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Applicability of Combined Drought Index in drought analysis over North Eastern Kenya

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Abstract
Droughts are hindrances to economic and social developments in many parts of the world, especially in developing nations like Kenya. In North Eastern Kenya (NEK), drought is very prevalent. The communities in the region are mainly dependent on animal farming, and drought occurrence leads to great socioeconomic setback. Drought indices used in most studies consider rainfall as the only parameter for assessing drought occurrences. This study analyzes drought in NEK using the Standardized Precipitation Index (SPI) and the Combined Drought Index (CDI) using rainfall and temperature values and Normalized Difference Vegetation Index values for the period 1980–2010. The results of the two indices show significant correlation. However, CDI is preferred in the analysis of the drought compared to the SPI as it gives drought in more detail, showing extreme, severe, moderate and mild. The study recommends the use of the two methods independently since they give similar results and further recommends trial in other parts of the country affected by drought.

Keywords Drought · Drought indices · NDVI · SPI · CDI · Kenya

1 Introduction

Weather and climate affect nearly all socioeconomic sectors (IPCC 2007). Thus, extreme weather events are known to cause a lot of socioeconomic losses. In Kenya and East Africa by extension, drought is one of the most frequent and devastating climate extreme phenomena. In this study, drought is a period of abnormally dry weather as a result of prolonged lack of water/rainfall that causes serious hydrological imbalances. The situation may be exacerbated by other conditions such as temperature, evaporation and cloudiness regimes. According to the previous studies, periods of unusually dry conditions are a normal feature of the climate (Mutua and Balint 2009; Khalili et al. 2011).

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Drought is one of the most widespread natural hazards in the world (Sheffield and Wood 2011). However, vulnerability of people to impacts of drought varies greatly depending on a number of factors, the key ones being awareness and the available resources. Drought is a very common phenomenon in North Eastern Kenya (NEK) and by extension the Great Horn of Africa. According to Nyamwange (1995), there is evidence of the occurrence of major droughts in the region starting as early as 1889 and the most severe drought occurring in 1984/1985. Other studies have since shown subsequent years of droughts in the region during 2008, 2009 and 2010 (e.g., Zwaagstra et al. 2010). In 2011, the Great Horn of Africa experienced one of the severest droughts in the recent history. The drought caused a serious food and water shortage that led to loss of lives of both animals and people. The drought was attributed to the failure of the 2010 October–December 'short rains' and the March–May 'long rains' (Funk 2011; Ongoma et al. 2015). The poor performance in rainfall was as a result of El Niño-Southern Oscillation (ENSO) events. In particular, La Niña is associated with below normal rainfall over East Africa which leads to drought events.

Drought has major economic and humanitarian impacts on rain-fed agriculture; thus, it affects the economies of most developing countries (Núñez et al. 2014) such as Kenya whose economic backbone is rain-fed agriculture. The sector contributes approximately 36% of the country's gross domestic product (GDP) (FAO 2005). The report further indicates that livestock sector accounts for 90% of employment and more than 95% of family incomes in arid and semiarid lands (ASALs). Thus, drought poses a serious hazard to livestock farming, a key economic activity in NEK and the nation at large. Drought-related impacts on human health, especially among children and the elderly, cannot be underestimated. In a recent study, Lillepold et al. (2018) observed that increased drought severity was associated with a nonsignificant decrease in height-for-age z-scores (HAZ) among Kenyan children. Similarly, Bauer and Mburu (2017) reported that here is a strong negative effect of drought on child health in a study carried out using 5 years of data (2009–2013) over Marsabit County in NEK.

According to studies (e.g., AMCEN 2011; Sheffield et al. 2012), there is a likelihood of an increasing frequency and intensity of extreme climate events. Other than La Niña, in reference to the 2016 drought over Kenya, Uhe et al. (2018) noted that the increasing temperature is partly responsible for the observed increase in intensity of droughts in the Kenya. For East Africa, global circulation models still show high uncertainty in rainfall representation (Ongoma et al. 2019), but currently, the region is recording a decrease in rainfall (Ongoma and Chen 2017), a worrying trend. The situation is currently termed as a paradox of East African climate given that models project an increase in wetness throughout the twenty-first century, the opposite of what is being observed (Ongoma et al. 2018a). This thus calls for accurate and reliable methods and approaches for detecting the occurrence and analyzing the extent of the drought.

Application of effective monitoring and early warning system is a key component in a drought policy (Botterill and Hayes 2012). For the monitoring to be successful, it is important to understand the features of the prevailing drought, spatial coverage, severity and duration. This information is obtained by the use of indices.

This study is based on the realization that there are no research works done over NEK using different indices in analyzing drought. Various other indices exist for drought analysis, such as: Palmer Hydrological Drought Index (PHDI; Palmer 1965), Palmer Drought Severity Index (PDSI; Palmer 1965), Surface Water Supply Index (SWSI; Shafer and Dezman 1982), Palmer Z-index, Crop Moisture Index (CMI; Palmer 1968), Reclamation Drought Index (RDI; Weghorst 1996), Effective Drought Index (EDI; Byun and Wilhite 1999) and Bhalme–Mooley Drought Index (BDI; Bhalme and

Mooley 1980), among others (Núñez et al. 2014; Redmond 2002; Quiring 2009; Zargar et al. 2011). From the wide range of the drought indices (DI), Standardized Precipitation Index (SPI; Mckee et al. 1993) is the most recognized and applied in both research and operational activities owing to its simplicity, adaptability to varying timescales and climatic conditions (WMO 2012). However, the method has limitations such as the probabilistic nature of the index (Agnew 2000; Blain et al. 2009). The common indices used in most studies consider rainfall as the only variable for assessing drought occurrences. Rainfall, as the only parameter, may not give a good indication of drought. Therefore, there is a need to consider more advanced measures or techniques that capture more information when analyzing drought (Song et al. 2013). On the basis of adaptability to local climatic conditions and limited data, Ntale and Gan (2003) found that SPI is the most appropriate in drought monitoring over East Africa. Their study evaluated the performance of three drought indices: PDSI, BDI and SPI, in monitoring drought over East Africa.

This study explored applicability of Combined Drought Index (CDI; Sepulcre-Canto et al. 2012), which takes into account more variables: temperature and vegetation in addition to rainfall data. Mutua and Balint (2009) used the CDI method in studying drought in Somalia, which neighbors NEK, while Ngaina et al. (2014) used SPI to monitor drought in Tana River County in Kenya, which is south of our region of study. This study tests the applicability of CDI in drought analysis over NEK and compares the performance of the two indices.

The remaining part of this study is structured as follows: Sect. 2 presents the area of study, data and methodology employed, while Sect. 3 contains the results and discussion. The conclusion and recommendations based on the findings are given in Sect. 4.

2 Data and methodology

2.1 Area of study

The main area of study is the larger NEK. The northern counties in consideration are Mandera, Wajir, Marsabit and Garissa. Northern Kenya has an arid and semiarid climate which is characterized by low(high) rainfall(temperature) (Ongoma et al. 2018b). Average annual amounts are generally below 500 mm and in some places below 200 mm. In this region, livelihoods are dominated by pastoralism where herders adapt to temporal and spatial variability of pasture and water by being nomadic. Drought is the major source of livestock mortality, and this may cause low living standards (Nyamwange 1995). High temperatures, strong winds, high rate of evaporation, little vegetation cover and low rainfall levels characterize the region with long dry spells. The plains routinely reach very high temperatures by midday, about 34 °C or above with little amount of rainfall (Fig. 1). The region exhibits arid and semiarid conditions. Figure 1 shows the area of study, and Table 1 shows the coordinates of the stations used.

NEK is highly vulnerable to the effects of floods as well. The local population's ability to respond to the shocks of these events is limited by conflicts over natural resources, mainly water and pasture.

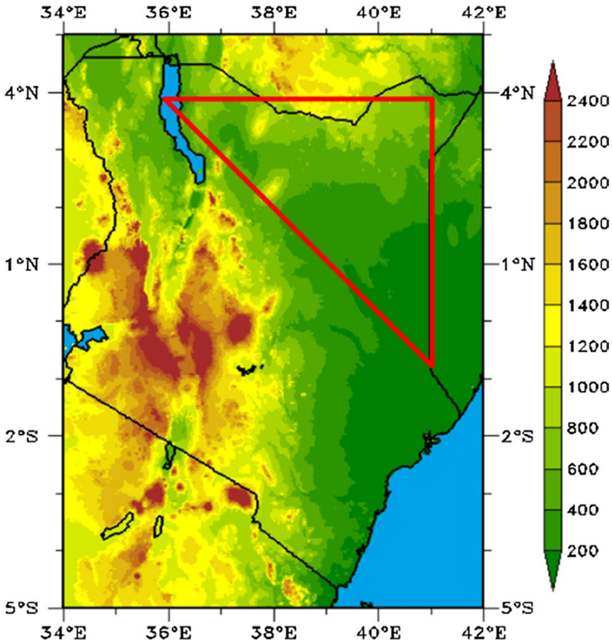

Fig. 1 A map of Kenya's topography. NEK region is enclosed by the red triangle. Topography is based on data provided by Hastings and Dunbar (1999)

Table 1 Location of some of the selected stations

Station	Latitude	Longitude	Area (km^2)	County population ('000)
Wajir	01°45′N	40°04′E	56,685.8	661,941
Mandera	04°16′N	40°06′E	26,474	357,576
Marsabit	02°19′N	37°58′E	66,000	121,478
Garissa	00°29′N	39°38′E	34,872.2	329,868

2.2 Data

The data that were used in the study are the daily rainfall and temperature values for some selected stations of NEK, Mandera, Marsabit, Wajir and Garissa for the period 1980–2010. The data were sourced from Kenya Meteorological Service (KMS). Normalized Difference Vegetation Index (NDVI) images were obtained from African Data Dissemination Service (ADDS). The images were converted into numerical data using the WinDisp software.

Data quality control helped check and detect errors in the data sets. Missing rainfall and temperature values (less than 5%) were estimated using Eq. 1:

$$X_{\mathrm{m}} = {}^{1}/_{N} \sum_{i=1}^{i=n} X_i, \tag{1}$$

where X_{m} is the missing data being estimated, X_i is the available data points and N is the total number of data points.

2.3 Methodology

A rainfall anomaly (Eq. 2) and time series were used to analyze the temporal variability of the rainfall, hence identifying the wet and dry years:

$$Z = \frac{(X - \overline{X})}{\sigma}, \tag{2}$$

where Z is the standardized anomaly, X is the variable in consideration, $\overline{X}$ is the mean value of the variable and σ is the standard deviation. The dry and wet years are determined using the criteria: $Z > 1$ for wet year, $1 \leq Z \leq -1$ in normal rainfall years and $Z < -1$ for dry year. The same thresholds have been successfully used in related studies over East Africa (Ongoma et al. 2015; Ogwang et al. 2015).

The study analyzed the drought over NEK using the SPI and CDI. SPI was developed to enhance detection of onset and monitoring of drought (Balint et al. 2011). It involves probability of precipitation for a given period and is negative for drought and positive for wet conditions. While a probability index considers only precipitation, SPI is flexible to measure drought at different timescales. CDI (Eq. 3) is used to calculate drought severity and involves the use of the weighted averages of precipitation (0.5), temperature (0.25) and soil moisture (0.25). Since the data of soil moisture are not easily available in enough densities, in most cases, the vegetation drought index is used (Balint et al. 2011):

$$\mathrm{CDI}_{i,m} = w_{\mathrm{PDI}} * \mathrm{PDI}_{i,m} + w_{\mathrm{TDI}} * \mathrm{TDI}_{i,m} + w_{\mathrm{VDI}} * \mathrm{VDI}_{i,m}, \tag{3}$$

where $\mathrm{CDI}_{i,m}$ is the Combined Drought Index, w_{PDI} is the Weighted Average Precipitation Index, $\mathrm{PDI}_{i,m}$ is the Precipitation Drought Index, w_{TDI} is the Weighted Average Temperature Index, $\mathrm{TDI}_{i,m}$ is the Temperature Drought Index, w_{VDI} is the Weighted Average Vegetation Drought index and $\mathrm{VDI}_{i,m}$ is the Vegetation drought Index.

According to Balint et al. (2011), drought is classified using CDI as tabulated in Table 2.

Simple correlation analysis was used to determine the relationship between the CDI values and the SPI values. The correlation coefficient was computed using Eq. 4:

$$R_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \cdot \frac{1}{n}\sum_{i=}^{n}\left(y_i - \bar{y}\right)^2}}, \tag{4}$$

where R_{xy} is the correlation coefficient between SPI and CDI values, X_i is the SPI figures, Y_i is the CDI values, $\bar{x}$ is the mean SPI rainfall figures, $\bar{y}$ is the mean CDI figures and n is the number of data points used.

The computed correlation values were tested for statistical significance using the student t test (Eq. 5).

Table 2 Categories of droughts using CDI

CDI value	Drought severity
> 1.0	No drought
1.0–0.8	Mild
0.8–0.6	Moderate
0.6–0.4	Severe
< 0.4	Extreme

Fig. 2 Wet and dry years over NEK for the years 1980–2010. The dotted lines denote dry (−1) and wet (+1) years

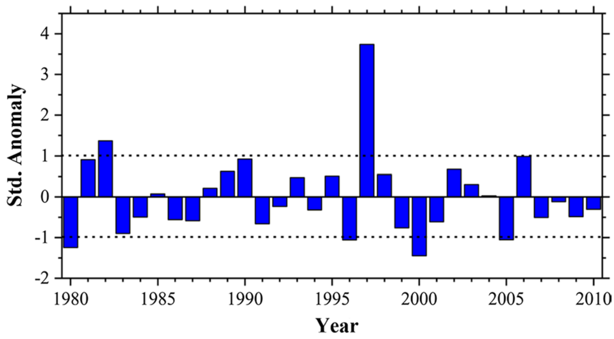

Table 3 Wet and dry years for the period 1980–2010 over NEK

Wet	Dry
1982 (1.368), 1997 (3.740), 2006 (1.000)	1980 (−1.245), 1996 (−1.058), 2000 (−1.449), 2005 (−1.055)

The respective standardized anomalies are given in the respective brackets

$$t_{n-2} = r\sqrt{\frac{n-2}{1-r^2}}, \tag{5}$$

where t is the value of the student t test, n is the number of observations and r is the correlation being tested.

3 Results and discussion

3.1 Results for the SPI analysis

The SPI was achieved by standardizing the rainfall values in the area of study. Figure 2 shows the rainfall anomaly distribution over NEK.

During the study period 1980–2010, the region experienced four dry years and three wet years. The wettest year over NEK was to be 1997. This was probably due to the strong El-Nino rains during that particular time generally over the entire Kenya and East Africa at large. In the year, floods associated with the heavy rainfall caused a lot of destruction in East Africa, especially in the ASALs that are not used to above normal rainfall (Little et al. 2001). The driest year was found to be 2000. The other notable dry and wet years are shown in Table 3.

3.2 Results for CDI analysis

The weights in Eq. 3 can be obtained according to various aspects that may include: the environment, geographical locations and the prevailing climatic conditions. This study

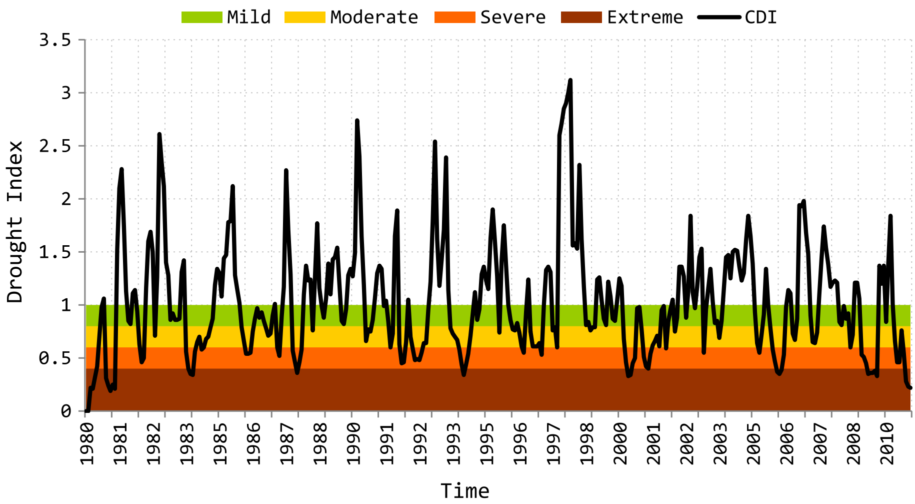

Fig. 3 Monthly drought index, CDI, over NEK for the period 1980–2010

used the climatic conditions of the area of study. The results obtained in Fig. 3 show that the drought within the NEK for the period 1980–2010 fell in all the categories of extreme, severe, moderate and mild (Table 4).

Some years did not record any form of drought. Good examples are 1981 and 1997, which were very wet.

From the results given in Table 4, drought is a common phenomenon in NEK appearing as extreme, severe, moderate or mild. Extreme and severe droughts tend to occur when there are La Niña conditions. The La Niña conditions occur when there is a decrease in the sea surface temperature in the eastern side of the Pacific Ocean, a condition associated with dry conditions in East Africa including NEK. The conditions enhance drought in the region. In Kenya, La Niña conditions were pronounced in the years 1984, 2000 and 2010; these are replicated in Table 4.

The results obtained for Mandera and Marsabit are shown in Figs. 4 and 5.

The results for drought analysis obtained from the CDI in Mandera station are shown in Table 5.

Most of the drought events recorded in the study period over Mandera are severe followed by extreme droughts.

Figure 5 and Table 6 show CDI over Marsabit during the study period: 1980–2010.

Analysis of the two individual stations shows that out of the years the severe droughts occurred in 1980, 1984 and 2010.

Table 4 Drought severity years based on CDI in NEK, 1980–2010

Extreme	Severe	Moderate	Mild
1980, 1984, 1998, 2000, 2009, 2010	1982, 1986, 1991, 1996, 1987, 2003	1988, 1999, 1990	1983, 1986, 1989

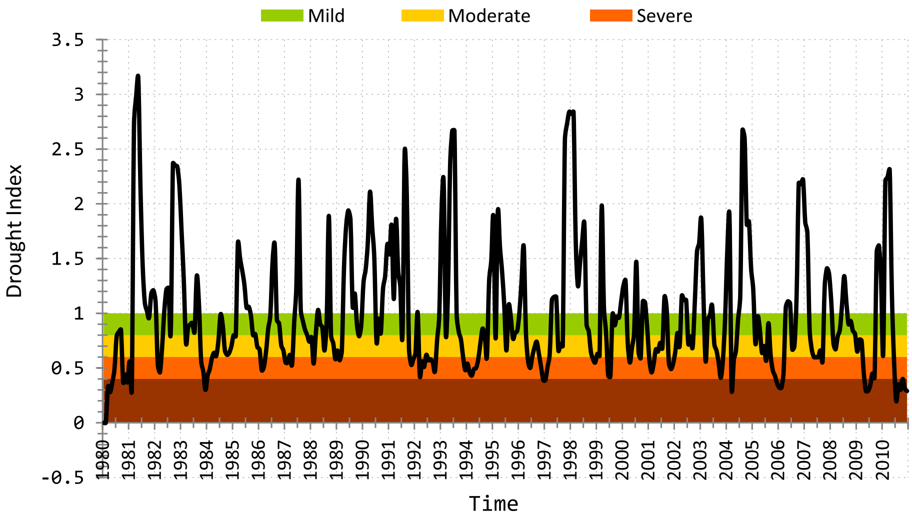

Fig. 4 Monthly drought index, CDI, over Mandera for the period 1980–2010

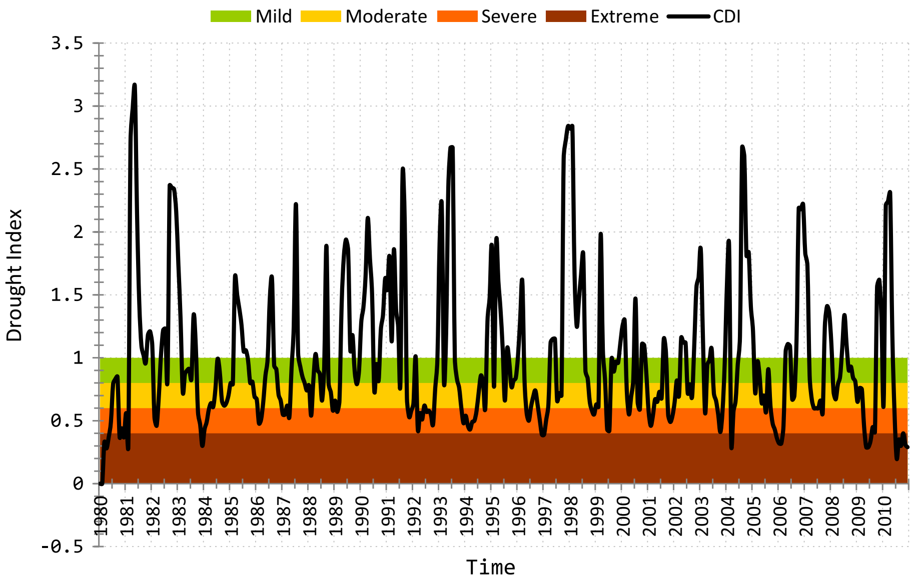

Fig. 5 Monthly drought index, CDI, over Marsabit for the period 1980–2010

Table 5 Drought severity years in Mandera station, 1980–2010

Extreme	Severe	Moderate	Mild
1980, 1996, 1999, 2004, 2009, 2010	1986, 1988, 1991, 1992, 1998, 2000, 2001	1983, 1984, 1990, 1995, 2002	1982

Table 6 Drought severity years in Marsabit station, 1980–2010

Extreme	Severe	Moderate	Mild
1980, 1984, 1994, 2000, 2006, 2010	1982, 1986, 1996, 1999, 2003	1983, 1991, 2002, 2007	1995

Table 7 Correlation between CDI and SPI in North Eastern Kenya, 1980–2010

Correlation	CDI	SPI
CDI	1	–
SPI	0.655	1

The year 1986 had severe drought across the four stations. These results are in agreement with Nyamwange (1995). There were years of no drought, which included 1990, 1993 and 1997. These may be due to the effects of enhanced rainfall performance over the years.

3.3 Comparison between SPI and CDI

The correlation done between the CDI and SPI values gave the values shown in Table 7.

The correlation coefficient is obtained at positive 0.655. Thus, the correlation between the two indices is found to be significant at 99% confidence level. This implies that the two methods of analyzing drought are highly correlated; hence, anything could be used to analyze the drought in the region independently. However, the CDI method is preferred to SPI since it takes into account more parameters than SPI.

4 Conclusions and recommendation

The importance of understanding the frequency, intensity and spatial distribution of drought over NEK and Kenya at large cannot be underscored. This study helps in assessing the performance of two drought indices, SPI and CDI, in measuring and monitoring drought over NEK. The results from this study show the comparison of CDI and SPI in analyzing drought in NEK. The study also shows the severity, intensity and variation of drought in various years. The correlation coefficient between the two indices was found to be significant. The CDI can therefore be used to analyze drought in the NEK region, and it is also preferred over SPI since it gives more information about drought. It recommends the use of either of the two indices in NEK for drought monitoring. It is also recommendable to have an assessment of CDI in other areas affected by drought, such as south eastern and coastal counties of Kenya.

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