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A probabilistic approach to drought frequency analysis in Mafube Local Municipality, South Africa

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ABSTRACT

Droughts are naturally occurring events that significantly and adversely impact on the world's economy, industries, environment and communities' well-being. An early detection of these events aid the development of mitigation strategies well in advance before they happen. The return period is one of the tools that helps make drought disaster risk reduction a possibility. Of all sectors that are negatively impacted by drought, agriculture is one such a sector that suffers most and which in turn reflects the impacts on communities whose livelihood is mainly dependent on rain-fed agriculture. Given the fact that Free State province was declared drought disaster-struck in the year 2015, The researcher found it imperative that a study in the Northern parts of this province (where most crop production is made) is conducted in the view to assist farmers, disaster managers, government authorities and all other relevant stakeholders with the basis on which mitigation strategies could be founded. Data provided by South African Weather Services (SAWS) was collected from only (Frankfort) located in Mafube Local Municipality. A Drought Calculator (DrinC) software was used to compute SPI series on only SPI-3 time scale since lower time scales are very relevant for agricultural purposes. Prior to the analysis, a regression analysis was conducted to check for significant correlations between time (water year) and SPI values. Then each seasonal SPI series was fitted to a suitable theoretical probability distribution aided by an Easyfit software and a Kolmogorov-Smirnov statistical test. The following probability distributions were found suitable for the four seasons; Inverse Gaussian, Cauchy, Laplace and Logistic probability distributions respectively. From each distribution, the probabilities for having moderate, severe and extreme drought events were estimated which were then used in the return period computations. The regression analysis found no significant trends in all four seasonal SPI series. The study also revealed Oct-Dec and Jan-Mar seasons with the shortest return periods, 11 and 12 years on moderate and extreme drought levels respectively.

Keywords: Standard Precipitation index; drought frequency; disaster; disaster risk reduction

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INTRODUCTION

Drought is a stochastic and unpredictable natural phenomenon which when occurs, stays over long periods (Fattahi *et al*. 2015: Seyhan, 1966.). These authors assert that drought is very difficult to detect its onset and end because of its unpredictability thereby reducing available water resources and the capacity of ecosystems maintenance. This natural phenomenon can be studied for several reasons spanning environmental and water resources viewpoints (Shahabfar and Eitzinger, 2013). It is therefore defined differently by several scholars however one of the definitions of this event is a normal recurring feature of climate may occur anywhere with varying characteristics and impacts (Raziei, *et al*. 2009). Most importantly, the successful management of water sources requires an in depth understanding of drought-cause drivers and processes. However climate change is said to affect this precious resource in the coming decades in many parts of the globe (National Resource Deference Council, 2016: Dunkel, 2009). South Africa was not an exception in the year 2015, where over 2.7 million households were affected and five out of nine provinces were declared drought disaster (News24, 2015). The Free State province in particular which is one of the few South African breadbaskets has been hard hit by this event and was found to be in 100% spatial extent by a study conducted by Hlalele, (2015a:Williams, 2014.). The drought severity in this province was more in the northern parts (Lejweleputswa to Fezile Dabi districts) down to Eastern parts (Thabo Mofutsanyane district) (Hlalele, 2015a). According to Hlalele (2015b) on his study on Bi-hazard assessment for timely and effective disaster management: Free State disaster, mostly vulnerabilities found were of mainly demographic nature. One of the municipalities which was in the top of the list, was Mafube located in the northern parts of the province ranked number 4 and 3 in terms of vulnerability and disaster risk level respectively. In the view of the above, the current study aims to characterize drought in Mafube District Municipality from a probabilistic approach for future drought monitoring, increased water resource management and increased resilience against adverse impacts of drought brought about rapid climate change variability. This study uses a drought standardized precipitation index (SPI) for characterizing the drought. The Knowledge of the frequency distribution of the drought events is useful as it contributes to the assessment of drought risks which have implications on the long term ecological, economic and social wellbeing of the biological and human communities that make use of water from the various streams in a basin (Agwata *et al*. 2014).

Standardized Precipitation index (SPI)

In 2009, an interregional workshop was held at the University of Nebraska-Lincon in the United States of America where over 22 countries were gathered on reviewing drought indices in use, Standardized Precipitation Index was recommended as an index that is best suited to characterize meteorological droughts (World Meteorological Organization, 2012: Franz *et al.* 2009). SPI is defined as a statistical indicator that compares the total precipitation received at a particular location during a period of n months with the long-term rainfall distribution for the same period of time at that location. (European Commission, 2011: Hyden, 1996). The best drought indicator was developed by Mckee *et al.* (1993) at Colorado University and at least data of 30 years is required for the computation of this index. . Each data set is then fitted into a Gamma function to define the relationship of probability of precipitation. The classification of the SPI is seen in table 1.

Table 1: The classification of the SPI Values

> 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.9 to 0.9	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
< -2	Extremely dry

Source: http://ecometrica.com/assets/Drought-Indices_and_Methodolgy_OE.pdf

The gamma distribution is defined by the following density function;

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0 \tag{1}$$

.

Where α and β are estimated for each station as well as for each month of the year.

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right)$$

$$\beta = \frac{\overline{x}}{\alpha}$$

where $A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n}$, and n = number of observations (2)

After these parameters have been estimated then their resulting values are used to calculate cumulative probability as;

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1} e^{-x/\beta} dx \tag{3}$$

In cases where t=x/β then an incomplete gamma function becomes

$$G(x) = \frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1} e^{-t} dt \tag{4}$$

Since gamma function is undefined at x = 0 then the cumulative probability is calculated from the following equation (Tsakiris *et al*. 2015);

$$H(x) = q + (1 - q)\,G(x) \tag{5}$$

Where *q* is the probability of a zero and *G(x)* the cumulative probability of the incomplete gamma function. If *m* is the number of zeros in a precipitation time series, then *q* can be estimated by *m/n*. The cumulative probability is then transformed to the standard normal random variable *z* with mean zero and variance one, which is the value of the SPI (Tsakiris *et al*. 2015).

Study area description

Mafube Local Municipality, a 3 971 km^2 of area is an administrative area in the Fezile Dabi District of the Free State province. The name is a Sesotho word meaning 'dawning of the new day'. Frankfort remains the growth point in Mafube, and plays a major role in terms of regional service provision and industrial and commercial development. Frankfort is situated 55km east of Heilbron and approximately 120km south-east of Sasolburg. Frankfort is a typically-developed small town, serving the predominant surrounding agricultural community. The Greater Tweeling area is located approximately 150km east of Sasolburg and 350km north-east of Bloemfontein, and is situated adjacent to the Frankfort/Reitz Primary Road. Other larger centres, such as Vereeniging and Vanderbijlpark, are all within 160km of Tweeling. Primary agricultural activities include sheep and cattle farming, maize, and sunflower seed production. The Villiers Town area is situated on the banks of the Vaal River, adjacent to the N3 National Road between Gauteng and Durban. In relation to other major centres, the town is located 120km from Johannesburg, 80km from Vereeniging and 117km from Sasolburg. Villiers is predominantly agriculture-orientated, where products such as maize, sunflower, wheat, grain, sorghum, meat and dairy are produced. Villiers functions as the main concentration point for products in the district, from where they are directly exported. The grain silos in Villiers, together with other grain silos in the district, have a storage capacity of 273 000 tons. The Greater Cornelia area is situated 40km east of Frankfort, 160km east of Sasolburg and 32km south-east of Villiers. The town is situated adjacent to the R103 Secondary Road between Warden and Villiers. Cornelia typically developed as a small town serving the predominant surrounding agricultural community (Department of local government, 2016). The following figure depicts the location of Mafube Local Municipality in South Africa.

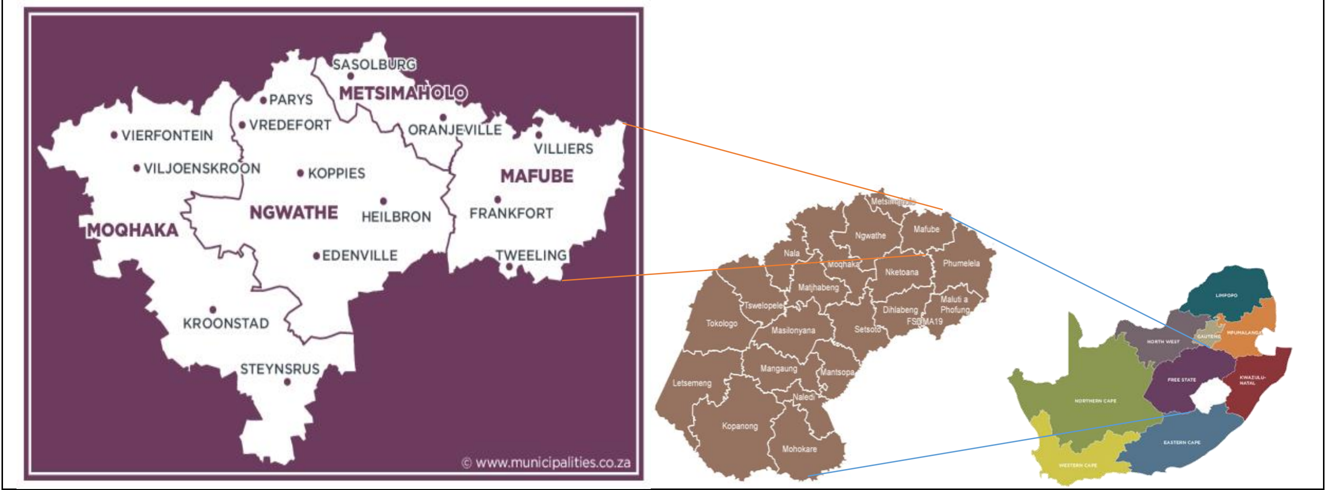


Figure 1: Fezile Dabi District showing Mafube Local Municipality in the Free State, South Africa

Source: http://www.localgovernment.co.za/provinces/view/2/free-state

METHODS AND MATERIALS

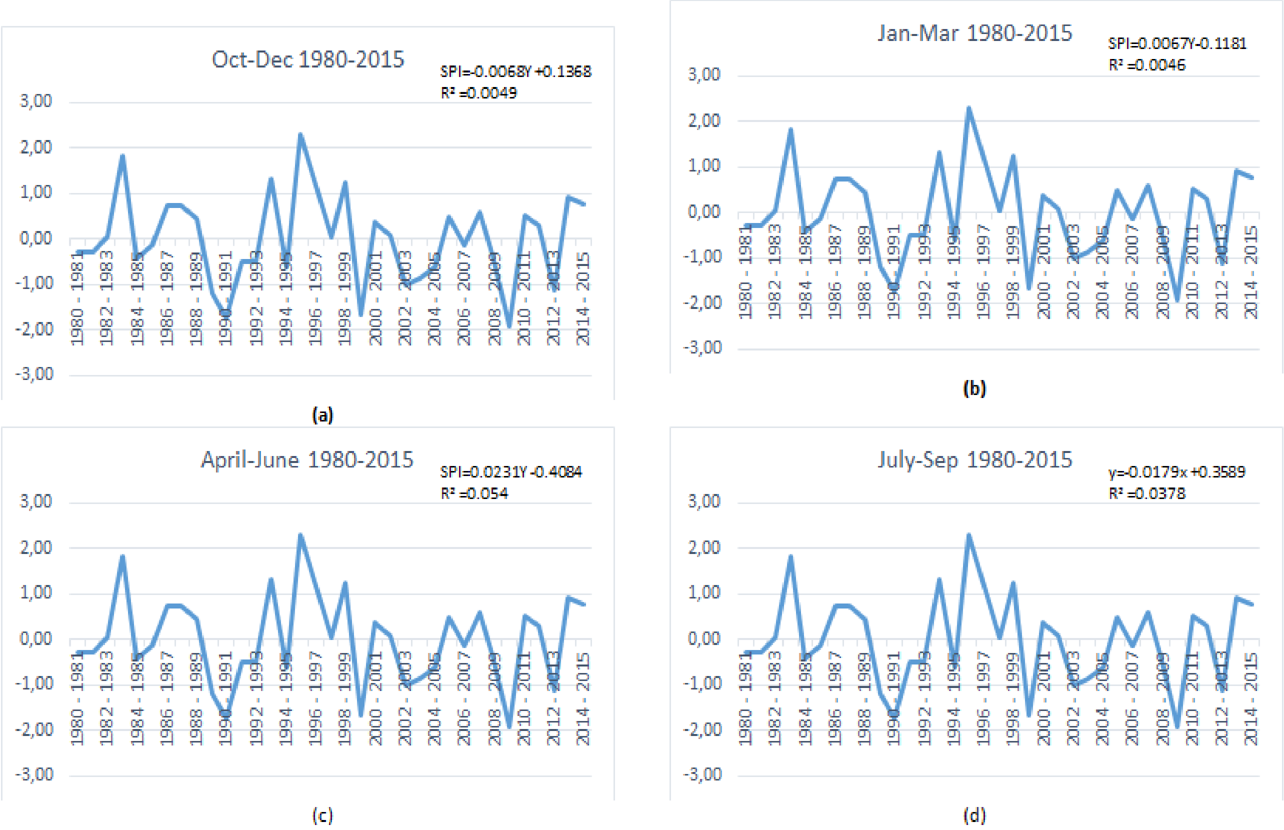
Data processing

Data was obtained from South African Weather Services (SAWS) from one weather station (Frankfort) in the Mafube Local Municipality. Fortunately no data was missing over a period of 35 years (1980-2015).

Methods

SPI values were then computed from Drought Calculator Software (DrinC) on only (SPI-3) time scale. Droughts at (1, 3, and 6) time scales are relevant for agriculture (*Tan et al*. 2015: Štěpánek, *et al*. 2013). Each seasonal SPI series was fitted to a suitable continuous probability distribution function using Easyfit software and Kolmogorov Smirnov Test. For each of the last three categories from table 1, probabilities were estimated from the determined distribution functions. Then the return periods were also calculated from the determined probabilities using the same drought categories from table 1, since drought severity increases with negative values. Finally a trend analysis was conducted to determine which of the seasons had significant trends of drought as depicted by drought Standardised Precipitation Index (SPI).

RESULTS AND DISCUSSION



(a) (b)

(c) (d)

Figure 2: SPI-3 Series; Oct-Dec (a), Jan-Mar (b), April-June (c) and July-Sep (d).

From figure 2 above, the SPI-3 series were computed from Drought Calculator (DrinC) for each season as shown. The seasonal series were then plotted against SPI values. The Jan-March season showed depicted an extreme drought in the hydrological years 1983 – 1984 and 2007- 2008. Similar events were experienced in April-June season in the years 1992 – 1993 and 1998 – 1999. For each of the four SPI-series, a spearman coefficient (r) was computed shown as coefficient of determination (R^2). All the seasons showed upward trends except the first and the last seasons which instead showed a downward trend. Although there has been some kind of a trend shown in all seasons, none of them was significant to make predictions of drought severity levels.

Table 2: SPI-3 seasonal fitted probability distributions

Drought category (SPI)	SPI-3 (X_1 <P(x) < X_2)			
	Oct-Dec (Inverse. Gaussian (3p)	Jan-Mar (Cauchy)	April-June (Laplace)	July-Sep (Logistic)
Moderate (-1.0 to -1.49)	0,08818	0,04613	0,06102	0,06963
Severely dry (-1.5 to -1.99)	0,03803	0,02512	0,03048	0,02976
Extremely dry (< -2)	0,01504	0,08196	0,03086	0,01971
Parameters:	⍰=13734,0 ⍰=23,485 ⍰=-23,471	⍰=0,52676 ⍰=3,9427E-4	⍰=1,3881 ⍰=0,0065	⍰=0,52135 ⍰=0,03686

After the SPI-3 computation from DrinC, each season's SPI series was fitted to a suitable probability distribution. The first season (Oct-Dec) followed an Inverse Gaussian probability distribution. Using category drought intervals as shown from table 2, probability values were estimated from Easyfit (StatAssist) function using the determined parameters as shown above. The other three seasons followed Cauchy, Laplace and Logistic probability distributions and their corresponding parameters as shown in the table. These marginal probabilities were then further used to establish the return periods for each season.

Table 3: Return period for each season

	Return Period (years) $T(x) = \frac{1}{(X1 < P(x) < X2)}$			
	Oct-Dec (Inv. Gaussian (3p)	Jan-Mar (Cauchy)	April-June (Laplace)	July-Sep (Logistic)
Moderate (-1.0 to -1.49)	11	22	16	14
Severely dry (-1.5 to -1.99)	26	40	33	34
Extremely dry (< -2)	66	12	32	51

The above table shows the seasonal return periods in years for each drought category. The return period T(x) was calculated from $T(x) = \frac{1}{(X1 < P(x) < X2)}$ where P(x) is probability of obtaining any SPI value in the interval indicated by the drought category. The P(x) was calculated from suitable probability distribution of the seasonal SPI values guided by a Kolmogorov-Smirnov test. This region seems to experience frequent moderate drought in beginning of the hydrological year (Oct-Dec). However, this is a very crucial time the growing of maize, sorghum, beans, etc. The Jan-Mar season is another important season where maize (staple food) needs a considerable amount of rain due to tasselling period. In this season, the study area experiences extreme drought episodes at the rate of 12 years per cycle. The last season only experience shorter return periods in the moderate drought category. This information therefore alerts farmers, disaster managers and all other relevant stakeholders in this region to set up contingency plans in drought disaster risk reduction. The growing and production seasons in particular, seem to be at higher risk than any other period of the year.

CONCLUSION AND RECOMMENDATIONS

In recent years, climate change and global warming have been a concern for many scholars having caused extreme events such as drought to provide (Cai *et al*. 2015: Apollov *et al*. 1964: Vicente-Serrano,2012: Raudkivi, 1979: Ho Ming and Yusof, 2012: Allaby, 2003: Cheng and Bear, 2010: Beven, 2006.). The study of drought frequency sets a basis for drought risk reduction, therefore the current study has shown such an importance in agricultural sector. All seasons have shown almost equal return periods on moderate drought level with Oct-Dec having the shortest return period. Jan-Mar season has shown a similar return period, but on extreme drought level. With the above findings, the government, NGO's and all other relevant stakeholders are therefore urged to put strategies such as provision/assistance of commercial farmers with irrigation systems and contingency plans in place. This will however, mitigate drought impacts not only in this region but in the Free State as a whole given that this province serves as a hub for maize production and other agricultural commodities on which the province is dependent for its people's livelihood and economy.

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