Science of the Total Environment 616–617 (2018) 73–89

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Drought evolution, severity and trends in mainland China over 1961–2013

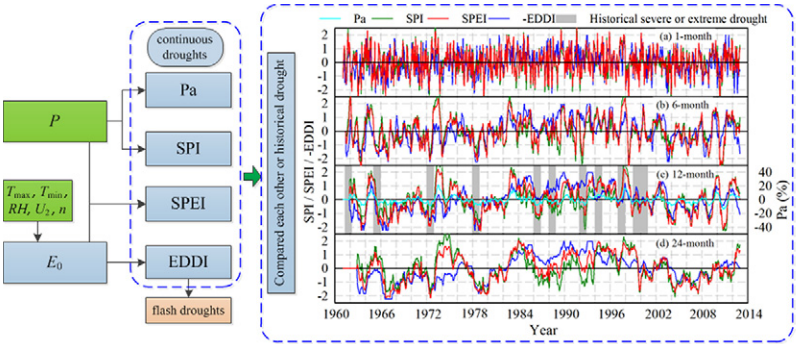
Ning Yao [a,b], Yi Li [a,b,*], Tianjie Lei [c,**], Lingling Peng [a,b]

[a] College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry University, Yangling, Shaanxi 712100, China
[b] Institute of Water Saving Agriculture in Arid Areas of China, Northwest Agriculture and Forestry University, Yangling, Shaanxi 712100, China
[c] China Institute of Water Resources and Hydropower Research (IWHR), Beijing 100038, China.

HIGHLIGHTS

- The Pa, SPI, SPEI and EDDI consistently implied an overall relief of drought conditions.
- Droughts evolutions were site-, regional-specific and complicated although relieved in recent 53 years in mainland China.
- The Pa, SPI and SPEI are used for determining continuous droughts and EDDI for identifying flash droughts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 August 2017
Received in revised form 31 October 2017
Accepted 31 October 2017
Available online 16 November 2017

Editor: Ouyang Wei

Keywords:
Drought index
Historical extreme drought event
Trend test
Timescale

ABSTRACT

Droughts have destructive impacts on crop yields and water supplies, and researching droughts is vital for societal stability and human life. This work aimed to assess the spatiotemporal evolution of droughts in mainland China over 1961–2013 using four drought indices. These indices were the percentage of precipitation anomaly (Pa), standard precipitation index (SPI), standard precipitation evapotranspiration index (SPEI) and evaporative demand drought index (EDDI) at multiple timescales ranging from 1-week to 24-month. The variations of the SPI, SPEI and EDDI were compared with historical severe or extreme droughts. The general increases of the Pa, SPI and SPEI, and general decrease of the EDDI, consistently implied an overall relief of drought conditions over 1961–2013. The different drought indices revealed historical drought conditions, including the national extreme droughts in 1961, 1965, 1972, 1978, 1986, 1988, 1992, 1994, 1997, 1999 and 2000, but various drought severity levels were classified for each drought event since the classification standards differed. Although the SPI and SPEI performed better than the EDDI and there were higher correlations between the SPI and the SPEI, all the indices were regional- or station-specific and have identified historical severe or extreme drought events. At shorter timescales, the EDDI revealed earlier onsets and ends of flash droughts, unlike those indicated by the SPI and SPEI.

Abbreviations: E_0, evaporative demand; EDDI, Evaporative Demand Drought Index; EMC, Entire mainland China; FAO56-PM, FAO56 Penman-Monteith equation; InsigDec, insignificant decrease; InsigInc, insignificant increase; METRIC, Mapping evapotranspiration with Internalized Calibration; MMK, modified Mann–Kendall; M, month; P, precipitation; Pa, percentage of precipitation anomaly; PDSI, Palmer Drought Severity Index; R, Correlation coefficient; RDTTA, ratio of drought-threatened area to total arable land area; RH, relative humidity; sc-PDSI, self-calibrating PDSI; SEBAL, Surface Energy Balance Algorithm for Land; SEBS, Surface Energy Balance System; SigDec, significant increase; SigInc, significant increase; SPEI, Standardized Precipitation Evapotranspiration Index; SPI, Standardized Precipitation Index; T_{max}, maximum temperature; T_{mean}, mean temperature; T_{min}, minimum temperature; U_2, wind speed; W, week.

[*] Correspondence to: Y. Li, College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry University, Yangling, Shaanxi 712100, China.
[**] Corresponding author.
E-mail addresses: liyi@nwsuaf.edu.cn (Y. Li), leitj@iwhr.com (T. Lei).

https://doi.org/10.1016/j.scitotenv.2017.10.327

The comparison of the different indices based on the historical drought events confirmed the uses of the Pa, SPI and SPEI for determining continuous droughts and that of the EDDI for identifying flash droughts.

1. Introduction

Droughts are one of the most destructive and costly natural disasters, with serious impacts on agriculture, water resources, ecology, and society (Lei et al., 2016; Mishra and Singh, 2010; Schubert et al., 2016). With recent global warming (IPCC, 2013), the percentage of dry areas in the world has increased by approximately 1.74% per decade from 1950–2008 (Dai, 2011). China has suffered long-lasting and severe droughts in the past (Chen and Sun, 2015; Dai, 2011, 2013; Zhang B. et al., 2016). The influences of drought have evoked high levels of interest outside of the scientific community (Leuzinger et al., 2005).

Based on their timescales and impacts, droughts are generally categorized into five types: meteorological droughts, agricultural droughts, hydrological droughts, socio-economical droughts, and droughts that impact stream health (Esfahanian et al., 2017; Heim, 2002; Wilhite and Glantz, 1985). Of these categories, meteorological droughts usually precede the others and are defined in terms of the magnitude of the lack of precipitation over a region over time. There are many meteorological drought indices (Heim, 2002; Wu et al., 2015), which can be generally classified as non-standardized (Arora, 2002; Budyko, 1974; Erinç, 1965; Sahin, 2012; UNEP, 1993), standardized, or combination indices. The non-standardized indices are always simple to compute using some available data but their ranges for classifying drought level are different. The standardized indices are complicated in computation but their drought level classifications are similar and comparable. The combination indices are the combination of the two. Non-standardized indices include the percentage of precipitation anomaly (Pa) (Van Rooy, 1965), aridity index (Arora, 2002; Budyko, 1974; Erinç, 1965), UNEP index (UNEP, 1993) and specific humidity-based index (Sahin, 2012). The China composite index is a typical combination drought index (China Meteorological Administration, 2006). There are several standardized indices, such as the Palmer drought severity index (PDSI) (Palmer, 1965), standardized precipitation index (SPI) (McKee et al., 1993), and standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010a). Each drought index has its own adaptability, advantages, and limitations. The PDSI was originally developed to measure the cumulative departure from the surface water balance and has been applied worldwide (Dai et al., 2004; Zhang et al., 2017). However, the PDSI lacks the multiscale characteristics of droughts (Wang Q. et al., 2015). The SPI is less complex than the PDSI and can be applied to any location or month-based timescale (Hayes et al., 1999) but does not reflect the drought conditions caused by warming because it only considers precipitation (Vicente-Serrano et al., 2010b; Zhang and He, 2016). The SPEI was proposed as an improved drought index compared to the SPI, which is suitable for studying the effects of global warming on drought severity (Begueria et al., 2014).

However, the abovementioned drought indices have difficulty capturing the rapidly evolving drought events, commonly called “flash droughts” (Senay et al., 2008; Svoboda et al., 2002). The rapid onset of flash droughts significantly reduces the time available for disaster preparation measures (Otkin et al., 2015). Soil moisture anomalies are useful for characterizing flash droughts (Mozny et al., 2012). However, the lack of spatial soil moisture data precludes its inclusion in flash drought monitoring (Ford et al., 2015). The evaporative stress index provides an early warning for flash drought development (Anderson et al., 2011; Otkin et al., 2015) but it has some limitations when applied to different regions (McEvoy et al., 2016). The newly proposed Evaporative Demand Drought Index (EDDI) is physically-based and multiscalar (Hobbins et al., 2016). It can serve as an indicator of both flash (at 1-, 2-, …, 12-week timescales; week is hereon simplified as W) and sustained droughts (at 1-, 2-, …, 48-month timescales; month is hereon simplified as M). The EDDI is a powerful tool for drought preparedness and capturing the precursor signals of water stress. The development, evolution, and spatiotemporal distribution of sustained droughts in China were previously investigated using the PDSI, SPI, and SPEI (Chen and Sun, 2015; Wang et al., 2016; Wang W. et al., 2015; Yu et al., 2014). However, few studies have assessed the applicability of the widely applied multi-scalar indices of the SPI and SPEI with Pa, and the newly proposed EDDI, in China.

In this research, meteorological data from 552 stations throughout the entirety of mainland China (EMC) over 1961–2013 were used to calculate Pa, the SPI, SPEI and EDDI at the 1-, 6-, 12-, and 24-M timescales, and EDDI at 1-, 2-, …, to 12-W timescales, respectively. The objectives are: (1) to analyze the spatiotemporal variations of the EDDI, SPI and SPEI at different timescales in different sub-regions of EMC; (2) to compare the effectiveness of the four drought indices in identifying historical severe or extreme drought events; and (3) to objectively assess the applicability of EDDI for characterizing flash droughts in China.

2. Data and methodology

2.1. The studied stations and the data sets

China has a descending 3-terrace-topography from the west to the east with much diversified topography (Fig. 1). There are different kinds of landscapes, such as plains, valleys, hills, mountainous, river systems, water bodies, plateaus, deserts, glaciers, basins, etc. (Zhao et al., 1999). The highest terrace is the Qinghai-Tibet Plateau with an average altitude of 4000 m. The lowest terrace consists of east China, adjacent to oceans. A total of 552 stations were selected to analyze drought conditions in EMC.

The observed weather variables including daily and monthly precipitation (P), relative humidity (RH), minimum ($T_{\min}$), mean (T_{mean}) and maximum temperatures ($T_{\max}$), wind speed (U_2), sunshine hour (n) and geographical data over the period 1961–2013 were collected from the Meteorological Data Sharing Service Network in China with strict quality control. The data quality and reliability were cross-examined using nonparametric tests including the Kendall autocorrelation test and Mann-Whitney homogeneity tests (Helsel and Hirsch, 1992). The results indicated that randomness and stationary of the weather data were fixed between the critical points at a 5% statistical significance level. The temporal coverage exceeded 99.7%. The missing data were interpolated using the arithmetic average of the neighboring days or months using a linear regression equation.

Considering the multi-year average T_{mean}, P and moisture conditions (Table 1), China is divided into seven natural sub-regions (Zhao, 1983), which include the temperate and warm-temperate desert of northwest China (sub-region 1), the temperate grassland of Inner Mongolia (sub-region 2), the temperate humid and sub-humid northeast China (sub-region 3), the warm-temperate humid and sub-humid north China (sub-region 4), the subtropical humid central and south China (sub-region 5), the Qinghai-Tibetan Plateau (sub-region 6), and the tropic humid south China (sub-region 7). The annual mean T_{mean}, RH, and P were lower in sub-regions 1, 2, 3 and 6 than in the other 3 sub-regions. The annual mean E_0 was lower in sub-regions 3 and 5 but higher in sub-regions 2 and 7.