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Comparison of Meteorological Drought Indices in Tanzania Using the Meteorological Drought Monitoring Software Package

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ABSTRACT

Low precipitation, substantial evaporation, and an unequal distribution of precipitation throughout the area are the characteristics of drought, a climatic abnormality. This study used the Meteorological Drought Monitoring (MDM) software and monthly rainfall data from the Tanzania Meteorological Authority (TMA) to examine and compare the Deciles Index (DI), Standardised Precipitation Index (SPI), Percent of Normal Index (PNI), Rainfall Anomaly Index (RAI), Z-Score Index (ZSI), China-Z Index (CZI), and Modified China-Z Index (MCZI) for drought monitoring in Tanzania from 1988 to 2017. It was found that ZSI represented the dry years better than other indices, followed by DI, RAI, PNI, SPI, CZI, and MCZI, based on the strength of the drought's detection throughout a monthly time scale. Seasonally, DI emerged as the most effective drought index for meteorological drought monitoring, trailed by PNI and SPI. In comparison to SPI and PNI, the ZSI index closely mimics Tanzania's climatological conditions on a geographical scale. The study also demonstrates that ZSI outperformed SPI and PNI in accurately determining the frequency of droughts with different severities.

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INTRODUCTION

The earth system continues to witness unprecedented climatic changes. An observed increase in the concentration of greenhouse gases (GHGs) in the atmosphere has altered the climate feedback mechanisms (Pedersen *et al.*, 2022). This has led to a "new norm" characterised by the unusual occurrence of extreme weather events such as droughts, floods, and heat waves (Eckstein *et al.*, 2019), whereas the impacts of extreme events vary in magnitude, with drought occurrence dominating various economic sectors (Sharma and Ravindranath, 2019). Some parts of Tanzania's northern and central regions experience drought more frequently (Kai *et al.*, 2021; Zuberi *et al.*, 2022). Furthermore, the drought circulation patterns observed in the Tanzanian region from 1998 to 2005 were similar to those experienced during a previous prolonged drought (1973–1976), suggesting that some predictability of drought may exist (Zuberi *et al.*, 2022).

Research shows that the frequency of drought occurrences will increase significantly in the future (Pedersen *et al*., 2022; Sharma and Ravindranath, 2019; Trenberth *et al*., 2014), mainly due to climate change and the rapid rise in population. Lack of water in stores such as rivers, lakes, reservoirs, and water stored underground naturally can lead to drought. Areas that depend on rainfall and surface water are more likely to experience drought. Surface water quickly evaporates in warm, dry conditions, leading to an increased risk of drought. As a regional occurrence, droughts negatively affect agricultural productivity and a region's socioeconomic standing. A drought is a temporary condition caused by a sustained lack of precipitation or shortage of water (Herrera-Estrada *et al*., 2017). The widely accepted taxonomy of drought includes meteorological, agricultural, hydrological, and socioeconomic droughts (Ali and Hamid, 2018). A lack of precipitation characterises a meteorological drought over weeks, months, or years (Escalante-Sandoval and Nuñez-Garcia, 2017). This is regulated by temperature in the form of evapotranspiration, in addition to a deficiency of rainfall.

Meteorological drought can be calculated by using several indices based on many factors. Indices are the characteristics or criteria used to describe drought conditions using precipitation, temperature, soil moisture, or other related drought indicators (Kim *et al*., 2016). These indices are essential because they serve as the foundation for drought management plans by identifying and monitoring drought conditions, determining the timing and severity of drought responses, describing and comparing drought events, and combining drought severity levels with drought responses (Ali and Hamid, 2018). Drought indices are derived from a combination of climatic and meteorological data, with precipitation playing the most significant role in defining the degree and severity of a drought (Pathak and Dodamani, 2020). Therefore, the selection of drought indices should be based on the quality and monitoring capacity of the available data. Various indices have been proposed for drought analysis, including the Standardised Precipitation Index SPI, the Percent of Normal Index PNI, the Deciles Index DI, the China-Z index CZI, the modified CZI MCZI, the Rainfall Anomaly Index RAI, and the Z-Score Index ZSI (Morid *et al*., 2006; Wang *et al*., 2017). The aim of this study is to compare the meteorological drought indices for assessing drought phenomena in Tanzania using Meteorological Drought Monitoring (MDM) software.

METHODS AND MATERIALS

Description of the Study Area

Tanzania is characterised by unimodal and bimodal rainfall seasons, which peak between November and April for unimodal, and between March and May and October and December for bimodal, respectively. It is geographically located near the equator in East Africa, at latitudes of 0° and 12° South and longitudes of 28° and 42° East, as shown in Figure 1. The average yearly rainfall of the country ranges from 550 mm in the country's centre to 3690 mm in some southwestern highlands. Year-round, temperatures are consistent, averaging 28 ^{o}C for daytime highs and 20 ^{o}C for nighttime. The highlands in the northwest are cold and temperate, whereas the coastal regions are hot and humid due to the tropical environment.

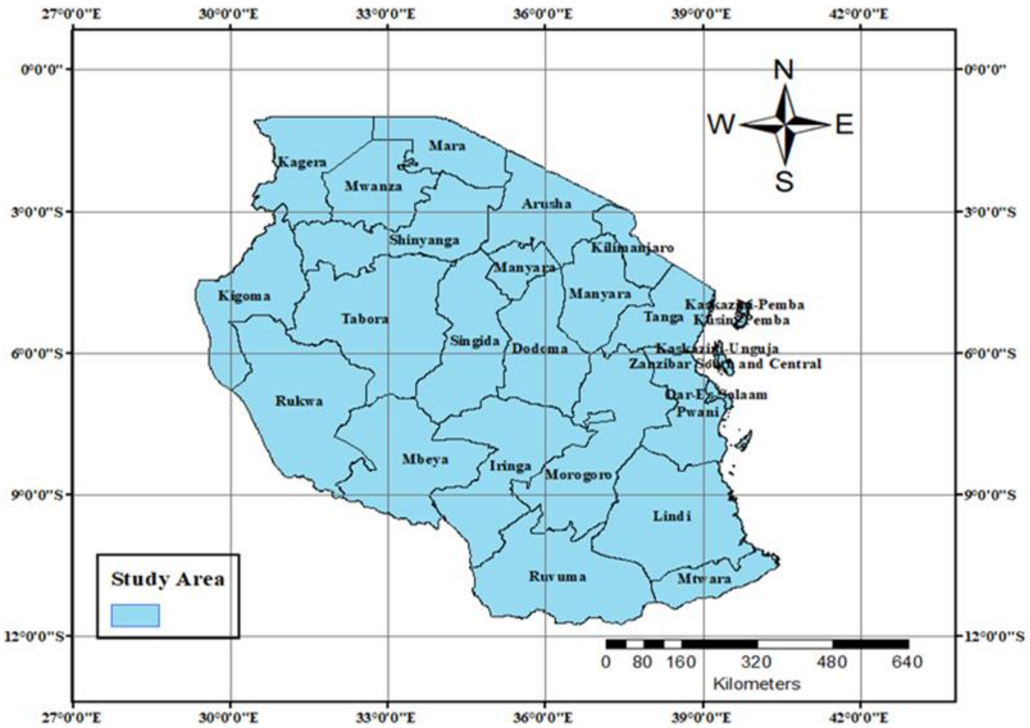

Figure 1: Description of the study area.

Data Collection

Monthly rainfall datasets observed from weather stations covering 1988 to 2017 were collected by the Tanzania Meteorological Authority (TMA). They were used to examine and compare the Deciles Index (DI), Standardised Precipitation Index (SPI), Percent of Normal Index (PNI), Rainfall Anomaly Index (RAI), Z-Score Index (ZSI), China-Z Index (CZI), and Modified China-Z Index (MCZI) for drought monitoring in Tanzania from 1988 to 2017 by using MDM. The distribution of weather stations used in this study is depicted in Figure 1.

Meteorological Drought Monitoring (MDM) Software package.

The MDM is software for calculating meteorological drought indices using precipitation-based indices. This tool has been improved for rain-based drought indicators and is freely available at https://www.agrimetsoft.com.
Additionally, the MDM software package allows the synoptic station data file to be loaded into the software for further analysis. In this study, the MDM package employed seven meteorological drought indices, namely SPI, PNI, DI, CZI, MCZI, RAI, and ZSI, to show drier or wetter than usual conditions in the form of yearly, seasonally, and monthly (Salehnia *et al.*, 2017; Ekwezuo and Madu, 2020).

Meteorological Drought Indices

Standardized Precipitation Index, SPI

The SPI is widely recognised and commonly employed as a drought index for describing meteorological droughts (Cunha *et al.*, 2018; Diani *et al.*, 2019). It works well with various timeframes (1, 3, 6, 12, 24, and 48 months), and the result values range from -2.0 to 2.0. The long-term precipitation records, ideally spanning 30 years, are the sole input for the SPI computation (Kobrossi *et al.*, 2021). The probability density function of the gamma distribution is used to compute the SPI because this distribution may fit precipitation data:

$$g(x) = \frac{1}{\beta^{\alpha} T(\alpha)} X^{\alpha-1} e^{-\alpha/\beta}, (x>0), \quad (1)$$

Percent of Normal Index, PNI

A proportion of average precipitation was used to describe the PNI percent of the usual rainfall (Kamalanandhini and Annadurai, 2021). PNI can be calculated monthly, seasonally, and yearly for various time scales. It has been discovered that PNI is relatively successful at describing drought for a single region or/and for a single season (Elhoussaoui *et al*., 2021). The calculation of PNI is as follows;

$$PN = \frac{Pi}{\bar{P}} \times 100 \quad (2)$$

where P_i is the precipitation in time increment i (mm), and $\bar{P}$ is the normal precipitation for the study period (mm).

Deciles Index, DI

The proposed technique, initially derived from monthly precipitation data over a significant period, entails arranging the totals in descending order to establish a cumulative frequency distribution (Yacoub and Tayfur, 2017). Subsequently, the distribution is partitioned into ten distinct portions or deciles. The bottom 10% of precipitation values in a dataset are not higher than the value of the first decile. The second decile falls between the bottom 10% and 20%, and so on (Myronidis et al., 2018). Any amount of precipitation (for example, from the current or previous month) can be compared to and interpreted in relation to these deciles. A drought calculation formula is given as follows;

$$P_i = \frac{i}{(n+1)} \times 100 \quad (3)$$

where P_i is the probability of rain in number in ith and n is the number of rainfall data.

China-Z Index, CZI and Modified CZI, MCZI

If the mean precipitation follows the Pearson type III distribution, the CZI produced by the National Climate Centre of China in 1995 can be used as an alternative to the SPI mentioned in the study by Dogan et al. (2012). The formula for CZI is as follows:

$$CZIij = \frac{6}{Csi} \times \sqrt{\frac{Csi \times \varphi tj + 1}{2}} - \frac{6}{Csi} + \frac{Csi}{6} \quad (4)$$

where *i* represent the time scale of interest and *j* represent the current month. CZI*ij* refers to the quantity of CZI for the current month (*j*) in period *i*. Cs*i* represents the coefficient of skewness, and φt*j* represents the standardised variation. Further details can be found in Kassaye et al. (2021). Additionally, the MCZI can be determined by using the aforementioned method, but replacing the mean precipitation with the median precipitation.

Z-Score Index, ZSI

Occasionally, the ZSI and SPI become intermingled. However, it can be more closely compared to CZI without the requirement of adjusting precipitation data to either the gamma distribution or the Pearson type III distribution (Elhoussaoui et al., 2021). With the following equation, ZSI can be calculated:

$$ZSI = \frac{Pt - \bar{P}}{SD} \quad (5)$$

where $\bar{P}$ is the mean monthly precipitation (mm), Pt is precipitation in a specific month (mm), and SD is the standard deviation of any time scale (mm).

Rainfall Anomaly Index, RAI

The RAI considers positive and negative anomalies as the two categories to be considered. The precipitation data is initially arranged in descending order. According to Aryal *et al*. (2022), when determining a positive anomaly, the average is calculated for the ten greatest values. Similarly, for a negative anomaly, the average is calculated for the ten lowest values. Equations 6 and 7 are used, respectively, to determine the thresholds:

$$RAI = 3 \times \left[\frac{(P-\bar{P}}{(m-\bar{P})}\right] \quad (6)$$

$$RAI = -3 \times \left[\frac{(P-\bar{P})}{(m-\bar{P})}\right] \quad (7)$$

Seven meteorological drought indices used in this study are listed in Table 1 with their respective classes.

Table 1: Classification seven meteorological drought indices

Drought classes	SPI	PNI (%)	DI (%)	RAI	Z-Score	CZI	MCZI	Class
Extremely wet	≥ 2	≥ 100	≥ 90	> 0.4	> 0.65	≥ 2	≥ 2	7
Very wet	1.5 to 1.99	90 to 100	80 to 90	0.4 to 0.3	0.65 to 0.25	1.5 to 1.99	1.5 to1.99	6
Moderate wet	1.0 to1.49	80 to 90	70 to 80	0.3 to-0.3	0.25 to -0.25	1 to 1.49	1 to 1.49	5
Near normal	-0.99 to 0.99	70 to 80	30 to 70	-0.3 to -1.2	-0.25 to -0.52	-0.99 to 0.99	-0.99 to 0.99	4
Moderate drought	-1.0 to 1.49	55 to 70	20 to 30	-1.2 to -2.1	-0.52 to -0.84	-1 to -1.49	-1 to -1.49	3
Severely drought	-1.5 to 1.99	40 to 55	10 to 20	-2.1 to -3.0	-0.84 to -1.25	-1.5 to 1.99	-1.5 to 1.99	2
Extremely drought	≤ -2	≤ 40	≤ 10	< -3.0	< -1.25	≤ -2	≤ -2	1

Degree of Dryness Index, DDI

Dry months are categorised as extreme, severe, or moderate based on the classification of any of the aforementioned indices into one of these three groups (Salehnia et al., 2017; Ekwezuo and Madu, 2020). The study region was analysed to determine the number of months each indicator experienced drought conditions, categorised into one of three categories, for each year. The months received from the extreme index scale were multiplied by a factor of three, those gained from the severe index scale were multiplied by a factor of two, and the months obtained from the moderate index scale were multiplied by a factor of one. Next, the number of months per year for each category was multiplied.

DDI = (Extreme drought months×3) + (Severe drought months×2) + (Moderate drought months×1).

$$DDI_y^{st} = \sum_{int=1}^{N_{int}} a_{int} \times N_{int,y} \quad (8)$$

$$DDI_y = \frac{[\sum_{st=1}^{N_{st}} DDI_y^{st}]}{N_{st}} \quad (9)$$

whereby,

DDI_y^{st} - refers to the degree of dryness index of the station for each year;

a_{int} - represents the severity of drought, where a value of 1 indicates moderate drought, a value of 2 indicates severe drought, and a value of 3 indicates extreme drought;

$N_{int,y}$, - represents the count of dry months for every drought classification in each calendar year;

DDI_y- is the mean value of the degree of dryness index for each year across all stations; and

N_{st} - is the number of stations

RESULTS AND DISCUSSION

Drought Characteristics in Monthly Time Scale

The seven drought indices, namely SPI, PNI, DI, CZI, MCZI, RAI, and ZSI, were computed for the entire country on a monthly basis from 1988 to 2017. The analysis results are effectively displayed in a tabular format, as depicted in Table 2. The analysis determines the significance of different classifications, including extremely wet, very wet, moderately wet, near average, moderately drought, severe drought, and extremely drought, by utilising the data available in the study area. Drought conditions were recorded in the years 1993, 1998, 2000, 2003, 2005, 2010, 2013, 2015, and 2016. In 1998, the RAI index achieved the highest score, with the DI, ZSI, PNI, CZI, MCZI, and SPI indices following in descending order. The RAI and ZSI indices are the most reliable measures for monitoring meteorological drought in Tanzania, as evidenced by their consistently high scores during the study period. The CZI, ZSI, and RAI values exhibited a high degree of similarity during the observation period.

Table 2: Comparison of seven meteorological drought indices

Year	SPI	PNI	DI	RAI	ZSI	CZI	MCZI
1988	1	1	3	7	4	1	1
1989	1	0	3	5	4	1	1
1990	2	6	10	15	12	1	1
1991	0	0	2	6	4	0	0
1992	6	6	10	14	12	6	3
1993	5	10	12	16	12	6	6
1994	0	0	0	2	0	0	0
1995	2	3	6	6	5	1	1
1996	0	3	7	13	9	1	0
1997	2	3	6	8	5	2	2
1998	6	7	12	14	11	6	6
1999	1	1	6	7	5	1	1
2000	5	6	12	16	13	5	5
2001	1	2	4	9	6	2	1
2002	2	3	6	7	6	1	2
2003	6	4	11	18	16	4	5
2004	3	4	6	10	7	3	2
2005	9	9	13	18	16	8	8
2006	1	1	2	3	2	1	1
2007	2	0	4	9	5	1	2
2008	0	1	4	6	3	0	1

2009	1	4	5	10	5	1	2
2010	5	8	10	12	10	6	6
2011	0	1	4	6	4	0	0
2012	6	5	11	13	12	6	5
2013	7	7	10	13	10	6	6
2014	0	0	0	2	0	0	0
2015	5	4	8	12	8	5	4
2016	11	16	21	25	21	10	10
2017	2	2	5	7	6	2	0

It is important to thoroughly analyse several indicators in order to choose the most suitable drought indices for a certain time period. An analysis was conducted on the frequency values of droughts, normal conditions, and wet conditions. These categories were used to group the frequency of the seven drought indices, as displayed in Table 3. The findings indicate that ZSI exhibited the highest proportion (64%), suggesting that ZSI is the most appropriate indicator for assessing drought frequency in comparison to DI, RAI, PNI, SPI, CZI, and MCZI on a monthly basis. The SPI and MCZI exhibited the highest proportion of 69% among the average category, with CZI, DI, PNI, RAI, and ZSI following suit. Furthermore, the RAI index revealed that the highest proportion, amounting to 51%, was observed in the wet category. This was followed by the PNI, DI, ZSI, MCZI, CZI, and SPI. Thus, the most appropriate indices for categorising drought, normal, and wet conditions were ZSI, SPI and MCZI, and RAI, respectively. By comparing the RAI and ZSI indices, it was shown that RAI more accurately depicted the extent of rainy years, whilst ZSI more accurately depicted the extent of dry years.

Table 3: The frequency of different categories of meteorological drought indices

Classification	SPI	PNI	DI	RAI	ZSI	CZI	MCZI
Drought	17%	30%	40%	37%	64%	17%	14%
Normal	69%	23%	29%	12%	08%	68%	69%
Wet	14%	47%	31%	51%	28%	15%	17%

Comparison of Drought Characteristics in Seasonal Time Scale

The study utilised the DDI to evaluate the characteristics of the drought on a seasonal basis, as presented in Table 4. Throughout the study period, DI consistently exhibited the highest level of dryness, with PNI and SPI following closely behind. However, in 2010 and 2012, SPI and PNI took the lead, with DI following behind. Based on the DSI values, the year with the most severe drought throughout the study period was 2016. This was followed by 2005, 2003, 1993, and 1992. When considering the accumulation of drought events across the entire study period on a seasonal basis, the

DI had the highest score, followed by the SPI and the PNI. As a result of its greater importance and value compared to the other two drought indices, the DI was the dominating index during the seasons. It reached its highest points in 1990, 1993, 1997, 1998, 2005, 2010, 2012, and 2016.

Table 4: Degree of Dryness Index (DDI) during the whole study period

Year	SPI	PNI	DI
1988	0	0	0
1989	0	0	0
1990	2	2	3
1991	0	0	0
1992	0	1	5
1993	1	3	5
1994	0	0	0
1995	0	0	1
1996	1	0	3
1997	1	1	4
1998	1	2	3
1999	2	0	0
2000	3	0	4
2001	1	0	2
2002	0	0	0
2003	4	0	5
2004	1	0	3
2005	1	2	5
2006	2	0	1
2007	1	0	1
2008	0	0	2
2009	0	2	3
2010	3	1	4
2011	0	0	2
2012	1	1	3
2013	2	0	3
2014	0	0	1
2015	1	0	3

2016	4	3	6
2017	1	0	1

During the DJF, MAM, JJA, and SON seasons, the DI was ranked first in determining the frequency of droughts with varying severities. The SPI was ranked second, except for the JJA season, where the DI was followed by the PNI, as shown in Table 5. The SPI showed the highest frequency for the expected condition, followed by PNI and then DI for all seasons. In the wet category, the observed phenomena showed that PNI had the highest percentage, followed by DI and SPI, for all seasons. The DSI values derived from the DI and SPI appear to be more responsive to the observed drought conditions compared to other drought indices.

Table 5: The frequency of different categories of SPI, PNI and DI

Classification	Frequency of SPI (%)				Frequency of PNI (%)				Frequency of DI (%)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Drought	17	20	13	27	13	10	33	23	40	40	40	40
Normal	66	63	67	56	27	43	20	30	20	20	20	20
Wet	17	17	20	17	60	47	47	47	40	40	40	40

Comparison of Drought Indices in Annual Time Scale

Table 6 displays the drought attributes based on annual rainfall events. The research area's available data is used to determine severity classifications, including extremely wet, very wet, moderately wet, near average, moderately drought, severe drought, and extremely drought. ZSI identified a greater number of drought episodes per year compared to other indices, with DI, SPI, and PNI following in that order. The study period witnessed severe drought years in 2003, 2005, 2012, 2013, and 2016, as indicated by all indexes. Furthermore, both indices indicated that the years 1997, 2002, and 2006 had the highest levels of precipitation during the study period.

Table 6: Comparison of the drought characteristics

Year	SPI	PNI	DI	ZSI
1988	Near normal	Wet	Very wet	Near normal
1989	Near normal	Wet	Very wet	Very wet
1990	Near normal	Wet	Very wet	Moderately wet
1991	Near normal	Wet	Very wet	Moderately wet

1992	Near normal	Normal	Weak drought	Slightly drought
1993	Near normal	Normal	Moderate drought	Severely drought
1994	Near normal	Wet	Moderate wet	Near normal
1995	Near normal	Wet	Near normal	Near normal
1996	Near normal	Normal	Weak drought	Slightly drought
1997	Extremely wet	Wet	Extremely wet	Extremely wet
1998	Near normal	Wet	Near normal	Weak drought
1999	Near normal	Wet	Very wet	Moderately wet
2000	Near normal	Normal	Severe drought	Severely drought
2001	Near normal	Normal	Near normal	Weak drought
2002	Moderately wet	Wet	Extremely wet	Very wet
2003	Extremely drought	Weak drought	Extremely drought	Extremely drought
2004	Near normal	Normal	Near normal	Weak drought
2005	Severely drought	Weak drought	Extremely drought	Extremely drought
2006	Extremely wet	Wet	Extremely wet	Extremely wet
2007	Near normal	Normal	Moderate drought	Moderate drought
2008	Near normal	Wet	Near normal	Weak drought
2009	Near normal	Wet	Near normal	Near normal
2010	Near normal	Normal	Weak drought	Slightly drought
2011	Near normal	Wet	Very wet	Moderately wet
2012	Moderately drought	Normal	Extremely drought	Severely drought
2013	Moderately drought	Normal	Severe drought	Severely drought

2014	Near normal	Wet	Near normal	Near normal
2015	Near normal	Normal	Moderate drought	Moderately drought
2016	Moderately drought	Normal	Severe drought	Severely drought
2017	Near normal	Wet	Near normal	Near normal

Table 7 demonstrates that ZSI exhibited the highest percentage (53%), indicating that ZSI is the most appropriate index for determining the frequency of droughts when compared to DI, SPI, and PNI on an annual basis. Conversely, the SPI exhibited the greatest percentage of 73% for the normal category, with PNI, DI, and ZSI following suit. Moreover, PNI appears to exhibit superior performance in accurately assessing wet conditions. Thus, the most prominent indices appropriate for categorising drought, normal, and wet conditions were ZSI, SPI, and PNI, respectively.

Table 7: The frequency of different categories of of SPI, PNI, DI and ZSI

Classification	SPI	PNI	DI	ZSI
Drought	17%	7%	40%	53%
Normal	73%	40%	27%	20%
Wet	10%	53%	33%	27%

According to the DDI analysis, ZSI had the highest number of drought episodes during the entire study period, followed by DI and then SPI. Table 8 demonstrates that the PNI is an inadequate metric for drought monitoring, as seen by the absence of any value for DDI.

Table 8: Degree of Dryness Index (DDI) during the whole study period

SPI Index	PNI Index	DI Index	ZSI Index
8	0	15	18

Spatial Variations of Meteorological Drought Indices

Figure 2 displays the regional distribution of drought features, which helps determine the most suitable drought index for identifying drought coverage and implementing practical actions. Areas in the northeastern section of the Lake Victoria zone are known for their severe and arid conditions, as indicated by the distribution of drought classes shown in Figure 2(a) using the PNI. Conversely, the central region of the country experiences extremely humid weather conditions. These conclusions are in direct opposition to the actual conditions of Tanzania's local climate. Therefore, the PNI is not an effective measure for illustrating the spatial variability of in drought conditions throughout the nation.

Additionally, the SPI analysis depicted in Figure 2(b) indicates that the northern and south-eastern regions of the country are subjected to severe and extremely severe drought, whilst the eastern and south-eastern areas encounter extraordinarily wet conditions. These findings contradict Tanzania's climatology, which is often characterised by abundant moisture in the coastal regions due to their proximity to the Indian Ocean. This resulted in a decrease in the accuracy of the SPI for assessing drought conditions in terms of geographical evaluation. In addition, the ZSI depicted in Figure 2(c) indicates that the coastal areas adjacent to Lake Victoria, the northern section of Lake Tanganyika, and the coastline regions had intense and very rainy weather conditions. Some regions saw moderately moist circumstances. The central part of Tanzania experienced severe drought conditions. The findings align with the country's climatology, making the ZSI the most comprehensive index for studying the spatial distribution of drought conditions in Tanzania.

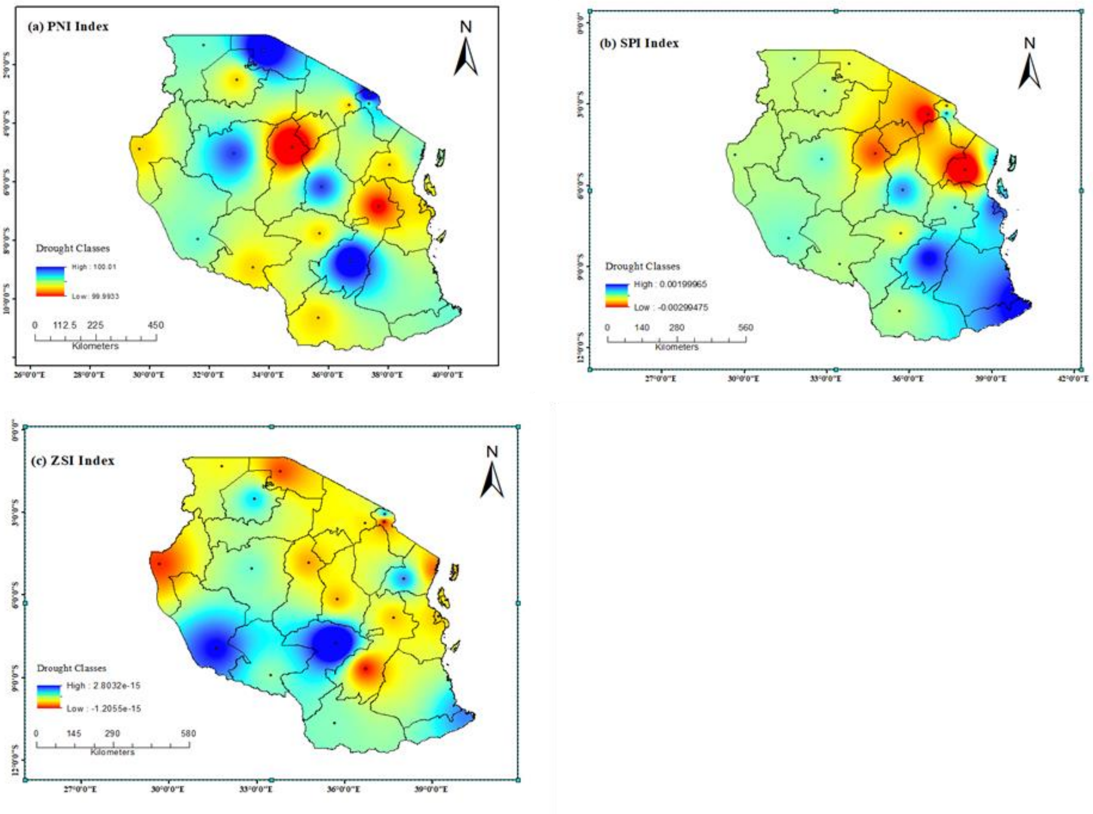

Figure 2: Shows drought indices characteristics in a spatial map.

CONCLUSION AND RECOMMENDATIONS

This study used monthly observed station data from TMA to compare the meteorological drought indices using the MDM software package. Among the seven drought indices used, the results show that ZSI is the most suitable index for determining the frequency of droughts, followed by DI, RAI, PNI, SPI, CZI, and then MCZI in the monthly time frame. DI and SPI seem more sensitive to droughts on a seasonal scale than other drought indices, with DI placed in the first category, followed by SPI. Additionally, based on the yearly time scale, the ZSI was the most suitable index for determining the frequency of droughts in the region. Furthermore, on the spatial scale that depicts the distribution of drought characteristics throughout Tanzania, ZSI is the most detailed index to investigate the spatial distribution of the drought conditions in Tanzania.

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