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Research papers

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).