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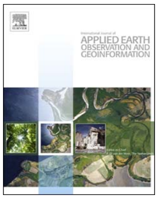

Research Paper

Temporal–spatial evolution of the hydrologic drought characteristics of the karst drainage basins in South China

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ABSTRACT

Hydrologic drought, as a typical natural phenomenon in the context of global climate change, is the extension and development of meteorological and agricultural droughts, and it is an eventual and extreme drought. This study selects 55 hydrological control basins in Southern China as research areas. The study analyzes features, such as intensity and occurrence frequency of hydrologic droughts, and explores the spatial–temporal evolution patterns in the karst drainage basins in Southern China by virtue of Streamflow Drought Index. Results show that (1) the general hydrologic droughts from 1970s to 2010s exhibited “an upward trend after having experienced a previous decline” in the karst drainage basins in Southern China; the trend was mainly represented by the gradual alleviation of hydrologic droughts from 1970s to 1990s and the gradual aggravation from 2000s to 2010s. (2) The spatial–temporal evolution pattern of occurrence frequency in the karst drainage basins in Southern China was consistent with the intensity of hydrologic droughts. The periods of 1970s and 2010s exhibited the highest occurrence frequency. (3) The karst drainage basins in Southern China experienced extremely complex variability of hydrologic droughts from 1970s to 2010s. Drought intensity and occurrence frequency significantly vary for different types of hydrology.

1. Introduction

As a globally common natural phenomenon, drought is a natural disaster that threatens human life and property safety (EU, 2007). From July 2009 to April 2010, five provinces with Guizhou as their center (Yunnan, Guizhou, Guangxi, Sichuan, and Chongqing) suffered an especially severe droughts once. According to statistics, 34.3612 million people and 10.3717 million large livestock had dyspepsia, whereas 43.9638 million mu of crops were affected. The direct economic loss caused by the droughts was more than RMB 2.6918 billion Yuan, whereas the agricultural economic loss was up to RMB 6.186 billion Yuan. Therefore, developing drought monitoring and prediction studies are imperative and urgent to protect human life and property safety. The AMS (1997) divided drought into the following categories based on different definitions: meteorological, hydrological, agricultural, and socio-economic droughts. Hydrological drought is an eventual and extreme droughts, and is the continuity and development of meteorological and agricultural droughts (Geng and Shen, 1992). During a hydrological drought, the river flows lower than its normal water-level (or water-line) because of the imbalance between rainfall and surface or underground water (Dracup et al., 1980; Feng, 1993).

The present studies on hydrologic droughts, the theory of runs is firstly applied to make quantitative expressions for the characteristics of hydrological droughts (Yevjevich, 1967), and study the characteristics of extreme hydrological droughts following the extremity of independent and dependent orders in normality, log normality, and γ distribution (Sen, 1977, 1990, 1991; Guven, 1983; Sharma, 1998). Utilizing the different drought indices like the Regional Drought Area Index (*RDAI*) of daily runoff series and Drought Potential Index (*DPI*) are to analyze the characteristics of regional hydrological droughts (Fleig et al., 2011), and study the relationship of double variables between the drought duration and intensity (Kim and Valdés, 2006; Panu and Sharma, 2009). Employing the Standardized Runoff and Rainfall Indexes (*SRRI*) are to study the influences of channel improvement and nonlocal diversion on the process and level of hydrologic droughts (Wen et al., 2011). The level, process, and recurrence interval of hydrologic droughts are studied by utilizing Palmer Drought Index (*PDI*), Soil Moisture Model (*SMM*), Runoff Sequence (*RS*), Standardized Rainfall Index (*SRI*), and Vegetation Health Index (*VHI*), respectively (Nyabeze, 2004; Mondal and Mujumdar, 2015). Some scholars make a

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time series analysis and random simulation for the hydrologic drought severity by using an autoregression model (Abebe and Foerch, 2008), and make the Probabilistic prediction of hydrologic drought by a conditional probability approach based on the meta-Gaussian model (Hao et al., 2016), the seasonal forecasting of hydrologic droughts in the Limpopo Basin by a statistical analysis method, respectively (Seibert et al., 2017). Rudd et al. (2017) was the first to use a national-scale gridded hydrologic model to characterise droughts across Great Britain over the last century, and it was found that the model can very well simulate low flows in many catchments across Great Britain. The threshold level method was also applied to time series of monthly mean river flow and soil moisture to identify historic droughts (1891–2015), and it was shown that the national-scale gridded output can be used to identify historic drought periods. Meantime, A small number of scholars explore the spatial–temporal distribution differences between the characteristics of the meteorological and hydrological droughts from the basin scale (Hisdal and Tallaksen, 2003; Tallaksen et al., 2009). Among domestic studies for hydrological droughts, the theory of runs is mainly applied to analyze the influence factors of runoff volume in dry season and the identification of hydrological droughts (Feng and Jia, 1997; Feng and Wang, 1997), and study the probability density and distribution functions of extreme hydrological drought duration (Feng, 1993, 1994, 1995). Using the fractal theory is to study the temporal fractal characteristics of hydrologic droughts, and estimate the hydrologic drought severity by the time fractal dimension (Feng and Jia, 1997; Feng and Wang, 1997). Employing the Copula Joint Distribution Function is to construct the joint distribution of hydrological drought characteristics (Zhou et al., 2011; Yan et al., 2007; Xu et al., 2010; Ma and Song, 2010). However, most of the researches are still taking the different drought indices to make the identification, characteristic analysis and prediction of hydrologic droughts, respectively. For example, Zhai et al. (2015) established a new hydrologic drought assessment index named Standard Water Resources Index (*SWRI*), and developed a basic framework of hydrologic drought identification, assessment and characteristic analysis by combining the distributed hydrologic model, Copula functions and statistical test methods. Zhao and Zhao (2016) selected the most suitable distribution from the logistic, normal, two-parameter log-normal, and Weibull probability distributions to establish the Standardized Streamflow Drought Index (*SSDI*), classified the drought magnitudes of hydrologic drought events by the *SDDI*, and validated the applicability and rationality of the *SSDI* based on the actual drought situations in the Fenhe River Basin. Wu et al. (2016) constructed a Regional Hydrologic Droughts Index (*RHDI*) combined with the percentages of runoff and precipitation anomalies, obtained the frequency of corresponding drought grades, and then determined the threshold value of the different drought grades based on the cumulative frequency of the *RHDI*. Tu et al. (2016) constructed the Copula Model of two-variable joint distribution of hydrologic drought characteristics based on the test method of Cramer-von Mises Statistics associated with Rosenblatt transfer, and analyzed the hydrologic drought characteristics under a changing environment in Dongjiang River Basin. Based on the Variable Infiltration Capacity (*VIC*) model, Ren et al. (2016) quantitatively separated the effects of climate change and human activities on runoff reduction, and analyzed the spatial-temporal evolution characteristics of hydrologic droughts by the Standardized Runoff Index (*SRI*). Li et al. (2016) analyzed the evaluation characteristics of the meteorological and hydrological droughts by using Standard Precipitation Evapotranspiration Index (*SPEI*) and Streamflow Drought Index (*SDI*), and discussed the response of hydrological droughts to meteorological droughts. He et al. (2015a) analyzed the spatial-temporal characteristics of the meteorological and hydrologic droughts by Standardized Precipitation Index (*SPI*), Standardized Discharge Index (*SDI*) and associated indicators with the trend, time lag cross-correlation across the Yellow River Basin (YRB) during 1961–2010. Zhang et al. (2016) constructed the Copula prediction model of hydrologic droughts based on the Copula Function and Runoff Distribution Function by the Standard Runoff Index (*SRI*) according to the seasonal runoff-related characteristics, and made an empirical analysis for the hydrologic station of the Aksu River West Bride.

However, the present studies on the hydrologic droughts in Karst basins, except for some relevant research contents of this team (He and Chen, 2013; He et al., 2013, 2014, 2015b), have not seen a more detailed study reporting.Thus, this paper is to take the Karst drainage basins as the study areas, make the identification and quantification for hydrologic droughts by utilizing the streamflow drought index (*SDI*), and study the spatial–temporal evolution rules of hydrological drought characteristics in the karst drainage basins in South China. Therefore, this study will set further foundation for the study on hydrological drought mechanism in karst drainage basins.

2. Study areas

South China is a typical distribution area of cone, pinnacle, and tower karsts with Guizhou, Yunnan, and Guangxi Provinces as its center. 55 hydrologic control basins are selected in this study as research areas in the typical Karst distribution areas in South China (Fig. 1). The research areas are located in eastern longitudes of 101°55′55″–110°55′45″ and northern latitudes of 22°42′57″–29°13′11″ with an average elevation of 1065.62 m and an area of 352,526 km^2. These areas include most of Guizhou Province (37.97%), the southeastern area of Yunnan Province (25.36%), and the northwestern and northern areas of Guangxi Province (36.67%). The rainfall in the humid climatic region of northern subtropics and sub-humid climatic region of south subtropics of the research areas are abundant but in an uneven spatial–temporal distribution. The average annual precipitation in these areas is between 1000–1300 mm, and the average annual temperature is 16 °C–23 °C. The Wumeng–Miaoling Mountains serve as the watershed of the research areas, which can be divided in the Yangtze and Pearl River Basins, respectively. In other words, the areas in north are the Jinshajiang River System, the Upper Yangtze River Mainstream System, the Wujiang River System, and the Dongting Lake System of the Yangtze River Basin; whereas the areas in south are the Nanpan River System, Beipan River System, Hongshui River System, and the Duliu River System (in Guizhou), Yuanjiang River System (in Yunnan), and Xijiang River System (in Guangxi) of the Pearl River Basin.

3. Data and methods

3.1. Hydrological data

Hydrological drought is the reduction and the cutoff of the runoff volume in surface and underground rivers, or the decline of water level in lakes and reservoirs (Van Loon and Van Lanen, 2012; Van Loon and Laaha, 2015; Mishra and Singh, 2010). 55 hydrological stations (including 25 in Guizhou, 19 in Guangxi, and 11 in Yunnan, Table 1) are selected in this study as research areas (Fig. 1) to study the average montly runoff volume from 1970 to 2013. All the data are from the hydrological data prepared by the Ministry of Water Resources of the People's Republic of China.[2] Interpolation is conducted using the interpolation method of cubic spline function due to lack of measured data. Data are standardized in this work because they are affected by basin area.

3.2. Identification of hydrological drought

Hydrological drought is the phenomenon when the river flow is lower than its normal value. In other words, the river flow cannot

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[2] Hydrologic Year Book of People's Republic of China *Hydrologic Data of Yangtzi River Basin*, Volume 6 and *Hydrologic Data of Pearl River Basin*, Volume 8.