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Analysis of spatio-temporal evolution of droughts in Luanhe River Basin using different drought indices

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Abstract

Based on the monthly precipitation and air temperature from 1960 to 1989 in the Luanhe River Basin, the standardized precipitation evapotranspiration index (SPEI) and standardized precipitation index (SPI) at three- and six-month time scales and the self-calibrating Palmer drought severity index (sc-PDSI) were calculated to evaluate droughts in the study area. Temporal variations of the drought severity from 1960 to 1989 were analyzed and compared based on the results of different drought indices, and some typical drought events were identified. Spatial distributions of the drought severity according to the indices were also plotted and investigated. The results reveal the following: the performances of different drought indices are closely associated with the drought duration and the dominant factors of droughts; the SPEI is more accurate than the SPI when both evaporation and precipitation play important roles in drought events; the drought severity shown by the sc-PDSI is generally milder than the actual drought severity from 1960 to 1989; and the evolution of the droughts is usually delayed according to the sc-PDSI. This study provides valuable references for building drought early warning and mitigation systems in the Luanhe River Basin.

Keywords: Drought index; Drought assessment; Self-calibrating Palmer drought severity index (sc-PDSI); Standardized precipitation evapotranspiration index (SPEI); Standardized precipitation index (SPI); Luanhe River Basin

1. Introduction

Droughts are the world's most damaging natural hazards (Keyantash and Dracup, 2002; Wilhite et al., 2007), affecting enormous portions of the world population (Wilhite, 2000). In recent decades, China has experienced severe droughts, which have caused large economic losses and severe societal damage every year (Xin et al., 2006; Lu et al., 2010; Wu et al., 2011), particularly in northern China (Liang et al., 2006; Qian et al., 2011; Wang et al., 2012). Many studies over recent decades have focused on the droughts in northern China. Because a drought index is an important means of monitoring and evaluating droughts, a number of drought indices have been developed and applied (Heim, 2002). At present, the self-calibrating Palmer drought severity index (sc-PDSI) (Wells et al., 2004; Yu, 2007) and the standardized precipitation index (SPI) (McKee et al., 1993) are the most widely used drought indices in global and regional drought monitoring, and the standardized precipitation evapotranspiration index (SPEI)

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(Vicente-Serrano et al., 2010) is becoming popular in drought assessment. Recently, the formulation of a multivariate drought index by assembling different components of the water cycle (such as precipitation, soil moisture, evaporation, and runoff), and geomorphologic parameters (Anderson et al., 2011, 2012; Hao and AghaKouchak, 2013, 2014; Brown et al., 2008; Zhang and Jia, 2013; Mu et al., 2013; Hao et al., 2014) has attracted wide attention. However, the applicability of a multivariate drought index is limited by the scarcity in observations of hydrological variables over a large spatial scale. For example, the soil moisture data needed in these approaches are difficult to obtain. Thus, drought indices based only on the easily obtained hydro-meteorological variables (e.g., precipitation and temperature) have gained wide acceptance. As a region prone to droughts, northern China has been a site for drought investigation and assessment by many researchers. Wang and Zhai (2003) calculated the Palmer moisture anomaly index (Z index) based on monthly precipitation from 1950 to 2000 and showed an increasing trend in drought intensity and frequency in northern China's main agricultural area. Zou et al. (2005) calculated the Palmer drought severity index (PDSI) based on the monthly air temperature and precipitation from 1951 to 2003 and demonstrated a significant increase in drought areas in northern China, which has suffered a severe dry period since the late 1990s. Yu et al. (2014) computed the SPEI based on monthly precipitation and air temperature from 1951 to 2010 and revealed that consecutive multi-year severe droughts were frequent in northern China and drought durations have expanded over decades, with the longest ones occurring during the 1990s and 2000s. Although these indices have been used in northern China, detailed comparison of their performances in the assessment of typical historical droughts has seldom been reported. The objective of this study was to investigate the applicability of the sc-PDSI, SPI, and SPEI by monitoring the spatio-temporal evolution of droughts from 1960 to 1989 in the Luanhe River Basin. According to the results of evaluation of drought evolution using different drought indices, three typical historical drought events, the 1962/1963 drought, 1972 drought, and 1989 drought, were identified, and more detailed analysis on the performances of these three drought indices in evaluating the three typical historical drought events was carried out. This study can provide valuable references for building drought early warning and mitigation systems in semi-arid and semi-humid regions.

2. Study area

The Luanhe River Basin, ranging from 115°34′E to 119°50′E and 39°02′N to 42°43′N, in the northeastern part of the North China Plain, has a drainage area of 44 750 km^2 and an average width of 103 km. Originating from the northern foot of the Bayanguertu Mountain in Zhangjiakou, in Hebei Province, the Luanhe River travels through 27 cities and counties of Hebei Province, the Inner Mongolia Autonomous Region, and Liaoning Province, and finally flows into Bohai Bay. The basin is inclined from northwest to southeast. It contains diverse geomorphic types, and a typical temperate continental climate prevails, where the average temperature is 23.9°C in July and −9°C in January. The annual precipitation ranges from 400 to 700 mm, with an annual mean precipitation of 520 mm, most of which falls from June to September, a period accounting for approximately 80% of the total annual precipitation. The basin contributes a large water volume to the Haihe River Basin and is the major water source for the cities of Tianjin, Tangshan, and Chengde. With global climate change, the intensity, duration, and frequency of droughts in the basin have shown increasing trends over the past decades. Drought-induced water shortage is increasingly becoming a critical constraint to the sustainable socio-economic development of Tianjin, Tangshan, and Chengde (Zhang et al., 2013a, 2013b). In addition, the influence of droughts is most serious in the agricultural sector, due to agriculture being the largest water user. Therefore, investigation of the spatio-temporal evolution characteristics of droughts using an appropriate drought index in the Luanhe River Basin is highly useful. The sub-basin, upstream of the Luanxian Hydrological Station, with a drainage area of 44 100 km^2 was selected as the study area (Fig. 1).

3. Methods and data

3.1. Methods

In order to determine which drought index can best monitor the evolution of droughts in the Luanhe River Basin, three drought indices (the sc-PDSI, SPEI, and SPI) were selected to evaluate the drought evolution from 1960 to 1989, a period that included several of the most severe droughts historically recorded. Since the SPI is widely used in China, only a brief introduction to the sc-PDSI (Wells et al., 2004) and SPEI (Vicente-Serrano et al., 2010) is given below.

3.1.1. sc-PDSI

The current PDSI value X_i is a weighted sum of the previous PDSI value X_{i-1} and the current moisture anomaly index Z_i, as shown in Eq. (1).

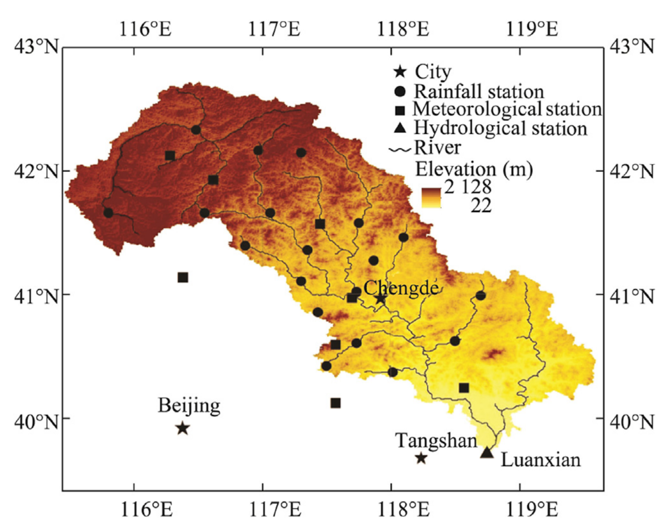

Fig. 1. Study area.