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Characterisation and prediction of meteorological drought using stochastic models in the semi-arid Chéliff–Zahrez basin (Algeria)

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ABSTRACT

Study region: North Algeria.
Study focus: The semi-arid to arid Chéliff–Zahrez basin faced several droughts with severe impacts on agriculture due to the high temporal and spatial distribution of rainfall. We explored the potential of the Standardized Precipitation Index (SPI), Markov chain models, the Drought Index and time series modelling to characterize meteorological drought. Time series of annual precipitation (1960–2010) from 65 meteorological stations across the basin were used. The basin was subdivided into five subbasins to account for spatial variability.
New hydrological insights for the regions: The analysis of the Standardized Precipitation Index showed few droughts in the period 1960–1970, whereas in the 1990s a multi-year drought occurred with SPIs as low as −2 (extremely dry) in many subbasins. The Markov chain analysis learnt that the probability of having two consecutive drought years appears to be higher in the southern subbasins. The Drought Index derived from transition probabilities indicates that the southern and the southwestern parts of the Chéliff–Zahrez basin are most drought prone. Time series modelling was applied to compute the SPI for different return periods (6-17 years). Eleven models were tested and it appeared that the Asymmetric Power Autoregressive Conditional Heteroskedasticity (APARCH) approach was best performing based on several information criteria. For a return period of 17 years, the SPI is lower than −1.5 (severely dry) in many subbasins.

1. Introduction

Algeria is known for its multi-year droughts. Long-lasting below normal rainfall in a semi-arid climate has devastating impacts on Algerian agriculture. Particularly, the western part of the country has experienced several major droughts during the 1940s and since the 1970s (Meddi and Hubert, 2003; Meddi and Meddi, 2009). Seltzer (1946) already presented a detailed analysis of rainfall across Algeria. He noted that variability in annual rainfall (1911–1938) in the high plains and the Saharan Atlas is less sensitive than in the northern regions of Algeria. Demmak (1982) compared rainfall departure from the average (deficit) in the period 1974–1992 with the deficit from the period 1913–1963 in Northern Algeria and found drier conditions in the last period, although some years in the first period also were dry (e.g. 1913 and 1940). They observed an increased deficit from east to west. Farmer and Wigley (1985) and Kadi

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(1995) reported on widespread drought during some years (i.e. 1937, 1961 and 1970). Matari and Douguedroit (1995), who divided West Algeria in several regions, noted that the 1940s drought is mainly due to a lower spring rain and those of 1980s to a decreased winter rain. The rainfall deficits in Northern Algeria are triggered by climate drivers, such as ENSO (El Mahi et al., 2012). The reported rainfall deficits caused serious socio-economic problems and it anticipated future deficits will impose increasing pressure on the scarce Algerian water resources, among others for supply of drinking water and irrigation (Khaldi, 2005). Adequate water resources management that is based on sound data should cope with these pressures, which particularly are felt during drought episodes. These data include both the state of an ongoing drought (monitoring, characterization) and drought states that can be expected on the basis of past events (prediction).

Drought is a relative phenomenon meaning that it is a deviation from normal hydrometeorological conditions. It deviates from aridity, which is a permanent feature of a dry climate (in this study low average rainfall), and is not water scarcity (long-term unsustainable use of water resources) (e.g. Wilhite and Glantz, 1985; Wilhite, 2000; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Sheffield and Wood, 2011). Indices are used to characterize the state of a drought. Many indices have been proposed depending on the aspect of the natural hazard that is addressed; impacted sector and on the scientific approach (e.g. Reyes-Gómez et al., 2006; Niemeijer, 2008; Wanders et al., 2010). Munger (1916) was one of the first, who proposed a drought index. The Blumenstock Index (Blumenstock, 1942) and the antecedent precipitation index (McQuigg, 1954) are other early phase examples. Palmer (1965) proposed the Palmer Drought Severity Index (PDSI), which depends on the soil water budget and it uses precipitation and temperatures data. The PDSI is widely used (e.g. Dalezios et al., 2000; Kim et al., 2003; Dai, 2012), but it has, despite using multiple sources of observations (precipitation and temperature) several limitations, among others the soil water balance used, including the approach to calculate the potential evapotranspiration, the temporal scale, the physical interpretation, inability to compute recurrence probabilities (e.g. Alley, 1984; Guttman, 1991, 1998; Guttman et al., 1992; Sheffield et al., 2012). Another, even more widely used drought index is the Standardized Precipitation Index (SPI), which was first developed by McKee et al. (1993). There are many drought studies using the SPI in different ways (e.g. Morid et al., 2006; Edossa et al., 2010; Pandey et al., 2010; Vasiliades et al., 2010; Vangelis et al., 2010; Orlowsky and Seneviratne, 2013; Joetzjer et al., 2013; Abdoulaye et al., 2014). The SPI also has been recommended by the World Meteorological Organization (WMO, 2006, 2012) as a drought indicator. In this study the SPI has been selected as the drought index.

SPI time series can be used to characterize the at-site severity of historic and ongoing drought events. Additionally, it can also be applied to predict sequences of drought and non-drought phases by using Markov chains. Markov chains have been widely used to analyse hydrometeorological conditions, see Paulo and Pereira (2007). More specifically for drought, Markov chains were used for transition probabilities of: (i) SPI (Edossa et al., 2010), (ii) hydrological drought characteristics (Dilek Eren et al., 2011), and (iii) water deficits (Arasteh and Mianehrow, 2004) in Central Iran. Markov chains also have been applied to investigate drought in Algeria. For instance, Meddi and Meddi (2009); Meddi et al., (2013a,b) found on the basis of precipitation data from the period 1930–2003 that in the western plains a dry year tend to be followed by another dry year (i.e. persistence). On the contrary, in the centre of the country the probability of a non-dry year after a dry year is higher than in the west. Lazri et al. (2015) used Markov chains to show that probability on a severe drought will considerably increase around 2041 relative to 2005. The at-site SPI analysis also has the potential for regionalisation. In several studies regionalization of hydrometeorological variables has been investigated. For example, in Algeria, Souag-Gamane et al. (2007) simulated daily rainfall fields in a semi-arid zone by principal component analysis, and Mehaiguene et al. (2012) regionalized flows and base flow in north-west. The SPI time series also offer the opportunity to estimate probabilities of SPI values (e.g. return periods of particular drought severity) by exploring theoretical models that describe the observed values. Wang et al. (2009) compared performance of several time series models to predict monthly discharge time series. Mishra and Desai (2005) applied ARMA and ARIMA models to forecast droughts using SPI series for the river Kangsabati (India).

The purpose of this study is to provide quantitative information on meteorological drought (Standardized Precipitation Index, SPI) for North African semi-arid climatic conditions using stochastic models, i.e. (i) at site and spatially-distributed probabilities on temporal transitions using Markov chains, (ii) recurrence probabilities using the best-suited time series model. It demonstrates for a North-Algerian river basin how a set of stochastic models can be developed to obtain probabilistic information on meteorological drought, which is essential for short- and long-term decisions on land and water management, in particular the development of land use, including rainfed and irrigated agriculture.

The paper starts with a general description of the Chéliff–Zahrez basin in North Algeria, including the precipitation data used, which we apply to show the potential of stochastic models to quantify meteorological drought for semi-arid conditions. Next, we give a brief description of the SPI, the stochastic models that we apply in this study with reference to the literature, i.e. Markov chains, including the regionalization approach, and the set of times series models, including the comparison criteria we used to select the best-performing model. The results include: (i) probabilities on transition (two states: dry and wet) for each rain station (at site) for the 1st order Markov chain, (ii) maps on the probabilities on transition for the Chéliff–Zahrez basin for the 1st order Markov chain, and (iii) at-site SPI for different return periods obtained with the best-suited time series model. Eventually, the detailed results for the Chéliff–Zahrez basin are compared with the outcome of more generic studies on meteorological drought in the region, and conclusions are given.

2. Study area

The Chéliff–Zahrez basin is located in the north of Algeria (Fig. 1). It occupies an area of 56,227 km^2 (0°18′–3°30′ East and 33°53′–36°34′ N). The basin is subdivided in five subregions, i.e. the Chéliff upstream Boughzoul and Zahrez, the Upper and Middle