1968.07	21	24.82	√
8	1968.08–1968.11	4	3.98	1968.10–1968.12	3	8.35	1968.10–1969.02	5	8.48	×
9	1969.07–1969.12	6	3.90	1969.09–1969.12	4	3.13	1969.07–1969.11	5	3.95	√
10	1971.03–1971.10	8	9.07	1971.04–1972.07	16	14.93	1971.03–1972.06	16	15.07	×
11	1974.01–1974.04	4	3.31	1974.02–1974.05	4	1.61	1974.02–1974.05	4	2.21	×
12	1974.07–1974.10	4	2.65	1974.08–1974.10	3	2.54	1974.08–1974.10	3	2.68	√
13	1977.01–1977.10	10	6.77	1977.03–1978.03	13	8.31	1977.01–1978.02	14	6.60	√
14	1978.05–1978.11	7	3.60	1978.06–1979.02	9	6.10	1978.07–1979.04	10	6.97	×
15	1979.06–1980.01	8	4.01	1979.06–1980.02	9	6.66	1979.07–1980.03	9	6.55	√
16	1980.06–1982.11	30	18.89	1980.06–983.01	32	21.95	1980.06–1982.12	31	20.35	√
17	1983.07–1984.03	9	10.03	1983.08–1984.04	9	10.96	1983.07–1984.07	13	9.39	√
18	1984.07–1984.08	2	0.62	1984.07–1984.08	2	1.60	1984.09–1984.10	2	0.79	√
19	1984.12–1985.01	2	2.28	1985.01	1	0.42	1984.12–1985.01	2	0.63	√
20	1985.10–1986.02	5	3.77	1985.11–1986.03	5	4.65	1985.12–1986.04	5	4.83	√
21	1986.08–1986.10	3	4.26	1986.09–1986.12	4	4.65	1986.09–1986.11	3	4.49	×
22	1987.06–1987.10	5	3.52	1987.06–1987.10	5	3.73	1987.06–1987.10	5	4.00	√
23	1988.06–1988.08	3	4.74	1988.06–1988.08	3	5.42	1988.06–1988.08	3	2.95	√
24	1990.12–1991.11	10	9.37	1991.03–1992.01	11	10.90	1991.02–1992.03	14	12.55	√
25	1993.09–1994.01	5	3.52	1993.09–1994.02	6	3.87	1993.09–1994.03	7	4.19	√
26	1995.04–1995.06	3	3.26	1995.05–1995.07	3	3.52	1995.05–1995.07	3	4.02	√
27	1995.10–1996.02	5	6.99	1995.11–1996.03	5	8.10	1995.11–1996.03	5	11.33	√
28	1999.02–1999.06	5	2.97	1999.04–1999.07	4	2.53	1999.03–1999.07	5	3.12	×
29	2001.12–2002.07	8	6.31	2002.03–2002.11	9	7.51	2002.01–2003.01	13	8.10	√
30	2003.03–2005.01	23	15.32	2003.04–2005.04	25	19.47	2003.03–2005.06	28	25.76	√
31	2009.01–2009.11	11	14.27	2009.03–2010.01	11	15.14	2009.01–2010.04	15	17.22	√

Note: "√" means the drought event is recorded and "×" is not.

a drought duration of 28 months and a magnitude of 25.76. In general, droughts in Jinjiang River basin were frequent and serious, especially before 1985.

4.2. Relationship model at the Anxi station

Relationships have been developed between the meteorological drought duration (or magnitude) and hydrological drought duration (or magnitude). These can be used in the long-term forecasting of hydrological drought duration or magnitude knowing the ongoing meteorological drought characteristics. According to the procedures shown in Fig. 3, three sample sets of drought characteristics statistics presented in Table 4 were used to establish the relationship with which hydrological drought responds to meteorological drought through cross-validation method. The first set of sample statistics was from No.1 to No.22, which was then further validated by using No.23 to No.31 (called models-1). The second set of sample statistics was from No.6 to No.26, which was then further validated by using remaining sample statistics (from No.1 to No.5 and from No.27 to No.31) (called models-2). The third set of sample statistics was from No.11 to No.31, which was then further validated by using No.1 to No.10 (called models-3).

4.2.1. Model construction

Using the fitting function from the statistical software Origin 8.0, the experiment suggested that the non-linear function model with three parameters can be better used than other parameters of function model to describe the relationship between hydrological and meteorological drought characteristics. In addition, the linear model of relationship between hydrological and meteorological drought characteristics was also established, which was used to be compared with the non-linear model, and these models were given in Table 5.

The range of R^2 fits for the duration were from 0.9088 to 0.9790, and for magnitude were from 0.8418 to 0.8780, respectively (passing the 0.05 significance test), and were shown in Fig. 5. Obviously, a close relationship between hydrological and meteorological drought was observed: with the increasing of the duration and magnitude of meteorological drought, the duration and magnitude of hydrological drought also increased. This was a significant realization with respect to hydrological drought early warning, based on meteorological drought.

4.2.2. Model validation

The efficiency of these relationship models were evaluated by using the remaining sample statistics in which the models-1 were evaluated by using the drought events from No.23 to No.31; the models-2 were evaluated by using the drought events from No.1 to No.5 and No.27 to No.31; and the models-3 were evaluated by using the drought events from No.1 to No.10 (shown in Table 4). The remaining sample statistics in Table 4 were not used in the processes of the model's construction. The *RE* values, between the simulated and observed values, were presented in Fig. 6. Clearly, the *RE* values for most of hydrological drought events of the models-1 were less than models-2 and models-3. In order to compare the goodness-of-fit of observed with the simulated values of hydrological drought events, the accuracy indices (*Ave*.AE, R^2 and N-Sc) were calculated and listed in Table 6. Obviously, all average measures of models-1 were better than that of models-2 and models-3. Additionally, the goodness-of-fit of $f_5(x)$ (logarithmic function model) was better than other functions in models-1, especially in terms of duration. And with the exception of the magnitude of the No.30 drought event (2003), the *RE* values for all hydrological drought events were less than 30% (Fig. 6). As the simulated values satisfied the observed values by the logarithmic function model (fitting functions (9) and (10) in Table 5), this model was thought to be a reliable representation of the relationship between hydrological and meteorological droughts.

4.3. Relationship at the Shilong station

4.3.1. Drought characteristics during periods of natural- and reservoir-influence

Previous research used the DCRT (Difference Curve-Rank test) approach to assess the abrupt points in the annual streamflow series, from 1960 to 2010, at the Shilong station and under the background of the regulation of the Shanmei reservoir. These studies found that there was only one significant change-point, in 1982, which was consistent with the completion of the Shanmei reservoir dam protection and impoundment expansion projects, from 1979 to 1982 (Wu et al., 2017). Therefore, 1982 was taken as the breakpoint between the period of natural-influence (1960–1982) and reservoir-influence (1983–2010). The distribution of hydrological drought characteristics in different periods was checked by using a box-plot method. And the distribution of hydrological characteristics from 1960 to 2010 at Anxi station was also checked. At the same time, the distribution of meteorological drought charac-

Table 5
Relationships of hydrological drought and meteorological drought at Anxi station.

Type	Fitting equation			
	Duration	R^2	Magnitude	R^2
Models-1	(1) $f_1(x) = 0.44514 + 1.11983x$	0.9121	(2) $f_1(x) = 0.04981 + 1.8626x$	0.8544
	(3) $f_2(x) = -2.07087 + 1.70846x - 0.02054x^2$	0.9387	(4) $f_2(x) = -0.6562 + 1.43258x - 0.01311x^2$	0.8522
	(5) $f_3(x) = -6.96727 + 5.11708x^{0.59018}$	0.9387	(6) $f_3(x) = -1.32909 + 1.93149x^{0.84677}$	0.8522
	(7) $f_4(x) = e^{3.94197 - \frac{17.83001}{x+3.11767}}$	0.9395	(8) $f_4(x) = e^{3.91366 - \frac{19.96321}{x+4.47916}}$	0.8497
	(9) $f_5(x) = -76.07725 + 28.40263\ln(x + 13.05878)$	0.9402	(10) $f_5(x) = -181.01902 + 51.08154\ln(x + 33.8271)$	0.8544
Models-2	(11) $f_1(x) = 0.71549 + 1.12321x$	0.9088	(12) $f_1(x) = -0.22777 + 1.28407x$	0.8418
	(13) $f_2(x) = -2.59171 + 1.90151x - 0.02623x^2$	0.9507	(14) $f_2(x) = -1.29908 + 1.63575x - 0.01835x^2$	0.8576
	(15) $f_3(x) = -8.28159 + 6.11392x^{0.55141}$	0.9451	(16) $f_3(x) = -1.48842 + 1.93136x^{0.87171}$	0.8563
	(17) $f_4(x) = e^{3.90508 - \frac{15.59739}{x+2.38471}}$	0.9548	(18) $f_4(x) = e^{4.00214 - \frac{19.95051}{x+4.18325}}$	0.8606
	(19) $f_5(x) = -65.36371 + 26.09689\ln(x + 10.65746)$	0.9508	(20) $f_5(x) = -202.96249 + 56.74472\ln(x + 35.02028)$	0.8580
Models-3	(21) $f_1(x) = 0.44297 + 1.14011x$	0.9492	(22) $f_1(x) = -0.49903 + 1.29702x$	0.8780
	(23) $f_2(x) = -2.86788 + 1.92508x - 0.0262x^2$	0.9728	(24) $f_2(x) = -1.33432 + 1.57518x - 0.01476x^2$	0.8721
	(25) $f_3(x) = -7.16595 + 5.15557x^{0.59934}$	0.9749	(26) $f_3(x) = -1.29953 + 1.70163x^{0.91385}$	0.8721
	(27) $f_4(x) = e^{3.95911 - \frac{16.54446}{x+2.51366}}$	0.9760	(28) $f_4(x) = e^{4.05038 - \frac{21.1794}{x+4.3364}}$	0.8734
	(29) $f_5(x) = -79.90137 + 29.77818\ln(x + 13.03749)$	0.9790	(30) $f_5(x) = -289.12613 + 74.30937\ln(x + 48.16858)$	0.8766

where "*f(x)*" and "x" respectively represent the hydrological and meteorological drought durations or magnitudes.

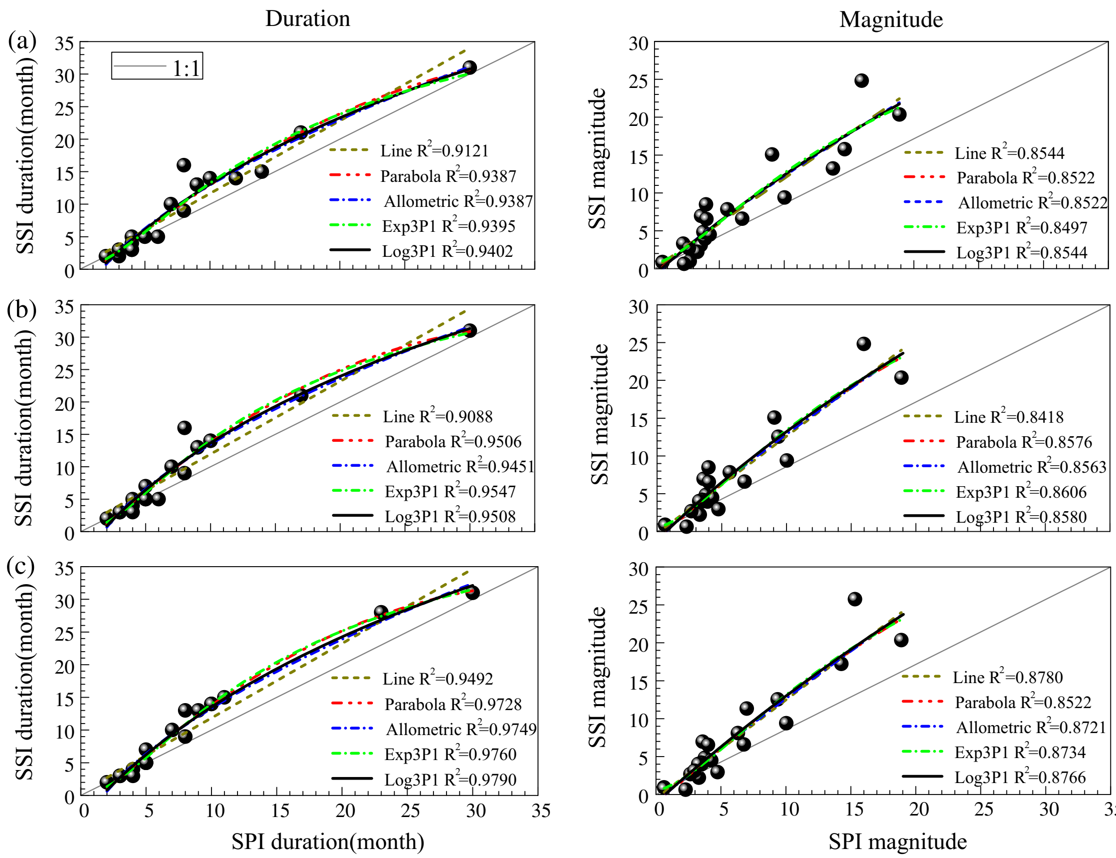

Fig. 5. Relationship with which hydrological drought responds to meteorological drought at Anxi station; (a) models-1, (b) models-2, (c) models-3.

teristics was analyzed together with that of the hydrological drought. Fig. 7(a) and (b) illustrate box-plots of the distribution of hydrological and meteorological drought characteristics, extracted using Table 4, for periods of natural-, reservoir-influence and 1960–2010, recorded at the Shilong and the period from 1960 to 2010 at Anxi station, respectively. It was apparent that the duration and magnitude of hydrological drought during the reservoir-influenced periods were lower than those during the naturally-influenced periods at Shilong station, especially the drought duration. However, the meteorological drought characteristics changed slightly from one period to the other. And the duration and magnitude of hydrological drought during 1960–2010 at Anxi station was similar to natural-influenced period of Shilong station.

4.3.2. Relationship between hydrological and meteorological droughts during periods of natural- and reservoir-influence

It has been established that the nature with which hydrological drought responds to meteorological drought for naturally-influenced (1960–1982) and reservoir-influenced (1983–2010) periods depended on the three parameters of the logarithmic function model (Fig. 8). The model results of two periods were summarized in Table 7. The R^2 fit was larger than 0.9326 and larger than 0.8794 for the duration and magnitude, respectively, which suggested that there was a close relationship between hydrological and meteorological drought for both periods. The R^2 fit during the reservoir-influenced period was better than during naturally-influenced periods ($0.9871 > 0.9326$, or $0.9661 > 0.8794$). The hydrological drought duration or magnitude in the reservoir-influenced period became substantially shorter or smaller than in the natural-influenced period, under similar meteorological drought partner.

4.4. Discussion

4.4.1. Threshold within which hydrological drought responds to meteorological drought

After further analysis of the fitting functions (9) and (10) for Anxi station, when the hydrological drought duration and magnitude were equal to 0, the values of the meteorological drought duration and magnitude were equal to 1.5048 and 0.7685, respectively (Table 8). Namely, from the perspective of drought duration, when the meteorological drought has lasted for 1.5048 months, the hydrological drought started to occur at the Anxi station and the magnitude of the meteorological drought would be at least 0.7685. These two values (1.5048 and 0.7682) can be defined as the threshold above which hydrological drought responded to meteorological drought. In other words, these two values can also be defined as the threshold above which meteorological drought developed into hydrological drought. Similarly, further analysis of the fitting functions (31) to (34) can also be used to obtain the threshold that hydrological drought responded to meteorological drought during both naturally-influenced and reservoir-influenced periods at the Shilong station (the third column in Table 8). When the meteorological drought lasted for a minimum of 2.0573 months and had a corresponding magnitude of 1.1963 during naturally-influenced periods, hydrological drought would occur, and when the meteorological drought lasted for a minimum of 0.4598 months and had a corresponding magnitude of 0.6341 during reservoir-influenced periods, hydrological drought would also occur.

Edossa et al. (2010) and Li et al. (2016) previously used the linear model in order to understand the relationships between hydrological and meteorological drought characteristics. To some extent the linear model can be used to reflect this relationship; however,

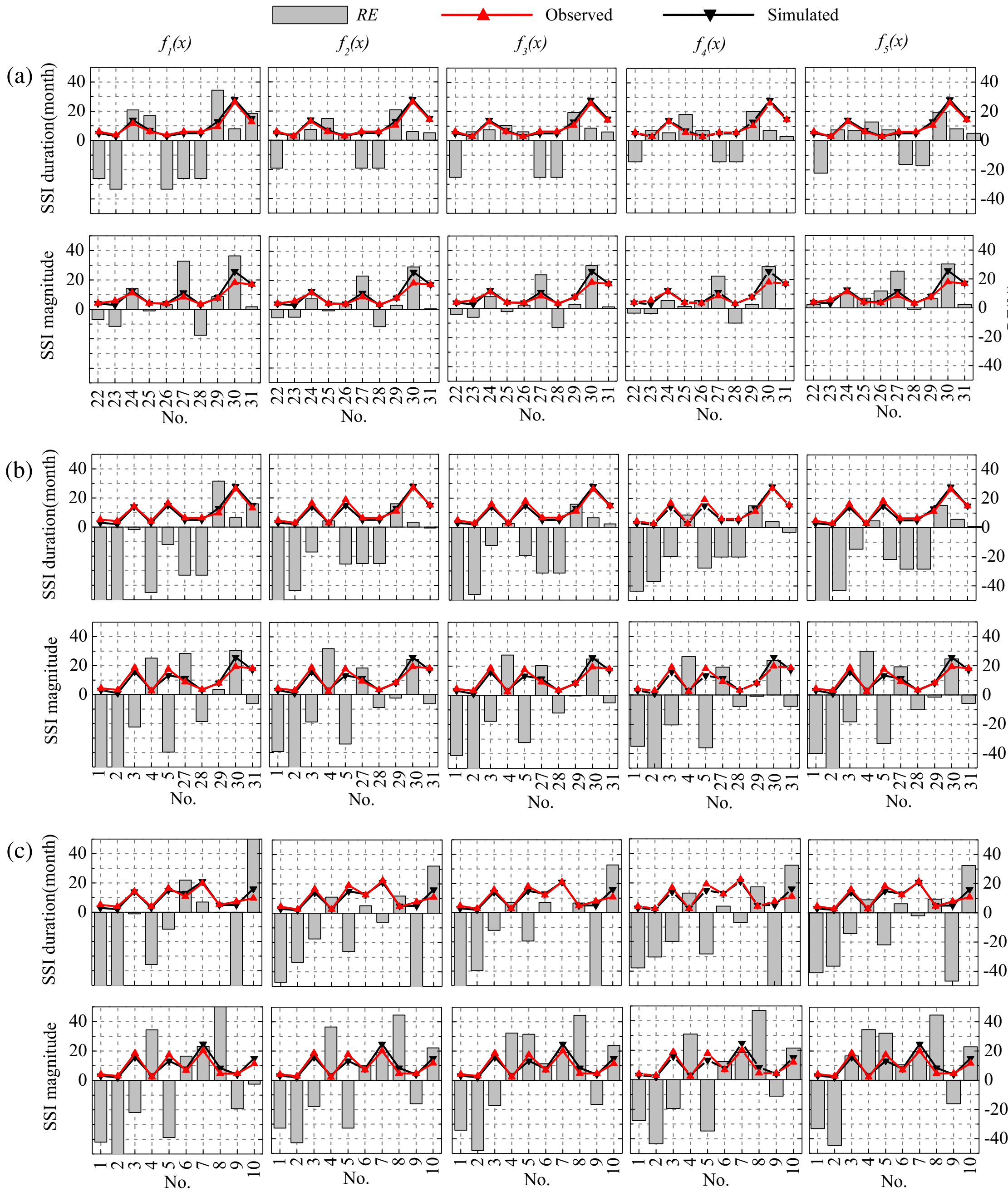

Fig. 6. Comparison of simulated and observed hydrological drought characteristics at Anxi station; (a) models-1, (b) models-2, (c) models-3.

this simple linear model is unlikely to sufficiently reflect the environmental influences on the relationship. Furthermore, they did not propose the concept of a threshold at which hydrological drought responded to meteorological drought. In fact when the hydrological drought duration and magnitude were equal to 0, the values of the meteorological drought duration and magnitude were equal to negative values for linear functions (e.g. the fitting functions of (1) and (2) in Table 5). We proposed non-linear models separately for periods with and without dam operation influence and improved the representation of the relationships.

In addition, Lopez-Moreno et al. (2013) and Lorenzo-Lacruz et al. (2013b) evaluated the time taken for hydrological drought to respond to meteorological drought using the Pearson correlation analysis method. However, the response severity was often overlooked in these studies, and the relationship with which hydrological drought responded to meteorological drought was not identified. Our recent study (Wu et al., 2016a) made use of Pearson correlation analysis method to analyze the response of hydrological drought to meteorological drought under the influence of Shanmei reservoir at Shilong station, and the results showed that the response time of hydrological drought to meteorological drought extended to certain extent. It illustrated how the evolution of hydrological drought responded to meteorological drought under impact of Shanmei reservoir, through analyses of trend change, decadal frequency change and periodic change. However, a clear relationship of hydrological drought and meteorological drought was not sought and provided. The new results as shown in Figs. 5 and 8 and the corresponding fitting function models have been comprehensively analyzed in order to understand the relationship between hydrological and meteorological drought. The concept of

Table 6
Statistics of accuracy indices.

Type		Duration			Magnitude		
		*Ave.*AE(%)	R^2	N-Sc	*Ave.* AE (%)	R^2	N-Sc
Models-1	$f_1(x)$	19.5784	0.9653	0.9856	19.0905	0.9285	0.9456
	$f_2(x)$	13.3120	0.9828	0.9897	18.2957	0.9247	0.9474
	$f_3(x)$	13.9743	0.9820	0.9872	18.9081	0.9256	0.9462
	$f_4(x)$	17.6892	0.9831	0.9902	18.3739	0.9229	0.9489
	$f_5(x)$	12.0341	0.9833	0.9885	17.5244	0.9249	0.9493
	Average	**15.3176**	**0.9793**	**0.9882**	**18.4385**	**0.9253**	**0.9475**
Models-2	$f_1(x)$	32.1706	0.9605	0.9809	41.1089	0.8601	0.9511
	$f_2(x)$	21.3419	0.9585	0.9814	38.9243	0.8589	0.9507
	$f_3(x)$	22.9832	0.9624	0.9834	39.8401	0.8604	0.9512
	$f_4(x)$	22.0070	0.9542	0.9546	38.4188	0.8571	0.8497
	$f_5(x)$	19.9754	0.9610	0.9829	39.2253	0.8597	0.9510
	Average	**23.6956**	**0.9593**	**0.9766**	**39.5035**	**0.8592**	**0.9307**
Models-3	$f_1(x)$	30.8198	0.8584	0.9545	25.6157	0.8430	0.9463
	$f_2(x)$	24.5439	0.8743	0.9566	25.0364	0.8436	0.9465
	$f_3(x)$	23.8592	0.8794	0.9629	25.4676	0.8443	0.9467
	$f_4(x)$	23.9940	0.8783	0.9012	24.3085	0.8397	0.9447
	$f_5(x)$	23.9443	0.9906	0.9615	25.1758	0.8444	0.9467
	Average	**25.4322**	**0.8962**	**0.9473**	**25.1208**	**0.8430**	**0.9462**

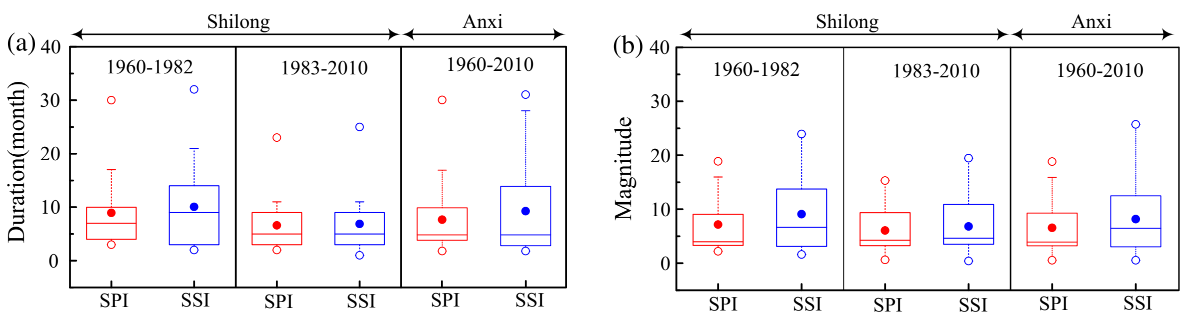

Fig. 7. Box-plots of drought characteristics for hydrological and meteorological events at different periods; (a) duration, (b) magnitude.

difference between the "relationship with which hydrological drought responds to meteorological drought" and "threshold with which hydrological drought responds to meteorological drought" was also made clear.

4.4.2. Impact on hydrological drought by Shanmei reservoir

The above results indicated that a decrease in hydrological drought duration and magnitude was associated with the regulation of the Shanmei reservoir. Fig. 9 showed the monthly inflows and outflows at the Shanmei reservoir, along with the monthly discharge at the Shilong station for periods of both drought and no drought, from 2001 to 2010 (a drought period was defined as drought events No. 29–31, otherwise defined as a period with no droughts). Furthermore, comparisons of average discharges of consecutive 90 days among dam inflow, outflow and discharge of Shilong station during the drought events from No.29 to No.31 (Table 3) were shown in Fig. 10.

It is apparent that when the discharge was high during a period with no droughts at the Shilong station, the inflow was higher than the outflow at the Shanmei reservoir (Fig. 9). Conversely, when the discharge was low during periods of drought at the Shilong station, the inflow was lower than the outflow, indicating that reservoir management tended to store water during periods of no drought and release water during droughts. The dam inflow was not lower than the outflow for all days during a drought event, but the dam outflow was manually increased for some days, making the outflow becoming gradually higher than the inflow along with occurrence of the drought (Fig. 10). In other words, this kind of reservoir managements helped to reduce the duration and magnitude of hydrological drought downstream of the reservoir.

The threshold of drought duration at Shilong was reduced from 2.06 to 0.46 months from the natural-influence period to reservoir-influence period (Table 8), i.e. the processes of drought propagation from meteorological to hydrological droughts were shortened. This threshold reduction was numerically caused by the change in duration (or magnitude) relationship between meteorological and hydrological droughts. The thresholds were derived simply from the relationship of hydrological drought index (e.g. duration) and meteorological drought index (e.g. duration), as defined above. Because the relationship itself changed between two periods of natural-influence and reservoir-influence, the derived thresholds changed too accordingly. As a result, the thresholds in the reservoir-influence period were smaller than the natural-influence period. A possible physically-based explanation of the shortened propagation was tried: during reservoir operation the river inflows were naturally stored and delayed in the reservoir, and the operation (storing and releasing water) did not usually apply to the initial low flows for a drought event. It mainly regulated or changed the severer low flows. Therefore, a small meteorological drought in the natural-influence condition, which could trigger a hydrological drought, would be at least as severe as those close to the thresholds (2.06 month duration and 1.2 magnitude); however, due to the existence of the reservoir and its water storage, a smaller meteorological drought (such as those thresholds of 0.46 duration and 0.63 magnitude) could trigger a hydrological drought during the reservoir-influence period.

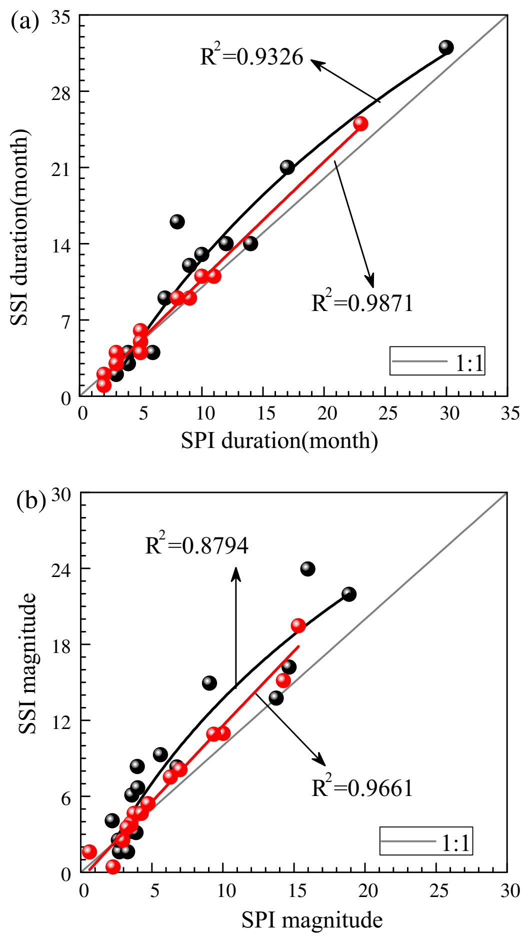

Fig. 8. Relationship with which hydrological drought responds to meteorological at Shilong station; (a) duration, (b) magnitude. Black and red lines represent natural-influenced (1960–1982) and reservoir-influenced period (1983–2010), respectively.

With respect to the changes of hydrological drought characteristics under the influence of large reservoirs, Wen et al. (2011), Zhang et al. (2013) and Leitman et al. (2016) found that if the reservoirs were reasonably managed (e.g. increasing water availability during dry seasons by reducing water availability during wet seasons), the hydrological drought duration and its severity downstream could be shortened and alleviated efficiently. These results are consistent with our research. However, these studies did not indicate the changes of threshold within which hydrological drought started to respond to meteorological drought under the influence of reservoirs. Additionally, it is worth noting that different reservoir operations (e.g. decreasing the streamflow in the river) may potentially extend the hydrological drought duration and strengthen the drought magnitude downstream. Lopez-Moreno et al. (2009) and Al-Faraj and Scholz (2015) took the trans-boundary rivers (Iraq and Iran, Spain and Portugal) as an example to come to this conclusion. Meanwhile, they also pointed out that upstream countries used the stored water within reservoirs during drought periods in order to meet domestic needs (e.g. irrigation, industrial and public supply water use), which potentially aggravated issues with water withdrawal in downstream countries, especially during periods of drought. In addition, Lopez-Moreno et al. (2013) and Lorenzo-Lacruz et al. (2013b) pointed out that the response time of hydrological drought to meteorological drought was extended by reservoir regulation of upstream.

Although the SPI was used as a meteorological drought index in our and others' researches, it has some limitations. For example, it is sensitive to the quantity and reliability of the data used to fit the distributions, probably 30–50 years are needed; it does not consider the intensity of precipitation and its potential impacts on runoff, streamflow and water availability within the basin system. These limitations are interesting topics which have not been considered in the present study, and should be addressed in future researches.

Table 8
SPI threshold for hydrological drought response to meteorological drought at Anxi station, and the SPI threshold in different periods at Shilong station in which the period of natural-influenced (1960–1982) and reservoir-influenced (1983–2010).

Type	Anxi station	Shilong station	
		Natural-influenced period(1960–1982)	Reservoir-influenced period(1983–2010)
Duration	1.5048	2.0573	0.4598
Magnitude	0.7685	1.1963	0.6341

5. Conclusions

There is a clear and regular relationship with which hydrological drought responds to meteorological drought. This relationship was better understood by establishing the non-linear relationship between hydrological drought and meteorological characteristics, from which the threshold with which hydrological drought responded to meteorological drought was obtained.

The regulation of reservoirs has significantly modified hydrological drought duration and magnitude, which, in turn, altered the relationship between hydrological and meteorological droughts and the thresholds. Both the hydrological drought duration and magnitude were decreased at the Shilong station due to operational management of the Shanmei reservoir, which increased water availability during periods of drought by reducing water availability in periods with no droughts. This relationship change under reservoir operation also altered the threshold with which hydrological drought responded to meteorological drought, which provided additional information for policy-makers to take an appropriate reservoir management in the drought periods.

The logarithmic function model with three parameters can be used to describe the relationship between hydrological and meteorological droughts. Its rationality and universality need to be further discussed because physical characteristics and human activities interact differently with droughts in different basins.

Table 7
Relationships of hydrological drought (SSI) and meteorological drought (SPI) at Shilong for the period of natural-influenced (1960–1982) and reservoir-influenced period (1983–2010).

	Natural-influenced period(1960–1982)	Reservoir-influenced period(1983–2010)
Duration(month)	(31) $f_5(x) = -86.25209 + 31.12234\ln(x + 13.92348)$ $R^2 = 0.9326$	(32) $f_5(x) = -1856.3431 + 327.81168\ln(x + 287.50377)$ $R^2 = 0.9871$
magnitude	(33) $f_5(x) = -47.58437 + 21.04394\ln(x + 8.39824)$ $R^2 = 0.8794$	(34) $f_5(x) = -1631.10999 + 297.43264\ln(x + 240.1653)$ $R^2 = 0.9661$

where "*f(x)*" and "x" respectively represent the hydrological and meteorological drought durations or magnitudes.

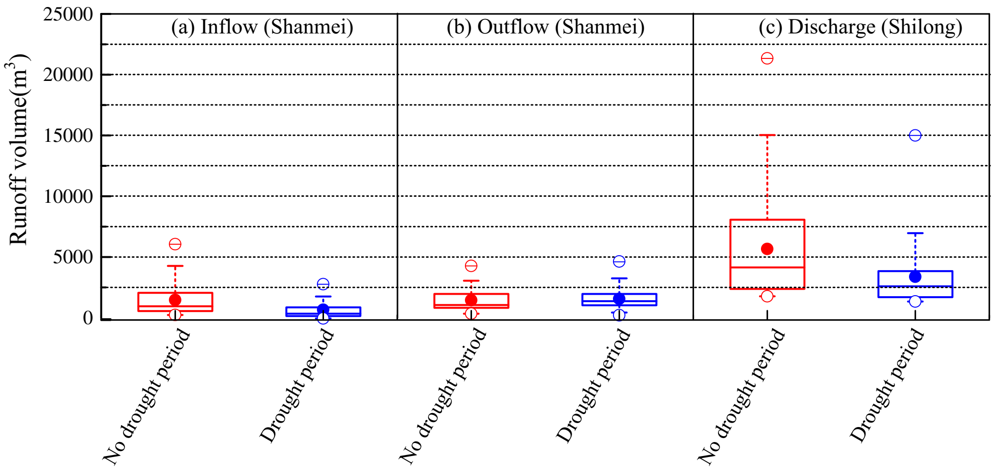

Fig. 9. Monthly inflows (a), outflows (b) variable at Shanmei reservoir and monthly runoff at Shilong station (c) for drought and no drought period during 2001–2010.

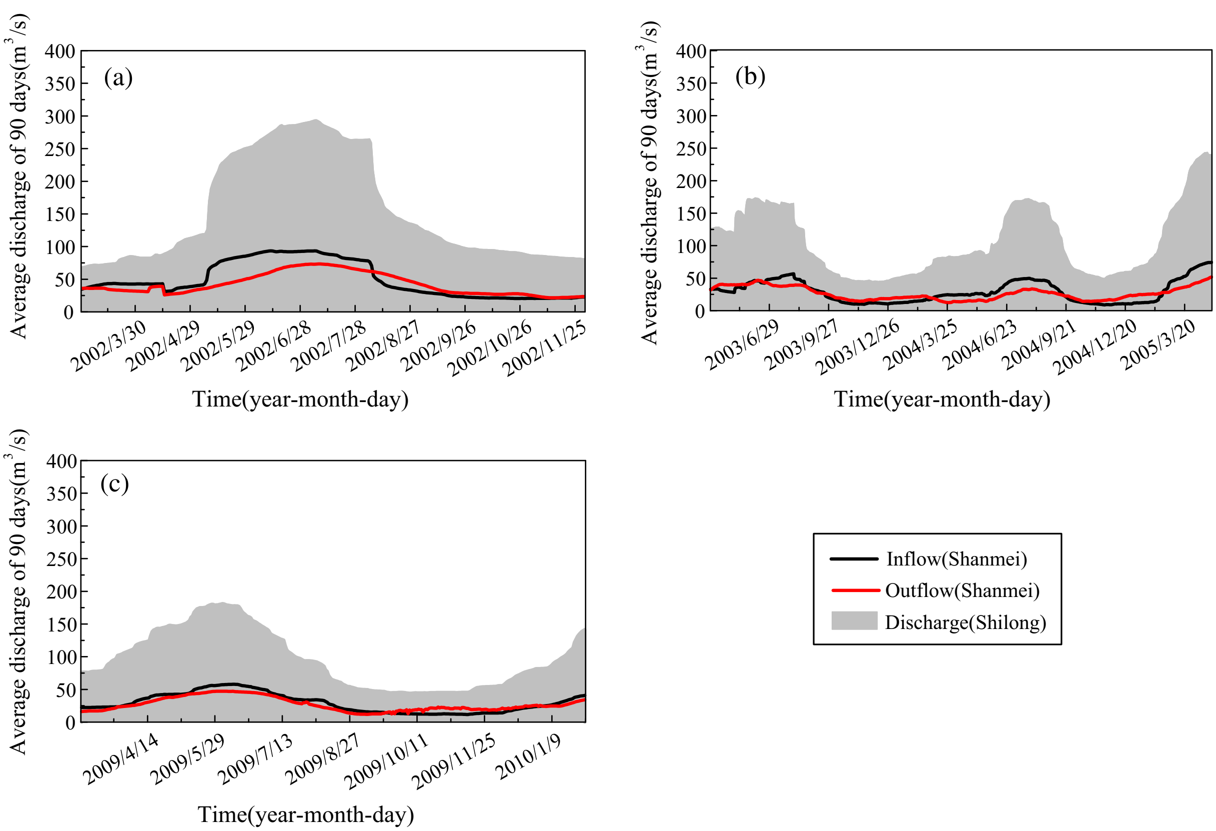

Fig. 10. Comparison of average discharge of consecutive 90 days between inflow, outflow and Shilong station during the drought events No.29–31.

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