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Analysis of long term drought severity characteristics and trends across semiarid Botswana using two drought indices

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ABSTRACT

Semiarid areas exhibit high climate variability whose frequency has increased in the recent past. This variability ultimately influences the spatial and temporal characteristics of droughts which in turn require a reliable drought index that can adequately characterize drought both in time and space. This study applied two drought indices viz.: Standardized precipitation index (SPI) and Standardized precipitation and evapotranspiration index (SPEI) at timescales of 1-, 3-, 6-, 12-, 18- and 24-months for a period of 1960–2016. The monotonic changes in drought severity were studied using Mann-Kendall *Z*-statistic and Sen's slope estimator. Both drought indices were able to detect the historical drought events of 1961/62–1965/66, 1980/81–1986/87, 1991/92, 2001/02–2005/06, 2009/10–2012/13 and 2014/15–2015/16. These events mainly coincided with El Niño years, hence the influence of El Niño southern oscillation (ENSO) on drought occurrence could not be ruled out. The drought evolutions were characterized by low frequency and longer durations at timescales of 12-, 18-, and 24-months. It was also observed that SPI overestimated drought severity during dry winter months while SPEI showed higher spatial coverage of drought vulnerability compared to SPI. Spatial and temporal trends of droughts showed significant wetting trends during the period 1960–1979 while during the entire period it was mostly drying tendencies after 1979/80. Pandamatenga and Shakawe showed higher vulnerability towards drying conditions during the period of analysis. The association between SPI and *SPE*I was also investigated using Spearman's rank correlation. Results from this analysis indicate that SPI accounts for > 50% of the variations in SPEI and the association was strongest (96%) at 12-months timescale. The influence of temperature on drought evolutions was demonstrated at Francistown with SPI recording positive trends and SPEI negative ones. This study concludes that with the ongoing global warming, SPEI proves more robust in characterizing droughts in semiarid areas. It is hoped that findings from this study will augment ongoing efforts of mitigating negative impacts of increased incidences of climate variability especially in areas of agriculture and water resource management.

1. Introduction

The advent of global warming and increased incidences of climate variability have made understanding of drought evolution more complex and yet drought severity has increased both in magnitude and duration in the recent past (Cook et al., 2014; Dai, 2011; Huang et al., 2016). Droughts manifests differently from other natural hazards such as floods (Heim Jr., 2002; Homdee et al., 2016; Van Loon and Laaha, 2015) in that their onset and cessation is not clearly defined. Droughts manifest in different forms at various time intervals. Drought initially occurs as a result of below normal rainfall for extended periods often referred to as meteorological drought (Sheffield et al., 2012; Van Loon, 2013; Vicente-Serrano et al., 2012). Continued below normal rainfall conditions will have drought progressing into agricultural, hydrological and later into social economical drought (IPCC, 2012; Masud et al., 2015; Wilhite, 2000). For this reason it is important to investigate drought severity at various timescales, sometimes over the year, to understand drought effects on various components of the hydrological cycle. However with the current global temperature rise, there has been a reported increase in evaporative demand further exerting pressure on water and agricultural resources (Vicente-Serrano et al., 2014; Wang et al., 2012). Nevertheless, it is not yet clear if indeed temperature rise automatically translates into increased evaporative demand since one school of thought argues that other meteorological variables such as

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wind, relative humidity and sunshine hours may not have varied to the same degree as temperature (McEvoy et al., 2012; Roderick et al., 2007; Vicente-Serrano et al., 2014). It thus becomes necessary to use more than one avenues of quantifying droughts to identify the most appropriate for a particular location of interest.

Due to the complexity of droughts, it is even more difficult to quantify them. The absence of direct methods to measure drought has prompted the use of drought indices which are proxies of drought impacts on hydrological systems (Sheffield et al., 2012; Shukla et al., 2011; Svoboda et al., 2016). Over time a number of drought indices have been developed and used in different parts of the globe to characterize droughts and their propagation in different compartments of the hydrological cycle. Some of the drought indices currently used are the Palmer drought severity index (PDSI) (Palmer, 1965), Drought severity index (DSI) (PaiMazumder et al., 2013), Standardized precipitation index (SPI) (McKee et al., 1993) and more recently Standardized precipitation and evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010) for characterizing climatic droughts. Soil moisture index (SSI) (Golian et al., 2015) and standardized stream flow index (SFI) (Byakatonda et al., 2018; Nalbantis and Tsakiris, 2009) have also been used to study drought propagation in the soil profile and overland flow respectively. In spite of these numerous drought indices, there are no clear guidelines on the most suitable drought index. However, the World Meteorological Organization (WMO) recommends that the choice of a particular index should depend on the availability of data and ease to apply (Masud et al., 2015; Svoboda et al., 2016). This study proposes to investigate the ability of SPI and SPEI to detect and characterize climatic droughts in Botswana. The choice was premised on the need to establish if indeed global warming has had an impact on drought characteristics across the study area due to its location in a semiarid region. Both these indices are multiscalar, only that SPI is precipitation dependent whereas SPEI incorporates both precipitation and evaporation. With the undeniable effects of climate change across the globe, it has become increasingly necessary to study the temporal and spatial variability of drought severity globally as a result of changing climate. This is even more vital in semiarid regions such as Botswana with endemic water shortages (GOB-MMEWR, 2006; Statistics Botswana, 2009). This intervention could help to improve drought preparedness and mitigation measures towards minimizing impacts of global warming in Botswana. The close interaction of drought and the hydrological cycle makes it imperative to generate knowledge on changing patterns of drought severity for sustainable water resources management (Das et al., 2016; He et al., 2015; Oguntunde et al., 2014).

Several studies have been conducted across the world in recent times to investigate drought characteristics and their trends. Das et al. (2016) investigated trends in drought severity using Mann-Kendall and Sen's slope estimator across India and reported increasing trends during the Monsoon in the east and central regions. He et al. (2015), while using SPI, were able to characterize droughts in southern China. Their study revealed that the region was more prone to both floods and droughts. Still in China, Liu et al. (2016) also characterized droughts at timescales of 1-, 3-, 6-, 12- and 24-months using SPI and SPEI in the Loess region. They reported weaker trends with SPEI compared to SPI. In Canada, Masud et al. (2015) investigated meteorological droughts using both SPI and SPEI. Through their study, it was concluded that the southern locations were more vulnerable to droughts. Golian et al. (2015) also applied two drought indices (SPI and SSI) to quantify drought severity in Iran. They applied the Mann-Kendall test and found that the northern and central regions of Iran were experiencing increasing trends in droughts. Increasing trends in drought severity in southern Europe were equally investigated by Vicente-Serrano et al. (2014) using various indices including SPI, SPEI and standardized stream flow index (SFI). Their study reported increased evaporative demand as a result of increasing temperature during the study period. In Bolivia, droughts were characterized by decadal variations by Vicente-Serrano et al. (2015). They also applied SPI and SPEI to characterize these droughts. They reported lower drought severity trends in the Amazon region. Edossa et al. (2014) also studied drought severity in South Africa and found drying tendencies mainly attributed to El Niño southern oscillation (ENSO) influence.

Botswana has been selected as a study area due to its location in a semiarid region with past incidences of more severe and frequent droughts (Byakatonda et al., 2018b). The most severe drought on record is the recent occurrence of 2015/16. This drought caused heavy agricultural losses and water shortages including drying of Gaborone dam which is the main source of water supply to the county's capital. In Botswana although SPI has been applied to study drought characteristics by Batisani (2011), trends in drought severity were not investigated. In another related study, Moalafhi et al. (2017) used SPI as one of the drought indices to assess performance of the Weather Research and Forecasting (WRF) model against mostly global gridded precipitation dataset over the Limpopo river basin. This basin is shared by four southern African member countries including Botswana. In their findings they reported that gridded data exhibited comparable characteristics with observed data. However use of gridded data has its own challenges as it sometimes lacks local attributes in terms of topography and vegetation effects (Usman and Reason, 2004). For this reason, the current study proposes the use of station based meteorological data. It is evident that SPI and SPEI have been extensively used globally but indices developed for one region may not be extrapolated to other regions (Dai, 2013; Heim Jr., 2002; Mishra et al., 2015). It is therefore necessary to adapt and test the ability of specific indices to characterize droughts locally. Besides, it is also necessary to periodically update these indices and detect any changes to facilitate regional water resource planning and management.

Due to the fact that SPI has been widely applied to characterize climatic droughts across southern Africa, Botswana inclusive and with the advent of global warming, it has become imperative to introduce SPEI with an evapotranspiration (ET) component. Hence this study attempts to appraise the ability of these two indices in detecting and characterizing climatic drought. The SPEI retains attributes of PDSI because of the ET component while maintaining the multiscalar nature of SPI (Byakatonda et al., 2016; Svoboda et al., 2016; Vicente-Serrano et al., 2010). The present study therefore intends to investigate drought characteristics and their temporal trends across Botswana at timescales of 1-, 3-, 6-, 12-, 18- and 24-months using SPI and SPEI. The study specific objectives are: (i) To characterize drought severity using SPI and SPEI at timescales of 1-, 3-, 6-, 12-, 18- and 24-months, (ii) Assess trends in drought severity using Mann-Kendall and Sen's slope estimator and (iii) Determine the association between SPI and SPEI across timescales using Spearman's correlation. The varied timescale allows investigation of the behavior of these climatic droughts as they interact with various components of the hydrological cycle. The 1–3-months timescale allows quantification of short term precipitation shortfalls and often referred to as meteorological or climatological drought. 3–6-months timescale accounts for moisture deficit over an agricultural season (Byakatonda et al., 2018c). This drought category is normally referred to as agricultural drought. The 6–12-months timescale depicts seasonal to medium term moisture deficits. It is an aggregation of deficits over an entire season say wet or dry season. Lastly, the 12–24 months timescale provides information on long term droughts which can be linked to river flow, reservoir storage and in some extreme circumstances to ground water storage. It is also often referred to as hydrological drought (Hayes et al., 2011).

2. Study area and data

2.1. Study area

Botswana, which is located in southern Africa, is situated between 18°S and 27°S often referred to as mid-latitudes. It also stretches between 20°E and 30°E, bordering Namibia, Angola, Zambia, Zimbabwe