Lemma et al. Environmental Systems Research (2022) 11:7
https://doi.org/10.1186/s40068-022-00251-x

Environmental Systems Research

RESEARCH

Open Access

Meteorological drought monitoring across the main river basins of Ethiopia using satellite rainfall product

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Abstract

Background: Drought is a recurrent phenomenon emerging from an inter-annual and intra-seasonal deficit of water across the atmosphere-to-aquifer continuum and these events are reported to be very severe in regions of Ethiopia. Availability of accurate precipitation observations significantly impacts the drought monitoring systems. These observations are scarce and sparsely distributed in countries like Ethiopia. To overcome such a problem, the use of satellite rainfall estimates with continuous and timely data at different spatio-temporal scales is opportune, provided their accuracy is well known. Among the currently available satellite rainfall products studies specifically in Ethiopia shown that Climate Hazard Group Infrared Precipitation with Station version 2 daily rainfall product (hereafter CHIRPSv2) has better performance and recommended as a valuable substitute for gauge rainfall data. Therefore, the current study focused on assessing the applicability of CHIRPSv2 for meteorological drought monitoring in Ethiopia. Due to the wide spatio-temporal variability of Ethiopia's climate, the performance of CHIRPSv2 rainfall product for meteorological drought monitoring has been assessed in selected river basins (Awash, Blue Nile, Baro, Danakil, Omo and Tekeze) of Ethiopia. For drought estimations, two well-known meteorological drought indices such as Effective Drought Index (EDI) and the Standardized Precipitation Index (SPI) have been utilized.

Result: The obtained results show that the CHIRPSv2 based EDI and SPI are able to identify all the historical drought events reported between 1982 and 2016 (such as 1984, 1992, 2003, 2009, 2011, 2012, and 2015). The time series plots of EDI and SPI values show that most of the drought events in the selected river basins occurred during their corresponding main and smaller rainy months. Detailed spatio-temporal investigations of the two worst drought years (1984 and 2011) and one drought-free year (2007) show that both the EDI and SPI could enable to identify the drought and drought-free areas correctly when compared with the available recorded historical droughts (RHD) across each river basin. Similarly, the temporal trends of EDI and SPI identified drought shows that frequency and severity of drought were higher during 1980s and 2000s than 1990s.

Conclusions: Such good agreement between the identified drought and historical drought indicates that CHIRPSv2 is a promising rainfall dataset, which could be used to develop drought monitoring and early warning system across different river basins of Ethiopia. Besides, the study helps to provide useful information for decision makers to implement different adaptation and mitigation measures of drought in the study area. The finding also will support to improve the existing drought monitoring and early warning system and to build resilience to drought at the river basin level.

Keywords: CHIRPSv2, Drought monitoring, EDI, Ethiopia, SPI, Satellite rainfall estimates, River basins

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Introduction

Drought is a recurrent phenomenon emerging from an inter-annual and intra-seasonal deficit of water across the atmosphere-to-aquifer continuum. In arid and semi-arid regions, however, its recurrence and effects are often more pronounced (Singh 2003). Among all-natural disasters, drought is a complex phenomenon that can cover a large geographic area and cause great damage (Masih et al. 2014; Suryabhagavan 2017). Definition of drought is region-specific, however, generally, it is defined using several variables such as physical, biological, and socio-economic characteristics (Zeleke et al. 2017; Wayne 1965). However, in all climatic regions' drought originates from a deficiency of precipitation over an extended period, usually a season or more (Zeleke et al. 2017; McKee et al. 1993). Due to erratic rainfall characteristics, drought has severely impacted East African countries (Bayissa et al. 2017) and in particular, Ethiopia records large scale droughts since the mid-1980s (Gidey et al. 2011).

As reported by Bayissa et al. (2015) over the past four decades many severe droughts have occurred in Ethiopia and due to that, over six million people suffered. Among these, the worst drought occurred from 1983 to 1985 with impacts throughout the country. Recently, similar severe drought events have occurred in most parts of Ethiopia in 2009, 2011 2012, 2014, and 2015 (Bayissa et al. 2015; Suryabhagavan 2017; EM-DAT 2017). About a century ago, the frequency of drought occurrence in the country was once every 10 years but, at present drought has become more frequent (occurring once every 2–3 years) (Gidey et al. 2011; Gizachew and Suryabhagavan 2014; Eshetie et al. 2016). Ethiopia being an agriculture-dependent country, these drought events have a substantial impact on the economy as well as on the livelihood of the majority of the agrarian community. Drought is commonly classified into several types: meteorological, agricultural, hydrological, and socioeconomic drought (Mishra and Singh 2010; Zhong et al. 2019). Among these, meteorological drought (simple absence/deficit of rainfall from the long-term average) is the first to occur whereas other droughts are its consequences (Lemma et al. 2017; Senamaw and Addisu 2021). Thus, the current study focuses on meteorological drought monitoring.

Precipitation is one of the primary variables for meteorological drought monitoring and is generally obtained from a ground network of rain gauges. However, the gauge networks are sparsely distributed across developing countries such as Ethiopia (Haile et al. 2013). As an alternate source, satellite, and re-analysis precipitation products provide near-global precipitation estimates at higher spatial and temporal resolution (Upadhyaya and Ramsankaran 2016). However, most of the satellite rainfall products are subjected to errors due to characteristics of remotely sensed datasets and underlying assumptions in retrieval algorithms. Therefore, evaluating the performance of each rainfall product before their use for meteorological drought monitoring is vital to have some level of guarantee (Diro et al. 2009; Maidment et al. 2014). Recently Lemma et al. (2019) evaluated several satellite and re-analysis precipitation products across Ethiopia. The authors compared five selected satellite rainfall estimates (ARC2, CMORPH, TAMSAT, TRMM and CHIRPSv2) and two reanalyses rainfall data (CFSR and ERA) with the ground based weather station rainfall data across the different rainfall regimes of Ethiopia which encompasses the six main river basins (Awash, Blue Nile, Baro, Danakil, Omo and Tekeze). The obtained evaluation results indicate that among the tested satellite and reanalysis rainfall products, the CHIRPSv2 rainfall product performs best across all rainfall regimes. Considering its best performance, a longer period of observations (starting from 1981 to present, > 35 years) and accuracy, Lemma et al. (2019) recommended Climate Hazard infrared precipitation station data (CHIRPSv2) for drought monitoring studies. CHIRPSv2 rainfall product was also evaluated at different parts of the world (for example; in Northeast Brazil (Paredes-Trejo et al. 2017), in West Africa, Burkina Faso (Dembélé and Zwart 2016), in China, Haihe River Basin and Mekong Basin (Gao et al. 2018; Hao et al. 2017), in Mozambique (Tote et al. 2015), in East Africa (Kimani et al. 2017) and other studies in Ethiopia (Funk et al. 2015; Dinku 2016; Bayissa et al. 2017; Ayehu et al. 2018). The overall findings of the mentioned studies indicate that CHIRPSv2 can be used as a valuable substitute for gauge rainfall data. Therefore, the overall objective of this study was to evaluate the potential of the CHIRPSv2 product for drought monitoring studies across the main river basins of Ethiopia.

To quantify, characterize and monitor drought events, various drought indices have been developed, however all of them have their specific strength and weakness (Mishra and Singh 2010; Dai 2011; Park and Kim 2014; Xu et al. 2015; Jain et al. 2015). Besides, describing the details of each index is not the main aim of this study. Some of these drought indices include; the Standardized precipitation index (SPI; McKee et al. 1993), Effective drought index (EDI; Byun and Wilhite 1999), Palmer drought severity index (PDSI; Wayne 1965), Modified perpendicular drought index (MPDI; Ghulam et al 2007), Rainfall anomaly index (RAI; van Rooy 1965), Deciles (Gibbs and Maher 1967), Crop moisture index (CMI; Palmer 1968), the soil moisture drought index (SMDI; Hollinger et al. 1993) and crop-specific drought index (CSDI; Meyer et al. 1993), and Surface water supply index (SWSI; Shafer et al. 1982). Among these various drought indices, EDI and SPI were chosen in this study. Here EDI was chosen due to its unique ability of considering the substantial amount of water resources generated by rainfall that occurred many months ago which may have already been lost due to outflow and evaporation than all of the existing drought indices (Byun and Wilhite 1999). EDI has already been tested across many regions of the world and uses precipitation as a single input, and also it is simple but effective to monitor meteorological droughts as compared to other complex indices (Byun and Wilhite 1999; Lweendo et al. 2017). Similarly, SPI was chosen because the World Meteorological Organization has recommended it as a standard index to be used throughout the world (Svoboda and Fuchs 2016). Moreover, it also requires only one input i.e. rainfall. Several previous studies conducted across different parts of Ethiopia have also reported that the SPI index can be reliably used for drought assessment. For example, Bayissa et al. (2015) at Upper Blue Nile, Suryabhagavan (2017) across different zones of Ethiopia, Viste et al. (2013) across entire Ethiopia, Gebrehiwot et al. (2011) at the northern highlands of Ethiopia, Edossa et al. (2010) at Awash River basin and Gidey et al. (2018) in Raya and its environs. Another main reason behind choosing two indices is to ascertain whether the deviation of the results w.r.t. observed/recorded drought events are due to rainfall data or due to the chosen drought indices, which otherwise may not be possible if we use only one drought index.

Considering all these facts, with a futuristic aim of developing a simple and effective national level drought monitoring system for Ethiopia using remotely sensed rainfall products, this study attempts to assess the potential of CHIRPSv2 daily satellite rainfall product using EDI and SPI indices by investigating historical droughts across the main river basins in Ethiopia.

Materials and methods

Description of the study area

Ethiopia lies in the north-eastern part of Africa between 3° N to 15° N and 33° E to 48° E. The complex topographical features of Ethiopia consist of rugged and high mountains, deep gorges with rolling plains, rivers and flat-topped plateaus. Elevation of the study area ranges from below sea level (− 152 m) in the northeast part of the country, particularly around Danakil depression, to 4600 m above sea level in the northern mountainous part of the country (Mount Ras Dashin). Ethiopia has 12 river basins; however, the major river basins are nine such as Awash, Blue Nile, Baro, Danakil basin, Genale, Omo, Rift valley, Shebelle, and Tekeze (Fig. 1) having different climate, topography, vegetation and rainfall distribution. According to the Ministry of Water Resources (MoWR) of Ethiopia, the total mean annual flow from all these river basins is estimated to be 122 billion m^3 (MoWR 1999). River flow and volume throughout Ethiopia is highly seasonal, with far-reaching implications for water accessibility, ecosystems, drought, and flooding.

Seasons, rainfall regimes and river basins of Ethiopia

Due to the spatio-temporal variability of rainfall in Ethiopia, rainfall periods are classified as main rainy season,

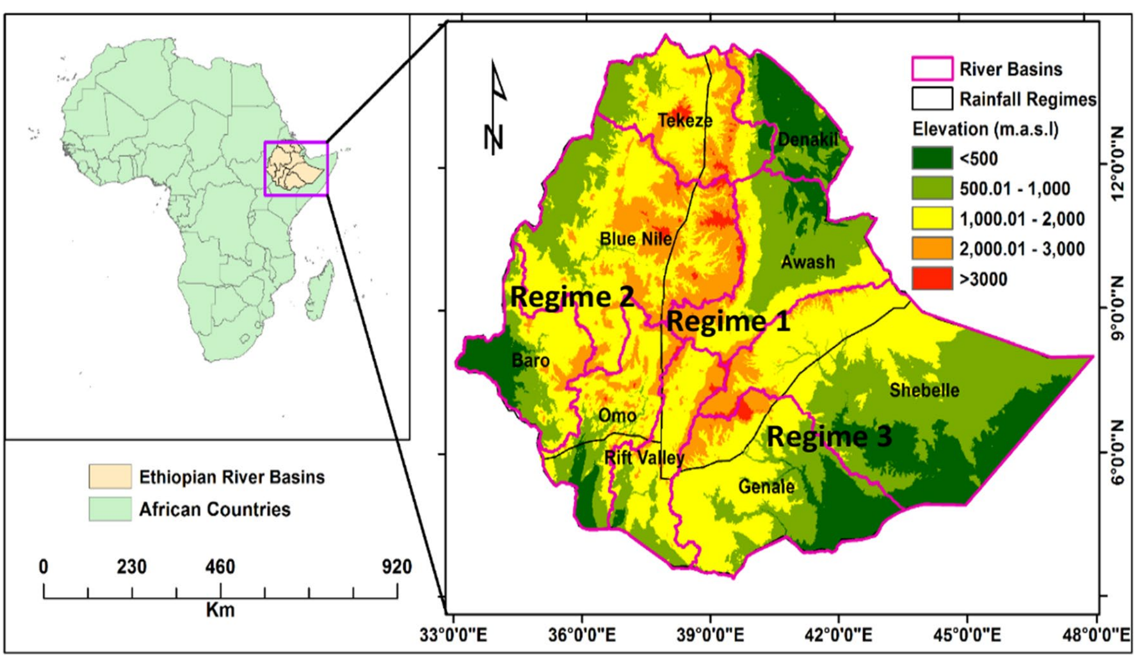

Fig.1 Location map of the study area showing African countries, Ethiopia and major river basins of Ethiopia

smaller rainy season, and dry season (Diro et al. 2009; Romilly and Gebremichael 2011). In general, the main rainy season covers from June to September. Whereas, smaller rainy season covers February to May and the third season is the dry season which covers from October to January. These three rainfall seasons are locally known as Kiremt, Belg and Bega respectively (Seleshi and Zanke 2004). The main rainy season contributes 50 to 80% of the total rainfall in Ethiopia (Gebere et al. 2015). However, the seasonal period varies across different rainfall regimes in Ethiopia. There are three major rainfall regimes identified by the National Meteorological Agency (NMA) of Ethiopia (NMA 1996). As shown in Fig. 1, Regime 1 encompasses the eastern and central parts of the country, and it has bimodal rainfall patterns (two rainy periods) (Lemma et al. 2017; 2019); February to May (Belg or smaller rainy season) and from June to September (Kiremt or main rainy season). Regime 2 is characterized by a long unimodal rainfall pattern from February to November (Lemma et al. 2017, 2019) and it encompasses the western parts of the country. Regime 3 comprises the southeast and southern parts of the country and characterized by two separate rainy periods (bimodal rainfall patterns) from October to November (Short or smaller rainfall periods) and from February to May (long rainfall period).

Within each rainfall regime, there is more than one river basin. Accordingly, this study considers only river basins such as Tekeze, Blue Nile, Awash, Danakil, Omo, and Baro river basins which fall under rainfall regimes 1 and 2 (Table 1). It shall be noted that June to September is the main rainfall season of rainfall regimes 1 and 2 river basins (Tekeze, Blue Nile, Awash, Danakil, Omo, and Baro).

Data used

Climate hazards group infrared precipitation with station data version 2 (CHIRPSv2)

CHIRPSv2 is a quasi-global (50° N to 50° S) precipitation product developed by the US Geological Survey (USGS) and the Climate Hazards Centre (CHC) at the University of California, Santa Barbara. It provides estimates at a spatial resolution of $0.05° \times 0.05°$ for more than 30 years i.e. from 1981–present with a latency period of 3 weeks (Funk et al. 2015). CHIRPS was specifically developed for climatological and drought monitoring applications in-particular to support the United States Agency for International Development Famine Early Warning Systems Network (FEWS NET) (Funk et al. 2015). Funk et al. (2015) highlight that CHIRPS fills the major gap for such applications by providing data for longer period and shorter latency. CHIRPS combine satellite only product (CHIRP) with climatology precipitation product (CHPclim) and station precipitation using a novel blending approach. Further details of the CHIRPSv2 rainfall product can be found in Funk et al (2015). In this study, we have obtained CHIRPSv2 daily rainfall product from http://chg.geog.ucsb.edu/data/chirps/ for the period 1981 to 2016.

Historical drought records

The historical drought information across Ethiopia for the present study is obtained from the Emergency Events Database (EM-DAT) at the Universite Catholique de Louvain, www.emdat.be. EM-DAT has a record of all types of natural disasters that occurred throughout the world. Various studies approved that several droughts have occurred across Ethiopia from 1983 to 2012 which is well-matched with the EM-DAT drought record (Suryabhagavan 2017; Lemma et al. 2017; Bayissa et al. 2017). The details of the historical drought events are given in Table 2. These historical drought records have been used for validation and inter-comparison purposes. It can be observed from Table 2 that the historical drought-affected regions are recorded at district, zonal, and state level, however, this study attempts at the river basin level. Therefore, for the sake of validation, the drought-affected regions are mapped with respect to the river basin they fall in as indicated in column 4 of Table 2.

Methodology

The general framework adopted for meteorological drought assessment using CHIRPSv2-based EDI and SPI drought indices across the main river basins of Ethiopia is shown in Fig. 2. In this study, the CHIRPSv2-based meteorological drought was assessed using monthly EDI and monthly SPI. Monthly scale drought assessment has been carried out to identify and indicate the onset and termination (cessation) of drought events. To provide a complete picture, temporal and spatial patterns of the identified drought events were analyzed for the entire study period (1982 to 2016). For validation, the recorded historical droughts (hereafter RHD) were used (Table 2). However, for a detailed analysis of the obtained results,

Table 1 Name of main river basins and rainfall regimes of the area

Name of river basin	Rainfall regime	Main rainy season	Smaller rainy season
Awash, Baro, Blue Nile, Danakil, Omo and Tekeze	Regimes 1 and 2	June to September	February to May

Table 2 Recorded Historical Droughts in Ethiopia (Source: EM-DAT: www.emdat.be 2017)

Starting month/year	Ending month/year	Drought-affected areas of Ethiopia	River basins	Total number of affected people
05/1983	12/1984	Wollo, Gondar, Gore, Tigray, Shoa, Harerge, Sidamo	All river basins	7,750,000
06/1987	12/1987	Ogaden, Eritrea, Tigray, Wello, Shewa, Gama, Gofa, Sidamo, Gondar, Bale	Danakil, Tekeze, Blue Nile, Awash, Rift valley, Genale, and Shebelle	7,000,000
10/1989	12/1992	Northern Ethiopia, Eritrea, Tigray, Wollo, Gondar, Harerge	Tekeze, Blue Nile, Awash, Danakil, Omo and Baro river basin	6,500,000
02/1997	12/1997	Borena, Bale (Oromiya state) South Omo zone, the Somali state	Rift valley, Genale, and Shebelle	N/A
09/1999	12/2000	Oromia, Amhara, Tigray Beneshangul Gumuz, Gambella, SNNPR, Somali provinces	All river basins	4,900,000
01/2003	12/2004	Tigray, Oromia, Amhara, Somali, Afar provinces	All river basins	12,600,000
11/2005	12/2006	Afder, Liben districts (Somali province), Gode zones (Shabelle district, Somali province), Borena district (Oromiya province)	Rift valley, Genale, and Shebelle	N/A
05/2008	12/2008	Oromia, Somali, Amhara, Afar, Tigray, SNNPR provinces	Rift valley, Genale, and Shebelle	6,400,000
01/2009	12/2009	Afar, part of Amhara, part of SNNP, Gambela provinces, Oromia, Somali and Tigray	Tekeze, Blue Nile, Awash, Danakil, Omo, Genale and Shebele	6,200,000
01/2010	10/2010	Afar, part of Tigray, part of Amhara, part of SNNP, Gambela provinces and part of Oromia	Tekeze, Blue Nile, Awash, Danakil,and Omo river basin	N/A
01/2011	12/2011	Somali, Oromia, Afar, Tigray, Amhara provinces	All river basins	4,805,679
01/2012	01/2012	Somali, Oromia, Afar, Tigray, Amhara provinces	All river basins	1,000,000
09/2015	01/2016	Somali, Afar provinces	Rift valley, Genale, and Shebelle	10,200,000

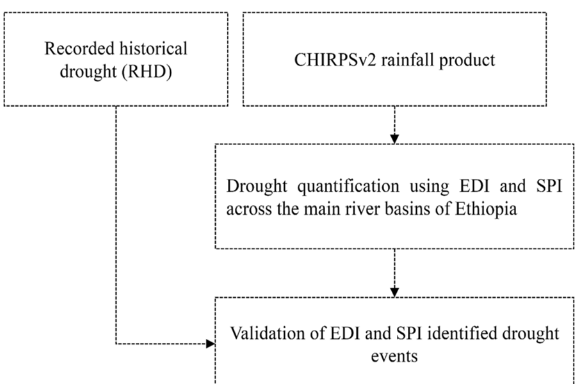

Fig. 2 The general framework adopted for meteorological drought assessment using CHIRPSv2 based EDI and SPI indices across the main river basins of Ethiopia

the results of the main and smaller rainfall seasons of two RHD years (1984 and 2011) and one non-drought year (2007) were selected. The 1984 and 2011 drought years were chosen because they are among the worst drought years in Ethiopia where many people were affected and it swept almost all regions of the country including those that were drought-free in the past (EM-DAT 2017). Whereas, the reason for considering non-drought (2007) year is to check whether CHIRPSv2-based EDI and SPI produce false positive or not. The historical drought maps were developed using licensed ArcGIS 10.1 software and Matlab software from the tabular data of the EM-DAT emergency events database (EM-DAT 2017).

It shall be noted that an inter-comparison of EDI and SPI performance is not the aim of this study. Rather, the interest (as mentioned in Introduction section) is to check the performance of CHIRPSv2 daily rainfall product for meteorological drought monitoring at the river basin level.

Effective Drought Index (EDI)

EDI has been selected for its unique ability to consider the substantial amount of water resources generated by rainfall that occurred many months ago which may have already been lost due to outflow and evaporation (Byun and Wilhite 1999). It was developed by Byun and Wilhite (1999) with a new concept of effective precipitation (EP). EP is the accumulation of the parts of precipitation of certain days before estimation time, which affects the available water resources at the estimation time (e.g., rainfall of 3 days prior to the present day can affect soil moisture of present-day). It is calculated by summing precipitation over time, considering the loss of rainfall due to runoff or evaporation over time (Byun and Wilhite

1999). To compute the severity and duration of drought events for each river basin in Ethiopia and considering the fact that the impact of drought at daily time scale is minimal, the monthly time scale EP has been used in this study.

The steps involved in the calculation of EDI are as follows: (i) Calculate the monthly EP. (ii) Calculate the 30-year mean EP (MEP) for each month. (iii) Calculate the deviations from the mean (DEP), which is the difference between the EP and MEP. (iv) Divide the DEP for each month by the standard deviation of DEP over the past 30 years. Thus, the first step in the calculation of EDI is to calculate EP. If P_i is rainfall 'm−1' months before the current month and N is the duration of the preceding period, then effective precipitation for the current month (EP_j) is given as;

$$\boldsymbol{EP_j} = \sum_{m=1}^{N}\left[\left(\sum_{i=1}^{m}\boldsymbol{P_i}\right)/\boldsymbol{m}\right] \tag{1}$$

For example, if N = 3 then EP = $P_1 + (P_1 + P_2)/2 + (P_1 + P_2 + P_3)/3$, where P_1, P_2, and P_3 are rainfall during the current month, previous month and 2 months before respectively. In the present study, the duration of the preceding period "N" was 12 (the rainfall value of the last 12 months is considered). Secondly, the average and standard deviation of EP values for each month were calculated and then the EP value of each month is converted to DEP as follows:

$$\boldsymbol{DEPj} = \boldsymbol{EP_j} - \overline{\boldsymbol{EP_j}(\mathbf{MEP})} \tag{2}$$

Where, DEPj is deviations of EP "j" month at a particular year from the long-term mean EP ($\overline{\boldsymbol{EP_j}}$). When DEP is represented by a negative number it signifies that the "j" month at that specific year is drier than the average, and while DEP is represented by a positive number it signifies that the "j" month at that specific year is wetter than the average. Finally, the EDI can be calculated as,

$$\mathbf{EDI} = \mathbf{DEP}/\mathbf{SD}(\mathbf{DEP}) \tag{3}$$

Where; SD is the standard deviation of DEP. As suggested by Byun and Wilhite (1999) the obtained monthly EDI values are then categorized into different drought severity categories which are similar to the SPI drought severity category shown in Table 3.

Standardized Precipitation Index (SPI)

To increase the confidence level of CHIRPSv2 rainfall product applicability for drought monitoring, SPI was also utilized. SPI can be calculated using monthly timescale at several time intervals (normally 1–48 months) by accumulating precipitation records before the standardized procedure, to represent short and long-term drought events (McKee et al. 1993). For example, the SPI with a time interval of one month (the so-called SPI-1) represents monthly drought, while the SPI at four-month' time interval (SPI-4) represents seasonal drought events. Accordingly, one, two, and four-monthly SPI values were computed for the period between 1982 and 2016 for each grid and then averaged at each river basin to represent the temporal pattern of drought.

Table 3 SPI and EDI based category of drought severity (Source: McKee et al. 1993)

SPI and EDI values	Category of drought severity
1.5 and above	Wet
0 < = 1.49	Normal
0 to − 0.99	Mild drought
− 1.0 to − 1.49	Moderate drought
− 1.5 to − 1.99	Severe drought
− 2 and less	Extreme drought

SPI index requires long-term precipitation records (> 30 years) and was computed based on the monthly precipitation totals. Most often the gamma distribution functions are found to fit the precipitation data well because the distribution of rainfall totals is not normally distributed (McKee et al. 1993). Hence, SPI was calculated by fitting a gamma distribution function to a given frequency distribution of precipitation totals for a given time at a particular station. Then it was transformed into a standard normal distribution with mean zero and variance of one, which is the value of SPI. As indicated in Table 3, the SPI values are categorized as mild, moderate, severe, and extreme drought. A detailed description of the SPI calculation can be found in McKee et al. (1993).

Results and discussion

The following sections discuss the temporal, spatial patterns and trends of drought identified across the main river basins of Ethiopia using CHIRPSv2-based EDI and SPI drought indices.

EDI-based drought assessment

EDI-based temporal pattern of drought

Time series plots of basin-wise average monthly EDI for the six river basins for the period 1982 to 2016 indicate that CHIRPS-based EDI can capture the droughts efficiently. This finding holds true for both, the smaller as well as the main rainfall season, in each river basin. For example,1984, 1985, 1986, 1994, 1995, 2002, 2009, 2011,2012, and 2015 were some of the RHD years in the country (Table 2). A Temporal drought analysis shows that CHIRPS-based EDI is able to correctly detect the RHD with different severity levels either during the main rainfall season, smaller rainfall season, or in both seasons. Moreover, the study highlights the importance of doing river basin wise analysis as the severity of drought varies from one basin to other basins at a particular year. On the other hand, EDI correctly identifies the year 2007 as a non-drought year in all the study river basins (Figs. 3 and 4), which is in agreement with the RHD information. This finding also agree with the finding of Mohammed et al. (2018) and Mekonen et al. (2020) who found that North eastern parts of Ethiopia are drought prone areas of the country. To have more insight into the performance, a detailed analysis of two historically worst drought years such as 1984 and 2011 and one non-drought year of 2007 (highlighted in Figs. 3 and 4) across the six river basins is reported in the following sections.

In 1984, the EDI shows negative values (EDI < 0) during both smaller rainfall season (Fig. 3a–d) and main rainfall seasons (Fig. 4a–d), indicating there was drought in 1984. The 1984 drought has occurred due to the deficit of rainfall during both rainfall seasons. However, the severity level of drought varies temporally across each river basin. On the other hand, during 2011 the EDI show negative values (EDI < 0) during smaller rainfall season (Fig. 3a–d) and positive values (EDI > 0) during the main rainfall season (Fig. 4a–d). This implies that the 2011 drought has occurred only due to the deficit of rainfall during smaller rainfall season. Previous studies at different parts of the mentioned river basins also reported similar findings during 1984 and 2011 (Gidey et al. 2011; Suryabhagavan 2017; Bayissa et al. 2017). In both the RHD years of 1984 and 2011, specifically during the main rainfall season, the EDI values indicate moderate to severe drought at Awash, Danakil, and Tekeze river basins. This is understandable because these river basins are usually drought-prone areas (rainfall deficit areas) of the country and previous studies also categorized them as drought-prone areas of the country (Gidey et al. 2011; Bayissa et al. 2017). In addition, the 1984 drought has started in February 1984 and ended in April 1985. However, the 2011 drought has started in February 2011 and ended in May of the same year 2011.

In 2007, during the main rainfall season (Fig. 3a–d) except for Danakil (shows mild drought during June) as well as during the smaller rainfall season (Fig. 4a–d) except for Awash and Danakil (show mild drought from

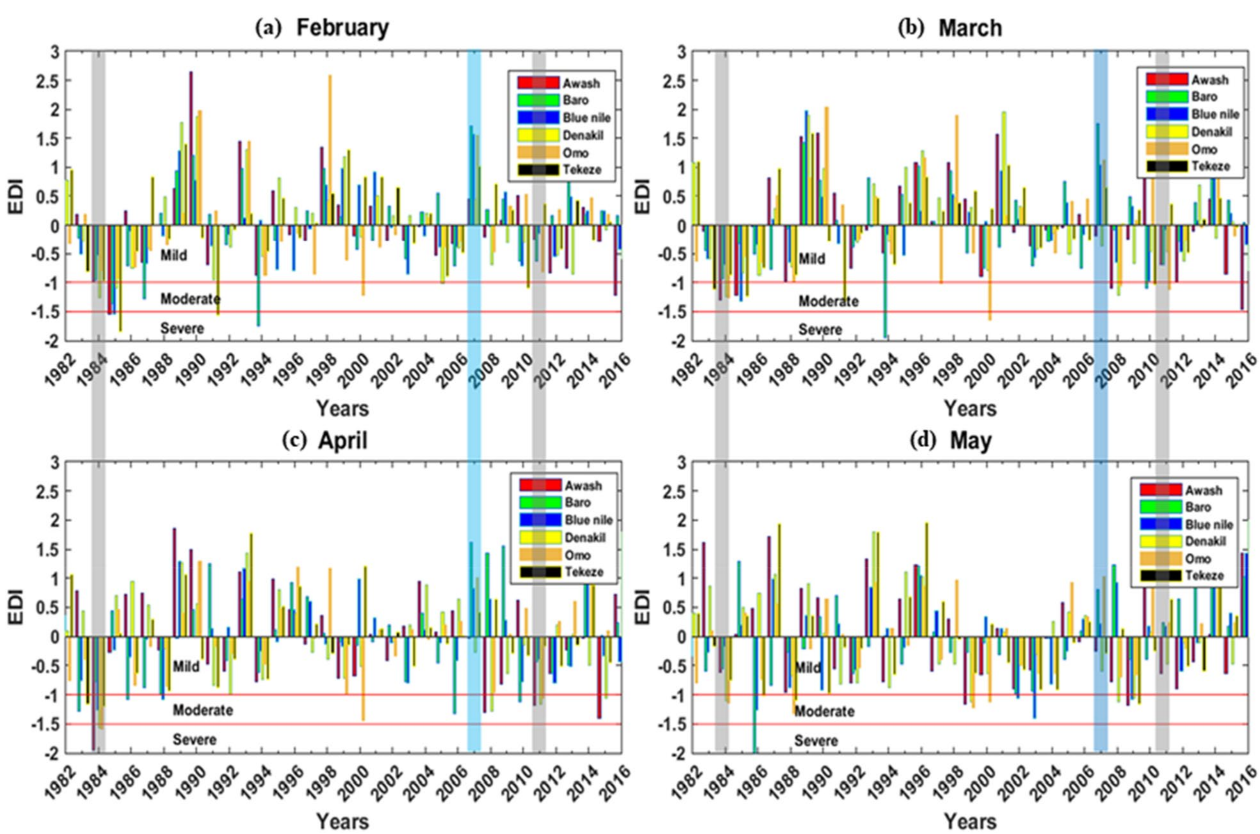

Fig. 3 Time series plots of basin-wide EDI values during smaller rainfall months (**a**–**d**) between 1982 and 2016

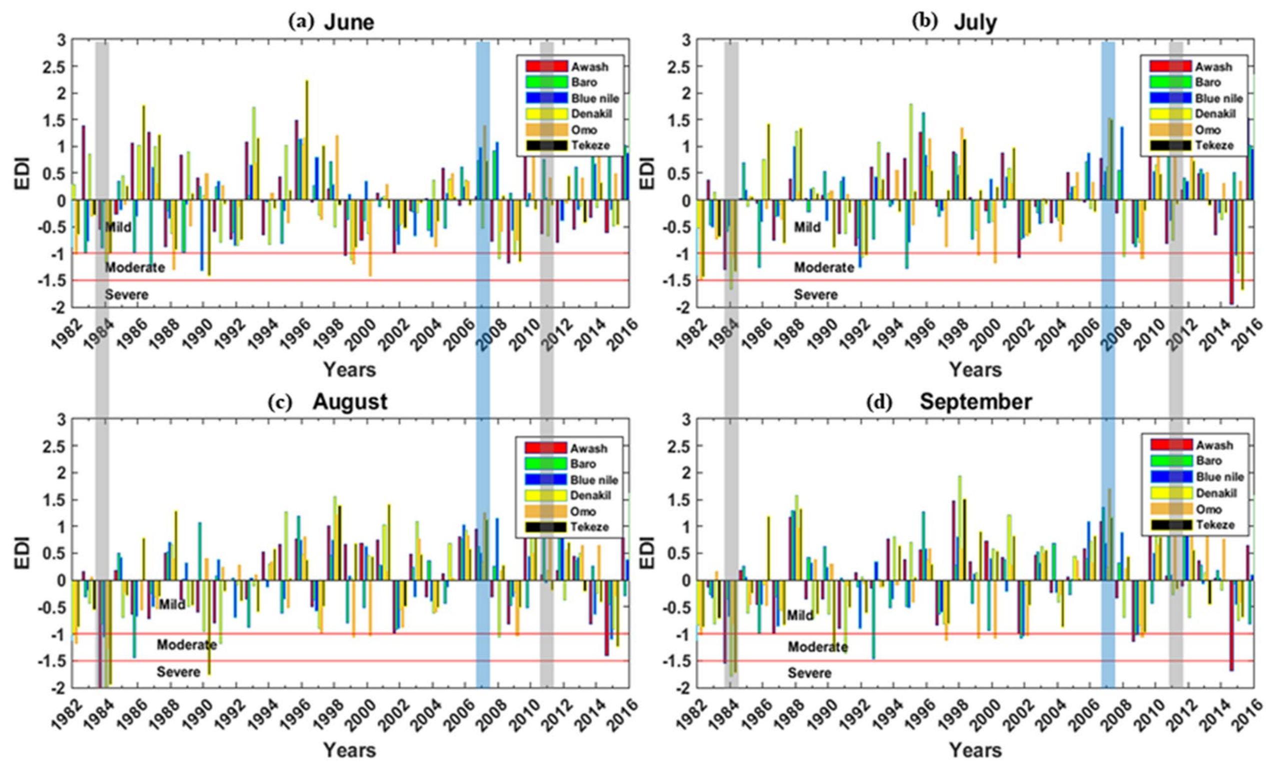

Fig. 4 Time series plots of basin-wide EDI values during main rainfall months (**a**–**d**) between 1982 and 2016

March to May), the EDI shows positive values (EDI > 0), indicating there was no drought.

EDI-based spatial pattern of drought

The temporal drought analysis represents only the average situations at each river basin; however, there is large variability within a basin. Therefore, representing the drought severity in grid-wise would be significant to study the spatial extents of drought severity. The obtained results (not shown here) for the early twenty-first century i.e. from 2000 to 2016 indicated that EDI detected correctly the spatial extent of the recorded historical droughts. However, for illustration purpose a detailed spatial assessment has been done only for the two historically worst drought years of 1984 and 2011 as well as one non-drought year of 2007 was reported hereunder.

Figure 5a and b show the maps of the RHDs in the six river basins during 1984 and 2011 respectively. All the selected river basins (except in the southwestern part of Baro, the northern part of Omo and southern tips of Awash and Blue Nile) were affected by the 1984 drought (Fig. 5a). Similarly, during 2011 (Fig. 5b) all the selected river basins (except Omo, Baro, and some portions of Blue Nile river basins) were affected by drought. The spatial maps of RHD for each study year across the selected river basins were also developed from the available RHD information (Table 2). This variability within the river basin also confirm that climate variability and associated extreme weather events are the possible cause for the occurrence of drought in different parts of each river basin.

Figures 6 and 7 show the EDI identified spatial pattern of drought in the selected river basins during smaller and main rainy months respectively. During smaller rainy months of 1984, Awash, Danakil, and Tekeze river basins were affected by moderate to severe droughts (Fig. 6a). During the same year, the Blue Nile river basin is partially affected by moderate drought severity. Likewise, during the smaller rainy months of 2011, mild to severe drought was observed in all the selected river basins except in Tekeze and Blue Nile river basins.

Similarly, during the main rainfall months of years, 1984 (Fig. 7a) and 2011 (Fig. 7b) EDI shows varied drought severity classes. In 1984, the major portion of the Blue Nile river basin, Baro and Omo basins show no drought (Fig. 7a). Likewise, in 2011, a major portion of the Blue Nile basin, and the Tekeze river basin show no drought (Fig. 7b). On the other hand, a major portion of the Awash and Danakil river basins show severe drought during the main rainfall months of 1984 and 2011. These results confirm that the 1984 drought has occurred due to the deficit of rainfall during both smaller and main

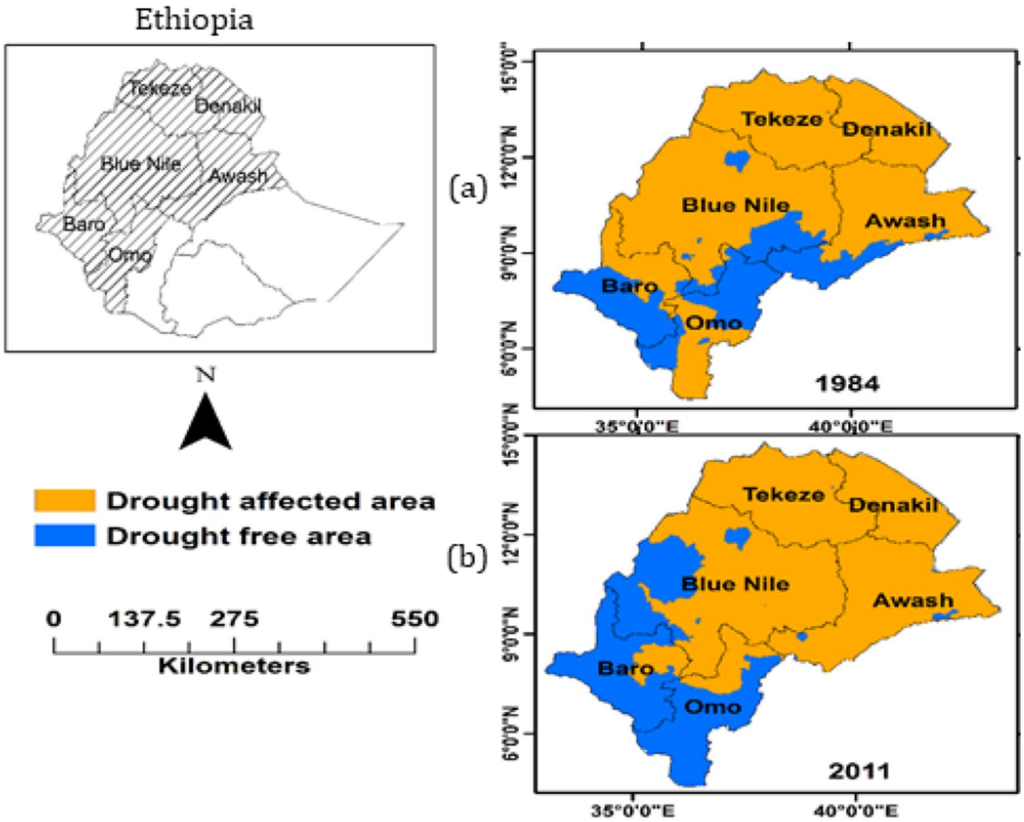

Fig. 5 Spatial pattern of the RHD in the selected river basins during (**a**) 1984 and (**b**) 2011. (Data source: www.emdat.be, developed from Table 2)

rainfall seasons, whereas in 2011 drought has occurred only due to the deficit of rainfall during smaller rainfall season. This finding coincides with the findings of previous studies at different parts of the mentioned river basins during 1984 and 2011 (Gidey et al. 2011; Suryabhagavan 2017; Bayissa et al. 2017). Besides, the spatial pattern of EDI identified drought during both smaller and main rainfall months of 1984 matches with the RHD maps of the selected river basins (Fig. 5a). Whereas in 2011, the spatial pattern of EDI identified drought matches with its corresponding RHD maps (Fig. 5b) only during smaller rainfall months. It indicates there is a discrepancy between the yearly RHD maps (Fig. 5b) and the monthly EDI identified drought patterns during the main rainfall seasons of 2011 (Fig. 7b). It is observed that in these two drought years, the drought severity is higher at Awash, Danakil, and Tekeze river basins. This is plausible because these river basins are usually drought-prone areas of the country and previous studies also identified as a drought-prone area of the country (Gidey et al. 2011; Viste et al. 2013; Bayissa et al. 2017; Suryabhagavan 2017).

On the other hand, as represented in Figs. 6c and 7c, during smaller and main rainfall months, the 2007 drought-free year is well captured by EDI except in some pocket areas (which shows only a mild drought) of the selected river basins. Hence, it can be concluded that CHIRPSv2 based EDI clearly identified both drought and non-drought years in the selected river basins.

SPI-based drought assessment

Temporal pattern of SPI identified drought

Here the seasonal SPI at two and four monthly intervals have been used to capture the drought events. This is because, at shorter time intervals (monthly SPI), the SPI values tend to fluctuate frequently above and below the zero-line depending on the monthly rainfall fluctuation (Ionita et al. 2016; Trenberth et al. 2014; McKee et al. 1993). Hence, the main and smaller rainfall months of the selected river basins drought was calculated using four months' time interval SPI (further referred to as SPI-4). Therefore, here only seasonal SPI (SPI-4) based temporal drought assessment results were reported. Also, the discussions are restricted to the two reported worst historical drought years of 1984 and 2011 as well as one non-drought year (2007) (highlighted in the figures) in the selected river basins. Figure 8a and b show the seasonal time series plots of SPI values in selected river

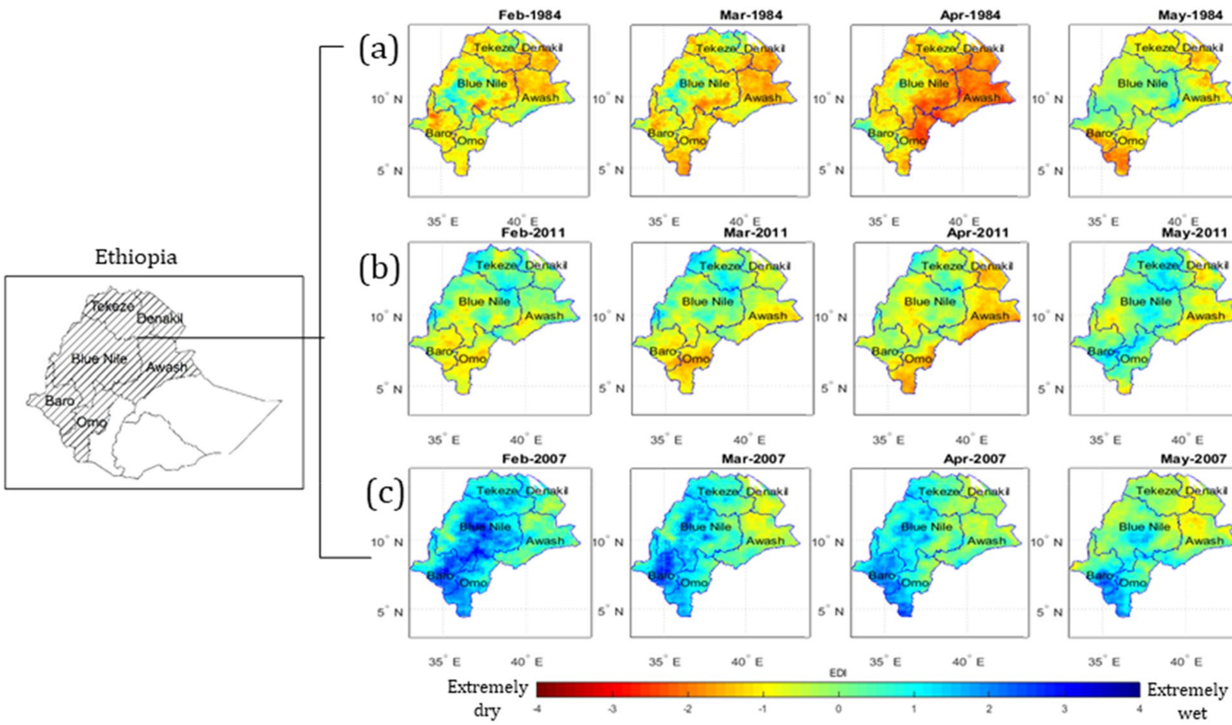

Fig. 6 Spatial pattern of monthly EDI values in selected river basins during smaller rainfall months in (**a**) 1984 drought year (**b**) 2011 drought year and (**c**) 2007 non-drought year

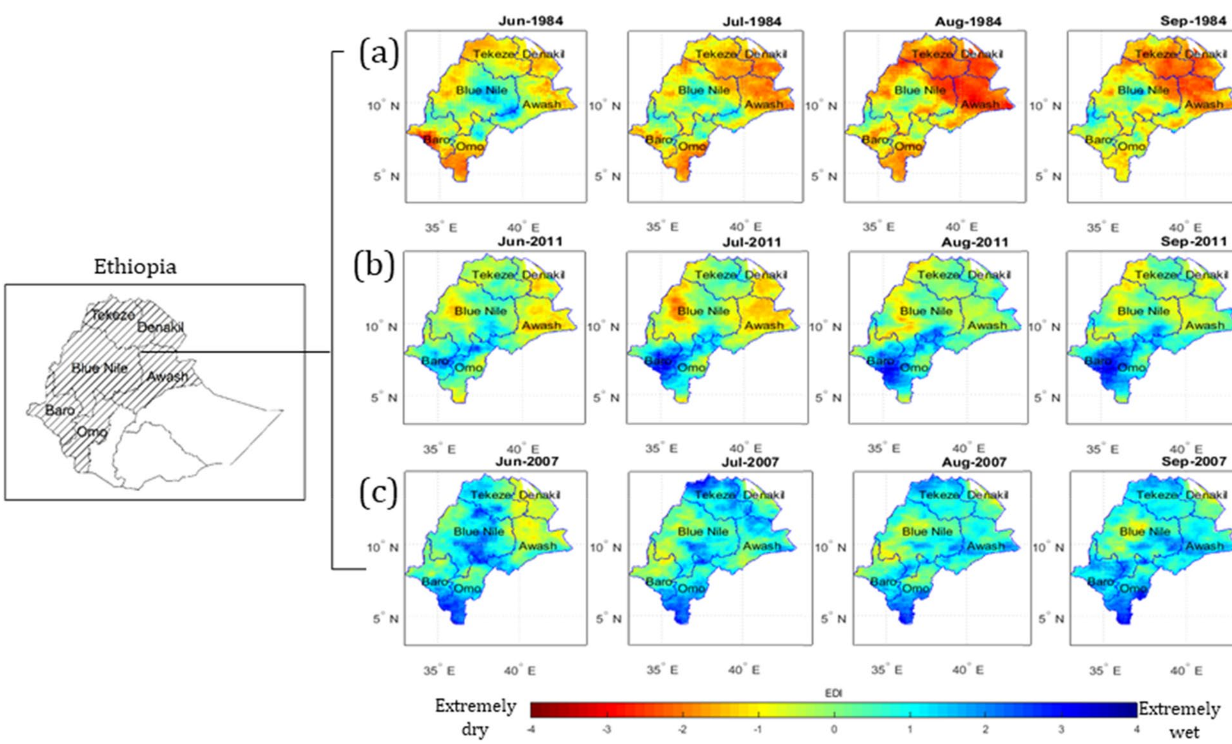

Fig. 7 Spatial pattern of the monthly EDI values in the selected river basins during main rainfall months in (**a**) 1984 drought year (**b**) 2011 drought year and (**c**) 2007 non-drought year

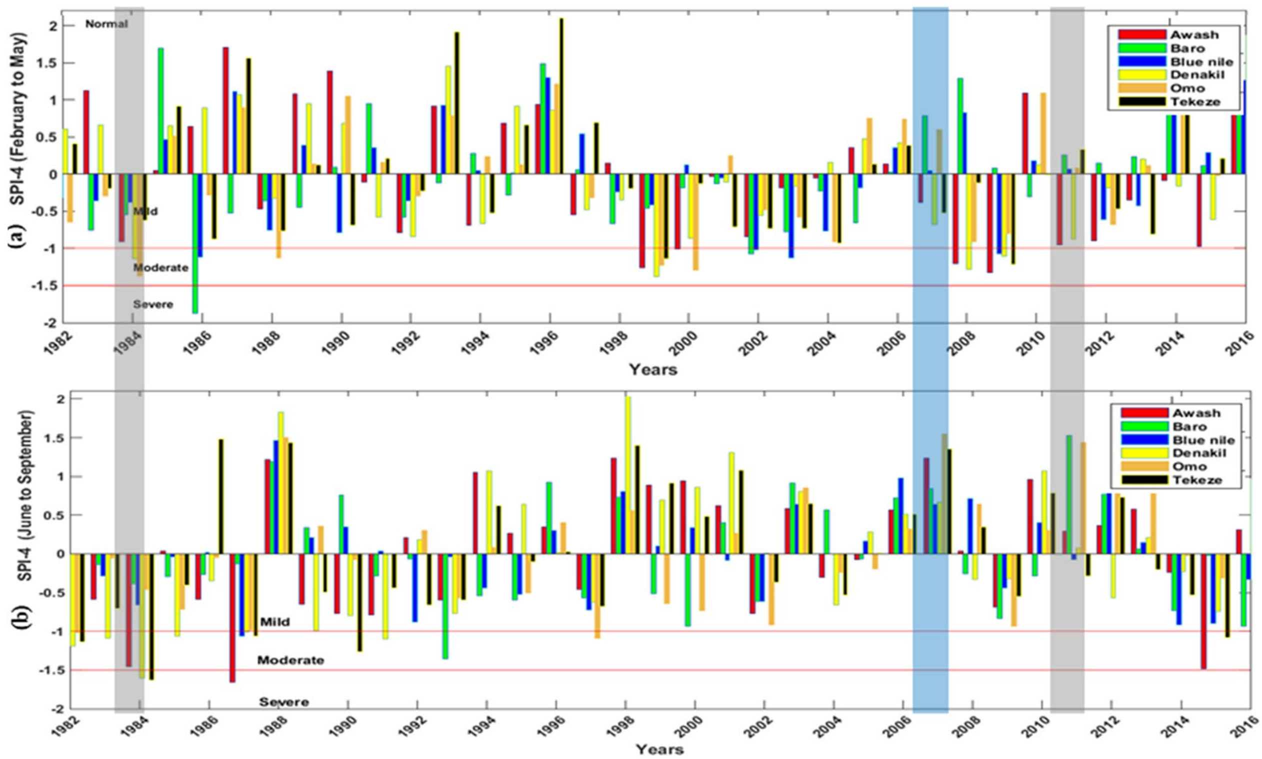

Fig. 8 Time series plot of basin-wide SPI values between 1982 and 2016 during (**a**) smaller rainfall season and (**b**) main rainfall season

basins during smaller and main rainfall seasons respectively. In 1984, during smaller rainfall season (Fig. 8a) and the main rainfall season (Fig. 8b), SPI was able to correctly detect the RHDs as reported in Table 2.

However, in 2011 during the smaller rainy season (Fig. 8a) except in Awash and Danakil river basins and during the main rainfall season (Fig. 8b) except in the Tekeze river basin drought was not captured by SPI. Whereas, in 2007 during both smaller and main rainfall season SPI showed no drought. Overall, the obtained results indicate that the temporal pattern of SPI identified droughts during smaller and main rainy seasons of 1984, 2007, and 2011 agrees with the temporal pattern of EDI identified droughts of the same years. In addition, this study agreed with the findings of Mekonen et al. (2020) that stated drought tends to be more frequent and more severe in main rainfall season in north east highland of Ethiopia.

Spatial pattern of SPI identified drought

Figure 9a–f show that SPI identified spatial pattern of drought in the selected river basins during smaller and main rainfall seasons of 1984 and 2011 as well as for 2007 drought-free year. Mild to extremely severe drought was observed by SPI at Awash, Danakil, and Tekeze during the smaller rainy season (Fig. 9a) and main rainfall seasons (Fig. 9b) of 1984. Whereas in 2011 mild to severe drought was observed in most of the regions of the selected river basins during the smaller rainy season (Fig. 9c). These results are clearly in line with RHD maps (Fig. 5a–b) and correlate well with the EDI identified drought patterns in the selected river basins (Figs. 6 and 7).

Likewise, as shown in Fig. 9e and f, the year 2007 was identified as drought-free year except in some pocket areas (such as Awash, Danakil, and Tekeze) which shows mild drought, particularly during the smaller rainfall season (Fig. 9e). Similar to CHIRPSv2 based EDI, CHIRPSv2 based SPI clearly identified both drought and non-drought years in the selected river basins.

Temporal trends of EDI and SPI identified drought

In this section the temporal trends of the detected droughts across each river basin using both EDI and SPI were described. Figure 10a–f illustrates the time series/trend of EDI and SPI-4 across the main river basins of Ethiopia for the period 1981 to 2016. As indicated on the trend plot the two drought indices (SPI and EDI) show a positive association and both of them detected most of the RHDs such as 82, 84, 88, 91, 92, 94, 2003, 2005, 2008, 2010, 2011, 2012, 2013, 2014 and 2015, however with

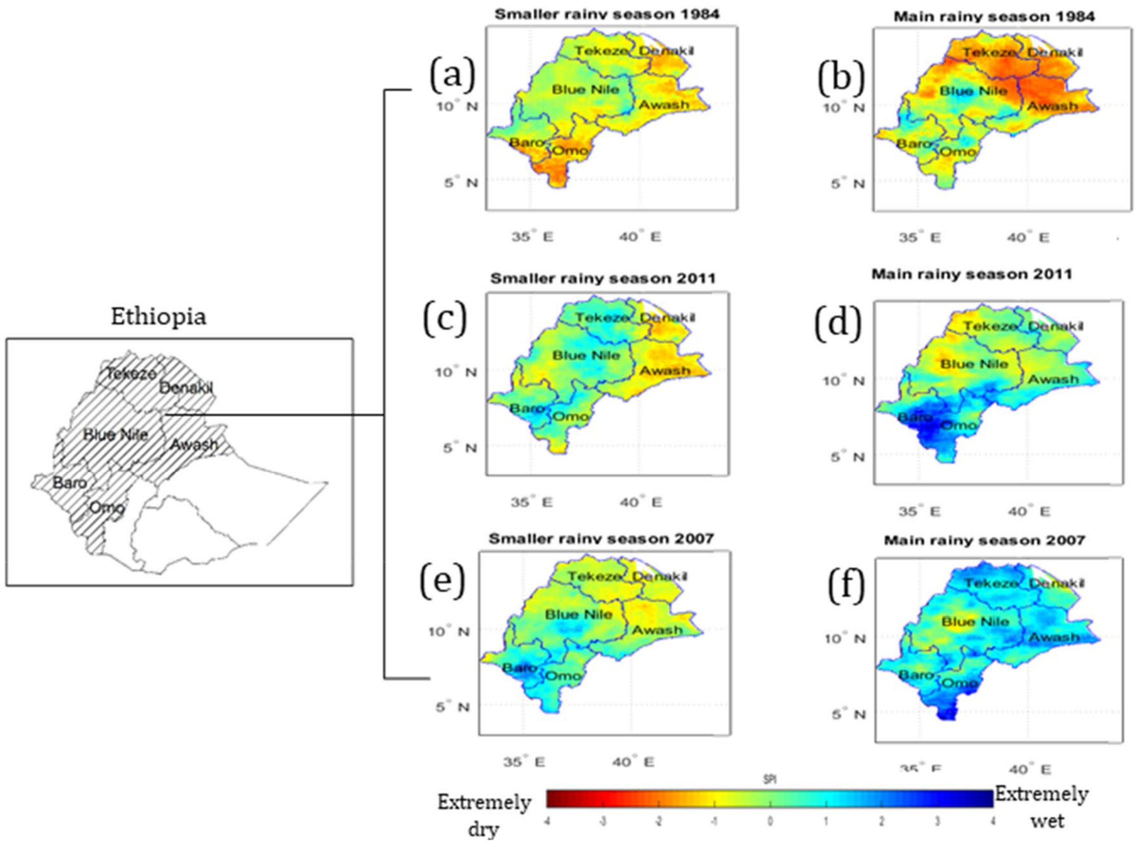

Fig. 9 Spatial pattern of seasonal SPI values in the selected river basins in 1984 and 2011 drought years and 2007 (drought-free year) during the smaller rainy season (**a**, **c** and **e**) and main rainy season (**b**, **d** and **f**)

different severity level, while in the other years positive EDI and SPI values were observed which indicate non-drought years. As seen in Fig. 10a–f, the frequency and severity of drought were higher during the 1980th and 2000th, while during the 1990th it seems less frequent and severe. Studies by Senamaw and Addisu (2021) also confirm that the drought will increase at an alarming rate due to climate change for the future in North eastern part of the country.

In almost all river basins both indices detected maximum severity during 1984/85, 1991/92, 2003, 2013 and 2014. Indeed, these years were among the worst drought years in the history of Ethiopia (Bayissa et al. 2015; Edossa et al. 2010; Yisehak et al. 2021). Many studies also show that severe drought have been occurred in these years and caused substantial damage in terms of life and economic losses (Edossa et al. 2010; Gebrehiwot et al. 2011; Bayissa et al. 2015; Yisehak et al. 2021). However, among the mentioned river basins Denakil, Awash and Tekeze were frequently strikes by meteorological drought. The current study coincides with Gidey et al. (2018) on the increasing frequencies and persistence of drought. Their findings stated that drought frequencies, durations, and severity are higher in the lowland area than in the mid and highlands during the last 15 years. Besides, this result also coincides with the work of Lemma et al. (2017) across rainfall regime 1 and 2 of Ethiopia.

Conclusions

This study presents an assessment of the potential of CHIRPSv2 satellite rainfall product for meteorological drought monitoring across the selected river basins of Ethiopia (Awash, Blue Nile, Baro, Danakil, Omo and Tekeze) using two drought indices i.e. EDI and SPI. The recorded historical droughts (RHDs) collected from EM-DAT for the periods starting from 1982 to 2016 are used as reference data. Accordingly, the CHIRPSv2 based monthly EDI and seasonal SPI (SPI-4) identified droughts were compared with the RHDs. The monthly and seasonal time series patterns of drought, particularly during main and smaller rainy months show that most of the RHDs such as 1984, 1992, 2003, 2009, 2011, 2012, and 2015 are generally detected by both drought indices. Both the temporal and spatial analysis shows

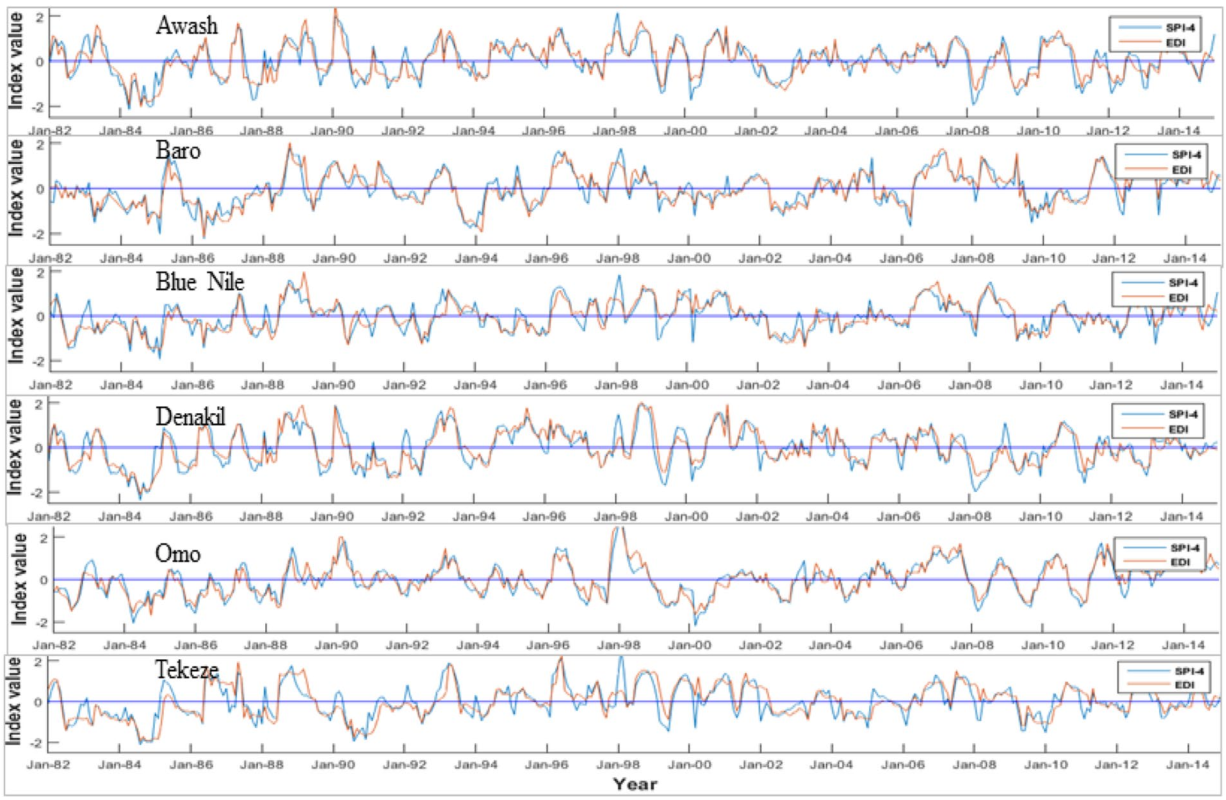

Fig. 10 Temporal trends of monthly EDI and SPI-4 identified drought across the main river basins of Ethiopia **a**) Awash **b**) Baro **c**) Blue Nile **d**) Denakil **e**) Omo **f**) Tekeze

that CHIRPSv2 rainfall product-based monthly EDI and seasonal SPI detected the RHD years, however, with different severity levels (mild, moderate, and severe) at each river basin. Considering the results of time series based comparisons, it can be said that the EDI vs SPI-4 are the most preferred drought indices for the main river basins.

The grid-wise spatial analysis of drought in each river basin highlights the importance of this study because it captures the spatial variations and identifies patterns of drought within a river basin. Besides, the monthly temporal drought pattern analysis also indicates the starting and cessation of drought occurrences across each river basin. The results show that both monthly EDI and seasonal SPI identified that some of the basins such as Awash, Tekeze, and Danakil river basins are frequently drought-affected areas of the country. These results are also in the agreement with few previous studies, where they stated that the most frequently drought-affected parts of Ethiopia are the southern, southeastern, and northeastern parts of the country. In general, the good agreement of CHIRPSv2 based monthly EDI and seasonal SPI identified drought with the RHD indicates that CHIRPSv2 could be a promising dataset for drought monitoring across different river basins of Ethiopia. Therefore, the CHIRPSv2 rainfall product could be a worthwhile solution to identify drought occurrences and to develop high-resolution drought monitoring and early warning system across the river basins of Ethiopia. Besides, the study helps to provide useful information for decision makers to implement different adaptation and mitigation measures of drought across the main river basins. The finding also will support to improve the existing drought monitoring and early warning system and to build resilience to drought at the river basin level. Further study also needed to find the cause and impacts of drought at smaller catchment levels.

Abbreviations

PDSI: Palmer Drought Severity Index; MPDI: Modified Perpendicular Drought Index; RAI: Rainfall Anomaly Index; CMI: Crop Moisture Index; SMDI: Soil Moisture Drought Index; CSDI: Crop-Specific Drought Index; SWSI: Surface Water Supply Index; MoWR: Ministry of Water Resources; FEWS NET: Famine Early Warning Systems Network; EDI: Effective Drought Index; SPI: Standardized Precipitation Index; CHIRPSv2: Climate Hazard Group Infrared Precipitation with Station version 2; RHDs: Recorded historical droughts; EM-DAT: Emergency Events Database; DEP: Deviation effective precipitation; EP: Effective precipitation; MEP: Mean effective precipitation; USGS: United States Geological Survey;

CHC: Climate Hazards Centre; CHPclim: Climatology precipitation product; NMAE: National Meteorological Agency of Ethiopia.

Acknowledgements
Estifanos Lemma acknowledges the financial support provided by the Ethiopian Ministry of Education to carry out this research. All the authors thank the National Meteorological Agency of Ethiopia for providing us monthly rainfall data free of charge. We also acknowledge the developers of Climate Hazard Group Infrared Precipitation with Station version 2 (CHIRPSv2) rainfall product for providing us the datasets free of charge. We thank the Emergency Events Database—Universite Catholique de Louvain (UCL)—CRED, D. Guha-Sapir for giving us the historical drought information.

Authors' contributions
EL was responsible for all activities of the research process such as the method selection, data compilation, entry, data analysis, and interpretation of the results as well as writing up of the manuscript. SU and RR were also involved in improving the quality of the manuscript by providing constructive guidance, critical comments and suggestions on the data analysis, interpretation and manuscript writings. All authors read and approved the final manuscript.

Funding
The study was financially supported by Ethiopian Ministry of Education.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors read the manuscript and agreed to publication.

Competing interests
The authors declare that they have no conflict of interests.

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Received: 30 December 2021 Accepted: 18 March 2022
Published online: 30 March 2022

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