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Evaluation of the standardized precipitation index in kestel, eastern Free State, South Africa

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Abstract
Extreme weather events have led to the collapse of food production systems, agricultural ecosystems, disruption of food systems causing food insecurities. The contrary effects of climate variability and change, refer to flooding, heat waves, frost, nevertheless this study examine drought, which occurs frequently in the Free State province where Kestel automatic weather station is located. The application of drought index analysis is required for drought assessment for decision making on adaptation and mitigation strategies on farm level. Understanding of drought severity and frequency plays a significant role in decision-making. For this study to analyse drought, Standardised Precipitation Index (SPI) in an index to characterise rainfall deficit for multiple time scales. Drought episodes has been experience at the study area, with 2015 recorded the severe drought occurrence. Thus, drought assessment is crucial to determine the duration and the frequency of episodes. The analysis indicate that severe drought occurred in 2015 with the value of drought index at SPI-1 (-1,5) in 1990, (-1,8) in 1993, (-1,6) in 1997, (-1.64) in 2001, and (-1.2) in 2007. SPI-3 the index value was (-1,8) in 2000, (-1,5) in 2002, (-2,2) in 2007, and (-1,3) in 2013. SPI-6 the index value ranged from (-,30 to -0,32) in 1992-1994, 1996, 1998, 2000, 2006, 2013, 2014, 2018 and 2019. SPI-9 the index value ranged from -1,08 to -1,15) in 1990, 1999, 2008, 2010 and 2019. SPI-12 (-1,3) in 1990, (-1,74) in 1992, (-1,97) in 2005 and (-3,02) in 2015. The results highlights the significance of the use of drought identification, its severity and impact of agricultural production. Characterisation of drought severity guides users for the implementation of drought relief policies and measures at farm level in Kestel area.

Keywords: standard precipitation index, drought, agriculture, decision making

Introduction

Water cycle elements such as soil water content, stream flows, water reservoirs and precipitation reveal high spatial temporal inconsistency. At irregular rainfall intervals, climate parameters display extreme behaviours, exerting substantial impacts on ecosystems and livelihoods. The intensification of weather extremes has notable impact on communities residing near river watersheds [1], [2]. Through observation, it is evident that social resilience to water-related disasters is a planned and slow process of developing substantial strategies and adoption of risk management measures [3]. Drought is a periodic feature of all climates, among the parameters the most devastating, multifaceted and so-called a natural disaster [4], [5]. This complex agrometeorological phenomenon habitually leads to severe impacts on the environment, agricultural ecosystems, society and economy. With the climate change pressures, the frequency, severity, duration and extent of droughts will likely escalate to the region, which were less prone to drought [3, 6, 7]. The severe impacts of droughts are observed in many sectors, but in the agricultural fraternity particularly in rural areas, the degree of exposure, susceptibility has further impact on the socio-ecological system. This highlights the requirement to understand drought occurrence, severity, frequency and management strategies, toward communities coping capacity and measures. The agricultural sector is a core component of the economy for food security and rural development and it contributes 3% to the national Gross Domestic Product [8]. In South Africa, commercial and resource poor farmers experience drought risks differently, since the latter have profoundly its risk profile and response to the former. World Meteorological Organisation (WMO), most resource poor farmers practise rain-fed agriculture, are highly dependent on climate-sensitive resources [3], [9]. Therefore, intensification of local level or farm level is fundamental for development of tailored agro-advisories. Further assessment of drought at farm or local level influence decision-makers on strengthening and development of drought monitoring and early development systems for future use [10, 12]. Drought is defined as a slow- moving natural hazard resultant to precipitation deficiency relative to the normal expected [10, 12, 13]. Precipitation deficiency lead to prolonged shortages in surface and groundwater, and thus affect the soil water content at a soil profile, which result to crop water deficiency.

Some researchers already endorsed the use of SPI to understand drought severity and the agricultural drought intervention measures. Other studies used SPI to determine drought persistence and duration, the characteristics of meteorological and agricultural drought [14, 15]. Research on drought impacts on agriculture, under rain-fed and irrigated conditions in selected provinces of South Africa [11]. Other studies investigated the socio-economic effects on the communities in the Eastern Cape province [16, 17]. McKee [18] carried out about SPI calculation method on drought time-scale and frequency [19]. Using these indices, the correlation between groundwater and hydrological extremes was conducted within the catchment [20]. World Meteorological Organisation endorsed the use of SPI as an important tool for drought monitoring to facilitate effective agricultural decision-making, and as a tool to forecast climate conditions on a range of time scale and may be utilised with other modelling approaches.

For operational purposes, using an index for drought classification is crucial for drought detection, real-time monitoring and development of early warning decision support systems [21, 22].These systems are developed to improve the user's capacity to cope with drought risks, by adhering to risk management cycle which constitute of protection and recovery. According to Wilhite *et al* [15, 21] the protection section entails four key factors which are preparedness for potential drought occurrence, development of mitigation strategies, using drought analysis tools for prediction and early warning to minimise the extent of disaster. Recovery factors are centred on conducting impact assessment, development of recovery strategies [21, 23]. Thus, the application of SPI in establishment of drought start to cessation period and describing meteorological drought conditions. Furthermore, SPI prescribe abnormal phenomenon to allow stakeholder to develop coping mechanisms.

Methodology

Rainfall observations from a specific Automatic Weather Stations were utilised to establish SPI time series baseline and ascertain drought episodes during 1990 to 2021 period. Predicted rainfall then further examined for drought episodes using SPI for the selected period. Annual rainfall time series for Kestel as presented in Figure 1.

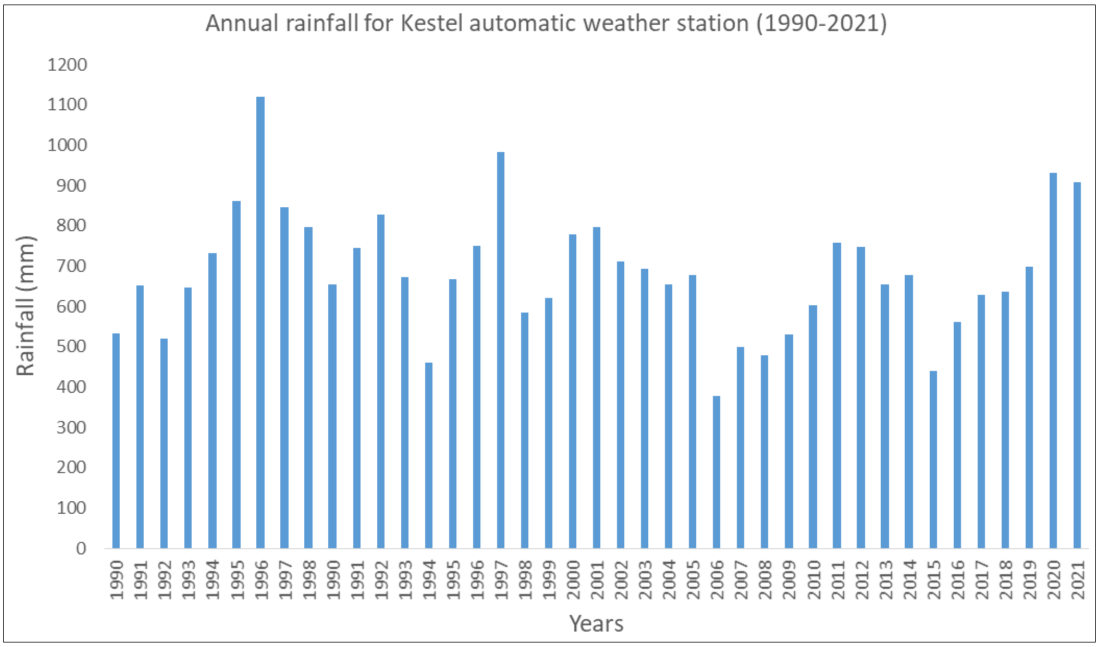


Fig 1: Kestel annual rainfall time series for 1990-2021 period

The Kestel automatic weather station is located in Thabo Mofutsanyane district, which is the eastern part of the Free State province. The province substantially contributes to the country's economy, to about 30% of maize production [1]. The provinces agriculture is enormously dependent on rain-fed production with about 10% under irrigation. Thabo Mofutsanyane district, receives total annual rainfall 601 to 650 mm [2]. The annual rainfall for Kestel town is about 878, 74 mm as represented in Figure 1. An analysed data, which was from 1990 to 2021 shows a variation in annual rainfall, with the highest at 1121.5 mm and the lowest at 367,64 mm, in 1996 and 2006, respectively Figure 1. An assumption developed to understand drought levels for the selected station. Further assessment on total monthly rainfall is represented in Figure 2. Monthly rainfall inconsistencies and irregularities indicate severity of prolonged dry spells, which may contribute to drought. Figure 2 observations was used as a baseline to establish SPI time series for Kestel and drought occurrence was identified during 1994, 2006 and 2015. The likelihood of experiencing severe drought phenomenon is approximately one in ten years period (Figure 1).

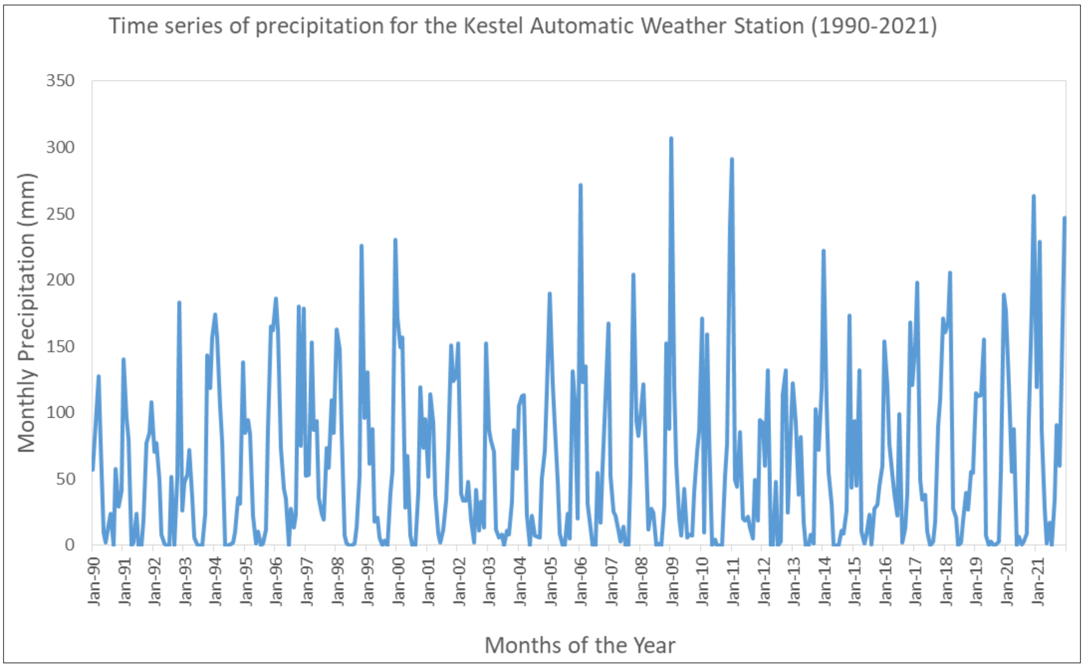


Fig 2: Time series of monthly precipitation for Kestel Automatic Weather station (1990-2021)

Table 1, shows different time scales of SPI, which is SPI 1, SPI 3, SPI 6, SPI 9 and SPI 12 with related agricultural impacts based on drought duration and its severity.

Table 1: Drought classification by Standardised Precipitation Indices (SPI) and its impact on agriculture [3, 4]

SPI Duration	Description	Possible Impacts
1 Month	Abnormally dry (Short-term conditions)	Short-term soil water content Crop stress during the growing season Pasture and crop not fully recovered
3 Month	Moderate drought (Short-medium term moisture conditions)	Some damage to crops and pastures Seasonal estimation of precipitation and water shortages developing
6 Month	Severe drought (Medium term trends in precipitation)	Likely losses of crop and pasture Potential for indicating precipitation over a distinct season Common water shortages and imposed water restrictions
9 Month	Extreme drought (Over medium term precipitation patterns)	If SPI 9< -1.5 severe impacts on agricultural commodities Such as, major crop-pasture failure and possible animal mortalities Wide spread water shortages and restrictions
12 Month	Exceptional drought (Long-term precipitation patterns)	Severe soil water content resulting to exceptional crop-pasture losses Shortages and low levels of water levels on streams, reservoirs and wells

Site Description and Precipitation Data

The historical rainfall data were collected from Kestel Automatic Weather station, which is located in the eastern part of the Free State province of South Africa. Kestel town situated in the foothills of the Rooiberge in the Maluti Mountains. Total annual rainfall based on July-June calendar varies from 601mm/year to 650mm/year in the Thabo Mofutsanyane district. Kestel was selected as the research study. It is located in the Latitude -28.3142, longitude 28.70859 with the Altitude of 1693m [5]. The rainy season stretches from October to April with the highest rainfall period occurring between January and March. In-season dry spells befall intermittently during the crop growth summer season affecting negatively on crop yield [6]. In In previous studies [5, 8], used description and linear regression to identify the probability of dry spell and wet spells as indicator for agricultural, hydrological and meteorological drought indicator, but thorough analysis for drought index is a necessity. This study is in agricultural area, which analysed 32 years of daily precipitation time series data, to comprehend climate variability and change by correlating the occurrence of wet spell and dry spell. The research area is active in agricultural activities, such as, zea mays, legumes, wheat, pasture, livestock and other cash crops.

Sustainable development strengthens the agricultural ecosystems by transforming the food systems for food security. Thus, the implementation of best-suited drought index on recorded climate stance was critical. The selection of this study area was due to its proximity to the land cover and land use toward agricultural decision-making. The 32 years (1990-2021) climate long-term data available from Agromet-Climate database [9], which had been subjected to quality control procedures prior analysis.

The Standardised Precipitation Index as Drought Indicator

The Standardised Precipitation Index (SPI) computation in this research was adopted following the method proposed by McKee [10, 11]. Future drought events prediction, was computed based on the observed rainfall data [9] from 1990-2021, a 32 years of long-term rainfall data. For the research area, the rainfall condition was described using gamma probability function, similar to method developed by McKee [10], and endorsed by other research on precipitation studies [10, 11, 12]. SPI can only be computed to long-term series rainfall, by the difference of mean precipitation divided by the standard deviation, the function will be normalised and standardised. The z-score of the distribution function represent the deviation event from the mean of rainfall data as the SPI value. Whereby, negative values directly imply the drought and positive values signify wet conditions of the region. SPI is the probability index describing the representation of irregular wetness and dryness and compares precipitation with its multiyear average. The time series could be modified for different time duration for total precipitation 1, 2, 3, 6, 9, 12 and 24 months. After determined function of probability density then the cumulative probability of observed precipitation could be computed. SPI is based on rainfall and indicates the meteorological drought spatially and temporally [12]. Accumulated precipitation was corresponded by zero value, and then the amount value from zero could be utilized to describe the risk management on whether wet or dry occurrence for a given season. Drought severity could be analysed by using the accumulated value of SPI.

When the SPI value is 1 and above, it means no drought occurs but when it is -1 or less, it signifies drought occurrence and its exactness. The lesser the negative SPI value the more severe drought duration is reflected. SPI interval revealed different exhibitions [3, 4, 12, 13, 5]. For example, SPI-1 described short-term conditions and the fluctuations in soil water content at vegetation growing seasons. The short-medium described within SPI-3, approximate seasonal conditions, while the six-month period displays the rainfall across distinctive seasons. Whereas, SPI-9, which is the nine-month SPI, when it is less than -1.5, is an indicative of substantial impacts in agriculture and other sectors, SPI-12 which is the twelve-month SPI is indicative to the regression of stream flows, reservoir and groundwater levels [14, 15]. To explore correlations of drought for Kestel town, monthly SPI for different durations: SPI1, SPI3, SPI6, SPI9 and SPI12 was used. The SPI values were computed based on long-term series of monthly precipitation within 32 years (1990-2021) to describe conditions according to SPIs.

Data Processing

This study selected five kinds of time scales, which are 1 (SPI-1), 3 (SPI-3), 6 (SPI-6), 9 (SPI-9), 12 (SPI-12) months. The flexibility of time scale is entirely tied to suitability duration to describe different drought types, which are, meteorological, agricultural and hydrological [16] correspondingly as the purpose of the case study. SPI values computation demonstrated the cumulative gamma distribution, which define the function of frequency or probability density function [10, 12]. The accumulated values of SPI could be key to analysing drought severity. SPI is simple the conversion of precipitation into a standard normal variable by the gamma distribution using the following formula:

$$SPI = \frac{x - x_m}{\sigma}$$

Where X = precipitation of the selected automatic weather station Xm = Mean precipitation and σ = standard deviation.

Table 2 defines the SPI values and the intensity of dryness and wetness [12, 15, 17]

Table 2: SPI values, dryness and wetness intensity [10, 12]

SPI values (thresholds)	Dryness/wetness intensity
2.0 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Very dry
-2 to less	Extremely dry

The formula proposed by McKee [10, 12] is as follows to compute the cumulative gamma distribution:

$$G(x_k) = \int_0^{xk} g(x_k)dx_k = \frac{1}{\beta^\alpha \Gamma(\alpha)}\int_0^{xk} t^{\alpha-1}\ e^{-\frac{xk}{\beta}}dx_k \quad (1)$$

Here x is the random variable, the α and β symbols define shape and scale parameters respectively, Γ is the usual gamma function, and $f(x) = 0$ for $x < 0$ [13, 18]. The α and β value should be higher than zero, while x is the representation of precipitation amount over the consecutive months k (based on selected time scale) in millimetre units.

SPI calculations included corresponding the gamma probability density function into the frequency distribution of rainfall for selected station. Based on McKee [10, 12] equation optimizing the estimates of α and β values is as follows:

$$\alpha = \frac{1}{4A}(1 + (1 + \frac{4A}{3})^{1/2}) \quad (2)$$

$$\beta = \frac{x}{\alpha} \quad (3)$$

Where: $$A = \ln(x) - \frac{\Sigma \mathrm{lin}(x)}{n} \quad (4)$$

The number of precipitation observations is represented by the symbol n, and x is mean precipitation over the time scale of interest. Thus, which signify observed rainfall data phenomenon for each month and the time scale per selected station, whereby, the cumulative probability is obtained using resulting parameters [10, 12] as demonstrated by McKee in equation 1. Whereby, the undefined gamma function for $x_k = 0$, then the value of G (x_k) becomes:

$$H(x_k) = q + (1-q).\ G(x_k) \quad (5)$$

Noted that H (x_k) refers to cumulative probability which is standardised wherewith to obtain the SPI value. And the q is the amount of zero rainfall. The cumulative probability is then converted into normal standard random variable Z, with an average value of zero and a variation of 1, thus the Z value obtained represent the SPI value. An equiprobability transformation occurs from the cumulative probability to the standard normal random variable Z with mean zero and variance one, where SPI takes on the value of Z. Normal standard value of random variable Z or SPI is transformed by utilising the following equation:
Whereby, Z or SPI for $0 < H(x_k) \leq 5$

$$Z = SPI = -(t- \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 + d_2 t^2 + d_3 t^3}\right) \quad (6)$$

Whereby: $$\left\{ t = \left(\ln\left(\frac{1}{(H[x_k])^2}\right)^{\frac{1}{2}}\right) \right. \quad (7)$$

Where, $c_0 = 2.515517,\ c_1 = 0.802853,\ c_2 = 0.010328,\ d_1 = 1.432788,\ d_2 = 0.189269,\ d_3 = 0.001308$

Whereby, the negative values are indicative of less than normal historical rainfall, as demonstrated in Table 2. [4] Kestel rainfall condition was described by using gamma probability function as was proposed by McKee [10, 12] and many other researchers who studied dry and rainy seasons [18-20]. Obtaining the SPI value, the function was normalized and standardized, so that z-score of the distribution function represent the deviation event from the mean of rainfall data as the SPI value. According to McKee [12] SPI is a probability index which described the representation of abnormal wetness and dryness and compares precipitation with its multiyear average.
SPI is a popular meteorological drought index, which is based on precipitation data [4, 10]. This statement is supported by the aims of National Disaster Management Center [21], National Agrometeorological Committee [22], National Drought Mitigation Center [4], Global Assessment on Disaster Risk Reduction [23] on indices, the goal is to determine the extent of drought and the best meteorological index and then develop adaptation strategies that all national meteorological services used standardised index [24]. The SPI would be used to make comparisons in drought extent and severity among districts, regions and countries, whereby, 30 to 50 years precipitation record is required and recommended for thorough statistical analysis [12, 24]. Presently, SPI has been widely used for research and operational approaches.
Then, the paper is based on assessment of drought for Kestel automatic weather station using the SPI values. The SPI value is set to zero. The wet and dry episodes are pronounced by the values above and below zero, correspondingly. Drought is determined to transpire if the value less than zero accumulates to the value of -1 or

lesser. SPI method is used in calculating drought severity in different time scales, typically applied in 1, 3, 6, 9 and 12 month duration. The drought levels are due to prolonged rainfall deficit and unpredictably affects soil water content, and different water resources, which contribute to meteorological, agricultural and hydrological drought, which has huge impact on socio-economic status. Then, the drought hazard and exposure has negative impact to the agricultural fraternity and exacerbate agricultural production to all levels of farmers, whether under rain-fed or irrigated, and/or crop production or animal husbandry or agroforestry. Lastly, the paper the results and identify adaptation strategies, including future research.

Results and Discussion

Study site

Kestel town, is located in the eastern part of the Free State province of South Africa and has been decided as the case study based on its agricultural activities and it lays on -28.3142 S 28.70856 E as represented in Figure 2.

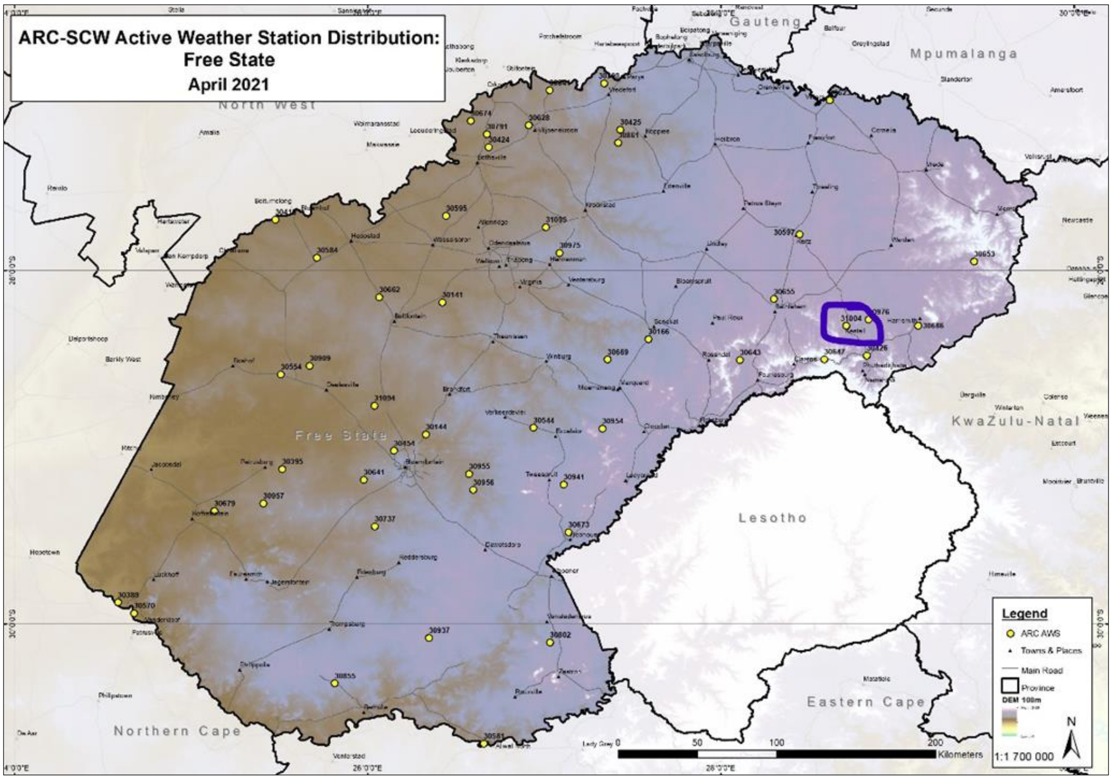
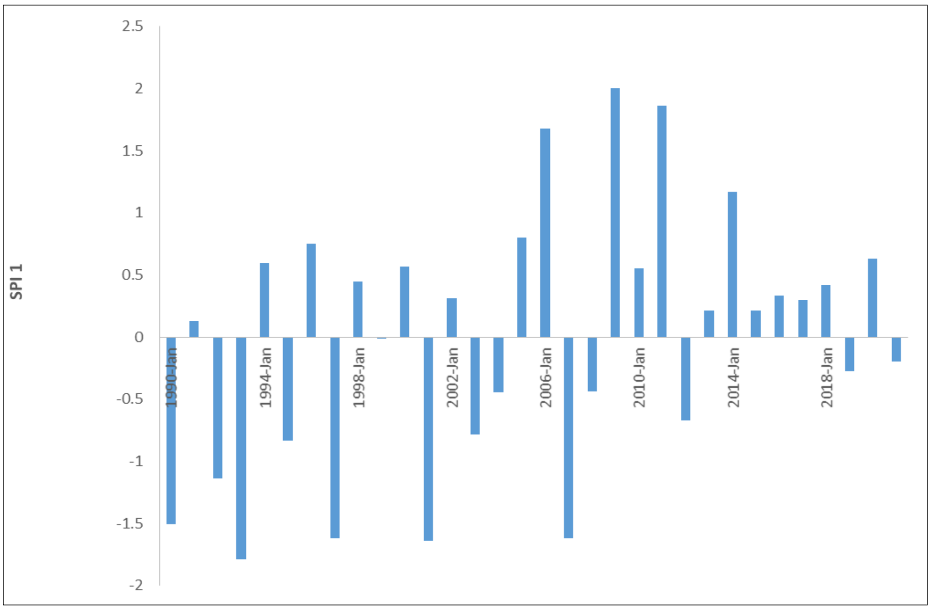


Fig 3: Free State active weather station map, Kestel selected research site south-eastern part, South Africa

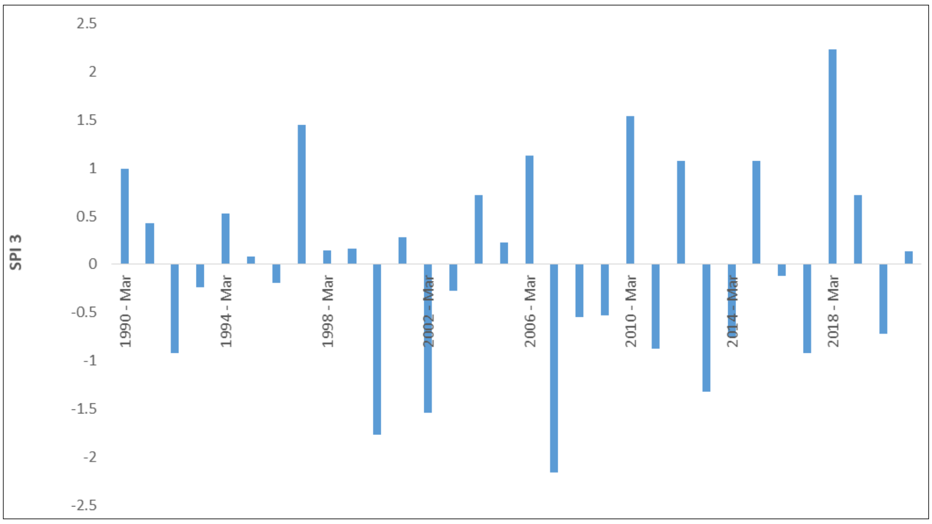
Drought at Different Time Series

The results of the historical annual rainfall from 1990 to 2021for Kestel automatic weather station is illustrated in Figure 1 and 2. The results indicate that 1994, 2006 and 2015 were the dry years being < 75% of the normal period and 1992, 1996, 1997, 2020 and 2021were the wet years >125% of the normal period. The year 2015 recorded the lowest annual rainfall, which is essentially referred to, as the warmest year on record in South Africa with below-normal at the selected weather station, across the country and in some countries globally.

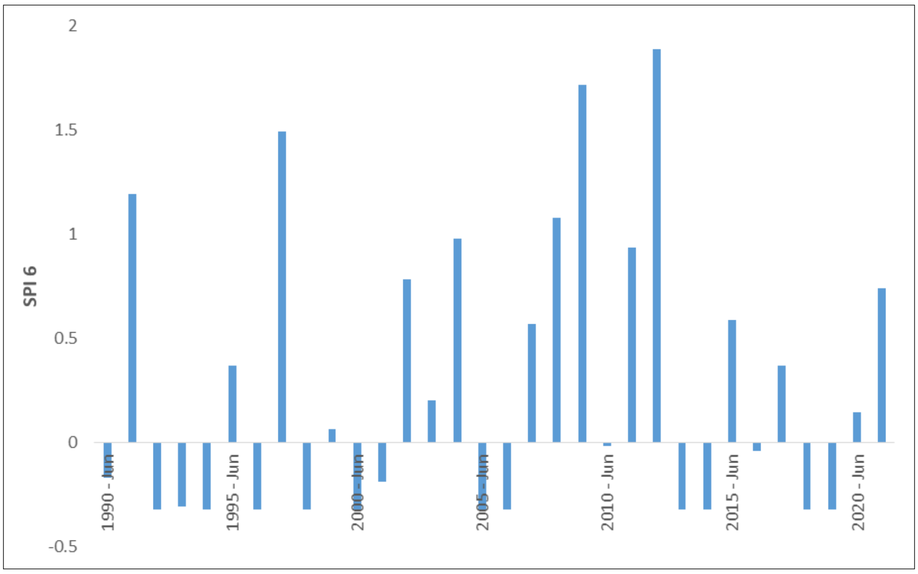
The calculation of SPI drought index for the selected historical data indicate different drought severity under drought criteria. The severe drought occurred in 2015 with the value of drought index at 1-month deficit or SPI-1 (-1,5) in 1990, (-1,8) in 1993, (-1,6) in 1997, (-1.64) in 2001, and (-1.2) in 2007 as shown in Figure 3(a). During the period of 3-month deficit or SPI-3 the index value was (-1,8) in 2000, (-1,5) in 2002, (-2,2) in 2007, and (-1,3) in 2013 as shown in Figure 3(b). The period 6-month deficit or SPI-6 the index value ranged from (-,30 to -0,32) in 1992-1994, 1996, 1998, 2000, 2006, 2013, 2014, 2018 and 2019 as shown in Figure 3(c). During the period 9 month deficit or SPI-9 the index value ranged from -1,08 to -1,15) in 1990, 1999, 2008, 2010 and 2019 as indicated in Figure 3(d). The period 12 month deficit or SPI-12 (-1,3) in 1990, (-1,74) in 1992, (-1,97) in 2005 and (-3,02) in 2015 as represented in Figure 3(e). Based on the analysis in Figure 3(a-e) and previous studies, there are dominating factors which could encourage thorough understanding of weather, climate patterns and the development of drought early warning systems. The soil water content deficit results to agricultural drought which eventual becomes a threat to agricultural production. The Kestel weather station has indicated erratic rainfall and weather anomalies, flooding occurrence, prolonged dry spells during the crop growth season, a potential shift in planting season, intensifying in the last decade, as the impact of climate change. The estimation of the SPI indices defined the appearance of climate inconsistency evident at the research station within 34 years.


SPI 1
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1990-Jan
1994-Jan
1998-Jan
2002-Jan
2006-Jan
2010-Jan
2014-Jan
2018-Jan

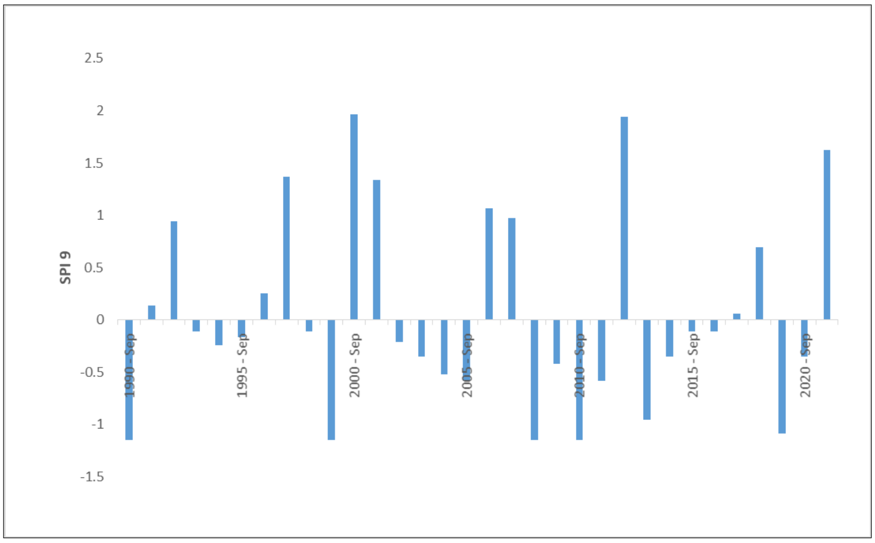
(a)


SPI 3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
1990 - Mar
1994 - Mar
1998 - Mar
2002 - Mar
2006 - Mar
2010 - Mar
2014 - Mar
2018 - Mar

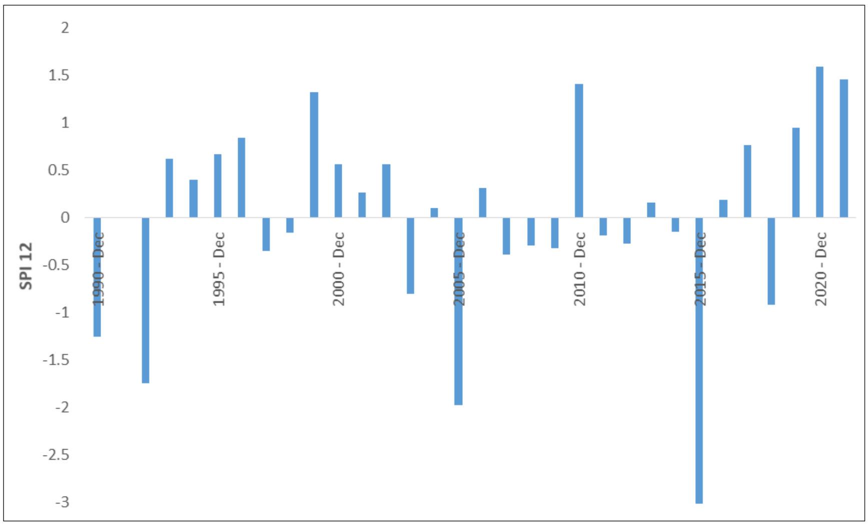
(b)


SPI 6
2
1.5
1
0.5
0
-0.5
1990 - Jun
1995 - Jun
2000 - Jun
2005 - Jun
2010 - Jun
2015 - Jun
2020 - Jun

(c)



(d)



(e)

Fig 3: SPI values for Kestel Automatic Weather Station with (a) 1-month time series, (b)3-month time series, (c) 6-month time series, (d) 9-month time series and (e) 12 month time series.

The independent drought thresholds were used to determine frequency in the SPI time series. The dissimilarity of month to month SPI (SPI-1to SPI-12) values on annual basis are indicated in Figure 5. The lower and continuation of the index during the growing season indicate the potential of prolonged dry spell that may extent to agricultural drought and lessening of crop yield, poor pasture and insufficient feed for livestock. The spike of SPI values for January 1991, April 1991, January 1993, January 1997, January 2001, January 2007, April 2012, November 2015, December 2015 and October 2019 were about the same (between -1,4 to -2,4), meaning that the intensity of drought differ from year to year and from month to month, as shown in Figure 5. The discrepancy of SPI in this regard is based on the utilisation of monthly precipitation, as it has no indication of the dry spell duration within the month. In Kestel crop flowering occur around about January, which is entirely based on the planting data and cultivar selection. Thus, the occurrence of prolonged dry spell in January may result to severe crop failure. Such the decision maker should be aware of this fact when using SPI.

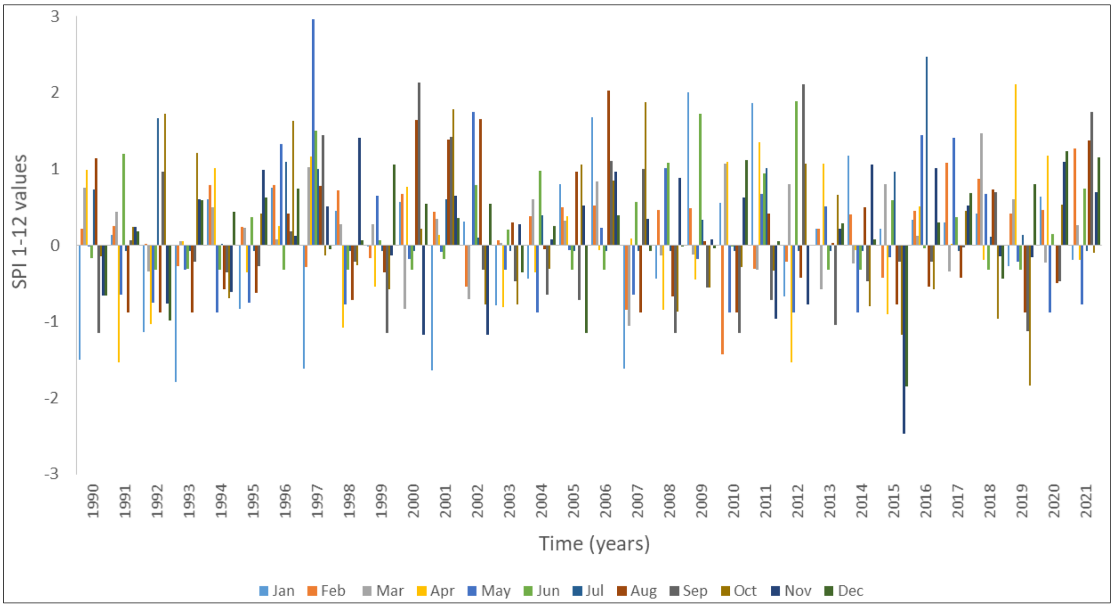


Fig 5: SPI 1-12 values derived from 1990-2021, indicating specific monthly variation records for Kestel area.

The conducted provided a significant spatial and temporal drought cycle variability. The Kestel has general pattern of SPI time series and trend as shown in Figure 6. By considering the graph illustrated for the station, episodes of severe droughts were observed at the particular station in 1991, 1993, 2005, 2007, 2010, 2015-16 and 2019. The findings in this study are compatible with the drought studies executed Abeola *et al*., in [2]. The severest drought ever experienced in the study area was observed in 2015-2016, as illustrated in SPI-12.

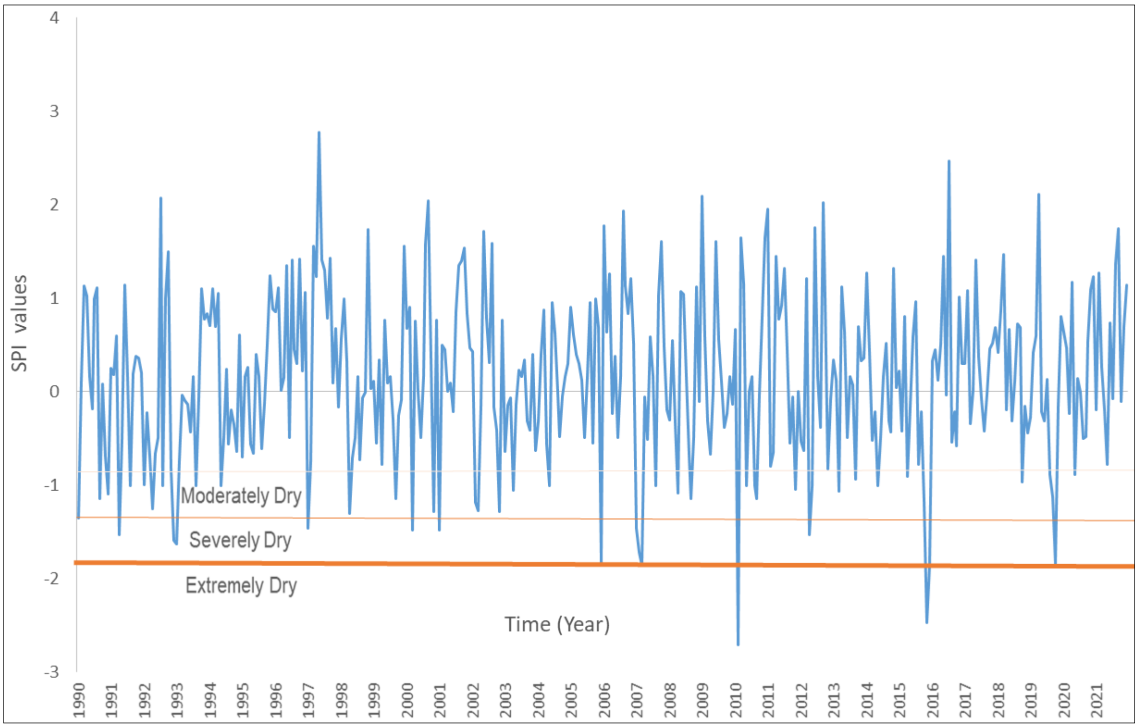


Fig 6: SPI time series for Kestel Automatic Weather Station for 1991 to 2021.

Conclusion

The gamma distribution was chosen to compute SPI for Kestel station using precipitation data recorded for the period extending from 1990- to 2021. The use of gamma was selected based on the precipitation period, which exceeds 30 years and the discernible pattern generated. Moreover, the unbiased drought thresholds are station specific for seasonal to sub-annual scales. Through analysis, the station drought extent and period increased with time for short and long time scale. Thus as a consequent of reduction in rainfall, contributing to low soil water content and increase in soil temperature resulting from climate variability and change. The increase in dryness affected crop development, pasture growth, livestock well-being, dam levels and river runoff negatively. The increase dryness resulting to meteorological, agricultural and hydrological drought.

The SPI value as occurred in Kestel automatic weather station has demonstrated different drought categorisation to each duration in all periods of severe drought occurrence. The severest drought at this research area was experienced in 2015-2016, as illustrated in SPI-12. During this, period, severe crop failure, livestock mortalities, food insecurities was observed at the study area and the country at large. The severe drought occurred in 2015 with the value of drought index at SPI-1 (-1,5) in 1990, (-1,8) in 1993, (-1,6) in 1997, (-1.64) in 2001, and (-1.2) in 2007. SPI-3 the index value was (-1,8) in 2000, (-1,5) in 2002, (-2,2) in 2007, and (-1,3) in 2013. SPI-6 the index value ranged from (-,30 to -0,32) in 1992-1994, 1996, 1998, 2000, 2006, 2013, 2014, 2018 and 2019. SPI-9 the index value ranged from -1,08 to -1,15) in 1990, 1999, 2008, 2010 and 2019. SPI-12 (-1,3) in 1990, (-1,74) in 1992, (-1,97) in 2005 and (-3,02) in 2015.

The quantification of drought severity levels, duration and frequency, through SPI valuation aids in an improvement to describe prolonged dry spells, rainfall irregularities, trends and patterns in the Kestel area. Knowledge on drought index is one of the major factors on operational farming decisions and selection of tailored adaptation and mitigation strategies towards increasing agricultural production, and dealing with climate variability and change. Such as knowledge could assist the farming fraternity to make adjustments on the following: planting dates, cultivar selection, crop varieties, sequential planting, planting density as some of the agricultural coping strategies. The level of farmer and agricultural advisor knowledge mainly affects the use of agrometeorological knowledge such as drought index at farm level in the district. Adoption of such knowledge may assist on-farm decision makers to implement drought relief policies, interpret complex weather/climate conditions and adopt climate-smart technologies toward strengthening agricultural ecosystems, food security and socio-economic status.

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