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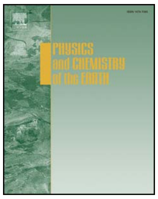

Relating the dynamics of climatological and hydrological droughts in semiarid Botswana

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ABSTRACT

Dynamics of droughts have been an associated feature of climate variability particularly in semiarid regions which impact on the response of hydrological systems. This study attempts to determine drought timescale that is suitable for monitoring the effects of drought on hydrological systems which can then be used to assess the long term persistence or reversion and forecasts of the dynamics. Based on this, climatological and hydrological drought indices characterized by Standardized precipitation evapotranspiration index (SPEI) and Standardized flow index (SFI) respectively have been determined using monthly rainfall, temperature and flow data from two major river systems. The association between climatological and hydrological droughts in Botswana has been investigated using these river systems namely: Okavango that is predominantly a storage type and Limpopo which is non-storage for a period of 1975–2014. Dynamics of climatological and hydrological droughts are showing trends towards drying conditions at both river systems. It was also observed that hydrological droughts lag climatological droughts by 7 months in Limpopo and 6 months in Okavango river systems respectively. Analyses of the association between climatic and flow indices indicate that the degree of association becomes stronger with increasing timescale at the Okavango river system. However in the Limpopo river system, it was observed that high timescales of 18- and 24-months were not useful in drought monitoring. 15-months timescale was identified to best monitor drought dynamics at both locations. Therefore SPEIs and SFIs computed at 15-months timescale have been used to assess the variability and long term persistence in drought dynamics through rescaled range analysis (R/S). H-coefficients of 0.06 and 0.08 resulted for Limpopo and Okavango respectively. These H-coefficients being significantly less than 0.5 is an indication of high variability and suggests a change in dynamics from the existing conditions in these river systems. To forecast possible changes, the nonlinear autoregressive with exogenous input (NARX) artificial neural network model has been used. Results from this model agree with those of the R/S and projects generally dry conditions for the next 40 months. Results from this study are helpful not only in choosing a proper timescale but also in evaluating the futuristic drought dynamics necessary for water resources planning and management.

1. Introduction

Drought is a form of hydrological extreme that is wide spread in temporal and spatial extent and is often referred to as ‘creeping disaster’ (Kundzewicz and Kaczmarek, 2000; Mishra and Singh, 2010; Van Loon, 2013). Impacts from droughts are likely to increase with the current rise in global temperature and reduction in precipitation (Dai, 2013, 2011; Solomon, 2007; Wada et al., 2011). Drought is not region specific, however most severe impacts of drought on population are seen to occur in arid and semiarid areas where available water resources are scarce even under normal conditions and the dwellers have limited adaptability options (De Stefano et al., 2012; Masih et al., 2014; Van Loon, 2013). This calls for studies on drought characteristics which will help in formulation of effective management strategies specific to these areas. Droughts have various definitions and classifications according to Wilhite (2000) and Sheffield et al. (2012). For purposes of this study, we shall confine ourselves to two common classifications viz: climatological and hydrological droughts. Climatological drought is defined as below normal precipitation coupled with increase in potential evapotranspiration covering large spatial extents for prolonged time periods (Rimkus et al., 2013; Van Loon, 2013; Van Loon and Laaha, 2015). While hydrological drought on the other hand is associated with below

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average surface water flow for prolonged periods (Feyen and Dankers, 2009; Mishra et al., 2015; Smakhtin and Hughes, 2004). Hydrological droughts depend on a number of processes including the atmosphere and a host of other factors in the terrestrial part of the hydrological cycle that govern moisture transport (Mishra and Singh, 2010; Rimkus et al., 2013; Van Loon, 2013). The atmospheric processes that govern both climatological and hydrological droughts are believed to be linked to climate variability and change (Jung et al., 2010; Lorenzo-Lacruz et al., 2010; Van Loon, 2013). Response of hydrological systems are closely associated with climatic conditions in that decrease in precipitation with rising temperatures, increases potential evapotranspiration which leads to depletion of water and moisture storage (Lorenzo-Lacruz et al., 2010; Van Loon, 2013; Vicente-Serrano and López-Moreno, 2005). All these interactions between climatic and hydrological process are a function of a timescale. Since the hydrological systems respond at varying timescales, it calls for determination of that particular timescale at which a high degree of association between climatic and hydrological conditions exist to facilitate proper drought management. Semiarid regions have been known to generally experience high climate variability resulting in varying drought severity and impacts (Bazza, 2002; Wilhite et al., 2007). In view of this, better understanding of drought severity needs to be represented through drought indices which are proxies of drought impacts in a broader scale (Hayes et al., 2011; Rimkus et al., 2013; Svoboda et al., 2001). Both climatic and hydrological indices are proposed to be determined at various timescales to characterize drought dynamics (Lorenzo-Lacruz et al., 2010; Nalbantis and Tsakiris, 2009). The Standardized precipitation evapotranspiration index (SPEI) which incorporates both precipitation and temperature (Svoboda et al., 2016; Vicente-Serrano et al., 2010) to determine drought severity is proposed for use in explaining the dynamics of climatic drought under variable climate. Similarly, Standardized flow index (SFI) which is analogous to SPEI and standardized precipitation index (SPI) in their multiscalar nature has been proposed to be used to quantify the hydrological droughts (Byakatonda et al., 2016; Lorenzo-Lacruz et al., 2010; Nalbantis and Tsakiris, 2009; Svoboda et al., 2016; Trambauer et al., 2014). It is in this context that it may be necessary to determine the commonality in timescale for both the SPEI and SFI such that a general procedure can be established to determine such indices across the region covering various watersheds. However in recent times, it has also been observed that droughts often extend over longer timescales sometimes over the years with continued dry spells into the next hydrological year hence impacting on stream flow and over-the-year reservoir storage. This has been attributed to increased incidences of climate variability under global warming scenarios in semiarid locations (Dai, 2013; Huang et al., 2016; Masih et al., 2014). It hence becomes imperative to investigate variability and long term persistence or possible reversion in the drought dynamics. To achieve this, the study proposes the use of rescaled range analysis (R/S) with its associated Hurst coefficient to investigate variability in the dynamics at an identified timescale (Hurst, 1951; Koutsoyiannis, 2003). Additionally for the benefit of operational hydrologists and water managers, it may be necessary to develop a likely futuristic scenario over a limited period such that necessary drought management strategies if required could be developed. Drought being complex and nonlinear in nature, use of artificial intelligence oriented models such as artificial neural networks (ANN) have been proposed to be utilized in development of futuristic drought severity dynamics. A Nonlinear autoregressive with exogenous input (NARX) neural network model has been selected for use in this study to develop the likely scenarios across the river systems. This model has been successfully applied in complex hydrological time series simulations and proven to outperform other network configurations (Byakatonda et al., 2018a, 2018b, 2016; Chang et al., 2014; Menezes and Barreto, 2008). Hence this study attempts to determine dynamics of climatic and hydrological droughts at timescales of 3-, 6-, 12-, 18- and 24-months. The study further determines the drought timescale that is suitable for assessing the effects of climatic droughts on hydrological systems at the same time evaluates variability in the dynamics at the identified timescale. Climatic drought indices are also simulated over a medium time period of 60 months.

2. Materials and methods

2.1. Study area

Botswana which is located in the mid-latitudes lies between 16° S and 29° S, it is classified as arid to semiarid (FAO, 2001). The annual rainfall ranges from 300 mm in the southwest to 600 mm in the northeast with rain onset in November and ceding in March (Byakatonda et al., 2018b). It is reported that about 90% of the rainfall is received during the summer months of November, December and January (GOB-MMEWR, 2006). Botswana is selected as a study area due to its semiarid location. The study area has been reported to be experiencing low rainfall with increasing temperatures in the recent past (Batisani, 2012; Kenabatho et al., 2012; Parida and Moalafhi, 2008). Besides, precipitation is the main source of fresh water supply in Botswana with Limpopo river system being a host to most dams that supply majority of the water both for domestic and industrial use (GOB-MEWT, 2012). The main challenge Botswana faces in development of surface water storage are the recurrent droughts and high rates of evaporation which range from 1800 to 2100 mm/yr, exceeding the annual rainfall (Byakatonda et al., 2016). This is mainly as a result of high temperatures experienced during the summer rain season as shown in Figs. 2a and 3a. The water resources in the study area are mainly confined in four river systems viz: Okavango, Makgadikgad, Limpopo and Orange (GOB-MMEWR, 2006). The main rivers in Botswana are transboundary making water resources development a multi stakeholder involving process. The Okavango and Limpopo which are transboundary have more perennial water sources on which Botswana depends. Most of the inland water sources drain to the Limpopo river system which is used for water supply. This study used Limpopo and Okavango river systems as study sites (Fig. 1).

2.2. Datasets

2.2.1. Meteorological data

Climatic data comprising of monthly rainfall, maximum and minimum temperature were obtained from the Department of Meteorological Services (DMS) of Botswana for a period 1975–2014. The data is from 6 synoptic stations, 3 from each of the river systems as shown in Fig. 1. Number of earlier studies in the region have reported a shift in the climatic regime since 1980/81 (Parida and Moalafhi, 2008). The shift may be attributed to inhomogeneity in the climatic time series. For this reason, homogeneity tests were carried out on the data from the 6 synoptic stations used in this study. The homogeneity testing techniques applied include the standard normal homogeneity test (SNHT) (Alexandersson, 1986; Alexandersson and Moberg, 1997), Pettit test (Pettit, 1979) and the Buishand test (Buishand, 1982).

2.2.2. Hydrological data

The hydrological data was provided by the Department of Water Affairs of Botswana (DWA). The data consisted of monthly discharge recorded at Mohembo on River Okavango for a period from 1975 to 2014. The second gauging station was recorded at Buffel drift on River Limpopo with data spanning from 1997 to 2014. These stations were selected due to availability of consistent data with less than 10% missing values.

2.2.2.1. Okavango river system. The main river that supplies this system is River Okavango which enters Botswana from Angola at Mohembo (Fig. 1) and ends up as delta. The river system has been classified as a Ramsar site and therefore has restrictions on the extent of water