Research article

Nationwide temporal variability of droughts in the Kingdom of Eswatini: 1981–2018

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ABSTRACT

For adequate mitigation and adaptation measures, it is essential to have detailed analysis of droughts patterns. This study determined the i) occurrence and severity of droughts ii) drought recurrence frequencies and iii) drought trends across different agro-ecological zones in the Kingdom of Eswatini for the period 1981 to 2018. A Standardised Precipitation Index (SPI) computed from long-term precipitation data measured from six meteorological stations was used to determine drought occurrence and severity. Python software (Version 3.6) was applied on the SPI values to predict the recurrence of drought events over time in years. The SPI showed that in the Highveld, 42% of the droughts were moderate, 32% were severe and the remaining 26%, which all occurred post 1980 were extreme (SPI -2.34 to -2.82). The Middleveld had an even proportion of drought categories (29–35%). The Lowveld recorded 62% of moderate, 8% severe and 30% extreme droughts of which 70% occurred post 2000. Moderate droughts were found to recur every 4–5 years while extreme droughts are expected every 13–21 years. These findings are essential for mitigation and adaptation measures geared towards the adverse effects of droughts.

1. Introduction

Drought is an insidious natural hazard that is related to the reduction in the amount of precipitation received over an extended period of time such as a season or a year (Mishra and Singh, 2010; Dai, 2011; Van Loon, 2015). Droughts occur nearly at all climatic zones, including high and low rainfall areas, and is a recurring phenomenon that adversely affects natural habitats, ecosystems, society and the economy (Heim, 2002; Bachmair et al., 2017). It affects the spatial and temporal changes in vegetation patterns of terrestrial ecosystems and leads to the degradation of aquatic life (Lake, 2003) as well as food web structures (Fernandez-Illescas and Rodriguez-Iturbe, 2004; Ledger et al., 2013; Gudmundsson et al., 2014). The diverse geographical and temporal distribution of droughts discernibly affects both surface and underground water resources leading to reduced water supply of water for irrigating crops, crop failure, reduced rangeland productivity and diminished power generation. Further, drought causes reduced volumes in streams and rivers, which impairs water quality (Wilhite, 2000; van Vliet et al., 2012).

There are generally four categorical classes of drought, and these include meteorological, hydrological, agricultural and socio-economic (Batisani, 2011). Specifically, socio-economic drought is normally considered a result of one or more of the other three classes. This study mainly focuses on meteorological drought, which occurs as a result of precipitation shortage over time (Keyantash and Dracup, 2002; Dai, 2011). In the existing literature, there is an array of indices that quantify and monitor meteorological droughts in different locations under specific environmental conditions. These include among others, the Palmer Drought Severity Index (PDSI), discrete and cumulative precipitation anomalies, surface water supply index, rainfall deciles, Drought Area Index (DAI) and Rainfall Anomaly Index (RAI) (Heim, 2000; Dai, 2011). One popular index widely used in literature is the Standardised Precipitation Index (SPI). The Standardised Precipitation Evapotranspiration Index (SPEI) is one of the latest and most robust indices for monitoring

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drought (Alsafadi et al., 2020), but uses both precipitation and temperature data, which is limiting if there is not adequate data recorded for both parameters. The SPEI was, however, not used in the present study. The SPI on the other hand is based only on long-term precipitation data, which is fitted to probability distribution functions (McKee et al., 1993; Komuscu, 1999; Jain et al., 2015). The accuracy and user-friendliness of SPI makes it popular (Guttman, 1998; Jain et al., 2015) and versatile for detecting even the occurrence of wet spells alongside the droughts across different time intervals. The SPI is effective at establishing the occurrence of drought at specific times based on long-term precipitation records, but it does not account for the frequency of recurrence across seasons.

The Intergovernmental Panel on Climate Change (IPCC, 2014) reported that the frequency of droughts is expected to increase in future, a scenario that requires an in depth understanding of drought patterns for specific localities. A better understanding of inter annual drought occurrences is crucial for mitigation and adaptation measures in agricultural planning and water resources management (Kampata et al., 2008; Tfwala et al., 2018; Gentilucci et al., 2020). The assessment of droughts at continental, regional and local scales is vital for planning and management of water resources (Masih et al., 2014).

Even though drought events have been reported to be increasing in the southern African region (Kruger, 2006; Rouault and Richard, 2003), they remain poorly described in many localities and thus do not reflect that different areas experience different challenges with varying intensities. This is particularly true in a country like the Kingdom of Eswatini where the occurrence of drought in the past has resulted in serious adverse effects, especially in the agricultural sector. For instance, the 2015/16 season was dry across the country and sugarcane, which is
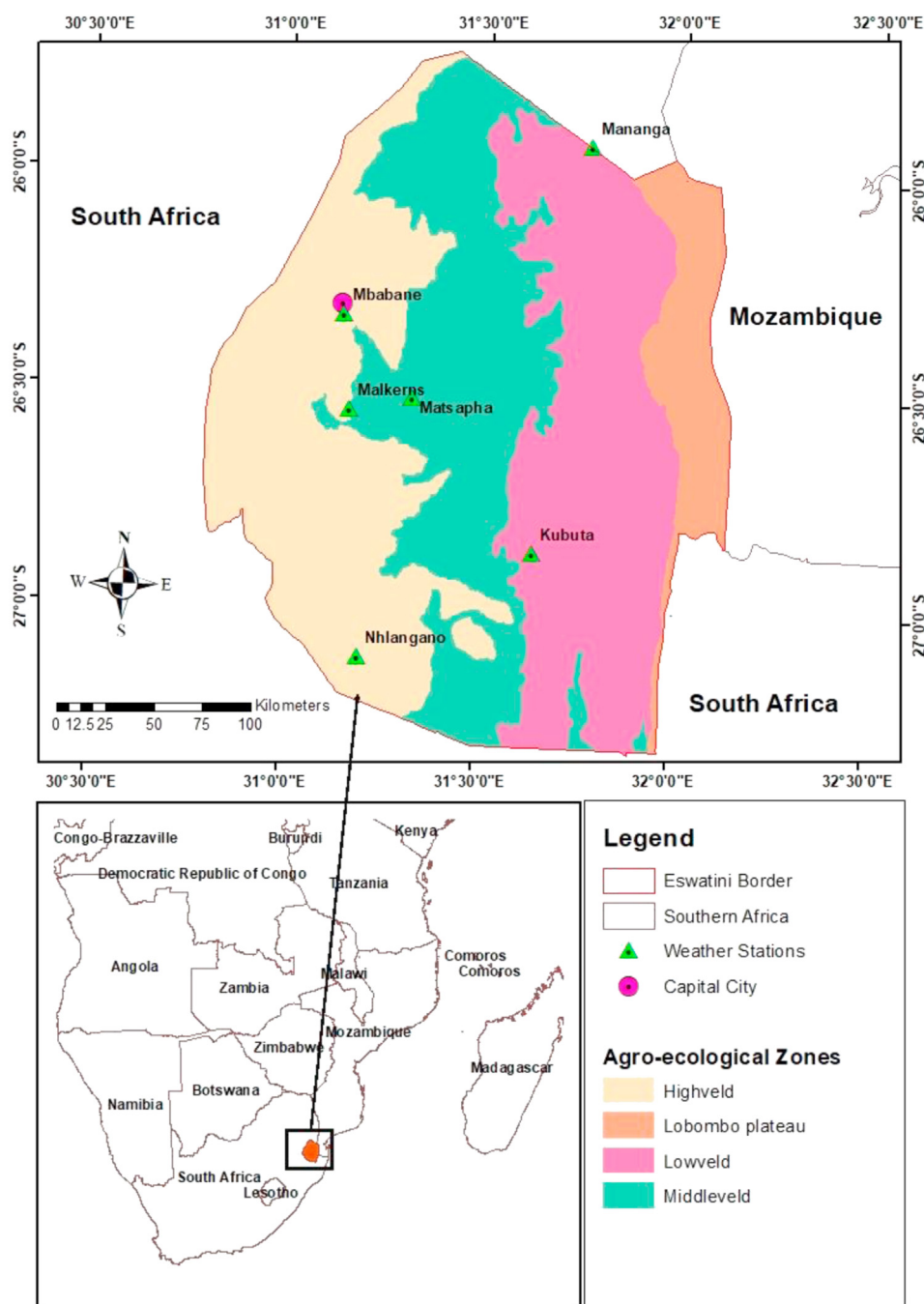

Figure 1. Map of Kingdom of Eswatini showing the agro-ecological zones and meteorological stations used in the study.

termed "Swazi gold", suffered a 30% reduction in revenue. Nationally, 47 000 cattle valued at E 264 million (>US$ 20 million) died during the same period. This research therefore seeks to answer questions like when is the next drought expected and what intensity will that drought be? These questions are pertinent for the different agro-ecological zones across the country as they are expected to vary. In the present study, the SPI was used to quantify the droughts that occurred during 1981–2018 using data gathered from selected meteorological stations. The objectives of this study were to determine i) the occurrence and severity of droughts, ii) the frequency of droughts and iii) general trends of drought occurrence and severity across agro-ecological zones of the Kingdom of Eswatini.

2. Materials and methods

2.1. Description of study area (Kingdom of Eswatini)

The study covered the entire country of the Kingdom of Eswatini, which comprises a total area of 17 364 km^2 and is landlocked between Mozambique and South Africa. Eswatini is divided into very distinct agro-ecological zones running from west to east (Figure 1). The western side of the country includes the mountainous Highveld region. This region is cooler and receives relatively higher rainfall than the rest of the regions in the country. The predominant agricultural activities of this region are forestry plantains and rainfed maize production mainly grown by smallholder farmers. Moving east, next to the Highveld is the Middleveld, which is characterised by undulating hills and flat plains. The

main activity in this region is also rainfed maize production. The Lowveld is typically dry and dominated by irrigated sugarcane plantations and livestock farming. Lastly, the Lubombo plateau is a relatively small strip on the eastern side bordering Mozambique and is similar to the Middleveld in terms of agricultural activity.

2.2. Climate of the Kingdom of Eswatini

The general climatic characterisation of the Kingdom of Eswatini is subtropical, with wet hot summers from October to March and cold dry winters from April to September. The physiographic zones clearly show different climatic conditions, ranging from sub-humid and temperate in the Highveld to semi-arid and warm in the Lowveld. The four agro-ecological zones have distinct elevations, landforms, geology, soils and vegetation. The long-term average rainfall figure for the Highveld, the Middleveld, the Lowveld, and the Lubombo Plateau are 950 mm, 700 mm, 475 mm, and 700 mm respectively. The rainfall patterns of the different meteorological stations are summarised in Figure 2.

2.3. Selection of meteorological stations

For this study, two meteorological stations (Mbabane and Nhlangano) were picked from the Highveld, two (Malkerns and Matsapha) from the Middleveld and two (Mananga and Kubuta) from the Lowveld (Figure 1). These stations were also selected, because they had high quality data with insignificant gaps. The Lubombo Plateau was excluded from the study, because there are no meteorological stations, has a similar climate
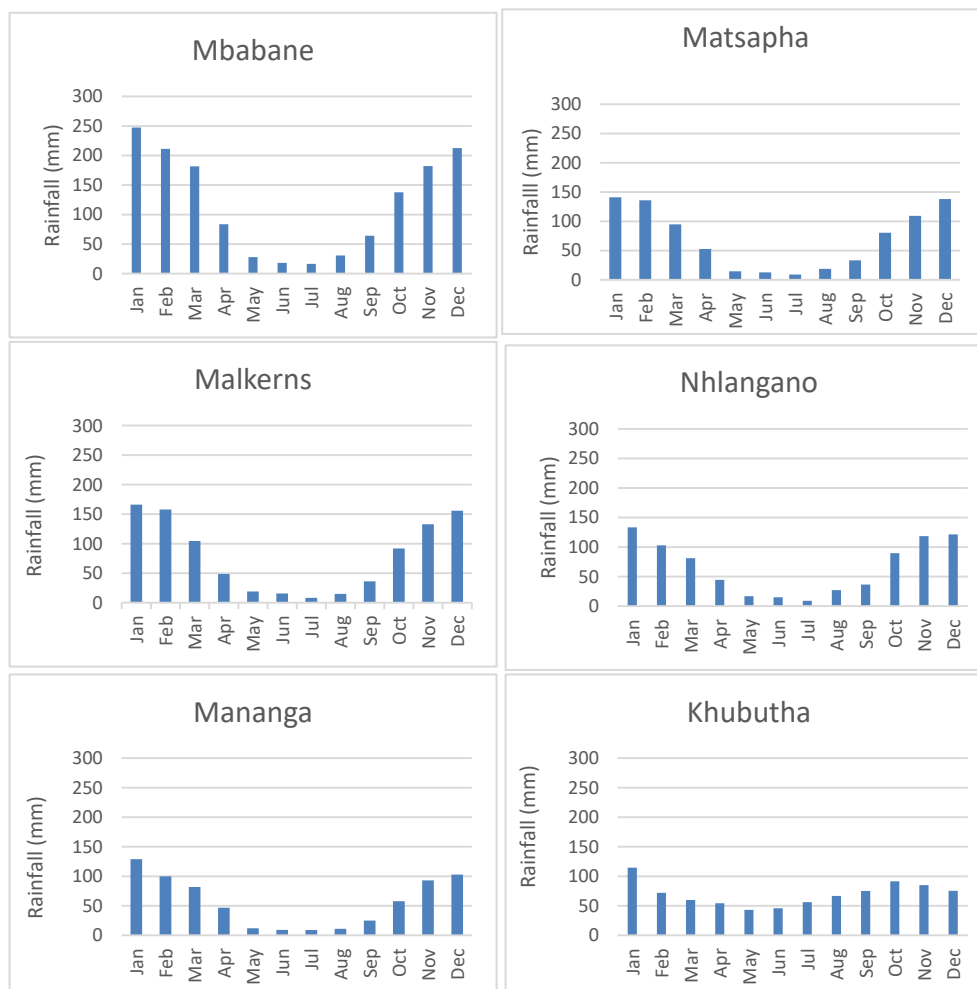

Figure 2. Summarised rainfall patterns for the meteorological stations used in the study computed from data spanning from 1981 to 2018.

to the Middleveld and occupies less than 10% of the total surface area of the country. Monthly rainfall data from 1981 to 2018 for all the meteorological stations were sourced from the Department of Meteorology, Ministry of Tourism and Environmental Affairs. The summary of geographical positions, elevation and average annual precipitation for the selected meteorological stations is presented in Table 1.

2.4. Calculation of Standardised Precipitation Index

The SPI was developed by McKee et al. (1993) to quantify and monitor precipitation anomalies with respect to long-term normal conditions for multiple time scales varying from 1, 3, 6, 12, 24 and 48 months. Its versatility allows it to monitor short-term water supplies, such as soil moisture, which is important for agricultural production, and long-term water resources, such as groundwater supplies, stream flow, lakes and reservoir levels. This study adopted the 12-month SPIbecause of its relevance to water resources in stream flows and reservoirs. To calculate the SPI, a long-term precipitation record from the desired station is first fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI is zero. The most commonly used distribution for calculating the SPI is the two-parameter gamma distribution with a shape and scale parameter (Shiau, 2020), which is defined by its probability density function as shown in Eq. (1) below:.

$$G(x) = \frac{1}{\beta^\alpha \tau(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \text{ for } > 0 \quad (1)$$

Where α is the shape parameter, β is the scale parameter, x is the precipitation value and $\tau(\alpha)$ is the gamma function. The gamma distribution is undefined for $x= 0$, but the precipitation may have a zero value. For a given zero value, the cumulative probability distribution is derived as follows (Equation 2):

$$H(x) = q + (1-q)G(x) \quad (2)$$

Where q is the probability of the zero precipitation value. The cumulative probability distribution is then transformed into the standard normal distribution to calculate SPI. The value of SPI indicates the strength of the anomaly whereby a negative SPI value indicates a drought year and vice versa, with the range from >-1 to <1 regarded as normal (Guttman, 1999). As shown in Table 2, these SPI categories were then used to characterise the intensity of drought. .

2.5. Frequency analysis

A frequency analysis was carried out using Python (Version 3.6) to calculate recurrences of drought events over time in years using the SPI values. The SPI values were then ranked and the probability of occurrences of drought was computed using Eq. (3) below following Baaqeel et al. (2016):

$$F = \frac{100(2m-1)}{2n} \quad (3)$$

Where m is a rank of each annual SPI while n is a total number of events. Thus, return period or recurrence (τ) was calculated using Eq. (4).

$$\tau = 100/F \quad (4)$$

2.6. Trend analysis of droughts

The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was applied across the whole range of SPI values in each of the meteorological stations. This was done to determine if there was any trend in the drought occurrence as shown by the trend of the SPI values for a given time period at a specific time-scale of the SPI computation, which was 12 months in the present study.

In the Mann–Kendall test, all the mean monthly precipitation values were arranged temporally and compared to subsequent data values. During this process, the initial value of the Mann–Kendall test, S, was considered to be no trend or zero trend (Kendall, 1975). If the next value was greater than the previous value, then it was considered incremental by +1. Conversely, if the value was lower than the previous value in the time series, it was considered decremental by −1. All the resultant incremental and decremental values gave the final S value, calculated using the following equations (Eqs. (5), (6), (7), and (8)):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sign(X_j - X_k) \quad (5)$$

Where $(X_j - X_k) = +1, \text{ if } (X_j - X_k) > 0 \quad (6)$

$$(X_j - X_k) = 0, \text{ if } (X_j - X_k) = 0 \quad (7)$$

$$(X_j - X_k) = -1, \text{ if } (X_j - X_k) < 0 \quad (8)$$

$X_1, X_2, ...X_i$ represents n data points, X_j represents the data point at time j, and n is the sample size.

The presence of significance between trends was tested by the normalised statistical test (Z-score) and computed using the following equations (Eqs. (9), (10), and (11)):

$$Z = \frac{S-1}{\sqrt{VAR(S)}}, \text{ if } S > 0 \quad (9)$$

$$Z = 0, \text{ if } S = 0 \quad (10)$$

$$Z = \frac{S+1}{\sqrt{VAR(S)}}, \text{ if } S < 0 \quad (11)$$

Where VAR refers to the variance of the population. Note that if the trend of the SPI values is decreasing it means that the droughts are generally increasing and vice versa.

The magnitude of the trend was calculated using the Sen's method (Sen, 1968; Dindang et al., 2013). Sen's method is useful for estimating the slope of a linear trend and has been widely used for determining the magnitude of the trend of time series data in hydro-meteorological

Table 1. Geographical positions, elevation and average annual precipitation for the selected meteorological stations in the Kingdom of Eswatini.

Station	Latitude	Longitude	Elevation (m.a.s.l)	Average annual precipitation (mm)
Mbabane	-26.33	31.14	1188	1410
Nhlangano	-27.12	31.20	1040	870
Malkerns	-26.55	31.16	734	946
Matsapha	-26.52	31.32	639	840
Mananga	-25.93	31.76	267	667
Kubuta	-26.87	31.46	529	826

Table 2. SPI values and corresponding classification describing the intensity of drought or wetness of a year relative 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

studies. Hence, the slope of all the data pairs was calculated using Eq. (12) (Sen, 1968; Dindang et al., 2013):

$$m_i = \frac{(X_j - X_k)}{(j-k)}, \text{ for } i = 1, 2, 3, \ldots, N \tag{12}$$

Where N is the number of data points in the time series; X_j and X_k are data values at times j and k $(j > k)$, respectively.

The median of these N values, m_i is Sen's estimator of the slope, which is calculated as follows (Equation 13):

$$\beta = \begin{cases} m\dfrac{N+1}{2}, & \text{if } N \text{ is odd} \\ \dfrac{1}{2}\left(m\dfrac{N}{2} + m\dfrac{N+1}{2}\right), & \text{if } N \text{ is even} \end{cases} \tag{13}$$

These procedures described above were computed using an Excel add-in, XLSTAT ver-2018.6, which was downloaded from the official website of XLSTAT software from the URL: https://www.xlstat.com/en /download.

3. Results

3.1. Drought occurrence and severity

The droughts in the Highveld, established from the 12-months SPI values covered all extents of severity from moderate to extremely dry. Out of the rainfall records between 1981 and 2018, there were ten (10) drought seasons in Mbabane (Figure 3). There were four moderate drought event SPI values between -1.02 and -1.49 in the years 1986/87, 1989/90, 2006/07 and 2017/18. Severely dry seasons at the same meteorological station (Mbabane) occurred in the years 1994/95 (SPI = 1.91), 2011/12 (SPI = -1.6) and 2014/15 (SPI = -1.58). The remainder (3) of the droughts were extreme where SPI values of -2.49, -2.34 and -2.82 were observed in the 1982/83, 1992/93 and 2015/16 seasons,
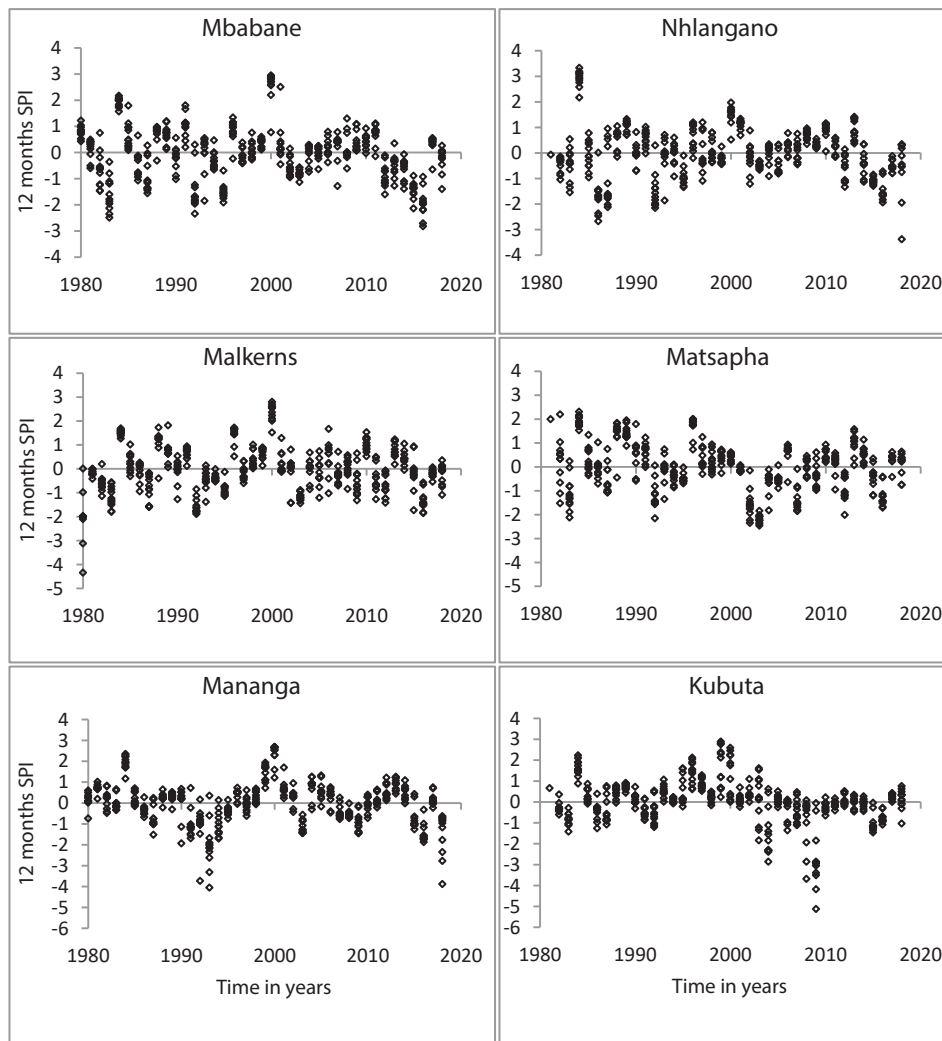
Figure 3. Standardised Precipitation Index values for selected meteorological stations in different agro-ecological zones (Highveld, Middleveld and Lowveld) of the Kingdom of Eswatini computed using precipitation data spanning from 1981 to 2018.

respectively. At the second meteorological station (Nhlangano) in the Highveld (Figure 3), nine drought seasons were observed. Four of these (1994/95, 1996/97, 2011/12 and 2014/15) were moderate with SPI values ranging from -1.09 to -1.34. Three seasons (1982/83, 2015/16 and 2017/18) were severely dry with SPI values varying between -1.54 and -1.95. Two seasons, 1986/87 (SPI = -2.37) and 1992/93 (SPI = 2.15) were extremely dry.

Drought occurrence in the Middleveld was represented by Malkerns and Matsapha. At Malkerns, 11 drought seasons were observed. Six of these were moderate with SPI values ranging from -1.11 to -1.42 in the 1990/91, 1994/95, 2002/03, 2008/09 and 2011/12 seasons. Severe droughts were observed in 1982/83 (SPI = -1.8) 1986/87 (SPI = -1.6), 1992/93 (SPI = -1.78) and 2015/16 (SPI = -1.73) seasons. At the second meteorological station in the Middleveld (Matsapha), six droughts were observed. The seasons 2006/07 (SPI = -1.85) and 2015/16 (SPI = -1.71) were severely dry. The seasons 1982/83, 1992/93, 2002/03 and 2011/12 (SPI values of -2.12, -2.15, -2.46 and -2.01, respectively) were all extremely dry.

The Lowveld experienced six droughts at Mananga between 1981 and 2018. Three moderate droughts were observed in 1993/94 (SPI = -1.38), 2002/03 (SPI = -1.42) and 2008/09 (SPI = -1.4). There was one severe drought with a SPI value of -1.87 during the 2015/16 season. The 1992/93 season at this meteorological station had an SPI value of -4.05, and the 2017/18 season had an SPI value of -3.88, which both indicated extremely dry conditions. At Kubuta, seven droughts were observed between 1981 and 2018. Five seasons (1982/83, 1986/87, 1992/93, 2006/07 and 2015/16) were moderately dry with SPI values between -1.03 and -1.42. The remainder of the droughts were extreme with SPI values of -2.86 during the 2003/04 season and -5.12 in the 2008/09 season.

3.2. Frequency of drought occurrence

The computed recurrence rate of droughts in the different agro-ecological zones in the Kingdom of Eswatini is presented in Figure 4. The frequency analysis revealed that moderate droughts are expected approximately every 4 years at Nhlangano and Mbabane. An extreme drought is expected after every 19 years at Nhlangano and after every 25 years at Mbabane. In the Middleveld, moderate droughts were observed to recur every 4 years at both Malkerns and Matsapha. Extreme droughts were observed every 12 and 15 years at Malkerns and Matsapha, respectively. In the Lowveld, the frequency analysis revealed that moderate droughts are expected every 4 years at Mananga and every 3 years at Kubuta. Extreme droughts in this agro-ecological zone were observed to occur once in 17 years at Mananga and every 9 years at Kubuta. The frequency of severe droughts fell between that of moderate and extreme droughts for all the agro-ecological zones.
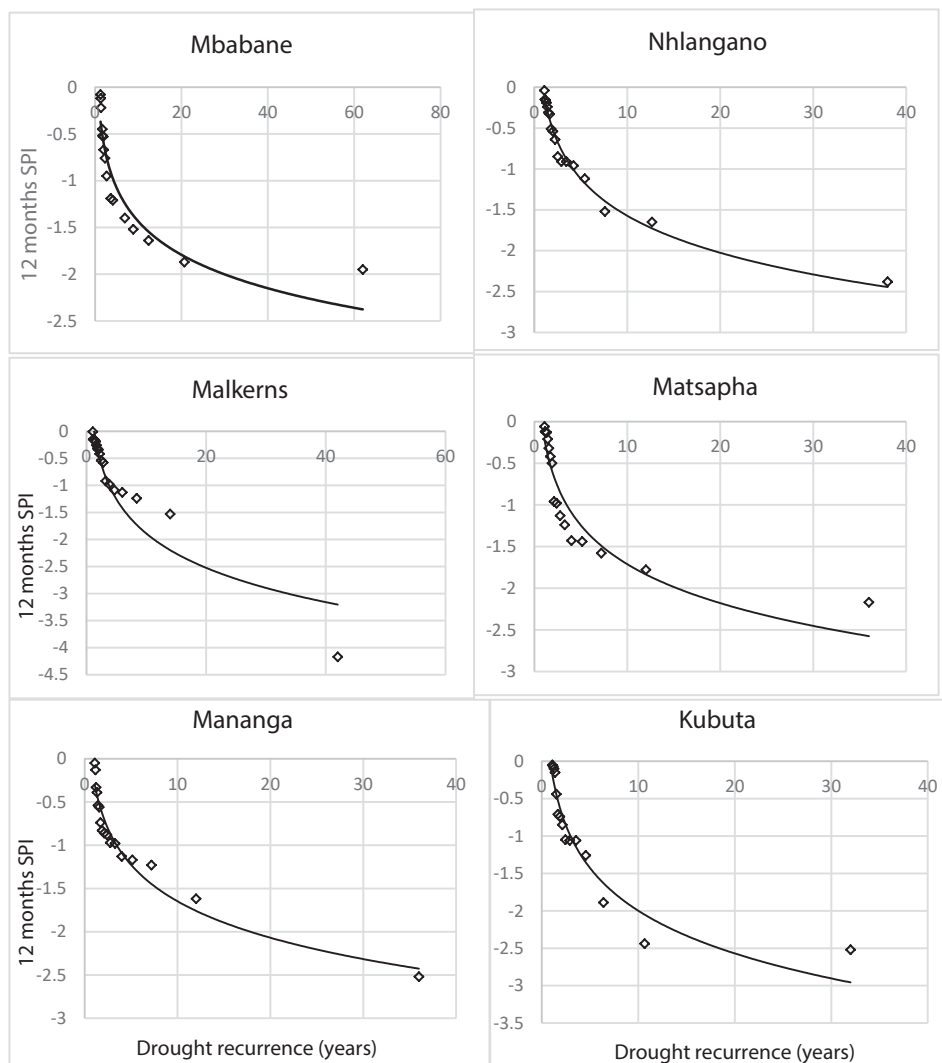

Figure 4. Drought recurrence for selected meteorological stations across different agro-ecological zones in the Kingdom of Eswatini

Table 3. Mann-Kendall analyses of SPI values across all the meteorological zones.

Parameter	Mbabane	Nhlangano	Malkerns	Matsapha	Mananga	Kubuta
Kendall's tau	-0.108	-0.198	-0.007	-0.086	-0.066	-0.115
S	-9529	-3682	-328	-7595	-3208	-9613
Var(S)	8320362	804939	3423385	8320360	3423385	7629758
P-value	0.001	<0.001	0.860	0.008	0.083	0.001
Sen's slope	-0.00005	-0.00017	-0.000004	-0.00004	-0.00003	-0.000044

3.3. Drought trend analysis

The results of the Mann-Kendall analysis applied to SPI values across all the meteorological stations are presented in Table 3. The P-values of all the stations except, Malkerns and Mananga, showed that drought trends were significantly changing. The slopes of all the trends were negative, including the two that were not significant, which showed that the droughts were generally increasing in most of the meteorological stations as the SPI values dropped by less than 0.001 per period of 12 months.

4. Discussion

4.1. Drought occurrence and severity

The majority (42%) of the droughts recorded by the two stations in the Highveld were moderate. Severe droughts constituted 32% and the remaining 26% of the droughts were extreme. The moderate and severe droughts were evenly spread across recorded data period. In the Middleveld, the proportion of moderate, severe and extreme droughts were generally equal (29–35%), and the distribution was even across the data recording period. The Lowveld recorded 62% of moderate droughts, 8% severe droughts and 30% were extreme droughts. About 70% of the droughts occurred after the year 2000. The recurring droughts have serious implications on food production in particular. As most of the crop production in the Highveld and Middleveld is rainfed, a single drought season adversely affects all sectors of production from crops to animal production. The small perennial streams that animals mainly use normally dry up during droughts and this leads to livestock death. River flow volumes decrease, which impacts negatively on irrigation agriculture. This puts pressure on sugarcane plantations as well as jobs and livelihoods for many of the citizens. Precipitation data recorded between 1953 and 2015 from ten meteorological stations across the Assandra Basin in Côte d'Ivoire was analysed by Santé et al. (2019). The authors found that the frequency and severity of droughts increased after 1970. Three out of the four recorded extreme droughts also occurred during this period. Other studies in the Southern African region have also reported findings similar to those of the present study. Rouault and Richard (2003) analysed precipitation data between 1921 and 2001 and reported more intense droughts in the 1980s and 1990s. Tfwala et al. (2018) also concluded that droughts were more prevalent and more intense in recent years, particularly after 1990. The present findings also reveal the same.

4.2. Frequency of drought occurrence

The study showed that recurrence increased with the severity of the drought. On average, moderate droughts are expected after every 5 years in the Highveld and after every 4 years in the Middleveld and Lowveld. Extreme droughts occur every 21 years, 14 years and 13 years in the Highveld, Middleveld and Lowveld, respectively. The frequency of severe droughts fell between that of moderate and extreme droughts for all the agro-ecological zones. The decrease of frequency of occurrence for more extreme meteorological (precipitation) phenomena at both ends (drought and extremely wet) has been reported (Dalezios et al., 2000). A more recent study in the Kingdom of Eswatini with more meteorological stations, but a slightly shorter period than the present study revealed that the light intensity droughts (mild and moderate) occur more frequently (Mulenga et al., 2019.

Droughts can have serious negative impacts on the human population and livelihoods by exacerbating food insecurity. 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 influence maintenance of valuable genetic diversity. The more frequent occurrence of droughts will therefore affect groundwater recharge and related ecosystem components.

Analysing precipitation intensities of the Ghaap Plateau, Tfwala et al. (2017) found that increasing recurrence intervals corresponded to extremely high intensity storms. Amrit et al. (2018) investigated the occurrence of droughts in north-western India and discovered that moderate droughts occur once every three to four years, severe drought occurs once in 10 years and extreme droughts occur once in 33 years. These findings agreed with the findings of the present study. Establishing this information is crucial for management of water resources and to accurately plan for mitigation and adaptation measures to address the negative impacts of droughts especially in agriculture.

4.3. Trends of droughts

The trends of droughts, as shown by the significant lowering of SPI values in most of the stations (four out of six), generally increased from 1981 to 2018. The study by Mulenga et al. (2019) reported a decreasing trend in the total annual rainfall. The issue of decreasing rainfall has been disputed by other researchers when the data recording period is as short as the report by Mulenga et al. (2019). The argument is that rainfall patterns follow cyclic patterns over the years (Tyson et al., 1975, 2002; Nel, 2009), meaning that it is very difficult to observe and conclude on a decrease or increase within a period of say thirty years. However, Gentilucci et al. (2020) also reported a decreasing annual rainfall trend in Italy, using data from 55 meteorological stations spanning over 60 years. The increasing trends of drought detected in the present study are in line with previous reports despite the arguments on the changes in total annual rainfall. Some of these reports have indicated that droughts are expected to increase in frequency and severity as a result of climate change, scenarios which will affect decreases in rainfall and increasing evaporation as a result of global warming (Sheffield and Wood, 2008; Dai, 2011). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) highlighted that more intense and longer droughts have been observed globally, particularly in the tropics and subtropics since the 1970s (IPCC, 2012). Southern Africa is characterised by a predominantly semi-arid climate with annual rainfall variability and droughts occur with high frequency and severity; the El Niño Southern Oscillation (ENSO) has been established to be the major driver of these droughts events (Manatsa et al., 2008).

5. Conclusion

The study described the occurrence, severity, frequency and trends of droughts in the Kingdom of Eswatini using the Standardised Precipitation Index (SPI). Three conclusions were drawn after analysing precipitation data between 1981 and 2018: 1) Droughts have increased in prevalence and severity after the year 2000, especially in the dry Lowveld. 2) The

frequency of droughts is higher in the dry areas of the country compared to the high rainfall areas. 3) The trends of droughts as determined by the Mann-Kendall analysis of the SPI values across the six meteorological stations revealed that the droughts are generally increasing. The findings concurred with other studies conducted in the region. Until recently, the limited quality of data from most meteorological stations limited the possibility of using other indices such as the SPEI, which requires many weather parameters. The findings of this study are essential for management of water resources and to accurately plan mitigation and adaptation measures to address the negative impact of droughts. This is particularly important for the Kingdom of Eswatini like in many other African countries where agriculture forms the backbone of the economy. Future research should explore the use of SPEI, as most of the stations started recoding air temperature in the 1990s. The spatial variability should also be investigated for more location specific insights on the drought dynamics of the country.

Declarations

Author contribution statement

Funding statement

Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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