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Research papers

Copula-based probability of concurrent hydrological drought in the Poyang lake-catchment-river system (China) from 1960 to 2013

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ABSTRACT

Investigation of concurrent hydrological drought events is helpful for understanding the inherent mechanism of hydrological extremes and designing corresponding adaptation strategy. This study investigates concurrent hydrological drought in the Poyang lake-catchment-river system from 1960 to 2013 based on copula functions. The standard water level index (SWI) and the standard runoff index (SRI) are employed to identify hydrological drought in the lake-catchment-river system. The appropriate marginal distributions and copulas are selected by the corrected Akaike Information Criterion and Bayesian copulas selection method. The probability of hydrological drought in Poyang Lake in any given year is 16.6% (return period of 6 years), and droughts occurred six times from 2003 to 2013. Additionally, the joint probability of concurrent drought events between the lake and catchment is 10.1% (return period of 9.9 years). Since 2003, concurrent drought has intensified in spring due to frequent hydrological drought in the catchment. The joint probability of concurrent drought between the lake and the Yangtze River is 11.5% (return period of 8.7 years). This simultaneous occurrence intensified in spring, summer and autumn from 2003 to 2013 due to the weakened blocking effect of the Yangtze River. Notably, although the lake drought intensified in winter during the past decade, hydrological drought in the catchment and the Yangtze River did not intensify simultaneously. Thus, this winter intensification might be caused by human activities in the lake region. The results of this study demonstrate that the Poyang lake-catchment-river system has been drying since 2003 based on a statistical approach. An adaptation strategy should be urgently established to mitigate the worsening situation in the Poyang lake-catchment-river system.

1. Introduction

Drought is the below-average water storage (e.g., rainfall, runoff and soil moisture) for a prolonged period in a give region (Akyuz et al., 2012). There are agriculture drought, meteorological drought and hydrological drought, in which hydrological drought is paid more attention for it relates to human activities directly (Long et al., 2013; Liu et al., 2017). Under the climate changing, hydrological drought events are intensified significantly all over the world, which would impact on agriculture, ecosystem and local socioeconomic development (Vandenberghe et al., 2011; She et al., 2013). Hydrological drought events are multidimensional hazardous phenomena, characterized by severity, duration, peak values and areal extent (Tsakiris et al., 2016; Xu et al., 2015). Investigation of the individual drought characterization cannot reveal the serious consequence of drought in reality (Genest and Favre, 2007; Liu et al., 2015).

Flexible copula function is one of the most useful methods used in multivariate frequency studies of hydrological droughts (e.g., Guerfi et al., 2016; Salvadori and Michele, 2015; Zhang and Singh, 2007). For a theoretical introduction to copulas, books of Nelsen (2006), Joe (2014) and Durante and Sempi (2015) can be referred. For a practical/engineering approach, articles of Genest and Favre (2007), Salvadori and Michele (2007) and Salvadori et al. (2007) can be referred. Generally, previous studies usually investigated the joint probabilities of different characterizations for a single hydrological drought event (Bargaoui and Bardossy, 2015; Renard and Lang, 2007; Zhang et al., 2015c). For example, Zhang et al. (2015c) studied the joint probability of drought duration and severity in the East River basin of China using a Plackett copula. Tsakiris et al. (2016) investigated the probability distributions of drought severity and areal extent using 2D Archimedean copulas in Greece. The advantage of copulas lies in their simple closed form, which can address a combination of margins to yield

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margin-free characteristics; thus, the method is easy to implement in hydrological practice (Genest and Favre, 2007; Kojadinovic and Yan, 2010; Vandenberghe et al., 2011). In addition, some researchers have attempted to study the joint distributions of different hydrometeorological variables at different locations (Liu et al., 2015; Rana et al., 2016). Liu et al. (2015) investigated the probability of concurrent meteorological drought events between the water source and destination regions of China's water diversion project from 1960 to 2013. Rana et al. (2016) studied the joint distribution of precipitation and temperature using multi-model ensemble data from the Columbia River Basin.

Poyang Lake, the largest freshwater lake in China, is one of few lakes that remains naturally connected to the Yangtze River (Guo et al., 2012; Hu et al., 2007). The lake receives water inflows from its catchment and discharges to the Yangtze River at Hukou (the junction of the Yangtze River and Poyang Lake) at the north end of the lake. The lake, its catchment and the Yangtze River form a natural lake-catchment-river system (Yang et al., 2016). The system comprises important ecological functions, such as serving as an important international wetland and the largest conservation area for migratory birds in the world (Feng et al., 2012a,b; Han et al., 2015; Shankman et al., 2006). Due to environmental changes, the system has experienced frequent hydrological drought events in past decades. These events influence the interactions between the lake and the Yangtze River, the ecological equilibrium of the lake and regional water resource management (Combes et al., 2013; Li et al., 2015a,b; Liu and Wu, 2016).

A number of studies have focused on the lake's low water levels, shrinking lake areas, hydrological droughts and floods, and other occurrences, in the Poyang lake-catchment-river system, especially after the impoundment of Three Gorges Reservoir (TGR) in 2003 (Mei et al., 2015; Yang et al., 2006; Yang et al., 2016). For example, Feng et al. (2012a) used multisource satellite data over a 12-year period to investigate the Poyang Lake drought in early 2011 and concluded that the drought was caused by significantly low precipitation. Liu and Wu (2016) quantified lake drought based on water budget analysis combined with remote sensing products and found that lake drought in the past decade was due to decreased inflow, increased outflow, reduced precipitation and increased evapotranspiration in the lake region. These results are helpful for understanding the dynamic responses of the system to hydrological extremes.

Moreover, some studies have attempted to investigate multivariate characterizations of hydrological droughts in the Poyang catchment (e.g., Chen et al., 2013; Liang et al., 2012; Sun et al., 2011). Sun et al. (2011) studied the joint probability behaviors of high flow and low flow in the major tributaries of the Poyang catchment. Chen et al. (2013) investigated the joint probability behaviors of drought duration and drought severity in the Poyang catchment using eight copula functions. However, the Poyang catchment, the Yangtze River and the lake form a complex system, the individual studies in each part can't reveal the inner connection of drought events. This study treats the lake, its catchment and the Yangtze River as a system, which is helpful for better understanding the intrinsic mechanism of extremes occurrences in Poyang Lake and the interactions between the lake and Yangtze River. Moreover, the standardized water level and runoff indexes are used for drought comparison. The indexes reflect water surplus and deficit directly in Poyang lake-catchment-river system with a consideration of human influence. Such a study is particularly important due to the increasing risks of hydrological extremes in Poyang Lake and the Yangtze River.

The objectives of this study are as follows: (1) analyze the probability of hydrological drought in Poyang Lake, its catchment and the Yangtze River, individually; (2) investigate the joint probability of concurrent drought in the lake-catchment-river system using copulas; and (3) discuss possible reasons for the intensification of hydrological drought during the past decade. The results improve the understanding of hydrological extremes in the Poyang lake-catchment-river system and are helpful for the water resource management of the lake and Yangtze River.

2. Study area and data

Poyang Lake (28.4° to 29.8° N, 115.8° to 116.7° E), which is located in the middle reaches of the Yangtze River, is the largest freshwater lake in China (Fig. 1). The seasonal water area fluctuates dramatically from approximately 3000 km^2 in wet seasons to less than 1000 km^2 in dry seasons (Wu and Liu, 2015). The lake receives inflows from the Poyang catchment, which encompasses a drainage area of 162200 km^2 and comprises 9% of the Yangtze River Basin. The lake exchanges water with the Yangtze River via a narrow channel at the Hukou outlet. The flood season of the catchment is from April to June, while the flood season of the Yangtze River is from July to September. The shift in flood seasons between the catchment and the Yangtze River turns Poyang Lake into a complex lake-catchment-river system (Yao et al., 2016). The combination of inflows from the catchment and the blocking effect (or the drainage effect) of the Yangtze River determine the water level of Poyang Lake (Shankman et al., 2006). The system has undergone significant alteration due to climate and human activities, especially the construction of TGR, which is the largest hydroelectric power station in the world (Gao et al., 2014; Sun et al., 2014).

The monthly water level time series from 1960 to 2013 at four hydrological stations (Hukou, Xingzi, Duchang and Kangshan) were selected to identify hydrological drought events in Poyang Lake. The average values of the four stations were calculated to reflect the average condition of the lake (Min, 2006; Yao et al., 2016). The monthly runoff time series collected at six hydrological stations located on the major tributaries of the Poyang catchment from 1960 to 2013 were used to analyze hydrological drought in the catchment. These data were obtained from the Jiangxi Hydrological Bureau of China. The monthly runoff time series (1960–2013) from Hankou hydrological station (approximately 600 km below TGR), which was obtained from the Yangtze River Hydrological Bureau of China, was used to quantify hydrological drought in the Yangtze River. In addition, a monthly precipitation dataset collected at 632 stations in the Yangtze River Basin was used to analyze the effect of precipitation variations on hydrological drought. This dataset was obtained from the National Climate Center of the China Meteorological Administration.

3. Methods

3.1. Hydrological drought definition in this study

Numerous methods, such as the standardized precipitation index (SPI), Palmer drought severity index and standardized precipitation evapotranspiration index, have been used to investigate regional drought events (Shukla and Wood, 2008; Vicenteserrano et al., 2010; Zhang et al., 2015a–d). The SPI is a widely used drought index and statistical indicator that describes precipitation variations (Hayes et al., 1999), which has been extended to study other hydrological variables, such as runoff, soil moisture, water level and lake area (Liu and Wu, 2016; Sheffield et al., 2004). In this study, the standard water level index (SWI, Bhuiyan et al., 2006) and the standard runoff index (SRI, Zhang et al., 2015c), as extensions of the SPI, are calculated as probability indicators based on the water level and runoff. The selection of SWI and SRI has two advantages: first, the impact of human activities on the Poyang lake-catchment-river system can't be neglected. The water level