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A new method and a new index for identifying socioeconomic drought events under climate change: A case study of the East River basin in China

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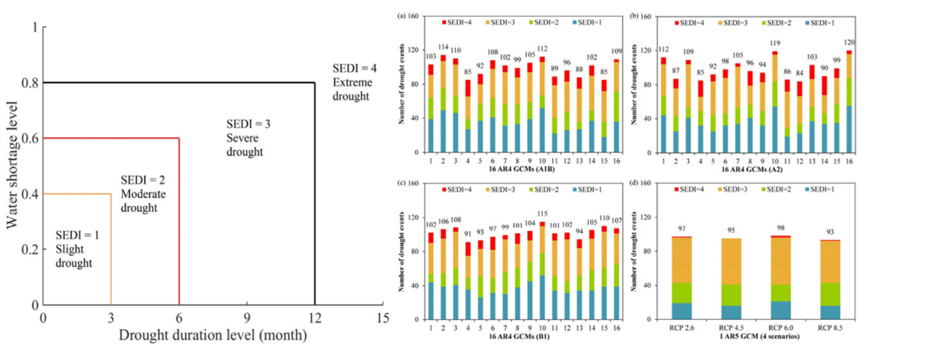
HIGHLIGHTS

- Development of a heuristic method for identifying socioeconomic drought events
- A new index, the socioeconomic drought index (SEDI), is proposed.
- Historical and future drought analyses under climate change are conducted.
- The impact of reservoir operation on drought analysis is discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Drought is a complex natural hazard that may have destructive damages on societal properties and even lives. Generally, socioeconomic drought occurs when water resources systems cannot meet water demand, mainly due to a weather-related shortfall in water supply. This study aims to propose a new method, a heuristic method, and a new index, the socioeconomic drought index (SEDI), for identifying and evaluating socioeconomic drought events on different severity levels (i.e., slight, moderate, severe, and extreme) in the context of climate change. First, the minimum in-stream water requirement (MWR) is determined through synthetically evaluating the requirements of water quality, ecology, navigation, and water supply. Second, according to the monthly water deficit calculated as the monthly streamflow data minus the MWR, the drought month can be identified. Third, according to the cumulative water deficit calculated from the monthly water deficit, drought duration (i.e., the number of continuous drought months) and water shortage (i.e., the largest cumulative water deficit during the drought period) can be detected. Fourth, the SEDI value of each socioeconomic drought event can be calculated through integrating the impacts of water shortage and drought duration. To evaluate the applicability of the new method and new index, this study examines the drought events in the East River basin in South China, and the impact of a multi-year reservoir (i.e., the Xinfengjiang Reservoir) in this basin on drought analysis is also investigated. The historical and future streamflow of this basin is simulated using a hydrologic model, Variable Infiltration Capacity (VIC) model. For historical and future drought analysis, the proposed new method and

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index are feasible to identify socioeconomic drought events. The results show that a number of socioeconomic drought events (including some extreme ones) may occur in future, and the appropriate reservoir operation can significantly ease such situation.

1. Introduction

Drought is regarded as a complex natural hazard that occurs in large areas over long time periods and may have highly destructive effects on a number of aspects, such as water supply, agricultural production, and ecological environment (e.g., Gan et al., 2016; Yoo et al., 2016; Cammalleri et al., 2017). Generally, drought can be classified into four categories, including meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought (Wilhite and Glantz, 1985; American Meteorological Society, 2013). Meteorological drought is often defined as a lack of precipitation over a region for a period of time; agricultural drought links various characteristics (e.g., soil moisture) of meteorological drought to agricultural impacts; hydrological drought is concerned with the effects of dry periods on surface or subsurface hydrology and water resources; socioeconomic drought is usually associated with supply of and demand for an economic good (water), which can also incorporate features of meteorological, agricultural, and hydrological droughts (Kifer and Steward, 1938; Wilhite and Glantz, 1985; Mishra and Singh, 2010). The former three have attracted the attentions of many researchers (e.g., Guttman, 1998; Heim, 2002; Narasimhan and Srinivasan, 2005; Shukla and Wood, 2008; Mishra and Singh, 2010; Morán-Tejeda et al., 2013; Moorhead et al., 2015; Serinaldi, 2016; Lin et al., 2017; Wu et al., 2017); however, to the best of our knowledge, it is only until recently that there have been a few studies focusing on socioeconomic drought (e.g., Eklund and Seaquist, 2015; Mehran et al., 2015; Huang et al., 2016), which occurs when water resources systems cannot meet water demand due to a weather-related shortfall in water supply (American Meteorological Society, 2013). A drought can be quantified at different levels of water deficiency, but it is difficult to identify a drought event through comprehensively evaluating both water shortage and drought duration. Therefore, it is still a challenging task to develop such a new method and a new index for rationally identifying drought events.

In the past several decades, numerous drought indices have been developed based on different parameters (e.g., Heim, 2002; Mishra and Singh, 2010; Moorhead et al., 2015; Etienne et al., 2016; Ndehedehe et al., 2016). For example, Palmer (1965) proposed the Palmer Drought Severity Index (PDSI) based on precipitation, reference evapotranspiration and soil characteristics, which could be used for evaluating the meteorological anomaly at a variety of time scales; Karl (1986) further developed the Palmer Hydrological Drought Index (PHDI) to better treat the beginning and ending times of droughts. The Standardized Precipitation Index (SPI), originated by McKee et al. (1993) based on only precipitation, is also a popular tool to investigate drought occurrence. Sivakumar et al. (2011) developed the Relative Water Deficit (RWD) using actual and potential evapotranspiration as inputs. Moreover, drought indices, such as Crop Moisture Index (CMI) (Palmer, 1968), Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982), Vegetation Condition Index (VCI) (Kogan, 1995), and Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), are all widely-used. However, all the above indices are used for assessing the effects of meteorological (e.g., PDSI, SPI and SPEI), hydrological (e.g., PHDI and SWSI) and agricultural (e.g., CMI, RWD and VCI) droughts. Moreover, these indices may have their own advantages and disadvantages. For example, SPI can be calculated for a variety of time scales, but the length of precipitation record and nature of probability distribution play a vital role in calculating SPI. PDSI is the first comprehensive index to assess the total moisture status of a region, but some rules (e.g., assuming that all precipitation is rain) to establish PDSI are arbitrary and PDSI is sensitive to precipitation and temperature (Mishra and Singh, 2010). SWSI is regarded to be complementary to PDSI, which has the synonymous scale with that used for PDSI and can monitor the impacts of hydrological droughts on urban and industrial water supplies, irrigation and hydroelectric power generation; however, the weights of the factors may vary with spatial scales and temporal scales due to differences in hydroclimatic variability (Wilhite and Glantz, 1985; Heim, 2002; Mishra and Singh, 2010). CMI is used as an indicator of the availability of moisture to meet short-term crop needs, but there is unnatural response to changes in temperature because of the dependence of the abnormal evapotranspiration term on the magnitude of potential evapotranspiration (Juhasz and Kornfield, 1978; Wilhite and Glantz, 1985; Mishra and Singh, 2010).

Due to continuous population growth, water demand has increased multifold and will keep increasing in future, probably causing more socioeconomic drought events around the world (Chen et al., 2016; Smirnov et al., 2016; Trinh et al., 2017). For this category of drought which is the least investigated, Mehran et al. (2015) proposed the Multivariate Standardized Reliability and Resilience Index (MSRRI) for assessing water stress due to both climatic conditions and local reservoir levels, and Huang et al. (2016) applied this index to examine the evolution characteristics of socioeconomic droughts in the Heihe River basin in China. However, this index only focuses on water shortage but does not include drought duration, which may also have crucial influences on drought analysis. Thus, it is vital to develop a new index for identifying socioeconomic drought events through integrating both water shortage and drought duration, especially in the context of climate change.

Climate change has been recognized as one of the major factors that have great impacts on drought (e.g., Hanson and Weltzin, 2000; Aherne et al., 2006; Hirabayashi et al., 2008; Ahn et al., 2016; Gizaw and Gan, 2017; Linares et al., 2017; Tietjen et al., 2017). Even a small change in climate may cause a dramatic change in hydrological cycle, leading to more frequent hydrological extremes (e.g., Pilling and Jones, 2002; Chen et al., 2011; Vicuna et al., 2013; Gu et al., 2015; Shi and Wang, 2015; Hoang et al., 2016; Shi et al., 2016a, 2017a). Globally, IPCC (Intergovernmental Panel on Climate Change) (2013) reported that the averaged land and ocean surface temperature had a warming of 0.85 °C over the period of 1880–2012 and a fast warming trend of 0.12 °C/decade over the period of 1951–2012. Regionally, a remarkable warming trend has been found in South China (e.g., Chen et al., 2011; Chan et al., 2012; Lau and Ng, 2013). Fischer et al. (2013) projected climate extremes in the Pearl River basin for the period of 2011–2050 using the daily output from the regional climate model COSMO-CLM, and the results indicated that warmer and drier conditions could be expected in the western and eastern parts, especially in summer and autumn.

In recent years, we have conducted several studies on climate change over the Pearl River basin (e.g., Niu, 2013; Niu and Chen, 2014, 2016; Niu et al., 2014, 2015, 2017). Niu and Chen (2014) investigated the terrestrial hydrological responses to precipitation variability over the West River basin with emphasis on an extreme drought event. Niu et al. (2014) revealed that the teleconnections between two climatic patterns (El Niño-Southern Oscillation, ENSO, and Indian Ocean Dipole, IOD) and hydrological variability, served as a reference for inferences on the occurrence of extreme hydrological events over the Pearl River basin. Niu et al. (2015) examined the spatio-temporal and evolution