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Monitoring droughts in Eswatini: A spatiotemporal variability analysis using the Standard Precipitation Index

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The spatiotemporal analysis of drought is of great important has been facing recurring droughts with negative impart on agriculture. re, environment and economy. In 2016, the country experienced the more evere drough n over 35 years estock dea s. The frequent resulting in food shortages, drying up of rivers as well as occurrence of extreme drought events makes the se of di ht ind es essential for drought monitoring, early warning and planning The aim of this assess the applicability of the Standard Precipation Ipex (SPI) for near real-time and retrospective drought monitoring in Eswatini. The cound 12-month SPI were computed to analyse severity and onset of meteorogical dreams by between 1986 and 2017. The to analyse severity and onset of meteor gical dre ni exhibits geo worst drought years being 1985–1966, 2005–26 and 2015–2016 agricultural Moderate droughts were the most A and temporal variability. of the country were vulnerable to mild and moderate droughts was low. Most parts agricultural droughts. Spatial applysis showed that the most severe and extreme droughts owveld and liddleveld agro-ecological zones. The 3-, were mostly experienced in th nducted January detected the onset of early season 6- and 12-month SPI computation drought, thereby affirming the application the index for monitoring near real-time and tini. Drought monitoring using SPI provides information retrospective drough for early warning, part ularly 1 ht-prone areas, by depicting a drought before the effects have begun to be

Keywords: stored precipitation index; drought; rainfall; spatial and temporal variability; Eswatini; a rught in intoring.

Intr ductio

Doug vis a pressing conomic, social and environmental issue that is of great importance to watini, unilar to the rest of southern Africa, where for the past few decades the region has been affected by recurring droughts which had negative impacts on rain-fed agriculture, environment, economy and the livelihoods of the people. The increased frequency in drought occurrence has triggered an increased scientific and social interest; this is in relation to future matic conditions in the region, especially where modelling experts have predicted that tught cars will be more common and severe in southern Africa and the impacts more sign at (IPCC 2012, 2013). To mitigate, therefore, the impending challenges, the key is to understand drought and its natural and social dimensions so as to enhance drought risk tragement. This is in an effort to increase society's coping capacity, which will in turn lead to greater resilience and a reduced need for government or donor interventions in the form of disaster assistance.

Drought is spatially variant and context dependent, thereby making it difficult to accurately describe. Although the effects and impacts of drought events are well documented, a standardised method for monitoring drought conditions and quantifying the severity of drought does not exist. The drought index, however, is the most common tool used for monitoring drought conditions. A drought index can be used to quantify the moisture condition of a region and thereby to detect the onset and measure the severity of drought events. Drought indices can be useful tools for providing information to decision-makers to predict crop yield (Kumar & Panu 1997), provide an early drought warning information (Lohani & Loganathan 1997; Lohani, Loganathan & Mostaghimi 1998), calculate the probability of drought termination

(Karl, Quinlan & Ezell 1987), determine drought assistance (Wilhite, Rosenberg & Glantz 1986) and make comparisons between different regions (Alley 1984, 1985; Dai, Trenberth & Karl 1998; Kumar & Panu 1997; Nkemdirim & Weber 1999; Soulé 1992).

Precipitation-based drought indices are being applied to characterise drought conditions (Tadesse et al. 2008). The challenge, however, is the absence of continuous spatial rainfall data coverage, thereby reducing the ability of monitoring and characterising detailed spatial and temporal patterns of drought (Manyatsi, Ntobeko Zwane & Dlamini 2015). The lack of agreed drought indicators and thresholds above or below by which a drought can be declared makes the objective of drought monitoring and drought declaration difficult and often late. This often results in loss of life and livestock, food insecurity and significant financial impact for the economy. The aim of this study was therefore to assess the applicability of the Standard Precipitation Index (SPI) for near real-time and retrospective drought monitoring in Eswatini. The efficient use of SPI can improve drought monitoring and early warning in Eswatini.

Standard Precipitation Index

Over the years, many drought indices were developed and used by meteorologists and climatologists around the w The most commonly used index worldwide though Standardised Precipitation Index (SPI). McKee in 1 developed the SPI during the early 1990s (McKee, Doesken Kleist 1993). The WMO in 2009 recommend main meteorological drought index that cour ld use ves et to monitor and follow drought conditions Currently, many scientists prefer the PI as dex for drought risk (Giddings et al. 2005; Gy nan 1999; i 1999; Jordaan 2011). The index is mmended bec allows the comparison between din nt climates and locations. It can be used to applyse drough. anomalously wet periods at a particular mescale for any location in the world with daily precipit fron records (McKee 1995; Moreira n indicator for drought et al. 2008). Using the as monitoring, early warning di ht disast declaration will limit the arbitra politicians with ision-ma scientifically ba d critei

The SPI can be atted for any location that has a long-term precipitation at a. The index can identify various drought types: hydrologic agricultural or environmental. The SPI is commonly calculated using 1-month, 3-month, 6-month, 9-month, 12-month and 24-month intervals. These timescales are appropriate for monitoring different types of drought and correspond to different drought impacts. The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Belayneh & Adamowski 2012; Edwards et al. 1997).

For an in-depth comprehension of the meaning of SPI, an understanding of the concepts related to SPI is essential. Mckee et al. (1993) and Jordaan (2011) reviewed and defined the SPI-related concepts as follows:

- Accumulated precipitation This is the total rainfall during specified period.
- Accumulated precipitation departure This is the amount by which the indicated accumulated precipitation is above or below the long-term average for exactly the same set of months.
- Accumulated precipital n per cen of average – The accumulated precipi ion, over the escale of interest the end o and extending through the last month indicated, divid by the lo term a rage precipitation, which would e expected to a ulate over the same multiplied by 100. set of mont and th
- Percentil or pure ty of nonexceedance This is the magnitude observe and regarded as the degree of 'un lness'.
- To escale. The number of months extending through to the end of the surrent month.

The SPI is based on statistical probability and was designed to be a spatial invariant indicator of drought. The index is ormally distiputed and is therefore useful to monitor dry ret per as because of the normal distribution. The SPI is able to categorise precipitation deficit for varying escales, such as weeks, months and years (McKee 1995). mmonly calculated using 1-month, 3-month, 6-month, 9-month, 12-month and 24-month intervals. These timescales reflect the impact of drought on agriculture, pasture or waterbodies (Bokal 2006; Guttman 1999), which are the various drought types: hydrological, agricultural or environmental. Soil moisture is sensitive to precipitation deficit over a short timescale, while groundwater, streamflow and reservoir storage reflect the longer-term precipitation deficits (WMO 2012). McKee et al. (1993) classified drought intensities resulting from the SPI.

McKee et al. (1993) used the classification system (Table 1) to define drought intensities resulting from the SPI. They also defined the criteria for a drought event for any of the timescales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less, and drought intensity can be calculated by summing the SPI values for all months within a drought event

TABLE 1: Drought classification based on Standard Precipitation Index.

SPI values	Class
≥ 2	Extremely wet
1.5-1.99	Very wet
1.0-1.49	Moderately wet
-0.99 to 0.99	Near normal
-1 to -1.49	Moderately dry
-1.5 to -1.99	Very dry
≤ 2	Extremely dry

Source: McKee, T.B., Doesken, N.J. & Kleist, J., 1993, 'The relationship of drought frequency and duration to time scales', in *Proceedings of the 8th conference on applied climatology*, vol. 17(22), pp. 179–183, American Meteorological Society, Boston, MA. SPI. Standard Precipitation Index.

(McKee 1995; McKee et al. 1993). The event ends when the SPI becomes positive. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation.

Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's 'magnitude' (WMO 2012).

Applied methodology

Study area

Eswatini is a landlocked nation almost entirely contained within the northeast corner of South Africa and located at the transition of the South African Plateau (reaching over 1500 m) to the Mozambican coastal plain. The country has a total area of 17 364 km² and has approximately 12 220 km² of agricultural land, or 71% of the total land area (FAO 2013). The country has four administrative districts (Hhohho, Manzini, Lubombo and Shiselweni) and is classified into four agro-ecological zones (AEZ), taking into account elevation, landforms, geology, soils, climate and vegetation: Highveld, Middleveld, Lowveld and Lubombo range.

The rainy season is from mid-October to mid-April, an dry season is from mid-April to mid-October. Mean ann rainfall ranges from about 700 mm to 1500 mm in the norther Highveld (Table 2) to 200 mm in the southern eld. The Middleveld annual rainfall ranges from 500 mm. The national long-term average rainfall is 8 mm p These large ranges indicate the fluctual Eswatini's climate. These climatic nditions country very vulnerable to meteor gical hazards drought, floods and gusty wind ıs v as lightening and epidemics during the wet and hot seas Mean annual temperature varies from 17 2 in the Highvela 22 °C in the Lowveld (Government of vaziland 2013).

Data set

The SPI was used for a hight monoring for the time series from the perior 1986 to 17. Representative meteorological stations of the Europia case. Consider the Europia case of the Europia

TABLE 2: Rainfall in the agro-ecological zones of Eswatini

Agra coological rang	Average reinfall		
Agro-ecological zone	Average rainfall		
Highveld	700–1550		
Middleveld	550-850		
Lowveld	200–550		
Lubombo Plateau	550–850		

Source: FAO AQUASTAT Survey, 2005, Irrigation in Africa in figures, viewed 08 December 2016, from http://www.fao.org/ag/aquastat.

natural drought conditions, raw precipitation data were used. All the chosen precipitation stations displayed good data quality with no data gaps in the time series. This is because only rainfall stations that had the complete 32-year data set were selected. There was therefore no data filling or corrective homogeneity enforced.

Computation of Standard Precipitation Index

The SPI was calculated according to the methodology explained by Giddings et a wever, the actual SPI d through computation was achig e use of DrinC software. The selection for software as based on its ed for the use in simplicity, such that it can easily ado ware package that Eswatini. DrinC is ool s user-frience r providing a sin thorough adaptable was developed interface for calcu tion of several drought indices (Tigkas, Vanelis kiris 2015 The software operates on platform a grammed in Visual Basic. Window

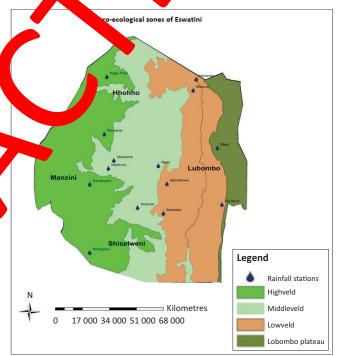


FIGURE 1: Map of Eswatini with agro-ecological zonation and the rainfall stations.

TABLE 3: Meteorological stations and their geographic coordinates.

Agro-ecological region	Station name	Latitude (S)	Longitude (E)	Time series
Highveld	Mbabane	-26.33	31.15	1986-2017
	Nhlangano	-27.12	31.20	1986-2017
	Mankayane	-26.67	31.05	1986-2017
	Mhlume	-26.03	31.15	1986-2017
Middleveld	Matsapha	-26.53	31.30	1986-2017
	Piggs Peak	-25.82	31.42	1986-2017
	Khubutha	-26.83	31.47	1986-2017
	Mpisi	-26.43	31.53	1986-2017
	Malkerns	-26.55	31.87	1986-2017
Lowveld	Big Bend	-26.85	31.87	1986-2017
	Sithobelweni	-26.88	31.62	1986-2017
	Mananga	-26.00	31.75	1986-2017
	Siphofaneni	-26.67	31.68	1986-2017

S, south; E, east.

A series of at least 30 years period of data was used to determine SPI values for 3-, 6- and 12-month timescales.

The Eswatini rainfall data set of 2006-2017 was obtained from the Eswatini Meteorological Services under the Ministry of Tourism and Environmental Affairs. The MS Excel data set was uploaded onto the DrinC software for manipulation. The SPI was calculated at 3-, 6- and 12-month timescales. The primary reference base in DrinC is the hydrological year (October-September); however, the study defined the hydrological year based on the Eswatini rainfall calendar. For the 3-month SPI, the hydrological year covered October, November and December. Ji and Peters (2003) found that the 3-month SPI is the most effective for monitoring drought impact on vegetation, especially when the 3-month period coincided with the peak growing season. The 6-month SPI hydrological year covered July to December, whereas the 12-month SPI hydrological year covered January to December. The 3-month SPI indicates the conditions of short-term drought, mostly soil moisture and drought stress with an impact on agriculture, while the 6- and 12-month SPI indicate medium- to long-term droughts which affect ground water supplies and pasture conditions. The study therefore mapped drought severity at 3-, 6- and 12-month timescales in the four agro-ecological regions of Eswatini. Month of December was chosen for calculating SPI for 3-, 6- and 12-month timescale as October is when the rainfall or agricultural season starts, whereas December is mid-season where the main crops (maize) will be flowering. The 3-month period October to December is therefore normally the critical w season, and therefore, the onset of drought in this period will affect crop production.

Spatial representation of SPI was performed using Arce. 10.1 where the geo-statistical method. kriging as chosen for the representation of spatial distribution and intensity of the drought for the selected drought years, 1985–1966, 2004–2c. 2005–2006 and 2015–2016, was krigged to allow spatial in a polation of drought across AEZ.

Ethical considerations

This material has considered public of a whole or in part elsewhere. The canuscript is not currently being considered for publication canotics, and All authors have been personally and active involved in substantive work leading to the manuscript, and will hold themselves jointly and individually responsible for its content.

Results and discussion

Precipitation over time

Precipitation level is an important factor affecting crop selection and ecological changes in a region. Precipitation over time graphs were made for all 14 stations in order to visualise the data time series of the precipitation values. Figure 2 presents the time series of the Eswatini's annual

average precipitation between 1986 and 2017. The analysis of the precipitation over time is important to improved understanding of hydro-meteorological processes and their long-term variations. This is because meteorological drought is considered a consequence of the negative deviation of rainfall from the mean and a most common indicator for drought (Wilhelmi & Wilhite 2002; Wilhite, Sivakumar & Wood 2000; WMO 2006). Cumulative rainfall calculations can be very useful with the prediction of dry periods and drought. The seasonal and the properties of the patterns are also important for drought thazars.

Figure 2 shows the mean storical mor ly rainfall for 14 selected rainfall sta the tim period 1986–2017. ons dun The rainfall patter between all L sed rainfall stations SS the moons of May and June being the dry was similar wi winter months, the rainfall was only received mostly be or not sinfall in the Lowveld AEZ. re eld with e progressive increase in the season which infall received started in September with the ths in December and January. December peak rainfall \ anuary coinc with summer crops' main vegetative development and reproductive stages. Prolonged rainfall stress in these months will result in reduced crop yields. nalysing the me series of the Eswatini's annual average ipitation om 1986 to 2017, it was clear that there were rainfall was below the national average. The otable years were 1986, 1990, 1992, 1994, 2002–2003, 2005, 008, 2011, 2014 and 2015–2016. The annual rainfall during the 32 years ranged from 363 mm in 2016 to 1309 mm in 2000, with an average of 819 mm. The lowest rainfall corresponds with the 2015–2016 El Nino, which was classified as one of the worse to occur in 50 years (Phys.org 2016).

Trend analysis was also performed on an annual scale to examine whether any trends existed in the data. The annual rainfall time series, averaged over the whole data set, is illustrated in Figure 3 with the corresponding Sen's slope

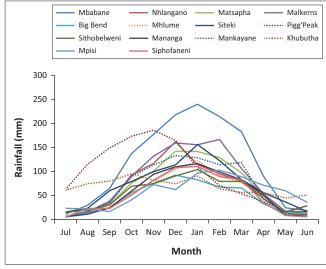


FIGURE 2: Mean historical monthly rainfall for Eswatini during the time period 1986–2017.

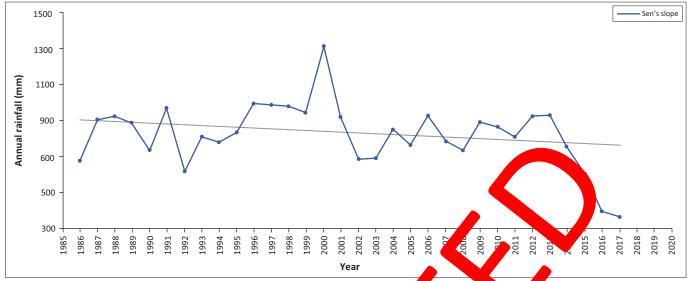


FIGURE 3: Annual rainfall trend for Eswatini (1986-2017).

TABLE 4: Mann-Kendall trend test and two-tailed test (annual precipitation).

Statistic	Value		
Kendall's tau	-0.161		
S	-80 000		
Var(S)	3 802 667		
p-value (two-tailed)	0.195		
Alpha	0.05		
Mean	819 mm		
Standard deviation	179		

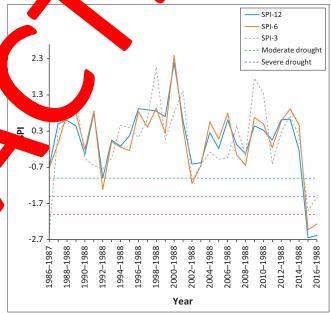
Trend equation: y -6.3389x + 13506; R^2 = 0.1103.

S, (Kendal score) indicates the slope of the trend (positive = upward, negative = downwa

plotted. The variability around the mean n) was evident and pronounced, indicating a decre me in annual rainfall. The standard deviation of shows higher values than the ave le. Furthe deviation from normal is consider Kendal test results (Table 4) indig decreasing to annual rainfall across all meteo ogica ations. The Sen's slope estimate of rate of decreage is -80 mm pe ar. However, Astically significan the decreasing rate is not si $\alpha = 0.05.$ strated patial variations of the The rainfall trends dem Lubombo Plateau agro-Highveld, Middleveld the Q Platea had the highest ecological regions. The Lube mean rainfall, wh he Low the lowest mean udy p rainfall over the od.

Drought severing imporal dynamics based on Standard Precipation Index

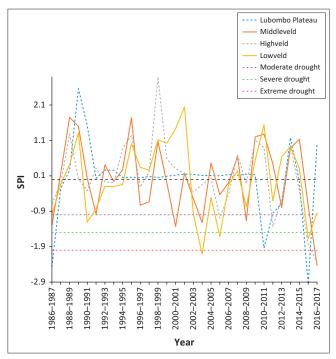
The study calculated for the time series 1986–2017 using the SPI on 3-, 6- and 12-month timescales corresponds to the past 3, 6, and 12 months of observed precipitation totals, respectively. These time scales reflect the soil moisture conditions (SPI-3) or the underground waters, river flows and lake water levels (SPI-12) (Bokal 2006; Livada & Assimakopoulos 2007; Rouault & Richard 2003). Overall, the temporal SPI analysis using McKee et al. (1993) SPI classification (Table 1) suggests that Eswatini experienced moderate to extreme drought episodes in the



SPI, Standard Precipitation Index.

FIGURE 4: Standard Precipitation Index values of Eswatini for three different timescales (3-, 6- and 12-months).

years 1986, 1990, 1992, 2006, 2012, 2014 and 2016. Moderate drought occurred in 1986, 1990 and 2012 (Figure 4), whereas severe drought occurred 1992 and 2006. The only extreme drought recorded was in 2016, which corresponds to the strongest El Nino period in over half a decade and the government drought disaster declaration in 2016 (NDMA 2016; Phys.org 2016; Swaziland National Vulnerability Assessment Committee 2016). The extreme drought result is consistent with the research by Rouault and Richard (2003) who highlighted that an SPI of -2.00 happens twice per century, from -1.5 to -1.99 about four times per century, and from -1 to -1.5 about nine times per century. The minimum SPI value (-2.95) detected in 2016 across Eswatini was persistent, with varying severity in the different AEZs (Figure 5).



SPI, Standard Precipitation Index; AEZ, agro-ecological zones.

FIGURE 5: Three-month Standard Precipitation Index values for the Highveld, Middleveld, Lowveld and Lubombo Plateau agro-ecological zones.

Differences were observed in the SPI results across different timescales. Moderate droughts were the most frequent w 3-, 6-, and 9-month categories, with the Middleveld ha the highest occurrences. In 1992, for example, the 6-mol and 12-month SPI indicated moderate drought, whereas th 3-month SPI showed no drought condition 2006, the 3-month SPI indicated severe drov itions, ild- to whereas the 6- and 12-month SPI indicated drought periods. The 3-month SPI especially in areas where it is nor ally dry a ught condition 3-month period. The differences in he short-term soil therefore be related, with the reg nse moisture conditions to precipitation de that short timescale for both 3-month 21 12-month SPI 3 da & Abu-4). In 2006, it is evident that a Romman 2017; WMO 201 drought event (as ind. the 3-month SPI) was ed b occurring in the middle longer-tom drought, as Alt. Therefore, it is evidenced by the 1 nth time le r are th Ith longer timescales important to con -month Si <u>derd</u> 2003). uault & (NDMC 2006;

Comparing the 3-mon. SPI across AEZs, most drought events were experienced in the Giddleveld and Lowveld zones. Extreme droughts were experienced in all AEZs in 1986 and 2016. When the 3-month SPI was calculated for the different AEZs, there were parallels with the drought periods that were declared and documented in the EM-DAT database (EM-DAT 2016). This means that within the country, there are spatial differences for drought severity and intensity. For moderate drought, however, the SPI calculation typifies the droughts, which were also declared in most of the AEZs. Therefore, the SPI can be used to typify drought by AEZ, with the Lowveld being the region that is most prone to drought.

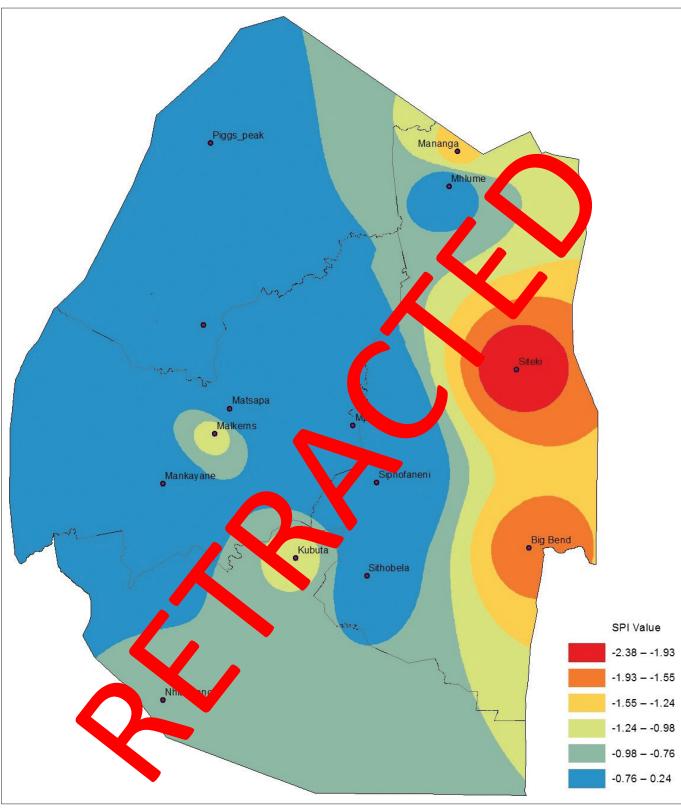
Drought severity spatial dynamics based on Standard Precipitation Index

Estimating agriculture drought severity at a station or AEZ provides useful information for drought planning and management. It is therefore important to assess the drought over a specified agro-ecological region. This allows the administrative areas that fall within these regions to plan effectively. The drought analysis based on these zones is useful for determining the spatial distribution and characteristics of drought waluating the most affected areas for a specific drought ent. To provide a complete picture of the ught hotpots Eswatini, spatial ing 3-mor h SPI values using analysis was performed by p. n extent of selected ArcGIS 10.1. Figure 6–9 depict spa drought years at Eswajni from 36 to 2016. All the re reclassified into four classes, that interpolated SPN ns I as no ought, from -1.5 to -1.0 as is, SPI val from -1 1.5 as severe drought and ≥ 2 drought, from modera ought category

986, modera and extreme droughts were mostly experienced in the Lowveld AEZ, whereas between 2004 and 2006 moderate to extreme droughts were experienced ountrywide. The results identified that there were erences i moderate, severe, extreme and no drought Menced in the study period. The 2015–2016 and the 2005–2006 droughts were most severe and can be d by spatial coverage indicated in red. The 1986 drought was less severe, with less spatial coverage (in red). Moderate and extreme droughts were mostly experienced in the Lowveld AEZ, whereas between 2004-2005 and 2005-2006 moderate to extreme droughts were experienced countrywide. There were significant differences in the drought severity across administrative areas and AEZs. Field surveys and information sourced from key informants have verified that these droughts were the most severe, with greatest impact being felt in the Lowveld and Middleveld. However, the impact of the 2015-2016 drought was felt countrywide with massive crop and livestock losses. Therefore, estimating drought severity at a station or AEZ provides useful information for drought planning and management. The spatial differences across the country therefore allow for localised drought monitoring, enabling more accurate area-specific results, and therefore area-specific drought management planning.

Conclusion and recommendation

The climate of the African continent and Eswatini in particular exhibits large geospatial and temporal variability. This study was focused on presenting the analysis of the temporal and spatial characteristics of droughts in Eswatini. The 3-, 6- and 12-month SPI were computed to determine drought severity and onset of meteorological drought in the country. Overall, SPI effectively described the drought conditions in Eswatini. The analysis of droughts during

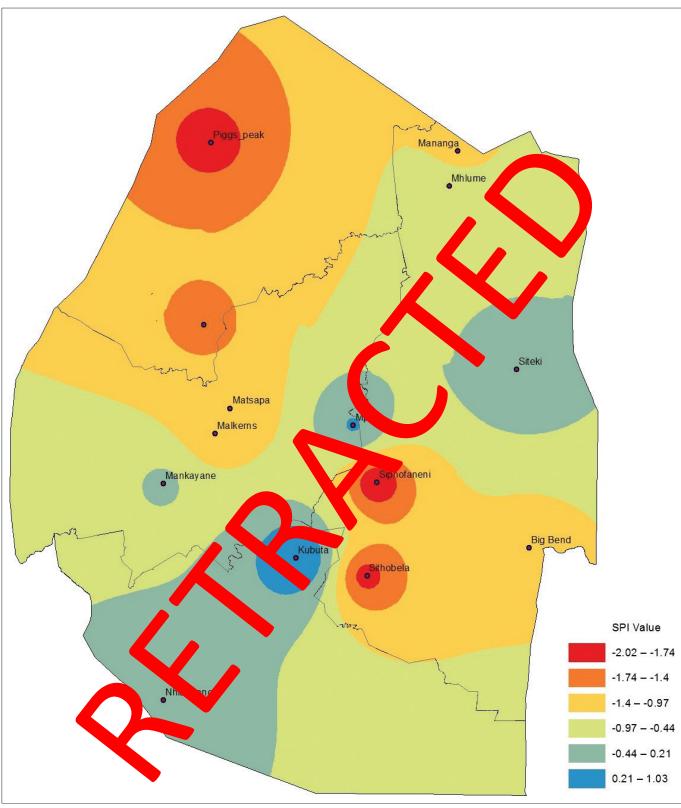


SPI, Standard Precipitation Index.

FIGURE 6: Standard Precipitation Index 3-month timescale during 1985–1986.

1986–2017 indicated that droughts have intensified in terms of their frequency, severity and geospatial coverage over the last few decades. The results demonstrated that moderate droughts are the most prevalent in Eswatini, while the frequency of severe and very severe droughts is low. Most

parts of the country were vulnerable to mild and moderate agricultural drought (3 and 6 months) timescales. The worst drought years were 1985–1986, 2005–2006 and 2015–2016 agricultural seasons, and this was evident from the SPI at 3-, 6- and 12-month timescales. The drought periods were

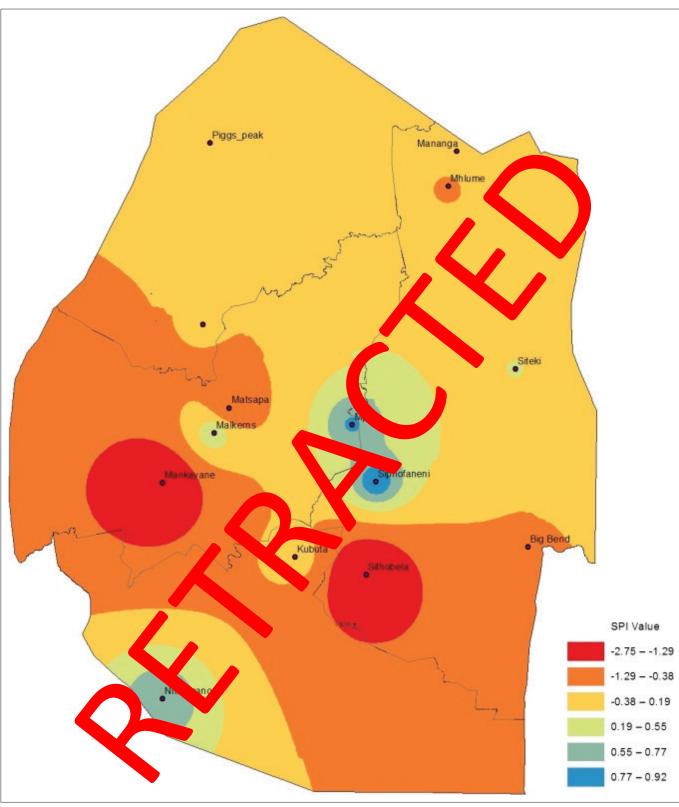


SPI, Standard Precipitation Index.

FIGURE 7: Standard Precipitation Index 3-month timescale during 2004–2005.

consistent with drought declarations by the government as well as EM-DAT database.

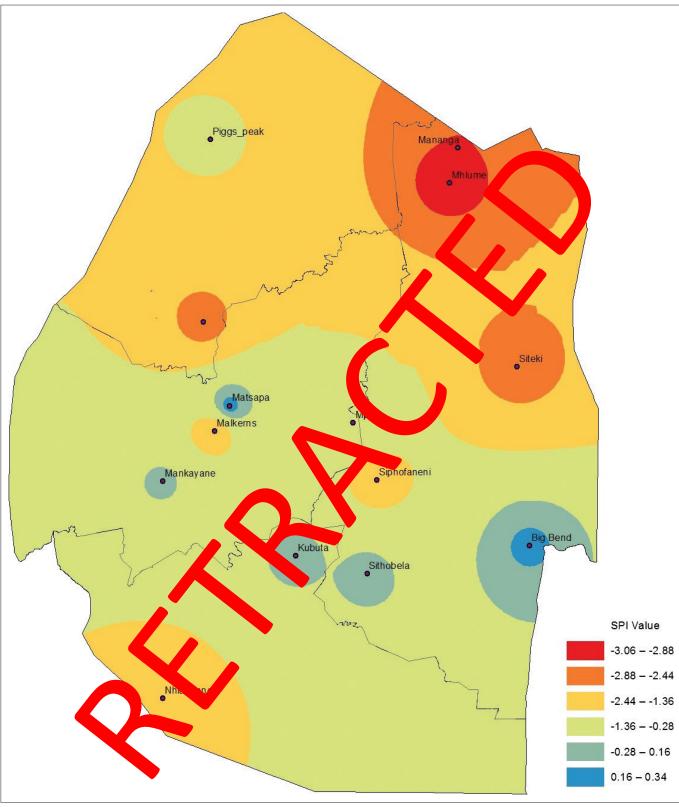
At national level and agro-ecological level, severe droughts were experienced in the last few decades, for instance, in 1990, 2001, 2004, 2006 and, recently, in 2016. There were temporal and spatial differences across the country and AEZs. The spatial SPI visualisation has the ability to provide drought management planners a tool for immediate drought categorisation. The drought analysis (using the SPI at



SPI, Standard Precipitation Index.

FIGURE 8: Standard Precipitation Index 3-month timescale during 2005–2006.

different timescales) affirms the applicability of SPI for drought monitoring in Eswatini. The spatiotemporal drought analysis can provide information for early warning, particularly in drought-prone areas, by depicting a drought before the effects have begun to be felt. Because of the differences in drought severity at different timescales, it is recommended that the SPI should be used for drought monitoring in combination with other indices and approaches such as vulnerability assessments and remote sensing.



SPI, Standard Precipitation Index

FIGURE 9: Standard Precipitation Index 3-month timescale during 2015–2016.

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

D.H.M. drafted the original manuscript, acquired and analysed the data and made interpretations. B.M. provided statistical analysis, modelling and data interpretation. This work is part of the Doctor of Philosophy (PhD) degree in

Disaster Management thesis, under the supervision of A.J.J. who guided with methodology and critically revised the original manuscript.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Disclaimer

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any affiliated agency of the authors.

References

- Alley, W.M., 1984, 'The Palmer drought severity index: Limitations and assumptions', Journal of Climate and Applied Meteorology 23(7), 1100–1109. https://doi. org/10.1175/1520-0450(1984)023<1100:TPDSIL>2.0.CO;2
- Alley, W.M., 1985, 'The Palmer drought severity index as a measure of hydrologic drought', JAWRA Journal of the American Water Resources Association 21(1), 105–114. https://doi.org/10.1111/j.1752-1688.1985.tb05357.x
- Belayneh, A. & Adamowski, J., 2012, 'Standard precipitation index drought forecasting using neural networks, wavelet neural networks, and support vector regression', Applied Computational Intelligence and Soft Computing 2012(2012), 6. https://doi.org/10.1155/2012/794061
- Bokal, S., 2006, Standardized precipitation index tool for drought monitoring Examples from Slovenia, Drought Management Centre for South-eastern Europe, DMC viewed 19 June 2017, from http://www.wamis.org/agm/meetings/slovenia10/SBokal-SPI.pdf.
- Dai, A., Trenberth, K.E. & Karl, T.R., 1998, 'Global variations in droy vet spells: 1900–1995', Geophysical Research Letters 25(17), 33 3370. os://doi.org/10.1029/98GL52511
- Edwards, C.D.C., McKee, T.B., Doesken, N.J. & Kleist, J., 199 sistorical drought in the United States', in 7th conference on climate annual meeting, Long Beach, CA, 02–07 February 7, pp. 125
- EM-DAT, 2016, The CRED/OFDA International Disast dabase, University tholique de Louvain, viewed 24 September 2017, from Lywww.emdat.be.
- FAO, 2013, Swaziland. Country brief, bioenerg and foo surity projects, viewed 24 October 2018, from http://www.fao.org/ Jenergy/foo surity/befs.
- FAO AQUASTAT Survey, 2005, Irrigation in fica in figures, view December 2016, from http://www.fao.org/ag/aquas
- Giddings, L., Soto, M., Rutherfor B.M. & Maarouf, A., 2005, 'Standardized precipitation index zones for Nov. 18(1), 33–56.
- Government of Swaziland, 2013, Swaziland, action plan 2014-2019. Strategy, Nin. of Tourism a Environmental Affairs, Mbabane, Swaziland.
- Gutman, G.G., 1999, 'Or e us ong Term', that a of land reflectances and vegetation indices a rived fro the advanced high-resolution radiometer', Journal of Geoph Cal Resear org/10.1029/19. 90106
- Hayes, M., Svoboda, M., & Widhalm, w., 2011, 'The Lincoln declaration on drought indices: Universe, teorological drought index recommended', *Bulletin of the American Meteoro*, 1275/2010BAMS3103.1
- Hayes, M.J., Svoboda, M.D., Wilhite, D.A. & Vanyarkho, O.V., 1999, 'Monitoring the 1996 drought using the standardized precipitation index', *Bulletin of the American Meteorological Society* 80(3), 429–438. https://doi.org/10.1175/1520-0477 (1999)080<0429:MTDUTS>2.0.CO;2
- IPCC, 2012, Managing the risks of extreme events and disasters to advance climate change adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, New York.
- IPCC, 2013, 'Summary for policymakers', in T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, et al. (eds.), Climate change 2013: The physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change, pp. 28, Cambridge University Press, Cambridge.

- Ji, L. & Peters, A.J., 2003, 'Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices', Remote Sensing of Environment 87(1), 85–98. https://doi.org/10.1016/S0034-4257(03)00174-3
- Jordaan, A.J., 2011, 'Drought risk reduction in the Northern Cape, South Africa', PhD thesis, University of the Free State, South Africa.
- Karl, T., Quinlan, F. & Ezell, D.S., 1987, 'Drought termination and amelioration: Its climatological probability', Journal of Climate and Applied Meteorology 26(9), 1198–1209. https://doi.org/10.1175/1520-0450(1987)026<1198:DTAAIC>2.0.CO;2
- Kumar, V. & Panu, U., 1997, 'Predictive assessment of severity of agricultural droughts based on agro – Climatic factors', JAWRA Journal of the American Water Resources Association 33(6), 1255–1264. https://doi.org/10.1111/j.1752-1688.1997. tb03550.x
- Livada, I. & Assimakopoulos, V.D., 2007, 'Spatial and temporal analysis of drought in Greece using the Standardized Precipitation dex (SPI)', *Theoretical and Applied Climatology* 89(3–4), 143–153. https://doi.org/10.007/s00704-005-0227-z
- Lohani, V.K. & Loganathan, G.V. 97, 'An early ring system for drought management using the Palm drought index', JAW Yournal of the American Water Resources Association 1375–1386. http://doi.org/10.1111/j.1752-1688.1997.tb03560.x
- Lohani, V.K., Loganathan J.V. & Mostage S., 199 Long-term analysis and short-term forecast of dry spells Calm Drought Severity Index', Hydrology Research 9(1), 21–40. https://doi.org/10.2166/nh.1998.0002
- Manyatsi, M.A., Nto Zwane C. & Dlamini, M., 2015, 'Evaluation of satellite rainfall estimates in Pazi d', American Journal of Agriculture and Forestry 3(3), 2015 98. https://org/10.116
- McKee, T.B. 195, 'Drought more ing we multiple time scales', in *Proceedings of 9th contence on applied content of 15*, 15–20 January, Dallas TX. American Met 15. Society, Boston, Na. p. 233–236.
- McKe T.B., Down N.J. & Kleist, J., 1993, 'The relationship of drought frequency and or the son to time scales', in *Proceedings of the 8th conference applied climato*, vol. 17(22), pp. 179–183, American Meteorological Society, Boston, MA.
- Moreira, E.E., Coelho, C.A., Paulo, A.A., Pereira, L.S. & Mexia, J.T., 2008, 'SPI-based drought category prediction using loglinear models', *Journal of Hydrology* 354(1–4), 116–130. https://pi.org/10.1016/j.jhydrol.2008.03.002
- MA, 2016, State ent by the right honourable Prime Minister, viewed 10 June 16, from his /ndma.co.sz/news/.
- NDMs. And is drought? Understanding and defining drought, National Climatic Data Center, viewed 10 May 2014, from https://drought.unl.edu/Education/DroughtIn-depth/WhatisDrought.aspx.
- L. & Weber, L., 1999, 'Comparison between the droughts of the 1930s and the 1980s in the southern prairies of Canada', *Journal of Climate* 12(8), 2434–2450. https://doi.org/10.1175/1520-0442(1999)012<2434:CBTDOT>2.0.CO;2
- Phys.org, 2016, Drought caused by El Nino threatening southern Africa: UN, viewed 27 December 2018, from https://phys.org/news/2016-02-drought-el-nino-threatening-southern.html.
- Rouault, M. & Richard, Y., 2003, 'Intensity and spatial extension of drought in South Africa at different time scales', Water SA 29(4), 489–500. http://doi.org/10.4314/ wsa.v29i4.5057
- Saada, N. & Abu-Romman, A., 2017, 'Multi-site modelling and simulation of the standardized precipitation index (SPI) in Jordan', *Journal of Hydrology: Regional Studies* 14(2017), 83–91. https://doi.org/10.1016/j.ejrh.2017.11.002
- Soulé, P.T., 1992, 'Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions', *International Journal of Climatology* 12(1), 11–24. https://doi.org/10.1002/joc.3370120103
- Swaziland National Vulnerability Assessment Committee, 2016, Swaziland National Vulnerability Assessment, Swaziland National Vulnerability Assessment Committee, Mbabane.
- Tadesse, T., Haile, M., Senay, G., Wardlow, B.D. & Knutson, C.L., 2008, 'The need for integration of drought monitoring tools for proactive food security management in sub – Saharan Africa', *Natural Resources Forum* 32(4), 265–279. Blackwell, Oxford. https://doi.org/10.1111/j.1477-8947.2008.00211.x
- Tigkas, D., Vangelis, H. & Tsakiris, G., 2015, 'DrinC: A software for drought analysis based on drought indices', *Earth Science Informatics* 8(3), 697–709. https://doi.org/10.1007/s12145-014-0178-y
- Wilhelmi, O.V. & Wilhite, D.A., 2002, 'Assessing vulnerability to agricultural drought: A Nebraska case study', Natural Hazards 25(1), 37–58. https://doi.org/10. 1023/A:1013388814894
- Wilhite, D.A., Rosenberg, N.J. & Glantz, M.H., 1986, 'Improving federal response to drought', Journal of Climate and Applied Meteorology 25(3), 332–342. https://doi. org/10.1175/1520-0450(1986)025<0332:IFRTD>2.0.CO;2
- Wilhite, D.A., Sivakumar, M.V.K. & Wood, D.A., 2000, 'Early warning systems for drought preparedness and drought management', in *Proceedings of an expert group meeting held in Lisbon, Portugal*, vol. 57, World Meteorological Organization Geneva
- WMO, 2006, Drought monitoring and early warning: Concept, progress and future challenges, WMO 1006, World Meteorological Organization, Geneva.
- WMO, 2012, Standardized precipitation index user guide, World Meteorological Organization, Geneva.

