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# Spatial and temporal drought incidence analysis in the northeastern highlands of Ethiopia

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## Abstract

This study investigated the space-time drought incidence in the northeastern highlands of Ethiopia using monthly rainfall data. It also aims to predict drought events for 100 years. The Standardized Precipitation Index (SPI) was used to compute the drought severity classes of rainy months and seasons at 1-, 4- and 8-months timesteps. The Mann-Kendall's test and Sen's slope estimator were used to analyze the trends of drought events and to determine the magnitude of change. Inverse Distance Weighted spatial analysis tool was used to illustrate the spatial patterns of the drought risk events. The study detected extreme severe droughts in the *belg* rainy months in March 2008 and April 1984. However, during the *belg* season, the year 1999 was the driest for the recorded periods. On the other hand, the extremely severe droughts were observed during the *kiremt* rainy months of July 1987 and 2015, August 1984, and September 2009. In general, 1984, 1987 and 2015 were the driest years recorded in the *kiremt* season. The study noted that the drought risk events of months in the *belg* season were threefold greater than that of the months in *kiremt* season under moderate drought intensity class. Equally, the drought risk events of months in *kiremt* season were threefold greater than that of the *belg* season under extreme drought intensity class. Complex spatial variations of drought risk events were also observed in 1-, 4- and 8-months timesteps. During the *belg* seasons, the southern half was subjected to more frequent drought risk events while the northern half experienced more frequent drought risk events during *kiremt* season. Almost the eastern half of the livelihood zones experienced higher drought frequency events than the other parts in the 8-month timestep. The observed space-time drought risk event analysis has shown a potential threat to the rainfed agricultural practices that have a great influence on the livelihoods of smallholder farmers. Hence, documentation and assessment of drought risk events based on the livelihood zones are essential for drought risk management, early warning responses, local-scale planning and food security management. Finally, the study recommended further research on additional indices of climatic variables such as evapotranspiration and soil water content.

**Keywords:** Livelihood zone, Belg and kiremt, Drought, Standardized precipitation index, South Wollo, Ethiopia

## Introduction

Drought is a commonly used term, but the most complex and least realized of all the natural hazards affecting more people than any other hazards (Wilhite 2000; Ashraf and Routray 2013). As opposed to other extreme events, (like floods, tornadoes, and hurricanes), drought develops slowly and steadily, making it difficult to determine the onset and end (WMO 2016). Generally, drought is related to a continual deficit of water below

average usually for a season or more (AghaKouchak and Nakhjiri 2012; Guha-Sapir et al. 2012; Dai 2011; Ashraf and Routray 2013; WFP 2014). Many scholars, for instance, AghaKouchak and Nakhjiri (2012), Jeyaseelan (2003) and Wilhite and Glantz (1985) classified drought as meteorological, hydrological, agricultural, and socio-economic based on the causative factors. These drought types share the deficiency of precipitation as a common phenomenon. Among these, the meteorological drought is the main driver; leading to the more likely occurrences of agricultural and hydrological droughts (WMO 2016; Zhan et al. 2016; Mpelasoka et al. 2008).

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Since drought is a recurrent climatic phenomenon, its outcome is manifested through immense damage to agriculture production, reduction of water supply and energy production, mass migration and loss of life (Masih et al. 2014). Writers such as –Sheffield and Wood (2007), Bannayan et al. (2010), and Degefu and Bewket (2015) differently showed that the causes and influences of drought in space-time on the environment are determined by the attributes of frequency, magnitude, intensity, and spatial extent. Likewise, Trenberth et al. (2011) reported that the magnitude, intensity, frequency and spatial coverage of the dry area has been doubled since the 1970s in Africa, East and South Asia, eastern Australia, Southern Europe, Northern and Southern America, most of Alaska, and Western Canada. Within the period 1960–2016, there were about 669 drought events reported across the world, and hence it has killed about 2.2 million people and affected over 2.6 billion people and an estimated economic damage of 146 billion US Dollar Centre for Research on the Epidemiology of Disasters/CRED (2016).

The vulnerability of developing countries to drought has risen by a factor of three in the decade of the 1990s compared with the 1960s (Mirza 2003). Much of the northern, southern, eastern and Sahelian African countries experienced the worst droughts in terms of the number of people killed and affected in 1972/73 and 1984/85 (Gommes and Petrassi 1996). For instance, of all the natural disasters, droughts account for only 8% of the global phenomenon. It also accounts for 25% in Africa between 1960 and 2006 (Gautam 2006). In the 1980s drought killed more than half of a million people in Africa (Dai 2011). In Sub Saharan African countries, crop production and food security are mainly threatened by drought where the effects are inter-temporal and long-lasting (Shiferaw et al. 2014). Africa stands first with a total of 289 reported the number of drought events that killed almost 700 thousand people and affected above 414 million people between 1960 and 2016 due to the induced drought frequency (Centre for Research on the Epidemiology of Disasters/CRED 2016).

Drought has a severe negative impact on key socioeconomic sectors of most Eastern African countries (Butterfield 2011). Its incidence has increased steadily in East Africa for the last five decades (Gautam 2006). For instance, deprivation associated with drought and food crises disaster victims for East African countries (Burundi, Djibouti, Ethiopia, Kenya, Somalia, and Uganda) increased from one million people in the 1980s to 21 million in the 2010s (Hao et al. 2014; Guha-Sapir et al. 2012).

In Ethiopia, extreme weather events owing to insufficient total rainfall amount and long dry periods affected the agro-socioeconomic environment in the northern, southern and eastern parts of the country and resulted

in great human sufferings and losses of life (Seleshi and Camberlin 2006). Precipitation exhibits great spatial variation both in annual average and inter-annually that could be taken as the major cause for the occurrence of the droughts in the country (Viste et al. 2013; World Bank 2006a, 2006b). In this regard, Viste et al. (2013) conclude that there are no years without drought in many parts of Ethiopia. Consequently, environmental and socioeconomic deprivation in Ethiopia happened due to the cumulative induced drought over several crisis seasons (Endale 1993). In the future, due to the increasing resource depletion, single-year droughts may be sufficient to cause severe hardship among vulnerable households (Webb and Von Braun 1990; Webb and Braun 1994).

Although the name “Water Tower of North-East Africa” has been given to Ethiopia, the country is one of the Horn countries highly vulnerable to drought (Gebrehiwot et al. 2011). The history of drought and associated disasters in Ethiopia traced back to 250 B.C. with a total of 39 periods of food shortage and excess mortality rate have been identified (Block 2008; Webb and Von Braun 1990; Webb and Braun 1994; Webb et al. 1992). Impacts of droughts in Ethiopia are perhaps the most widely publicized given their severity and frequency (Gautam 2006). As recent literature ratifies, Ethiopia’s history has been periodically marked by major drought incidences for the period 1950–2016 (Table 1).

Drought frequency in Ethiopia has been increasing. For example, in the 1970s and 1980s drought usually occurred once per decade (Block 2008; United Nations Environment Program/UNEP 2011). It was also about twice every 3 years between 1980 and 2004 (World Bank 2006a, 2006b) and once a year between the 1990s and 2011 (Viste et al. 2013). The estimated human cost caused by drought in Ethiopia between 1972 and 1984 were about 1.2 million people (United Nations Environment Program/UNEP 2002). These evidences showed that Ethiopia is often stricken by droughts in the 1970s and 1980s resulted in widespread poverty, economic stagnation, depletion of household assets and savings, and excess mortality (Dorosh and Rashid 2013). South Wollo, located in the northeastern highlands of Ethiopia is an epicenter for drought and famine for many years. The zone is a drought prone area and faces the horrible combination of both high risk and low potential as well as chronic food insecurity (World Bank 2006a, 2006b).

Of the total recorded drought years (1953–2016) in Ethiopia, Wollo experienced about 72% of the drought events (Little et al. 2006). In fact, the existence of diverse agroecology enables the zone to raise different types of livestock and to produce cash and food crops (ANRSPC 2017; 2018). But, the agricultural activities are entirely rainfed except in a few localities where there are small-

**Table 1** Reported drought years, regions affected, causes and severities since the 1960s in Ethiopia

Year	Region Affected	Causes and severity description
1957/58	Tigray and Wollo	Rain failure in 1957; locusts and epidemic in 1958 and about 100,000 people died
1962/63	Western Ethiopia	Very severe
1964–66	Tigray and Wollo	About 1.5 million people were affected and about 300, 000 livestock died
1971–75	Ethiopia	Sequence of rain failures; estimated 250,000 dead; 50% of livestock lost in Tigray and Wollo
1978/79	Southern Ethiopia	Failure of Belg rain & 1.4 million people were affected
1982	Northern Ethiopia	Late Meher rains & 2 million people were affected
1984/85	Ethiopia	Sequential rain failure; 8 million people affected;
1987/88	Ethiopia	7 million people were affected
1990–92	Northern, Eastern, and SW Ethiopia	Rain failure and regional conflicts; estimated 4 million people suffering food shortage
1993/94	Tigray and Wollo	Widespread food insecurity (7.6 million people were affected), but few deaths or cases of displacement were reported.
1997	Borena, Bale, Omo, Somali	Almost 986, 000 people affected
1999	N. & S. Wollo, Wag, Himra; Tigray; B. Gumu, Gambela, Oromia, SNNPR, Somali	Almost 5 million people affected
2003/4	All Regions	Over 13 million people affected, but the response mitigated the worst potential outcomes.
2005	Somali, Oromia	Almost 2.6 million drought disaster affected people
2008/9	All regions	Almost 12.6 million People were affected.
2011	S & E. Oromia, Somali	Severe food insecurity and 4 million people affected
2015/16	N., E, & SW Ethiopia	About 10.2 million people were affected

Source: Degefu 1987; Webb and Von Braun 1990; Webb and Braun 1994; Webb et al. 1992; Philip et al. 2017

scale irrigation and water harvesting practices (SWAD 2018). Dominant cereal crops produced in the region include teff (*Eragrostis tef*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and pulses (*Leguminosae/ Fabaceae*). Nevertheless, the larger reliance on agriculture-based income, which is under the sensitivity of nature exposed the people to food deficiency (Little et al. 2006; Kahsay 2013). All these attributes contributed to the reduction of productivity in the zone. This might be the reason that the zone is exposed to food shortage and dependent on safety nets for many years. Therefore, an assessment of the spatio-temporal drought risk events is imperative for policy makers and practitioners in the area under study.

The classification and representation of observed spatio-temporal drought risk events using SPI are vital in operational monitoring for policy decisions. Accordingly, many studies, but different in study periods and spatial coverage related to drought were documented in Ethiopia using SPI (e.g. Suryabhagavan 2017; Degefu and Bewket 2015; Viste et al. 2013; Gebrehiwot et al. 2011; Williams and Funk 2011; Edossa et al. 2010; Korecha and Barnston 2007; Segele and Lamb 2005; Seleshi and Zanke 2004). Many of these studies documented either temporal or spatial or both to show the most common

SPI-values of 3-, 6-, 9-, 12-, and 24-months timesteps. However, the SPI can be computed at any timescales for any set of successive months of 1-month up to 72-months. The spatial and temporal drought event analysis for SPI 1-, 4- and 8-months timesteps are not included in their studies. Therefore, the analysis of the space-time pattern of drought risk events of this study is based on the rainy months and seasons of 1-, 4- and 8-months timesteps,. The space-time drought risk events of the small and big rainy months as well as seasons (SPI: 1-, 4- and 8-months timesteps) are appropriate for planning and management of drought and related risks at the local-scale level. This study, therefore, aims to characterize the spatial and temporal drought incidences as a function of frequency, magnitude, intensity and severity status using the SPI model over the northeastern highlands of Ethiopia.

#### **Drought quantification: the standardized precipitation index**

Drought indices are essential to characterize several drought features such as the onset and cease time of drought, drought duration, areal extent, severity and frequency at global, regional and local level (Piechota and Dracup 1996). Owing to the complexity of drought, numerous operational drought indices have been developed and used by meteorologists and climatologists around

the world (WMO 2016; Dai 2011). In the international works of literature, a large number of studies acknowledge numerous indices in the detection, analysis, and monitoring of drought events for recent and projected changes (Loukas and Vasilades 2004). Among the numerous indices, the most commonly used drought index with its strengths and weaknesses is the Standardized Precipitation Index (SPI) (McKee et al. 1993).

The SPI is relatively new application, gaining worldwide acceptance and widely used at present because of its powerfulness, effectiveness, flexibility, versatile and standardized nature (Beth and Brown 2003; WMO 2012; Tsakiris and Vangelis 2004; Mashari Eshghabad et al. 2014). Hence, choosing a precipitation-based drought measure (SPI model) is preferred for its low data requirement and computational simplicity for developing countries like Ethiopia where the access to data is limited (Viste et al. 2013; Degefu and Bewket 2015).

SPI values in one region can be directly compared to SPI values in a completely different climate zone. It can monitor the onset, intensity, and duration of drought (Hayes et al. 1999; Loukas and Vasilades 2004). The SPI is a very suitable index to study the geospatial and temporal variation of drought with spatially invariable results for historic time series analysis (Masih et al. 2014; Guttman 1998). The ideal strength of SPI is that precipitation anomalies can be consistently calculated over flexible time scales in a consistent fashion. Similarly, drought information can be provided promptly for operational drought-monitoring applications (AghaKouchak and Nakhjiri 2012). Even, following the discussion at (WMO 2009), drought experts made a consensus agreement to recommend the SPI for the characterization of meteorological droughts (Hayes et al. 2011). The SPI measures moisture to quantify the precipitation deficit for multiple time scales at any one location and reflects the impact of drought on a range of meteorological, agricultural and hydrological applications (Marimon 2016; Degefu and Bewket 2015; Loukas and Vasilades 2004). The SPI can be calculated at various timescales for any set of successive months of 1-month up to 72-months that one wishes to detect and to illustrate the effect of drought (Viste et al. 2013; Stagge et al. 2015; Padhee et al. 2014; Beth and Brown 2003; AghaKouchak and Nakhjiri 2012). But statistically, 1–24 months is the best practice range of application (Guttman 1999). The short period time scales SPI-values (1-, 2-, 3-, 4-, 5- and 6-months) are appropriate and paramount for measuring the effect of drought on agriculture, soil moisture and crop yield reduction (Bussay et al. 1998; Morid et al. 2006; Szalai and Szinell 2000).

A 3-month SPI reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation. In primary agricultural regions, a 3-month

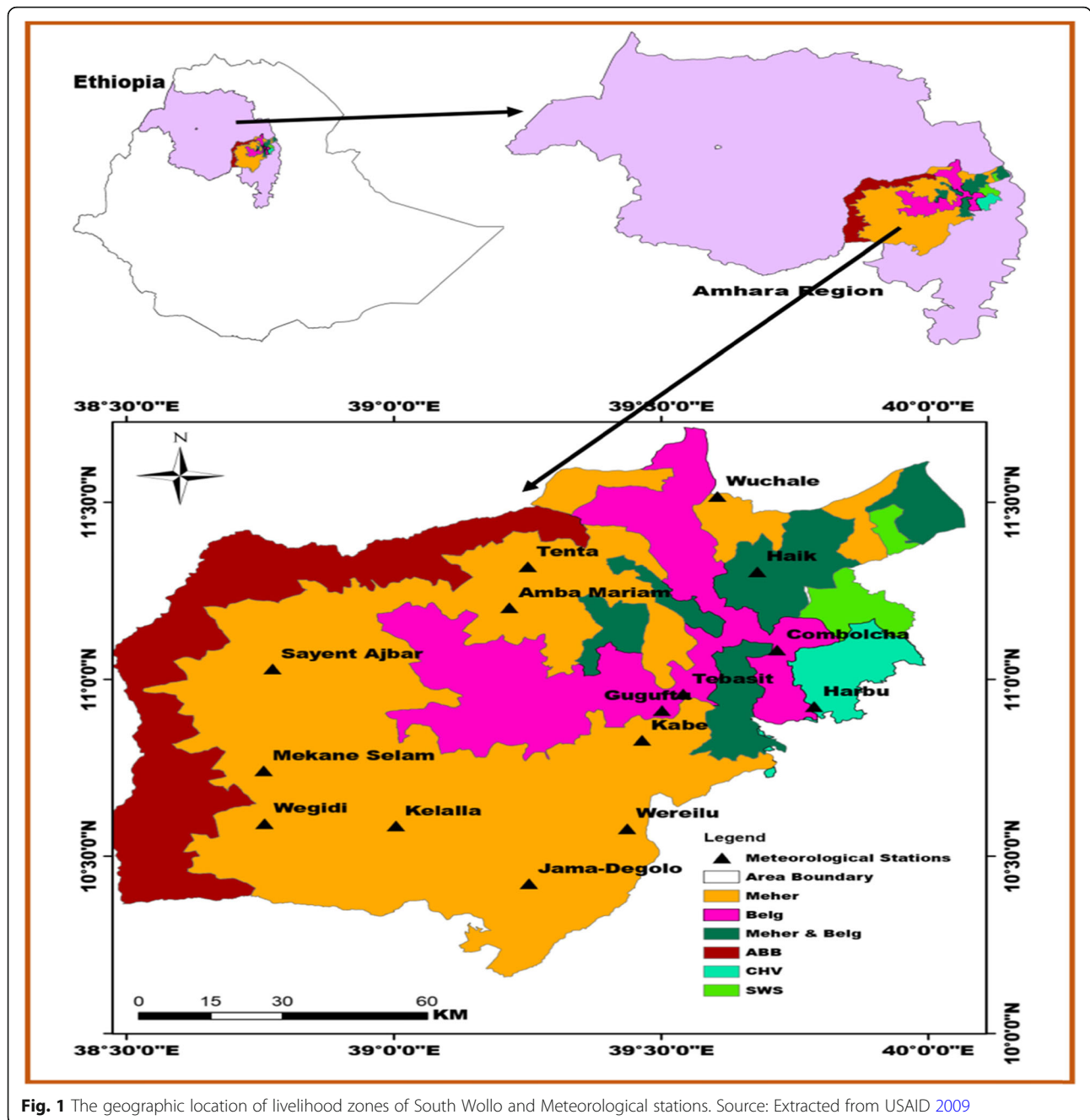
SPI might be more effective in highlighting available moisture conditions than the slow-responding Palmer Index or other currently available indices (WMO 2012). As compared to other indices, SPI is an appropriate index for drought analysis to East African countries indicated by various studies. For instance, Ntale and Gan (2003) suggested that SPI is more suitable for monitoring droughts in East Africa because (i) it is easily adapted to the local climate, (ii) it needs a modest data requirement, (iii) it produces spatially consistent results, and (iv) it can be computed almost at any time scale.

## Materials and methods

### Description of the study site

South Wollo is one of the eleven administrative zones of the Amhara National Regional State which is located between 10°10'N and 11°41'N latitudes and 38°28'E and 40°5'E longitudes (Fig. 1). The total area of the Zone is about 18,157.48 km<sup>2</sup>, which is divided into 19 rural districts and four administrative towns (Dessie, Kombolcha, Haik, and Mekaneselem) (ANRSPC 2017). Of the total area, 36.3%, 13.5%, 18.3% and 31.9% are covered by arable land, forest and bush lands, grazing land, and others (e.g. bare land, buildings, water bodies), respectively (SWAD 2018). The landscape of the South Wollo zone comprises highly diversified and dissected topography (rugged terrain with very steep slopes). Elevation ranges from 927 m (over the dry plain/*Arabat*) in the east to 4261 m above sea level (Mount *Ambaferit*) in the west (SWAD 2018; Little et al. 2006). It has six livelihood zones, namely, Abay-Beshilo Basin (ABB), Chefa Valley (CHV), *Meher-Belg* zone, *Belg* zone, *Meher* zone and eastern lowland sorghum and cattle (SWS) (USAID 2009).

The Zone is characterized by a distinctive bi-modal rainfall regime, locally known as *kiremt* and *belg* seasons. *Kiremt* is the big rainy season usually extending from June-to-September, and *belg* is the small rainy season extending from February-to-May (National Meteorological Services Agency of Ethiopia/NMSA 1996; Degefu 1987; Korecha and Barnston 2007; Conway 2000a, 2000b). Crop production in the entire livelihood zones follow these rainfall regimes but varies among the livelihood zones. Accordingly, the livelihood zones of ABB, SWS *Meher* and CHV are dependent on big *kiremt* rainfall for the cultivation of both long and short cycle crop production. Conversely, *Belg* and *Meher-Belg* crop productions follow the bimodal rainfall regimes (the small *belg* and big *kiremt* rains) leading to two harvest periods. The mean annual rainfall ranges between 500 and 900 mm in the *Kolla* (arid and semi-arid) area and 950–1100 mm in the *Woina Dega* (semi-humid) and *Dega* (cool and humid) areas. The average annual temperature also ranges from 15°C to 20°C (SWAD 2018). Between 1901 to 2016 the minimum temperature ranges were



**Fig. 1** The geographic location of livelihood zones of South Wollo and Meteorological stations. Source: Extracted from USAID 2009

6.43<sup>0</sup>c in December and 11.82<sup>0</sup>c in June while the maximum ranges were 22.93<sup>0</sup>c in August and December and 29.13<sup>0</sup>c in June.

Based on the population statistics of ANRSPC (2017), the South Wollo zone has a total population of nearly 3.1 million of whom 49.5% were males and 50.5% females. The zone is one of the densely populated areas of the country with 171 persons per km<sup>2</sup>. The old-style subsistence farming (a mix of both grain production and rearing of livestock) is the primary form of economic activity in all livelihood zone

of the study area (ANRSPC 2017; SWAD 2018). Even though the small and large-scale irrigation practices are very minimal, the zone is known by many large and small rivers categorized into two major drainage basins (Abay and Awash accounting for about 82% and 18% of the area, respectively) (SWAD 2018). Cattle, goats, sheep, and equines are the major livestock in the area. However, the contribution of livestock to the livelihood of the people is constrained by the prevalence of livestock diseases (USAID 2009; Little et al. 2006).

### Data sources and data analysis techniques

For the characterization of spatial and temporal drought incidences as a function of frequency, magnitude, intensity, and severity status, long-term meteorological data were acquired from the Ethiopian National Meteorological Agency (ENMA-Kombolcha Regional Meteorological Station). Since rainfall is not normally distributed, a gamma probability distribution has been found fitting to the precipitation time series frequency distribution for the computation of SPI (Khan and Gadiwala 2013). The gamma probability density function is expected to fit with the frequency distribution of precipitation over the period (1981–2017). For the time scales of 1-, 4- and 8- months, alpha ( $\alpha$ ) and beta ( $\beta$ ) parameters of the gamma probability density function were estimated. As a result, the cumulative probability distribution function is approximated into the standard normal cumulative distribution probability function with a mean of zero and a standard deviation of one to determine the probability distribution function. Conceptually, the SPI is equivalent to Z- score, the number of standard deviations that the observed value would deviate from the long-term mean. The statistical procedure is:

$$SPI = \frac{X_i - \bar{X}}{\sigma} \quad (1)$$

Where:  $x_i$  = observed precipitation value of the selected period during the  $i$  th year;

$\bar{X}$  and  $\sigma$  = the mean and the standard deviation respectively over the selected period.

In this study, SPI was computed for shorter-term and intermediate periods to quantify drought events at 1-, 4- and 8-months timesteps to represent agricultural/meteorological droughts. The 1-month SPI (analogous to the percent of normal precipitation) reflected short-term conditions of soil moisture and crop stress during the growing season while the 4-months SPI represented the short and medium-term moisture conditions applied for the seasonal estimation of rainfall. The 4-months accumulation of SPI was calculated for May and (September) to assess the seasonal drought of *belg* and (*kiremt*). This is because of the 4-month definition of seasons in Ethiopia are the most commonly used (Viste et al. 2013). The 8-months timestep accumulation of SPI was computed for September (February-to-September), which was also a good indicator to assess the drought condition of slowly maturing long-cycle crops like sorghum and maize that typically planted during the *belg* season and harvested following the *kiremt* season.

In the computation of SPI, the SPI\_SL\_6.exe file programming which was available at <http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx> has been employed. The criteria employed by McKee et al.

(1993) and WMO (2012), have been applied in the quantification and classification of SPI drought severity status of the study. In the computation of drought status classification of this study, only months with  $SPI \leq -1.00$  were considered to be as drought initiation and cessation since mild drought (SPI between  $-0.99$  and  $0.99$ ) showed only a slight variation from the normal rainfall distribution (Łabędzki 2007; Sternberg et al. 2011; Degefu and Bewket 2015). Therefore, using the SPI\_SL\_6.exe file programming, moderate drought (SPI between  $-1.00$  and  $-1.49$ ), severe drought (SPI between  $-1.50$  and  $-1.99$ ) and extreme drought ( $SPI \leq -2.00$ ) were generated and presented in the form of time series graphs and maps.

Temporal drought event characteristics (frequency, magnitude, intensity and severity status) were computed using one of the most common models, SPI analysis parameters. Drought frequency is the return period between drought events that have severity threshold values of  $SPI \leq -1$ . The magnitude of drought event corresponds to the cumulative water deficit during the drought period below some threshold (SPI-values  $\geq -1$ ) (Thompson 1999) and drought intensity ( $D_I$ ) is the ratio between the drought magnitude and the duration of the event computed as:

$$D_M = - \sum_{i=1}^n SPI_{ij} \quad (2)$$

$$D_I = \frac{D_M}{D_d} \quad (3)$$

Where:  $D_M$  = drought magnitude,

$n$  = number of months with drought event at  $j$  timestep;

$D_d$  = drought duration.

However, drought severity ( $D_S$ ) should not be misguided for intensity, which is generally signified to the lowest SPI-value of the drought event (Spinoni et al. 2014). The number of droughts per 100 years for different timesteps of the rainy months and seasons (SPI:1-, 4- and 8-months) of the study as used by (Łabędzki 2007; Sternberg et al. 2011; Degefu and Bewket 2015; Ghosh 2019) which was estimated as:

$$N_{i,100} = \frac{N_i}{i \times n} \times 100 \quad (4)$$

Where:

$N_{i,100}$  = the number of droughts for a timestep  $i$  in 100 years;

$N_i$  = the number of years with droughts for a timestep  $i$  in the  $n$ -year set;

$i$  = the timesteps (1-, 4- and 8- months) and.

$n$  = the number of years in the data set (37 years).

Furthermore, the MK (Mann Kendall) trend test (Kendall 1975; Mann 1945) has been computed to check the statistical significance (increasing and decreasing trends) for rainy months and seasons of SPI: 1-, 4- and 8-months timesteps. The relative strength of MK trend test in time series analysis has been quantified using Sen’s (1968) slope estimator. As indicated by Chattopadhyay and Edwards (2016), Sen’s slope estimator has been the commonly used estimator due to its relative insensitivity and robustness to extreme values. The MK statistic *S* of the series *x* is calculated as:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sgn}(X_j - X_i) \tag{5}$$

Where:

*N* = the number of data points;

*X<sub>i</sub>* and *X<sub>j</sub>* = the time series observations. Assuming (*x<sub>j</sub>* - *x<sub>i</sub>*) = *θ*, the value of *sgn* (*θ*) is computed from:

$$\text{sgn}(\theta) = \begin{cases} +1 \dots \dots \theta > 0 \\ 0 \dots \dots \theta = 0 \\ -1 \dots \dots \theta < 0 \end{cases} \tag{6}$$

While Positive values of *S* indicate increasing trends, negative *S* indicates decreasing trends. Under the hypothesis of independent and randomly distributed random variables, for large samples, when *n* ≥ 10 (in some papers *n* ≥ 8), the *σ* statistic is approximately normally distributed, with zero mean and variance as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{7}$$

As a consequence, the standardized normal deviate (*Z*-statistics) distribution has been then calculated as:

$$Z = \begin{cases} \frac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sigma} & \text{if } S < 0 \end{cases} \tag{8}$$

While Positive values of *Z* signify increasing trends, negative *Z* signifies decreasing trends. In the spatial analysis of drought severity status, Inverse Distance Weighted, IDW average interpolation method was used in the ArcGIS. The SPI values generated from SPI\_SL\_6.exe file programming was used as an input for mapping the spatial distribution of drought severity status. As a consequence, the 1-, 4- and 8-months timesteps spatial distributions of drought incidences were mapped.

## Results

### Characteristics of drought events: frequency, magnitude, intensity and severity

Table 2 shows the observed drought frequency, magnitude, intensity and severity of the small, big, and long-term rainy months and seasons as computed using SPI. The highest frequency of drought years for the small rainy months within the moderately to extremely dry (SPI ≤ -1.00) found to be 9 years; in February and May account for about 24% of the total years over the study period. The drought magnitudes of the small rainy months were ranged from -9.45 in March to -11.83 in May. Nevertheless, the drought intensity found to be between the moderately dry in May with SPI = -1.23 and severely dry in March with SPI = -1.58. The extreme severe droughts were observed in March 2008 and April 1984 with the severity of peak SPI-values of -2.49 and -2.23, respectively. Likewise, the highest drought frequency in the big rainy months was 6 years in June that account for 15% of the total drought risk years. The observed magnitude of drought events ranged from -9.7 in July to -5.69 in September. The moderately dry drought intensity was observed in June, July, and September while the extremely dry drought intensity was observed in August. The worst droughts were recorded in July 2015, August 1984, and September 2009 with the severity peak of SPI values of -2.82, -3.61, and 2.31, respectively.

Seasonally, the drought frequency for SPI 4-months of both *belg* and *kiremt* as well as long-term season of SPI 8-months at the end of May and September account for about 4 years (9%) of the total drought years under study. A slight difference in the observed drought risk magnitude was shown among the SPI4-months (*belg* and *kiremt*) and SPI8-months (long-term) seasons. Nonetheless, the drought intensity was varied from severely dry in SPI4-months (*belg*) and SPI8-months (long-term) seasons with SPI = -1.92 and -1.79 respectively to extremely dry in SPI4-months (*kiremt*) season with SPI = -2.0. The SPI 4- and 8-months experienced severe drought events in 1984, 1999 and 2015 with severity peak SPI-values of -2.83, -2.84 and -2.32, respectively.

### Temporal trends of drought events

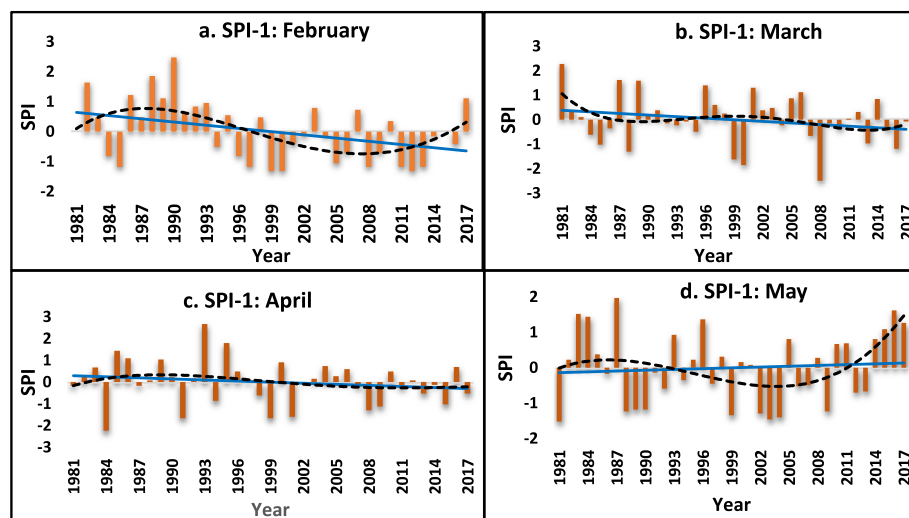
Using the SPI, the drought condition of the study for rainy months (SPI-1), *belg* and *kiremt* (SPI-4), and long-term (SPI-8) rainy seasons covering the period of 1981–2017 were examined. A mix of dry and wet years have been observed in February, March, April, and May as well as *belg* season but with temporal variation in severity, magnitude and intensity (Fig. 2a-d and Fig. 4a). Several drought risk incidences with SPI ≤ -1.00 were detected. It was observed that March 2008, April 1984, and the *belg* season of 1999 were characterized by extreme drought events with SPI ≤ -2 in the past 37 years.

**Table 2** Drought risk characteristics of the rainy months and seasons for  $SPI \leq 1.0$  values

Month	Observed Drought risk				
	Frequency (years)	Magnitude	Intensity	Severity Peak SPI-Value	Year/s
February	9	-10.92	-1.23	-1.32	1999, 2000, 2012
March	6	-9.45	-1.58	-2.49	2008
April	7	-10.58	-1.5	-2.23	1984
May	9	-11.83	-1.37	-1.52	1981
Feb-to-May ( <i>Belg</i> : SPI-4)	4	-7.66	-1.92	-2.84	1999
June	6	-7.3	-1.22	-1.78	1981
July	5	-9.7	-1.94	-2.82	2015
August	3	-7.1	-2.37	-3.61	1984
September	3	-5.69	-1.9	-2.31	2009
June-to-Sept ( <i>Kiremt</i> : SPI-4)	4	-8.03	-2	-2.32	2015
Feb-to-Sept (SPI-8)	4	-7.14	-1.79	-2.83	1984

Severe drought events with SPI values between -1.5 and -1.99 were also observed in March (1999 and 2000) and April (1991, 1999 and 2001). Moreover, the largest drought risk events (about 23 years) for February, March, April, and May were shown under the moderate drought intensity class. Nevertheless, 6 and (2) years were under the severe and (extreme) drought intensity classes. Drought ends when the SPI value becomes positive while drought begins when SPI value becomes negative. Since drought ends when the SPI value becomes positive, the increasing drought frequency of February found to be by far the highest (Table 2). This increasing drought frequency of February was substantiated by a significant decline of rainfall as revealed in the MK trend test (Table 3) and regression trend line (Fig. 2a).

Similarly, Fig. 3a-d and Fig. 4b signify a mix of drought and wet frequencies in the timesteps of SPI1-month observations (June, July, August and September) and SPI4-months of the current season. A mix of dry and wet years have been observed in June, July, August, and September as well as *kiremt* season but with temporal variation in severity, duration, magnitude, and intensity. It was witnessed from Fig. 3a-d and Fig. 4b extreme drought events with  $SPI \leq -2$  were investigated in July 1987 and 2015, August 1984 and 1993, September 2009 and *kiremt* season of 1984, 1987 and 2015. Severe drought also was detected in June 1981, July 1981 and 1984, and September 1984. Moreover, moderate drought events were detected in June 1982, 1985, 1987, 1988 and 2017, July 1992, August 1990 and September 1997. It



**Fig. 2** SPI 1-month anomalies and trends of *belg* rainy months: (a) SPI-1: February; (b) SPI-1: March; (c) SPI-1: April; (d) SPI-1: May



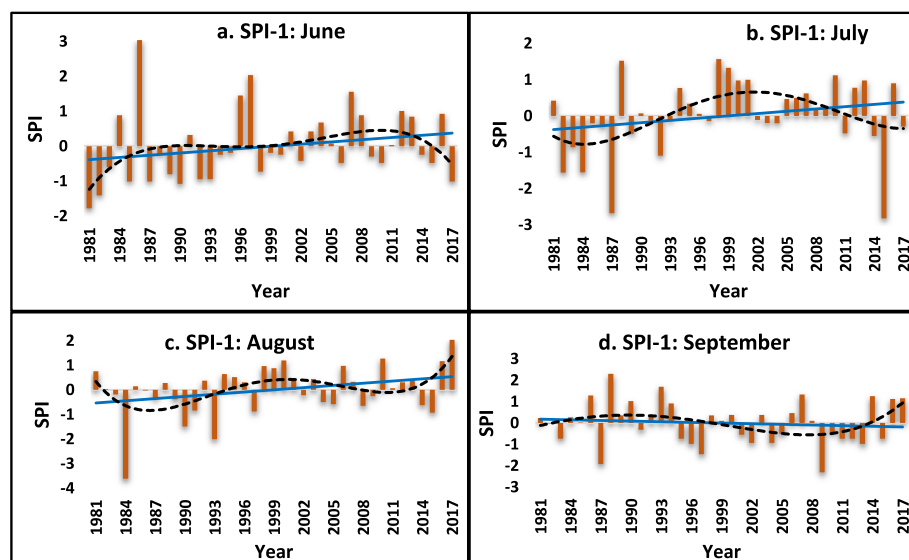
**Table 3** Mann-Kendall’s trend analysis and the probability of drought events per 100-year for the rainy months and seasons at 1-, 4- and 8-months timesteps

SPI timesteps	Months/Season	MK test	P-values	Slope	Probability of drought events per a 100-year
1-month	February	<b>-0.2539**</b>	0.0305	-0.0366	24
	March	-0.1388	0.2337	-0.0189	14
	April	-0.1508	0.1952	-0.02	19
	May	0.0693	0.556	0.0149	24
	June	<b>0.2493**</b>	0.0327	0.0311	16
	July	0.1851	0.1105	0.0291	14
	August	0.1458	0.2092	0.0188	8
	September	-0.0532	0.6559	-0.0077	8
	4-month	Feb-to-May	-0.1583	0.1736	-0.0248
June-to-Sept		0.2122	0.067	0.0281	11
8-month	Feb-to-Sept	0.1414	0.2238	0.0161	11

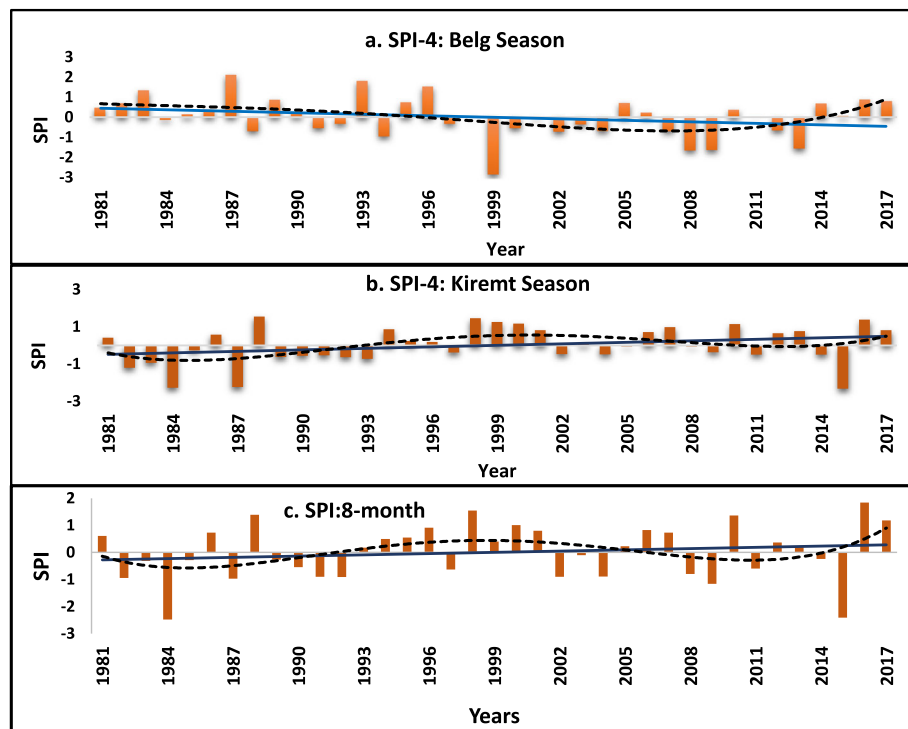
Note: \*\* is statistically significant at  $P < 0.05$

was also shown in Fig. 4c that moderate drought event was detected in 2009 while extreme droughts were detected in 1984 and 2015 during the long-term rainy season of SPI 8-month timestep. Furthermore, the largest drought event years (about 8 years) for June, July, August and September were shown under the moderate drought intensity class while three and (six) years were under the severe and (extreme) drought intensity classes. Seasonally, *belg* and (*kiremt*) were under severe and (extreme) drought intensity classes for 3 years while 2 years of the long-term season (SPI8-months) were under extreme drought intensity class. However, values of SPI1- (June, July, August) months and SPI 4- months (*kiremt* season) showed increasing trends except SPI1-month of September.

Incidences of drought trends and its probability per 100-years over the small and big rainy months (SPI-1) and seasons (SPI-4 and SPI-8) timesteps were shown (Table 3). The Mann-Kendall trend test of SPI-values showed statistically significant decreasing and (increasing) trends for small and (big) rainy months of February and (June) at  $p < 0.05$ . However, the 1-month timestep values of March, April, September and 4-month timesteps of February-to-May showed statistically non-significant decreasing trends. The 1-month timestep values of May, July, August, and 4-month timestep (June-to-September) on the other hand showed statistically non-significant increasing trends. The 8-month long-term seasonal timestep (Feb-to-Sept) value also showed a statistically non-significant increasing trend.



**Fig. 3** SPI 1-month anomalies and trends of *kiremt* rainy months: (a) SPI-1: June; (b) SPI-1: July; (c) SPI-1: August; (d) SPI-1: September



**Fig. 4** The SPI anomalies and trends of the rainy seasons. **a** SPI-4: *belg* season (February-to-May); **b** SPI-4: *kiremt* season (June-to-September) and **c** SPI-8 long-term seasons (February-to-September)]

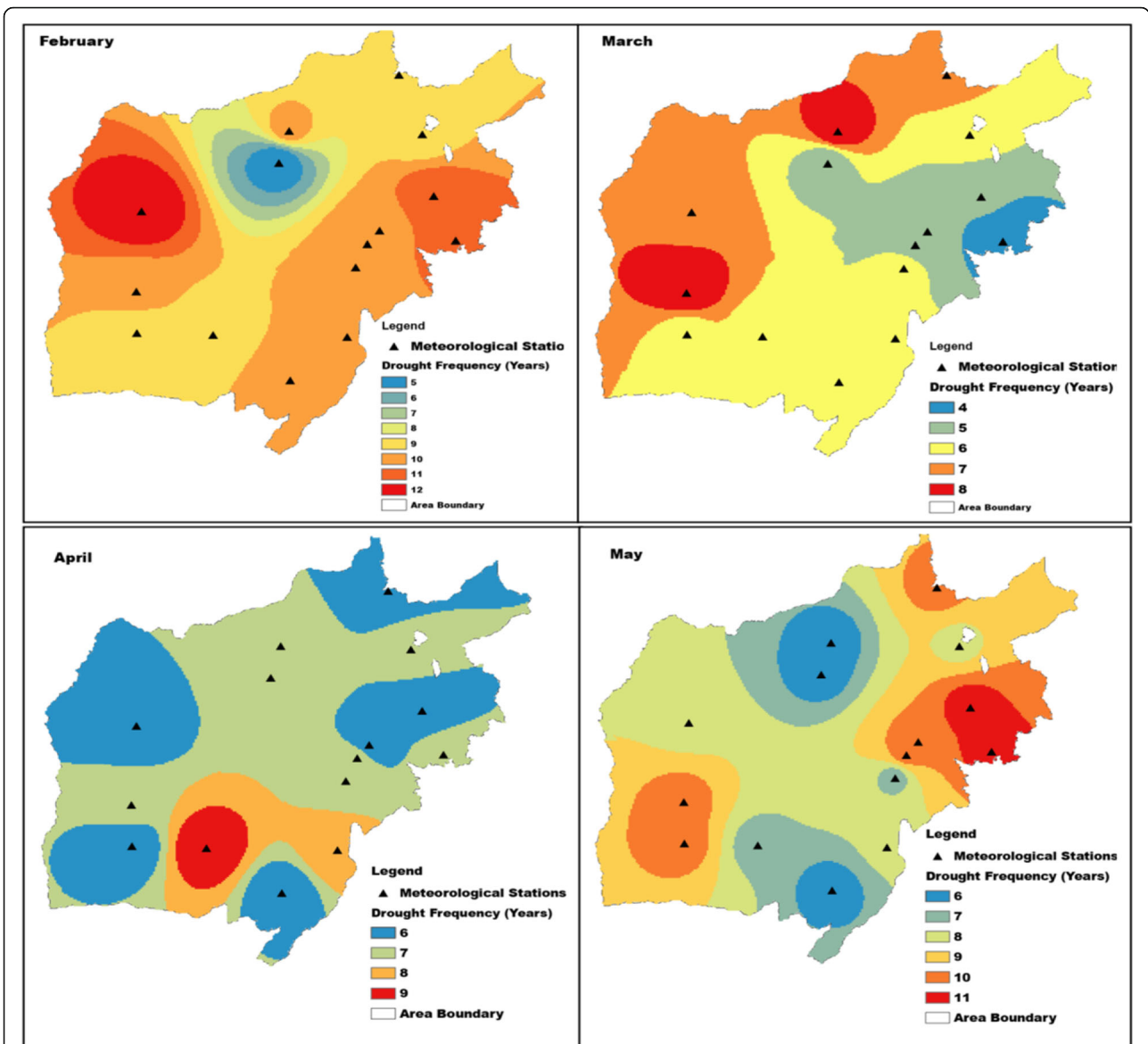
The predicted number of droughts for 100 years rainy months and seasons timesteps of 1-, 4- and 8-months based on eq. (4) is also presented (Table 3). The maximum predicted drought frequency events (except for August and September) were expected to be in the shorter timesteps of 1-month as compared to 4- month and 8-month timesteps. The 1-month predicted drought frequency events expected to be between 24 and (8) years for February and May and (for August and September). The seasonal predicted drought frequency events of all the 4-month (Feb-to-May and June-to-Sept) and 8-month (Feb-to-Sept) expected to be 11 years.

#### Spatial patterns of drought incidence

The spatial patterns of drought frequency incidence maps for 1-, 4- and 8-months timesteps for moderately dry-to- extremely dry intensity classes of drought events were depicted in Figs. 5, 6 and 7. The spatial pattern of drought risk frequency maps over the livelihood zones in the small rainy months (February, March, April, and May) was exhibited complex and high local-scale variation as indicated in Fig. 5. All the livelihood zones (ABB, *Meher*, *Belg*, CHV, *Meher-Belg*, and SWS) except around the station of Amba Mariam exposed to more frequent drought risks ranged from 9 years (24%) to 12 years (33%) of the total observation years. The drought frequency of March found to be higher in the northern,

western and southern parts of the ABB, *Meher*, *Belg*, *Meher-Belg* livelihood zones that ranged from 6 years (15%) to 8 years (21%) of the total observation periods. Except for the areas around the stations of Kelala and Wereillu, which experienced the highest drought risks (8–9 years) in the south, the remaining livelihood zones' drought frequency during April varied from 6 years (15%) to 7 years (18%) of the total study periods. Similarly, the eastern part including ABB, *Meher-Belg*, SWS, *Meher*, CHV, and *Belg* livelihood zones and the western part of ABB, *Meher* experienced frequent drought risks ranged from 9 (24%) to 11 years (30%) of the total study years during May.

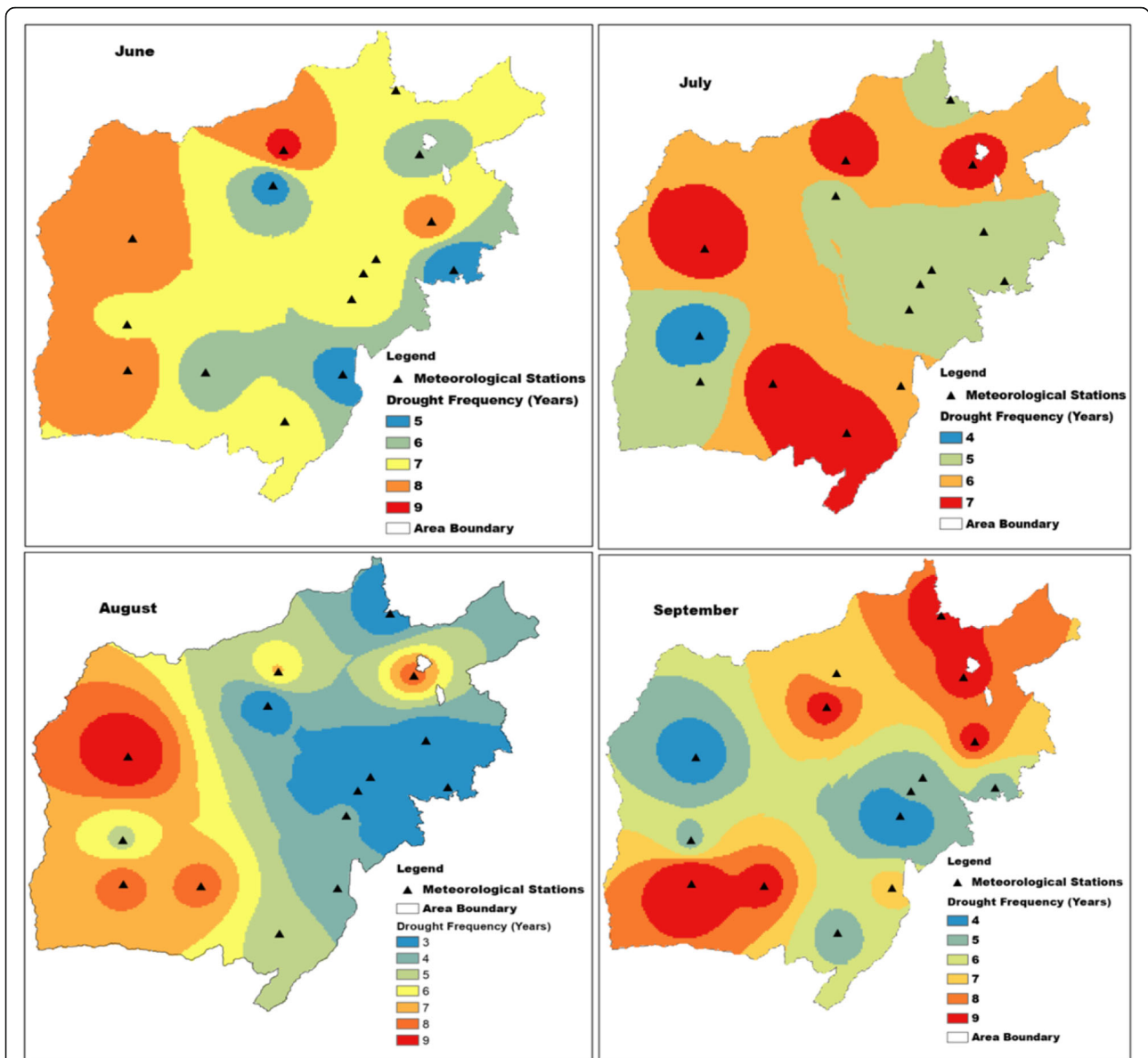
The spatial pattern of drought frequency maps in the big rainy months (June, July, August, and September) also revealed the complex and high local-scale variation as indicated in Fig. 6. It was found that all the livelihood zones except the eastern and southeastern periphery (ABB, *Belg* and CHV) experienced more frequent drought risks ranged from 7 years (18%) to 9 years (24%) of the observation periods during June. More frequent drought events ranged from 6 to 7 years, which accounts between 15 and 18% experienced during July in the northwest, southern and northern parts of *Meher*, ABB, *Meher-Belg*, SWS, and *Belg* livelihood zones. The incidences of drought frequency during August were found to be ranged from 3 years (6%) to 6 years (15%) in the



**Fig. 5** The 1-month timesteps spatial pattern of drought frequency events ( $SPI \leq -1.0$ ) for the small rainy months of February, March, April, and May

eastern half including all the livelihood zones while the western half, including ABB and *Meher* livelihood zones covered about 7 years (18%) and 9 years (24%) of the study period. During September, the incidence of drought frequency was found to be more pronounced in the northeastern and southwestern parts including ABB, *Meher*, *Belg*, and *Meher-Belg* livelihood zones that varied from 7 years (18%) to 9 years (24%). However, incidences of drought frequency varied between 4 years (9%) and 6 years (15%) in the northwestern, southern and southeastern parts including ABB, *Meher*, *Belg*, *Meher-Belg*, CHV, and SWS livelihood zones of the study area.

Figure 7 presents the spatial pattern of drought frequency maps for 4- and 8-months timesteps of *belg* and *kiremt*, and the long-term (both *belg* and *kiremt*). The SPI4-months of *belg* season the northern half, including *Belg*, *Meher-Belg*, CHV, and SWS livelihood zones (where *belg* crop harvesting dominate) experienced drought frequency events varied from 4 to 6 years (9–15%) while the southern half, including ABB and *Meher* livelihood zones experienced 7–9 years (18–24%) of drought frequency events of the total observation periods. Conversely, during SPI4-months of *kiremt* season, the southern half comprising part of ABB, *Meher*, *Belg*, and CHV livelihood zones (where *kiremt* season crop

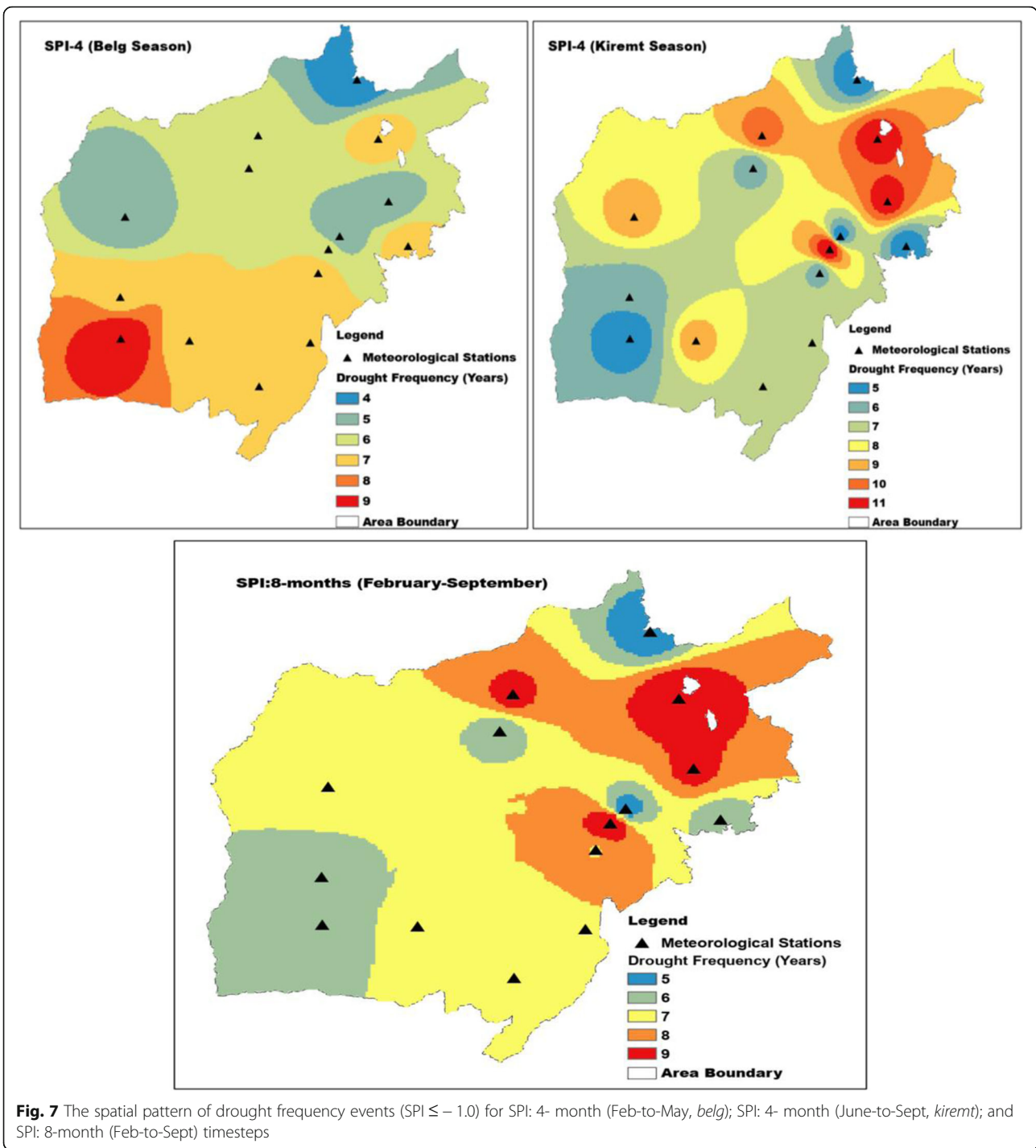


**Fig. 6** The 1-month timesteps spatial pattern of drought frequency events ( $SPI \leq -1.0$ ) for the big rainy months of June, July, August, and September

harvesting dominate) experienced 5–7 years (12–18%) drought frequency incidences while the northern covering parts of ABB, Meher, Belg, Meher-Belg, SWS, and CHV were experienced 8–11 years (21–30%) of drought frequency events of the total observation periods. The long-term spatial tendency of drought incidences (February-to-September) were also observed in SPI:8-months. Almost the eastern half except around the stations of Wuchalle and Kombolcha, experienced 8–9 years (21–24%) drought frequency incidences. The southern and western parts on the other hand experienced 5–7 years (12–18%) drought frequency occurrences of the total study periods.

### Discussion

The rainfed agricultural activities of the study area depend on two rainy seasons: *belg* and *kiremt*. However, the incidence of drought disaster due to the shortfall of rainfall was the most important concern of this study. In this study, the temporal and spatial spread of drought frequency, magnitude, intensity and severity have been examined. Of the total observation years, the highest drought frequency was detected for February. The study results indicated that March 2008 and April 1984 were the most severe drought months. However, the *belg* season in 1999 was the driest year during the record. In agreement with this, Conway (2000a, 2000b) and Viste



**Fig. 7** The spatial pattern of drought frequency events ( $SPI \leq -1.0$ ) for SPI: 4- month (Feb-to-May, *belg*); SPI: 4- month (June-to-Sept, *kiremt*); and SPI: 8-month (Feb-to-Sept) timesteps

et al. (2013) reported that the *belg* season in 1999 was the driest year during the record over Ethiopia. A general tendency of increasing drought risk frequency has been observed in the study period of *belg* rainy months and season. The MK test for *belg* rainy months and season (1-and 4-months) timesteps also verifies the general decline of rainfall. Lyon and DeWitt (2012) and Lyon (2014) also showed the decline of rainfall or increase

frequency of drought incidences for March-to-May months. The increasing of drought incidences in the 4-months *belg* season was detected due to a rainfall deficit in the rainy months of February-to-May. The relative abrupt decline was seen since 1996, which is concurrent to Funk et al. (2005) at the national level. Multiple study reports in agreement with this study revealed that the greatest continual decline of rainfall has occurred during

the *belg* season in the post-1980s (Tierney and Ummenhofer 2015; Funk et al. 2008; Funk et al. 2005). For example, in 1984, 72% of Ethiopia's regions were affected by drought in the *belg* season (Shanko and Camberlin 1998).

Likewise, the highest drought frequency was observed in June during the big rainy months. However, extremely severe droughts were detected in August 1984, July 1987 and 2015, and September 2009. Thus, 1984, 1987 and 2015 were the three driest years in the record. Drought risk frequency and magnitude were more pronounced during the months of *belg* as compared to *kiremt*. Nonetheless, the drought risk intensity was more weighted during the months of *kiremt*. In agreement of this, Viste et al. (2013), Segele and Lamb (2005) reported that the *kiremt* season of 1982, 1984 and 1987 was severely dry over Ethiopia, particularly in the northeastern half of the country, which primarily caused by the missing rain in July and August. Lyon (2014) also revealed that the *kiremt* season (June, July, and August) rainfall during 1982 and 1984 was below-average rainfall for prolonged drought events that lead to the most devastating impact for 1950–2010 in northern Ethiopia. Further, Jjemba et al. (2017) and Philip et al. (2017) reported that the worst drought of 2015–16 in the northern and central part of Ethiopia because of *belg* rains had failed and soon after, *kiremt* rains were severely delayed, erratic and below the long-term average (deficit of 167 mm). Segele and Lamb (2005) also revealed that the greatest damaging droughts in Ethiopia are connected with the failure of *kiremt* rains. Specifically, Suryabhadgavan (2017), testified that South Wollo as one of the highest peaks of drought recorded area in 1984. A general decreasing trend tendency of drought events has been observed during 1-, 4- and 8-months timesteps of *kiremt* season. The MK test also confirms increasing trend tendencies, but it was only statistically significant for June.

A cyclical oscillation of wetter and drier events has shown in 1-, 4- and 8-months timesteps. Wetter conditions were illustrated in the period of the 1990s. In contrast, increasing drought risk event frequencies were illustrated in the 1980s and 2000s (Fig. 3b-c) and (Fig. 4b-c). In corroboration of this, for the 1970s onwards, drought has occurred during *kiremt* season in 1982, 1984, 1897, 1990, 1991, 1995, 1997, and 2002 due to the deficit of rainfall in June, July, August, and September (Conway 2000a, 2000b; Korecha and Barnston 2007). The influence of rainfall deficit during the *kiremt* season affects a significant portion of the county. For instance, in 1984 about 53% of the regions of Ethiopia were affected by drought in the *kiremt* season (Shanko and Camberlin 1998).

The 8-month long-term time step (Feb-to-Sept) demonstrated the drought events for the 1980s and 2000–2015. The 1984 and 2015 were the foremost terrible

years on the record (Fig. 4c). Similarly, Funk et al. (2005) reported that 1984 stands the main horrible year on the record although the 1997, 2002 and 2004 undergone poor rainfall in the long-term (March-to-Sept), *belg* and *kiremt* seasons. March-to-Sept rainfall totals have also exhibited dry periods in the mid-1980s and mid-2000s. The drought risk events of months in the *belg* season were threefold greater than the months in *kiremt* season under moderate drought intensity class. Conversely, the drought risk events of months in *kiremt* season were threefold greater than that of the *belg* season under extreme drought intensity class.

In the 100-years, the predicted drought frequency events for 1-month timesteps were relatively more frequent than the 4- and 8-months seasonal timesteps except for August and September. In agreement with this, Łabędzki (2007) and Degefu and Bewket (2015) reported that drought events of shorter timesteps occur more frequently and last a shorter time than drought events of longer timesteps, which are more concentrated and last longer (changes slowly). However, Sternberg et al. (2011) reported contrasting results that frequency of drought events have been the lowest at 1-month timesteps and highest for the longer 17-months timestep.

The spatial distribution of drought frequencies was exhibited by the presence of complex patterns for 1-, 4-, and 8-months (Figs. 5, 6 and 7). The northern and (southern) half during 4-month *belg* and (*kiremt*) seasons experienced less frequent drought risk events. Conversely, the southern and (northern) half during 4-month *belg* and (*kiremt*) seasons experienced a higher frequency of drought events. Almost the eastern half except around the stations of Wuchalle and Kombolcha, experienced the most drought frequency events while the southern and western parts experienced less drought frequency occurrences during the long-term 8-month timestep. In this regard, *belg*, and long-term (in both *belg* and *kiremt*) seasons crop harvesting areas were more exposed to frequent drought risks. The 4-month of *kiremt* season drought frequency pattern influenced and manifested over the 8-months drought frequency spatial pattern.

#### Potential implications of drought incidences

The SPI values of the rainy months of 1-month as well as 4- and 8-months timesteps had an illustrious impact on the rainfall of the study periods that reflects the prompt occurrence of agricultural drought. In this regard, Łabędzki (2007) confirmed that the 1- to 6-months timesteps of SPI values soundly reflects well the quick development of agricultural drought, the exacerbating of the actual state of water conditions and the negative effects of rainfall deficit in agriculture (soil moisture, groundwater table depth, crop yield). The recurrent

incidence of droughts for 1-, 4-, and 8-months has important implications on the socio-economy of rainfed agricultural practices and productions for smallholder farmers. The incidences of drought owing to the short-fall of rainfall during the months of *belg* (Feb-to-April), *kiremt* (June-to-Sept) and long-term rain (Feb-to-Sept) seasons were influencing the agricultural production. The greatest drought risk incidence of months in the *belg* and (*kiremt*) seasons under moderate and (extreme) drought intensity classes highly impacted the agricultural practices. The influence of moderate and extreme drought risk expected to be via the timely deficit of rain at planting and critical stage of crop growing that finally exposed the society to shift to food aid. For example, the reports of Viste et al. (2013), Block (2008), Prasad and Staggenborg (2009), World Bank (2006a, 2006b) and United Nations Environment Program/UNEP (2011) revealed that from the 1970s onwards, the decline of rainfall amount and the increasing frequency of drought directly influenced water shortages and limited crop growth and development, and reduced yield. This further threatened millions of people in the country that demanded emergency humanitarian assistance. In relation to this, Webb et al. (1992), Von Braun (1991), and Webb and Von Braun (1990) also indicated that the primary effects of drought on crop production and yields were quite strong. For instance, a 10% decline in rainfall results in an average reduction in cereal yields of about 4.2%.

The deficit of February-to-May rainfall is also be threatening those slowly maturing long-cycle crop production like sorghum and maize in the long-cycle crop growing areas of the study planted during *belg* and harvested after *kiremt* seasons. Degefu (1987) and Funk et al. (2005) report that poor *belg* season rainfall performance not only affecting *belg* crops but also adversely impacting the long-season crop production such as sorghum and maize, the country's major food crops. The detected incidence of drought risks of 8-months (Feb-to-Sept) was also influencing the long-cycle crop production such as Sorghum, Maize, and Millet growing areas (*Meher-Belg* livelihood zones) owing to deficit of rainfall in *belg* and *kiremt* seasons. In this regard, Funk et al. (2012) revealed that insufficient amount of *belg* and *kiremt* rainfall likely have negative impacts on agricultural production of slowly maturing varieties of crops (Maize, Sorghum, and Millet) and food availability. Mahoo et al. (2013) also reported that recurrent drought, changes in the consistent crop planting and shift in crop types, as well as rainfall variability related with the amount, timing, and intensity, are impacting the agricultural practices leading to frequent crop failures, losses of life and property. This means that more frequent droughts, and drier climate in general, maybe producing repeated

shocks that increase vulnerability and then step up to a cycle of poverty (Funk et al. 2012). Mekonen and Berlie (2019) and McSweeney et al. (2008) also reported that the respective decreasing and increasing trends of rainfall and temperature were the potential threats to the agricultural sector through pest intensification.

## Conclusions

This study presented the spatiotemporal drought risk events in the northeastern highlands of Ethiopia using Standardized Precipitation Index, SPI. The results of the study confirm that highly complex and localized temporal and spatial patterns of drought risk events were detected. This helped to identify and characterize local droughts. The majority of 1–4- and 8-months timestep underwent severe and extreme ( $SPI \leq -1.50$ ) drought events. However, the detected frequency and magnitude of drought risk events were more pronounced during the rainy months of the *belg* season.

The 1-month *belg* and (*kiremt*) rainy months experienced the largest drought risk events under the moderate and (extreme) drought intensity classes. Moreover, the 4-month *belg* and (the 4- month *kiremt* and 8-month long-term) seasons experienced the largest drought risk events under the severe and (extreme) drought intensity classes. Increased drought risk frequency events were observed in the 1980s and 2000s onwards for *kiremt* and long-term seasons. A steady increased drought risk event frequency was detected since 1980s during *belg* season. In the spatial pattern of drought, the southern part during *belg*, the northern and eastern during *kiremt* and the eastern half during the long-term rainy seasons experienced more frequent drought risk events.

The observed temporal and spatial drought risk events indicate a potential threat to the rainfed agricultural practices that gradually jeopardized the smallholder farmers to food insecurity and socio-economic vulnerability. The findings of this study also could be a rudimentary stage to enhance drought risk management strategy through the appraisal of the rainfed agricultural practices in the study area. Therefore, the documentation and informed assessment of drought frequency, magnitude, intensity and severity based on the livelihood zones are essential for drought risk management, early warning responses, local-scale planning, and food security management. Finally, the study recommended further research on additional indices of climatic variables such as evapotranspiration and soil water content.

## Abbreviations

ANRSPC: Amhara National Regional State Plan Commission; CRED: Center for Research on the Epidemiology of Disaster; IPCC: Intergovernmental Panel on Climate Change; MK: Mann Kendal; NMSA: National Meteorological Service Agency; PDSI: Palmer Drought Severity Index; SPI: Standardized Precipitation Index; SWAD: South Wollo Agriculture Department; UNEP: United Nations

Environmental Program; WFP: World Food Program; WMO: World Meteorological Organization

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### Authors' contributions

The first author collects and analyzes the data, and wrote the manuscript. All authors read, edit and approved the manuscript.

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### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Competing interests

The authors declare that they have no competing interests.

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