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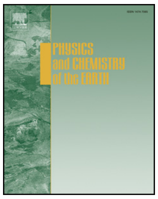

Drought dynamics and interannual rainfall variability on the Ghaap plateau, South Africa, 1918–2014

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ABSTRACT

With drought expected to increase in frequency and severity as a result of climate change, drought and rainfall variability assessments at interannual time scales using long-term rainfall data are necessary to develop drought mitigation strategies and planning measures, especially in semi-arid and arid environments where drought impact is expected to be adverse. The objective of this study was to determine the occurrence and severity of droughts and interannual rainfall variability trends in the Ghaap plateau, Northern Cape Province, South Africa. This study was based on long-term rainfall data for three meteorological stations (Postmasburg, Douglas and Groblershoop) from 1918 to 2014, sourced from the South African Weather Services (SAWS). Calculation of the Standardized Precipitation Index (SPI) showed that more droughts occurred since the 1990s; these droughts were all moderately dry with SPI values ranging between −1.03 and −1.46, except for the 1992 drought at Groblershoop which was severe. The longest drought duration on record in the study area was 2 years. Fitting of the long-term rainfall data to a non-parametric spline smoother revealed that the total annual rainfall, number of rainfall days and extreme rainfall events were essentially stable. The total annual rainfall, however, followed a secular pattern of fluctuations over the years.

1. Introduction

Drought - a complex natural hazard characterised by below-normal precipitation beyond a given threshold over time, impacts ecosystems and society in several ways (Dai, 2011; Vincente-Serrano et al., 2011; Van Loon, 2015). Drought affects terrestrial ecosystems leading to changes on the spatial and temporal patterns of vegetation (Fernandez-Illescas and Rodriguez-Iturbe, 2004; IPCC, 2014; Gudmundsson et al., 2014; Taufik et al., 2015), aquatic degradation (Lake, 2003) and food web structure (Ledger et al., 2013). In addition, drought results in water shortage, threatening irrigation for crop production, electricity generation and impairing water quality (Wilhite, 2000; Tallaksen and Van Lanen, 2004; Sheffield and Wood, 2007; van Vliet et al., 2012). Conventionally, drought is classified into four types: meteorological, hydrological, agricultural and socio-economic. The latter form of drought may be considered a consequence of one or more of the other types of drought. The meteorological drought, which is the focus of the present study, occurs as a result of precipitation shortage for prolonged period of time (Keyantash and Dracup, 2002; Batisani, 2011; Dai, 2011).

Various indices have been developed and applied to quantify and monitor meteorological drought development. These include discrete and cumulative precipitation anomalies, rainfall deciles, Palmer Drought Severity Index (PDSI), Drought Area Index (DAI) and Rainfall Anomaly Index (RAI) (Heim, 2000, 2002; Keyantash and Dracup, 2002; Vincente-Serrano et al., 2011; Dai, 2011). The precipitation anomalies and deciles are simple to compute, but they are especially less informative and can easily show end of a drought period even if the precipitation received is not enough to terminate the water shortage. Even though the PDSI, DAI and RAI are robust, they involve complicated computations and are not versatile. DAI for instance was developed specifically for Indian conditions. In addition to these indices is the Standardized Precipitation Index (SPI) which is based on long-term precipitation data fitted to probability distribution functions (McKee et al., 1993; Guttman, 1998; Komuscu, 1999; Jain et al., 2015; Van Loon, 2015).

The SPI is recommended because of its accuracy and simplicity (Guttman, 1998; Komuscu, 1999; Jain et al., 2015), and versatility allowing it to also detect the occurrence of wet spells at different time

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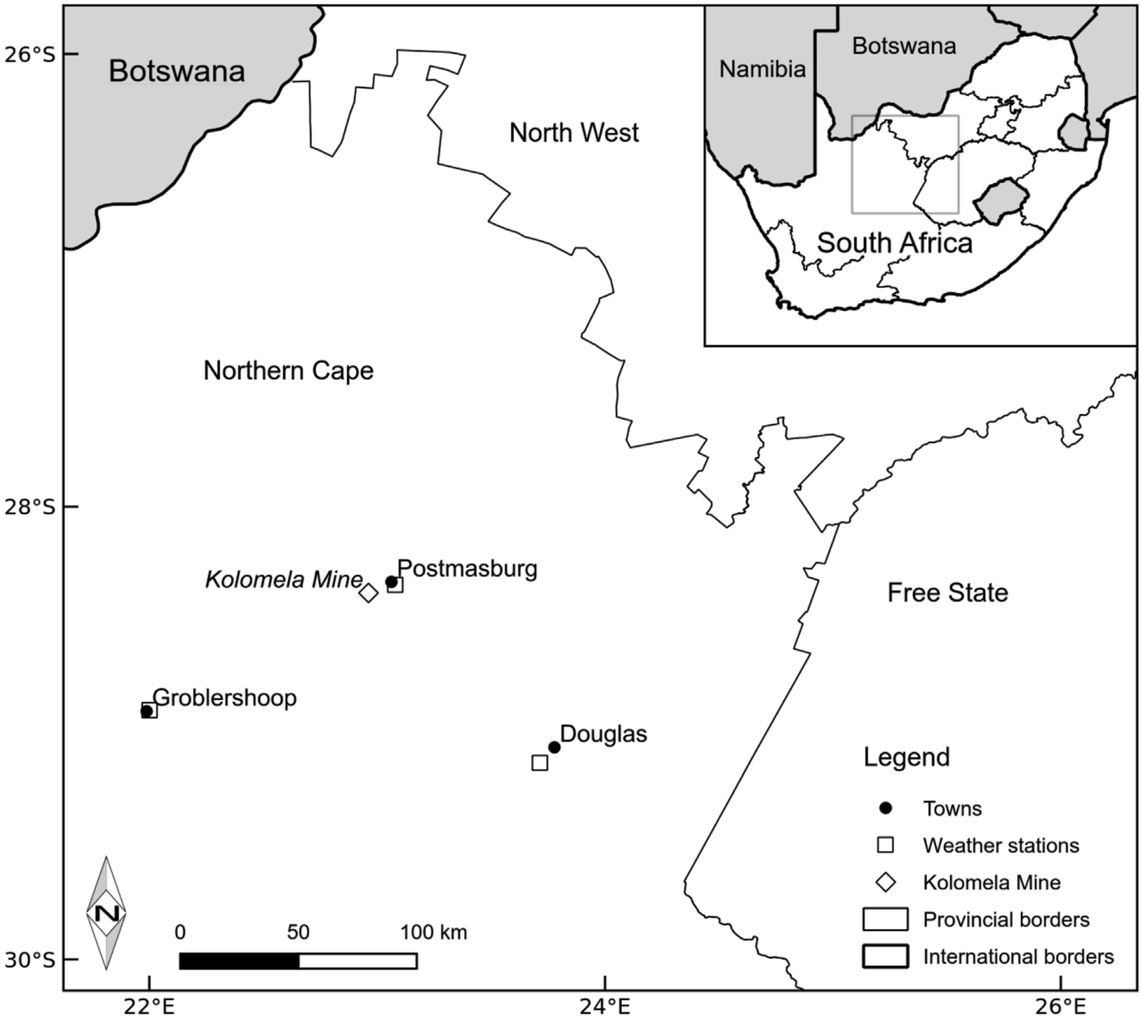

Fig. 1. Location of selected weather stations in the Northern Cape Province, South Africa used for the characterizing drought and analysis of rainfall trends.

scales (Xie et al., 2013; Van Loon, 2015), and is applicable to detect even the hydrological and agricultural droughts. For instance, at time scales of up to 6 months the SPI is useful for agricultural planning, while at longer time scales it is utilised to detect hydrological drought essential for monitoring groundwater levels, stream flows and dam levels (Batisani, 2011). This versatility of the SPI makes it relevant across different sectors such as groundwater management during mining operations, agricultural water management and sustainable management of nature (flora and fauna). The SPI has been applied effectively in dryland regions (Manatsa et al., 2008; Batisani, 2011; Al Asheikh and Tarawneh, 2013).

In the future, droughts are expected to increase in frequency and severity as a result of climate change which will effect decreases in regional rainfall, but also because of increasing evaporation driven by global warming (Sheffield and Wood, 2008; Dai, 2011). According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), more intense and longer droughts have been observed globally, particularly in the tropics and subtropics since the 1970s (IPCC, 2012). In Southern Africa, which is largely semi-arid and characterised by high interannual rainfall variability, droughts occur with high frequency and severity, and El Niño Southern Oscillation (ENSO) has been established to be the major driver (Manatsa et al., 2008). In South Africa, Rouault and Richard (2003) analysed drought using the SPI between 1921 and 2001 and found that droughts have become more prevalent since the 1960s, and more intense within the last 2 decades.

Indeed, the SPI is an attractive tool for detecting the occurrence of drought at specific times within a historical precipitation record. But, it does not account for rainfall trends at inter-annual time scales which may also be linked to the ENSO. Yet, a better understanding of inter-annual rainfall trends is also important for developing rainfall runoff relationships, which are crucial for agricultural and water resources management (Kampata et al., 2008; Parida and Moalafhi, 2008; Tfwala et al., 2017). This is particularly important for a country like South Africa, which is characterised by high prevalence of droughts and erratic rainfall events (Schulze, 2008).

Drought assessments using long-term rainfall data are important at local, regional and continental scales (Masih et al., 2014). Although drought events are increasing in South Africa (Kruger, 2006; Rouault and Richard, 2003), they remain poorly described in the Ghaap plateau despite the field observation that natural vegetation is on the verge of "ecological collapse" due to climate change. As drought occurrence and rainfall variability are some of the main factors driving agricultural activities and nature conservation in these drylands, accurate quantitative information of not only drought, but also interannual rainfall variability are needed to provide context-specific guide on the development and implementation of better drought mitigation strategies and improved planning measures. The objective of this study was to determine the occurrence and severity of droughts and interannual rainfall variability trends in the Ghaap plateau, Northern Cape Province, South Africa. The plateau falls within arid and semi-arid climatic zones, making it more prone to the adverse impacts of drought and related

Table 1
Geographical positions, elevation, data recording years, average annual rainfall (Av.R), reference evapotranspiration (ETo) and aridity index (AI) for Postmastburg, Douglas and Groblershoop in the Ghaap plateau.

Weather station	Latitude	Longitude	Elevation (m)	Period	Years	Av.R (mm)	ETo (mm)	AI
Postmasburg	−28.35	23.08	1323	1918–2014	97	317	1710	0.19
Douglas	−29.13	23.71	1013	1960–2014	55	312	1586	0.20
Groblershoop	−29.90	22.00	871	1939–2014	76	201	1641	0.12

rainfall variability.

2. Materials and methods

2.1. Site description

Ghaap Plateau is situated between Kimberley and Upington, north of the Orange River to the Kuruman Hills. Its altitude varies between 900 and 1600 m above sea level. The topography is comprised of undulating hills, with moderate slopes and flat plains. The mean annual precipitation ranges between 250 and 400 mm, majority of it falling between November and April. July is the driest month with absolutely no rainfall while March receives the highest amount of rainfall. The average maximum temperature is 17 °C in June and 31 °C in January. The region experiences its coldest temperatures during June and July with a mean cold temperature of 0 °C.

The main economic activity on the plateau is open cast mining, which depend primarily on groundwater resources. Second to the mining activity, the population is dependent on rainfall driven activities, including agricultural production and nature conservation. The site is on shallow sandy soils of the Hutton form with red Aeolian sand of the Kalahari group overlying the volcanics and sediments of the Griqualand West Supergroup that outcrops in some places (Mucina and Rutherford, 2006). The predominant vegetation type is the Savanna Biome, which is composed of the Kuruman Mountain Bushveld and Postmasburg Thornveld.

2.2. Selection of meteorological stations and source of rainfall data

For this study, three meteorological stations (Postmasburg, Douglas and Groblershoop) were selected for analysis (Fig. 1). There are only a few long-term stations in the Northern Cape Province due to the sparse population (Kruger, 2006), and this was also confirmed a by a more recent study by Tfwala et al. (2017) that estimated precipitation intensity-duration-frequency curves and their uncertainties for Ghaap plateau. The network of recording rainfall stations in the plateau with record lengths longer than 30 years is relatively sparse. For those stations available, rainfall data contain numerous errors, inconsistencies and periods of missing data. (Tfwala et al., 2017).

In this study, rainfall stations were selected based on availability of high quality rainfall data and their proximity to the Kolomela mine, which is the main experimental site. Daily rainfall data for all the meteorological stations were obtained from the South African Weather Services (SAWS). Before analysing the data for the parameters of interest in this study, correlation analysis of the annual rainfall data between the three stations was done. The correlation for each pair of stations was calculated using the years where both of the stations in the pair in question had data. The correlation coefficients were 0.70 between Postmasburg and Douglas, 0.52 Doulas and Groblershoop and 0.34 between Postmasburg and Groblershoop. These correlation relationships were significant ($P < 0.01$), even though the correlation between Postmasburg and Groblershoop was not strong. These results suggest that the stations provide a reasonably good representation of the plateau (given the paucity if weather stations), despite the distances between them.

2.3. Calculation of aridity index

Aridity Index (AI), a numerical expression of the degree of dryness of the climate was calculated for each meteorological station (Thornthwaite, 1948). The total annual evapotranspiration (ETo) data was sourced from the Agricultural Research Council (ARC) of South Africa. AI was calculated following UNESCO (1979):

$$AI = P/ETo \tag{1}$$

Where, P is the mean annual rainfall. According to this classification, $AI < 0.03$ is hyper-arid zone, $0.03 < \ < 0.2$ is an arid zone, $0.2 < \ < 0.5$ is semi-arid zone, and $AI > 0.5$ is sub-humid. Table 1 shows the geographical position, elevation and record length of rainfall data, average annual rainfall, ETo and AI.

2.4. Calculation of standardized precipitation index

The SPI was calculated on an annual basis to identify drought years and the severity using long-term rainfall data for the three meteorological stations. The three-parameter Gamma distribution – which includes a threshold parameter – was fitted by maximum likelihood (SAS procedure UNIVARIATE) (SAS, 2013), separately to the annual rainfall data of the three meteorological stations. Where the initial estimate of threshold parameter was negative (namely for the Groblershoop and Douglas data), the scale and shape parameters of the Gamma distribution were re-estimated with the threshold parameter fixed at zero. The fitting procedure produces a histogram of the data, overlaid with the fitted Gamma distribution. Furthermore, a non-parametric Kernel density estimate of the distribution of the data was plotted together with the histogram and the fitted Gamma distribution. Given estimates, $\hat{\sigma}$ and $\hat{\alpha}$ of the threshold, scale and shape parameters of the Gamma distribution, respectively, the transformed value of total annual rainfall, in other words, the Standardized Precipitation Index (SPI), was calculated as follows:

$$SPI(x) = q_{Norm}(F(x; \hat{\lambda}, \hat{\sigma}, \hat{\alpha})) \tag{2}$$

where is the cumulative distribution function of the Gamma distribution with threshold parameter, scale parameter, shape parameter, and is the quantile function of the standard Normal distribution. The SPI categories were then used to characterise the intensity of drought as depicted in Table 2. According to Guttman (1999), negative SPI value indicates a drought year and vice versa, with the range from > -1 to < 1 regarded as normal. The longest duration of drought was taken

Table 2
A list of SPI classes describing the intensity of drought or wetness of a year in relation to the long-term average rainfall (Guttman, 1999).

SPI value	Classification
2.0 +	Extremely wet
1.5 to < 2.0	Very wet
1.0 to < 1.5	Moderately wet
> -1.0 to < 1.0	Near normal
−1.0 to > −1.5	Moderately dry
−1.5 to > −2.0	Severely dry
−2.0 and less	Extremely dry

as the longest period of successive dry years within the record of rainfall data (Al Asheikh and Tarawneh, 2013).

2.5. Determining trends of annual rainfall, rainfall days and extreme rainfall events

The trends of total annual rainfall for the three meteorological stations over time were determined by applying a non-parametric smoother to the long-term rainfall data, namely a generalized additive model assuming a Gamma error distribution and using a spline smoother. A generalized cross-validation method (SAS, 2013) was used to determine the degrees of freedom for the spline smoother such that the prediction error of the model was minimized.

Additive models generalize linear models by modelling the dependency between the mean response and a covariate through smooth non-linear functions in addition to the linear function of the covariate. Generalized additive models further accommodate distributions of the response variable other than the Normal. For a response variable y (total annual rainfall) the generalized additive model employed in this study was in the form:

$$\eta = \beta_0 + \beta_1 X + s(X) \tag{3}$$

where $\eta = g(\mu)$ is a monotonic function of the mean, $\mu = E(y)$ of the response, β_0 and β_1 are intercept and slope parameters, and $s(X)$ is a smooth function (here: non-parametric spline function) of the covariate X (here: time in years).

The Gamma error distribution was chosen because rainfall data is i) generally right-skewed, ii) non-negative and iii) has the variance that increases with the mean (heteroscedasticity). To verify the sensitivity of the Gamma distribution, the generalized additive model was also fitted assuming the Log-normal and Normal distributions (Hastie and Tibshirani, 1990; SAS, 2013).

In the same manner, the non-parametric smoother was also applied to extreme daily rainfall and to the number of rainfall days (1 mm or more). Regarding the number of rainfall days, the generalized additive model was, however, fitted assuming a Poisson Error Distribution, and the logarithm of the number of days (365 or 366 for leap years) was fitted as an offset variable. Observed and fitted (Gamma, Log-Normal and Normal) values of total annual rainfall, extreme daily rainfall and number of rainfall days were plotted using SAS.

3. Results

3.1. Drought occurrence, severity and duration

Out of the total of 97 years of records at Postmasburg (Fig. 2A), there were 4 moderately dry years. These were in the years 1993, 1994, 2012 and 2013 with SPI values of −1.26, −1.20, −1.29 and −1.4, respectively. The longest drought duration of 2 consecutive years was recorded from 1993 to 1994 and from 2012 to 2013.

With the record of rainfall data from 1960 to 2014 at Douglas (Fig. 2B), the first drought occurred in 1992 with SPI value of −1.39 followed by others in 1996 with SPI value of −1.12, 2005 with SPI value of −1.42 and lastly in 2013 with a SPI value of −1.36. All drought years at this location were moderate (SPI -1 to > -1.5). There were no consecutive dry years without an interruption of either a normal or a wet year in this location throughout the years of data record.

At Groblershoop (Fig. 2C), the drought years and wet years were consistent throughout the 76 year record period. There were 9 drought years spread from 1941 to 2012 with SPI values ranging from −1.46 to −1.03, except for 1992 which was severely dry (SPI of −1.74), the rest of the droughts were moderate. The longest drought of 2 years was recorded from 1965 to 1966.

Worth mentioning is the fact that in all the stations there have been years which were wet to extremely wet. After the year 2000, there were no wet years at Postmasburg and Douglas; At Groblershoop, where the distribution of drought years and wet years was similar throughout the study period, wet years were observed even during the last decade.

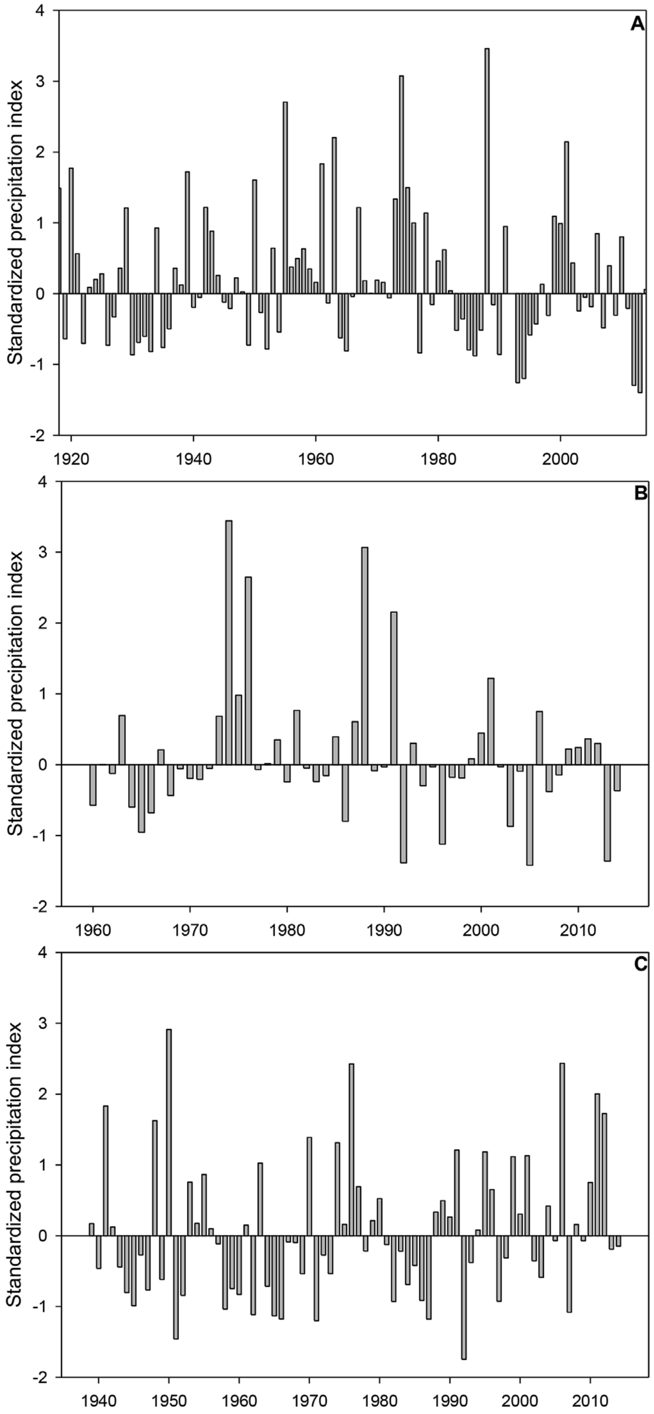

Fig. 2. Standardized Precipitation Index for (A) Postmasburg (97 years), (B) Douglas (55 years) and (C) Groblershoop (76 years) in the Ghaap plateau, Northern Cape Province, South Africa.

3.2. Trends of annual rainfall, rainfall days and extreme rainfall events

At the three meteorological stations studied, there is no evidence of an increase or decline in total annual rainfall over the rainfall data recording periods under analysis (Fig. 3A–C). However, cyclic trends ranging from 18 to 22 years were observed at Postmasburg. The difference between an adjacent pair of a peak and a trough was up to

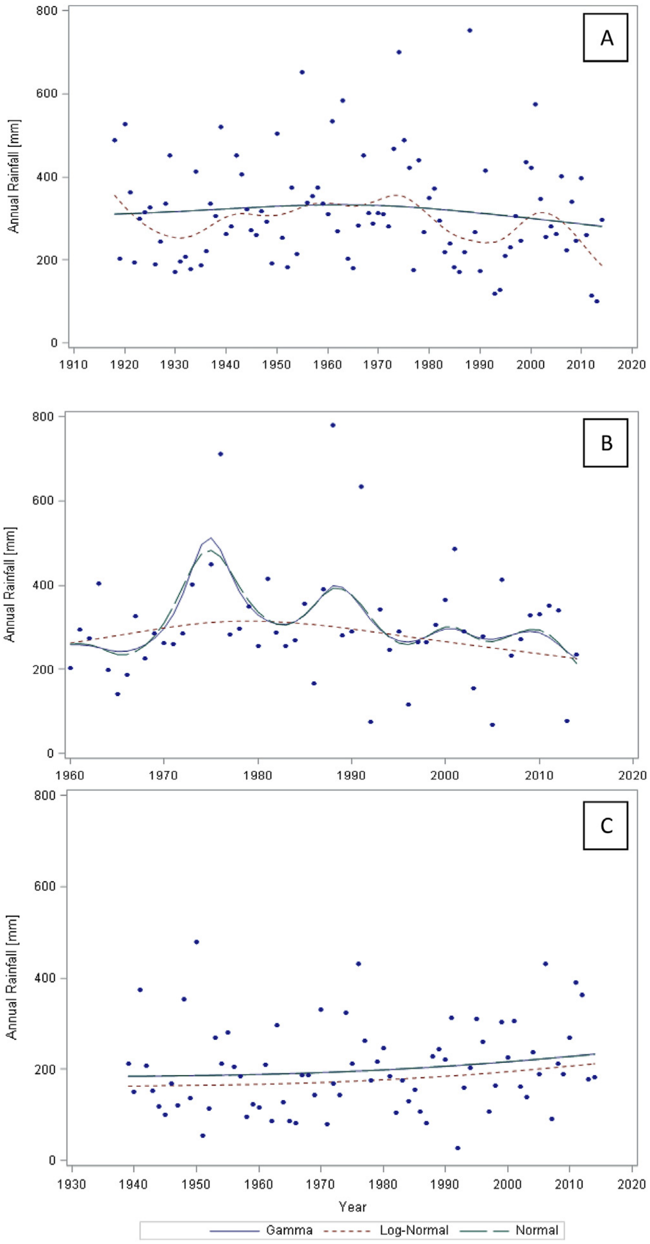

Fig. 3. Observed (dots) and fitted (lines) values of total annual rainfall for A) Postmasburg (97 years), B) Douglas (55 years) and C) Groblershoop (76 years) for the Ghaap plateau computed using Gamma, Log-normal and normal distribution functions.

90 mm. At Douglas, cycle lengths (peak to peak or trough to trough) ranged between 12 and 16 years. The difference between troughs and peaks adjacent to each was up to 250 mm at this meteorological station. Worth noting was that the differences between adjacent peaks and troughs at the two stations occasionally were small, that is, on average these differences were about 50 mm or less. Likewise, the overall rainfall trend was not showing changes at Groblershoop, where not even cyclic patterns of rainfall were evident.

The number of rainfall days (Fig. 4A–C) and the extreme rainfall events (Fig. 5A–C) seemed stable in all the meteorological stations throughout the recording period. At Douglas though, these parameters (Figs. 4B and 5B) showed some irregular fluctuations which at the end of the day even up to constant trends.

Finally, regarding the results presented in Figs. 3 and 5 we can note that the three alternative distributions used (Gamm, normal and log-normal) yield similar estimates of the long-term trends, which suggests that the results are not sensitive to the assumption of the gamma distribution.

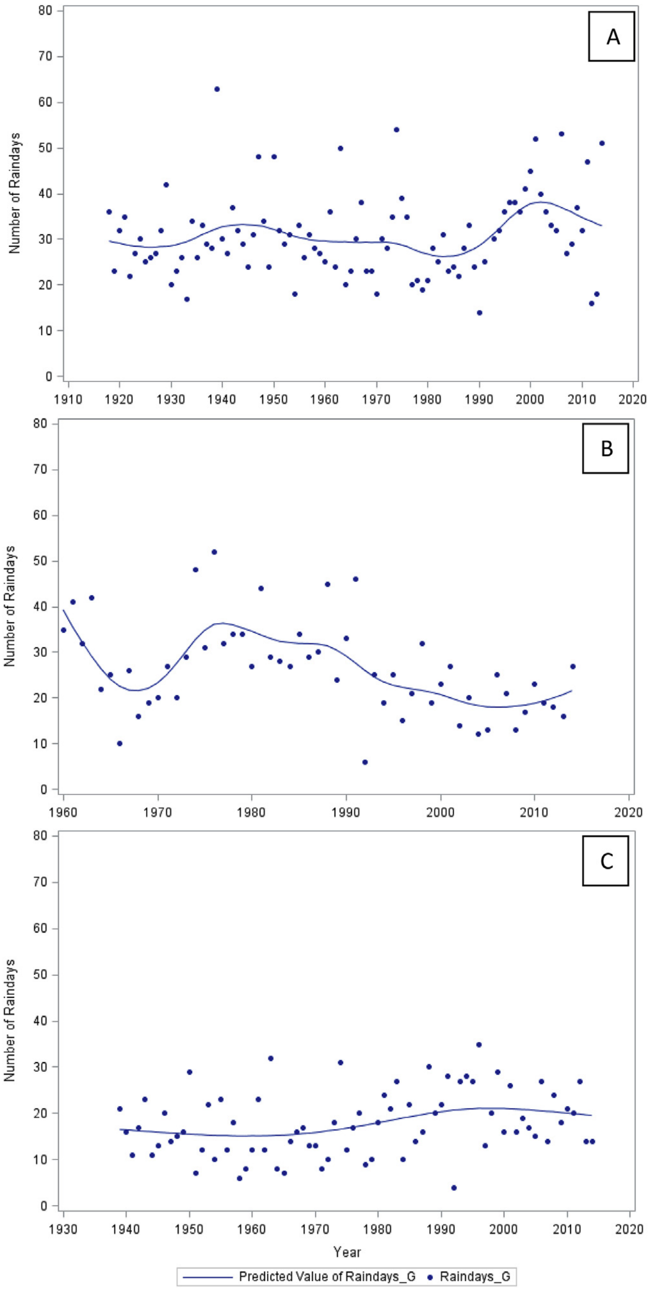

Fig. 4. Observed number of rainfall days (dots) fitted (lines) using Poisson error distribution for A) Postmasburg (97 years), B) Douglas (55 years) and C) Groblershoop (76 years) in the Ghaap plateau.

4. Discussion

4.1. On drought occurrence, severity and duration of the Ghaap plateau

All the droughts at Postmasburg and Douglas occurred between 1992 and 2013, while at Groblershoop they were evenly distributed throughout the rainfall record period. Wet to extremely wet years were diminishing during this period at the stations where droughts were more prevalent. A study by Rouault and Richard (2003), investigating the intensity and spatial extension of droughts in South Africa, concluded that the most intensive droughts occurred in 1983 and 1992.

In the present study, most of the droughts were moderate according

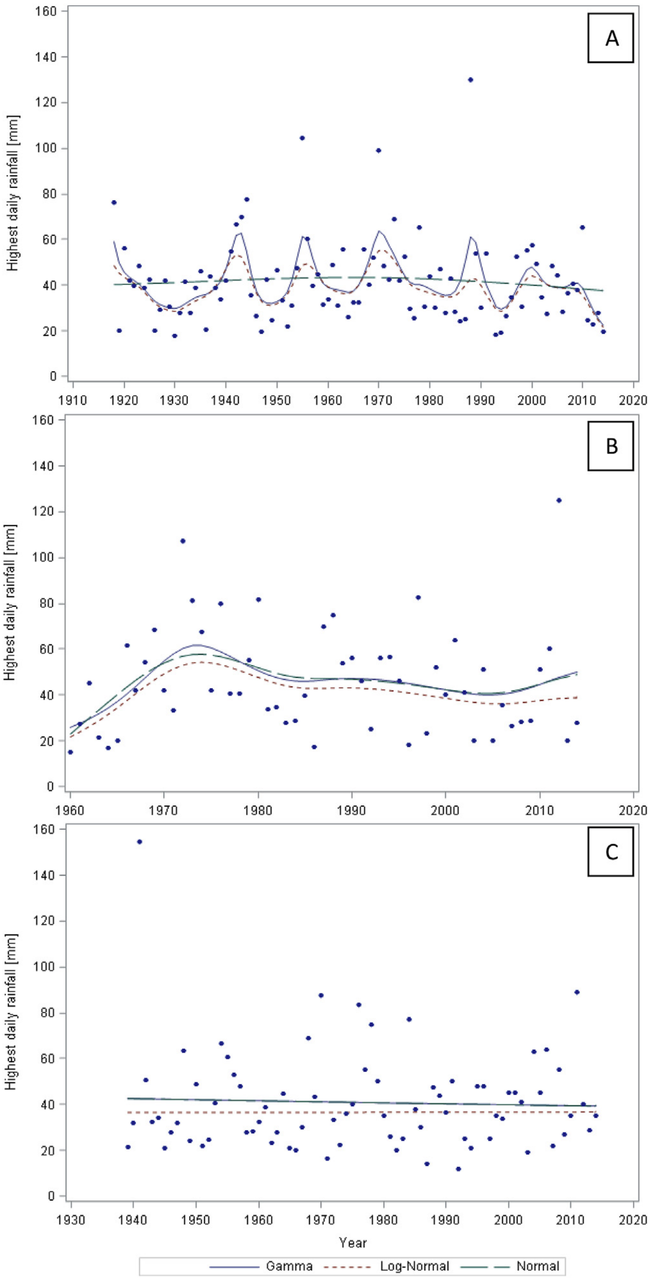

Fig. 5. Observed extreme daily rainfall events and fitted using Gamma, Log-normal and normal for A) Postmasburg (97 years), B) Douglas (55 years) and C) Groblershoop (76 years) in the Ghaap plateau.

to the classification by Guttman (1999), with SPI values ranging from −1.03 to −1.46, except for the one year (1992) which was severely dry (SPI of −1.74) at Groblershoop. Similarly Batisani (2011), used the SPI to analyse droughts in Botswana and reported SPI values of −1.16 to 1.29, which fall within the range of droughts reported in the present study. In agreement with our findings, Manatsa et al. (2008) using SPI to analyse rainfall data from 1900 to 2000, also identified moderate droughts in Zimbabwe. The occurrence of the anomalous SPI value of −1.74 at Groblershoop in 1992, however, concurs with the findings of Manatsa et al. (2008) who also revealed that the 1991–1992 drought was the most extreme during the 20th century. This was further corroborated by Masih et al. (2014), whose comprehensive review of droughts on the African continent confirmed extremely unique droughts for the years 1991–1992.

Notably, the longest duration of drought on the plateau for the record of rainfall data was 2 years for all the meteorological stations. The SPI analyses drought in terms of rainfall, and in future studies it would be ideal to also consider indices like the Standardized Precipitation-Evapotranspiration Index (SPEI) that look into other climatic factors such as temperature.

4.2. *Trends of annual rainfall, rainfall days and extreme rainfall events*

Overall, the total annual rainfall at the Ghaap plateau was essentially stable over the record periods studied. This finding is in contrast to studies done in the neighbouring Vaalharts area in the Northern Cape Province, where Ademeyo et al. (2014) reported declining annual rainfall for the period between 1983 and 2010. Their report was consistent with Parida and Moalafhi (2008), who pointed to a decrease in the annual rainfall from 1981 for similar arid and semi-arid environments in Botswana. However, in line with the findings of the present study are those reported by Tyson et al. (1975) who analysed data from 157 weather stations across South Africa between 1880 and 1972, and reported constant trends of rainfall. Similar to findings of this study, they also reported the secular nature of rainfall patterns in many parts of the country. Tyson et al. (2002) and Nel (2009) also reported the secular fluctuations of rainfall trends over southern Africa and the KwaZulu Natal Drakensberg region, respectively. In both of these studies, no overall changes in the rainfall trends were reported. Tyson et al. (1975) argued that several decades of rainfall data are required to establish rainfall trends, something which might raise questions on the work reported by Ademeyo et al. (2014) where less that 30 years of data was analysed, and that of Parida and Moalafhi (2008) where data from 1961 to 2003 was used. Similarly to the total annual rainfall, the number of rainfall days and the occurrence of extreme rainfall events did not show any evidence of an increasing or decreasing trend.

Drought, a recurring natural hazard in the Ghaap plateau varies in occurrence and intensity and this has implications for the mining and agricultural activities as well as nature conservation via poor recharge of surface and groundwater resources. The Kolomela mine, for instance, relies entirely on groundwater resources for water needs of the mining operations and further supply water to surrounding communities. Droughts can also negatively impact the human population and pastoral livelihoods by exacerbating food insecurity and degradation of pastures. A number of tree species, especially in such dry environments, use substantial amounts of water to meet transpiration requirements (Evaristo and McDonnell, 2017), as such poor recharge of groundwater reserves due to recurring droughts will negatively impact on maintenance of valuable genetic diversity. Farming operations, especially drinking livestock also heavily rely on groundwater sources. The more frequent occurrence of droughts will therefore impact on groundwater recharge and hence the ecosystem components that are supported by groundwater sources.

The establishment of the SPI values which is useful for determining drought occurrence and severity, and the determination of the interannual rainfall variability is crucial, especially in the context where drought is expected to increase in frequency and severity in the future as a result of climate change (Sheffield et al., 2012). Accurate quantitative information on drought and interannual rainfall variability is necessary to better prepare for such catastrophes (Vincente-Serrano et al., 2012; Masih et al., 2014). Considering that more droughts have occurred post 1990 in the Ghaap plateau, which is predominantly arid, assessments of drought occurrence and severity and interannual rainfall variability in other dryland regions in the country are key to effectively manage the adverse impact of drought on water resources and food security.

5. Conclusions

The objective of this study was to determine the occurrence and severity of droughts, and to assess rainfall trends at the Ghaap plateau, which is located in the Northern Cape Province of South Africa. Two main conclusions can be drawn out from this study; i) droughts have become more prevalent in the plateau post 1990, and a majority of them are moderate, and ii) there is no evidence of change in total annual rainfall, numbers of rainfall days and extreme rainfall events in the plateau. The rainfall trends follow secular fluctuating patterns over the years. Such information can be used in climate models as a predictive tool for early warning against immediate future precipitation shortfalls and forecasting of droughts in the long-term. Drought and rainfall variability assessment could be useful for improved mitigation strategies and better planning measures. However, further studies should consider incorporation of other climatic parameters such as temperature to have a holistic perspective of the anticipated climatic variability at regional and continental levels. Even more so, it is essential to understand the impacts of drought and rainfall variability on water resources under changing climate whereby drought is expected to increase in frequency and severity.

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