scientific reports

OPEN

Integrated assessment of meteorological, hydrological and agricultural drought in Abaya Chamo sub Basin, Ethiopia

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The Abaya Chamo sub basin is susceptible to drought of moderate to severe intensity, which significantly impacts the sub basin's agricultural production and local community life. We investigate drought characteristics in the Abaya Chamo sub basin using data from 1981 to 2021 and a variety of drought indices, including the Standardized Precipitation Evapotranspiration Index (SPEI) to identify meteorological drought, the Standardized Stream flow Index to assess hydrological drought, and the Standardized Soil Moisture Index (SSMI) to evaluate agricultural drought. The results indicate that all indices captured historical drought episodes, with only minor variations. Additionally, the findings show that the proportion of dry months exceeded that of rainy months between 1981 and 2021, showing that aridity increased during this period. We also identify drought trends that vary by watershed and by drought type. This study reveals that the sub basin experienced the maximum drought intensity, as computed using the SPEI, SSI, and SSMI, with index values of -2.5, -2.8, and − 2.4, respectively. The Gelana catchment experienced the most severe drought, while the Bilate catchment faced less severe drought. Overall, the study indicates severe to moderate drought of substantial magnitude that varied across the sub basin. These findings will guide drought planning and management in the Abaya Chamo sub basin and raise stakeholders' awareness of how precipitation, runoff, and soil moisture can be used to describe drought. Consequently, the study suggests that stakeholders and policymakers implement early warning systems and adaptive measures for water resource management, and develop comprehensive drought risk management plans to improve regional food security.

Keywords Meteorological drought, Hydrological drought, Agricultural drought, Drought indices, Abaya chamo sub basin

Hydroclimatic extremes, such as droughts and floods, are projected to increase in frequency and intensity as a consequence of global warming, with their cumulative impacts potentially presenting significant risks to both human and natural systems[1]. Numerous such extreme events have already been documented worldwide, and it is anticipated that their frequency, duration, and intensity will increase in response to ongoing climate change[2,3].

Developing countries are highly vulnerable and have less capability to cope with the impact of hydroclimatic extremes than developed ones. That is mainly true in the continent of Africa where the sub-Saharan countries are highly vulnerable[4]. Agriculture is the main source of income for millions of people in Africa. An average of 65% of the labor force in the continent depends on farming and 32% of gross domestic product is earned from agricultural products[5]. Specifically, Ethiopia is prone to severe and frequent drought events[6–8] where its main economy, agriculture, is highly affected, resulting in loss of life and property. Studies have shown that droughts in Ethiopia are becoming more frequent and severe, affecting food security and leading to complex socio-economic problems[9–11]. These studies indicate high spatiotemporal characteristics of drought, necessitating detail region wise evaluation of different types of drought.

The southern part of Ethiopia, where the Abaya Chamo sub basin is located, has been impacted by exacerbated hydroclimatic extremes such as very intense precipitation and prolonged drought. These events have severe impacts on different socioeconomic sectors, such as agriculture, water resources, health, ecosystem services, and

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urban infrastructure[12,13]. In southern Ethiopia, approximately 90% of the population relies heavily on agriculture for their sustenance, livelihood, cash income, and as a source of raw materials for various industrial needs[11,14]. The Abaya Chamo sub-basin is marked by considerable variability in both temperature and rainfall, which influences the accessibility of water resources. This variability poses serious challenges, especially in light of the region's rapid population increase, excessive water extraction, and problems like silt buildup and sedimentation in lakes, leading to various forms of environmental decline[15]. A study by[16] found that drought is common and severe in the region. Another study also evaluated drought events in the Abaya Chamo sub basin using data from 1988 to 2015 and found that moderate to severe droughts affected more than half of the sub basin's region in 1990–1991, 1994, 1997, 1999–2000, 2002, 2004, 2008, 2011–2012, and 2015.

According to[17] the sub basin experiences droughts every three years due to the Indian Ocean Dipole (IOD), La Niña or El Niño episodes. Another study in Southern Ethiopia found that moderate to severe drought conditions occurred often between the months of March to June and September to November. Among other years, the driest years were 1984, 1985, 1992, 1999, 2000, 2001, and 2011[18].

Similarly[19], revealed that the majority of meteorological stations experienced moderate to severe droughts in often received years (e.g., 1999, 2000, 2002, 2005, 2009, and 2010), meaning that the research region experienced severe drought. Besides, they stated that the SPI-3 averaged 17 severe, and 4 extreme drought events, while the SPI-12 averaged 15 severe, and 3 extreme drought events. Further, the study reported that Ethiopia's historic drought years were 2000–2001, 2009–2010, 2014–2015, and 2021–2022.

The drought investigation revealed that the southern region has experienced mild to severe droughts in the past, which is consistent with the region's meteorological drought assessment across time. The SPI-3 indicated the occurrence of moderate-to-severe and moderate-to-extreme drought cases in the early twenty-first century, whereas the SPI-12 indicated an overall increase in the occurrence of severe drought across the study area, with an observed intensity of 1.54 and a cumulative frequency of 64 months during the study period. More than half of the meteorological stations examined demonstrated the severity of notable drought years, such as 2015–2016, 2009–2010, and 1999–2000[19].

Furthermore, a recent study by[20], on drought susceptibility in a watershed within the Abaya Chamo area discovered that a spatial coverage of 23.16% and 70.23% of the watershed is susceptible to severe and moderate drought, respectively. This revealed that 93.39% of the watershed is vulnerable to droughts, potentially jeopardizing the local community's livelihood.

A number of studies have been conducted on drought characterization at national level[6,7,10,21] and regional level[11,22,23]. These studies mainly focus on meteorological drought and large areas, which makes getting tailored information difficult. Besides, the studies mainly use a single drought index, which makes its reliability difficult for risk assessment and decision making, as drought is a complex phenomenon influenced by various climatic and hydrological factors[24].

Using multiple drought indices allows for a more comprehensive assessment by integrating various indicators of drought severity, duration, and impact. This multidimensional approach enhances the accuracy and reliability of drought assessments, ensuring that local variability in climate and hydrological conditions is captured. Utilizing multiple indices helps to elucidate drought, allowing researchers to analyze correlations between meteorological conditions and their impacts on hydrological and agricultural resources over time. In this study, we get emphasis on specific sub basin and comprehensive analysis of different droughts in the Abaya Chamo sub basin using multiple drought indices.

Materials and methods

Study area description

The Abaya Chamo sub-basin, located in the Rift Valley Lakes Basin (RVLB), consists of two connected lakes, Lake Abaya and Lake Chamo, with several major rivers draining into Lake Abaya and smaller streams flowing into Lake Chamo. As illustrated in Fig. 1, the region is located between 37°E-38°E longitudes and 5°–8° N latitude, with elevations ranging from 1090 m to 3439 m above mean sea level (amsl)[25]. The sub basin's formation is linked to volcanic activity, which resulted in a fault-bounded valley surrounded by volcanic mountains and hills. The transition from continental to oceanic rifting has resulted in seismic and volcanic activity in this area. Its climate ranges from semi-arid to humid and temperate, with an annual average rainfall of 665 to 1240 mm[26]. The basin has bimodal rainfall patterns and high spatiotemporal variability in rainfall and temperature, which affects water resources and agricultural productions. Rapid population growth, industrial development, urban expansion, water abstraction, and environmental degradation all have an impact on regional water availability and distribution[17].

To generate the study area map, we used ArcGIS Pro (online) version 3.5, which is managed by Arba Minch University and has the subscription ID 9,971,089,858: https://www.arcgis.com/index.html. We generated the study are map in ArcGIS by sequentially adding the Africa, RVLB, and Abaya Chamo sub-basin shapefiles as separate layers. Distinct fill colors highlight the Abaya Chamo sub-basin to emphasize the study region, with labels for key attributes. The map includes a scale bar, a north arrow, and a legend.

Data

To analyze drought characteristics, we collected monthly rainfall, maximum temperature, and minimum temperature data from 32 meteorological stations for the period 1981–2021, provided by the Ethiopian Meteorology Institute (EMI). Stream flow data from ten gauging stations for 1990–2020 were obtained from the Ministry of Water and Energy (MoWE). The locations of meteorological stations are shown in Fig. 1, while the stream flow gauging stations are described in Table 1 and illustrated in Fig. 2, respectively.

To display the location of stream flow gauging stations on a map, point data were plotted atop a base map using ArcGIS Pro online version 3.5. The geographical coordinates (latitude and longitude) for each stream

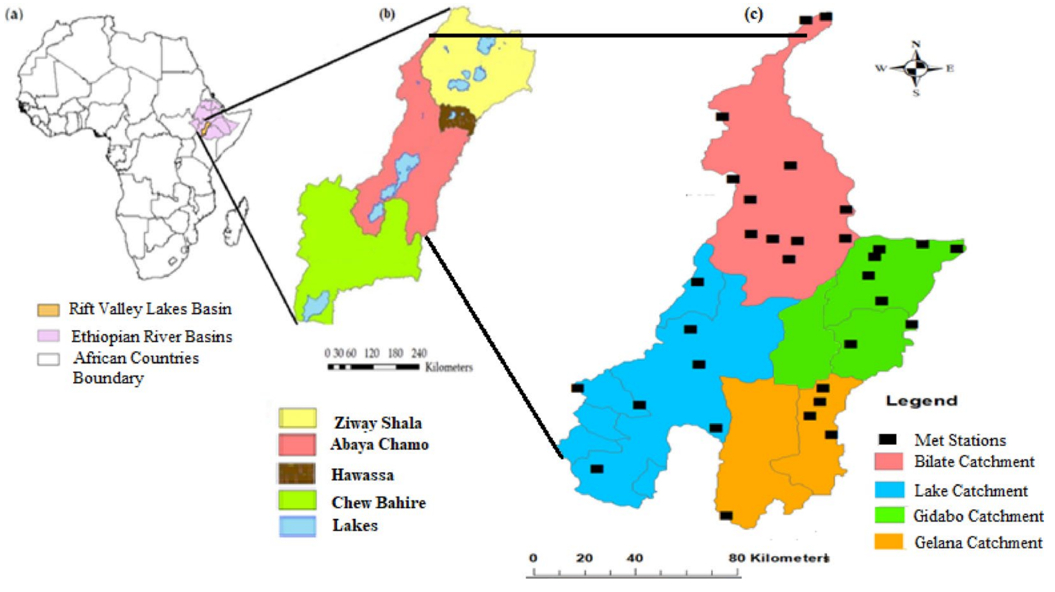

Fig. 1. Study area map: (**a**) Africa (**b**) RVLB (**c**) Abaya Chamo sub basin.

No	Station name	Latitude	Longitude	Alt. (m)	Area (km^2)	Minimum discharge (m^3s^{-1})	Maximum discharge (m^3s^{-1})	Annual mean discharge (m^3s^{-1})
1	Forty-spring	6.00	37.5	1201	37	0.00	0.33	0.20
2	Bilate	6.95	38.1	1361	1980	0.00	167.5	22.10
3	Gato_Gidole	5.68	37.4	2087	148	0.00	210.4	0.44
4	Gelana	6.15	38.2	1617	1123	0.07	18.0	4.59
5	Gidabo	6.75	38.3	1762	646	0.00	92.5	6.00
6	Hamessa	6.57	37.8	1618	19	0.00	23.6	0.91
7	Kulfo_Sikela	6.01	37.3	1203	364	0.00	169.4	10.60
8	Sala (Dilla)	6.39	38.2	1515	67.5	0.04	44.61	3.72
9	Lake Abaya	6.42	37.8	1200	1162	0.00	4.82	1.54
10	Lake Chamo	5.83	37.5	1200	317	0.00	11.31	2.19

Table 1. Basic information of the ten hydrological gauge stations in Abaya Chamo sub basin.

flow gauging station were obtained in CSV (Comma Separated Values) format. These coordinates were then converted to a point layer in ArcGIS. Ashapefile of Abaya Chamo sub-basin was added to provide geographic context. Station symbols were designed to be clear and visible, and each station was labelled with its gauging station name. Finally, a river network layer was included to illustrate the stations' proximity to streams.

In addition, the study retrieves monthly soil moisture data for the Abaya Chamo sub-basin at a spatial resolution of 0.10 degrees for the period 1981–2021 from NASA GES DISC website (https://earlywarning.usgs.gov/fews/ewx_lite/index.html).

Before using the data for drought analysis, we examined for both higher and lower outliers based on the skewness coefficient and corrected them using the sub basin's historical average data[27]. Furthermore, the study examined data consistency using the double-mass curve approach, and a homogeneity analysis was performed to identify changes in the statistical properties of the time series data using the standard normal homogeneity (SNH). The missing data was filled out using the Inverse Distance Weighting (IDW) Method, where the weights for each sample are inversely proportional to their distance from the point being estimated[28,29].

Methods

Several indices have been developed to describe different types of droughts. Based on data availability in the study area and their reported robustness, we employ the three most commonly used drought indices: the Standardized Precipitation Evapotranspiration Index (SPEI)[30], Standardized Stream flow Index (SSI)[31], and Standardized Soil Moisture Index (SSMI)[32,33]. A time series of observed rainfall, temperature, stream flow, and soil moisture data is used to calculate drought indices.

A drought event is defined as a time in which the SPEI, SSI, or SSMI values are consistently negative and less than the – 1.0 criterion for more than two consecutive months. It stops when the indices' values turn positive[34,35]. More negative numbers represent more severe situations. The results of each measure can be used to describe

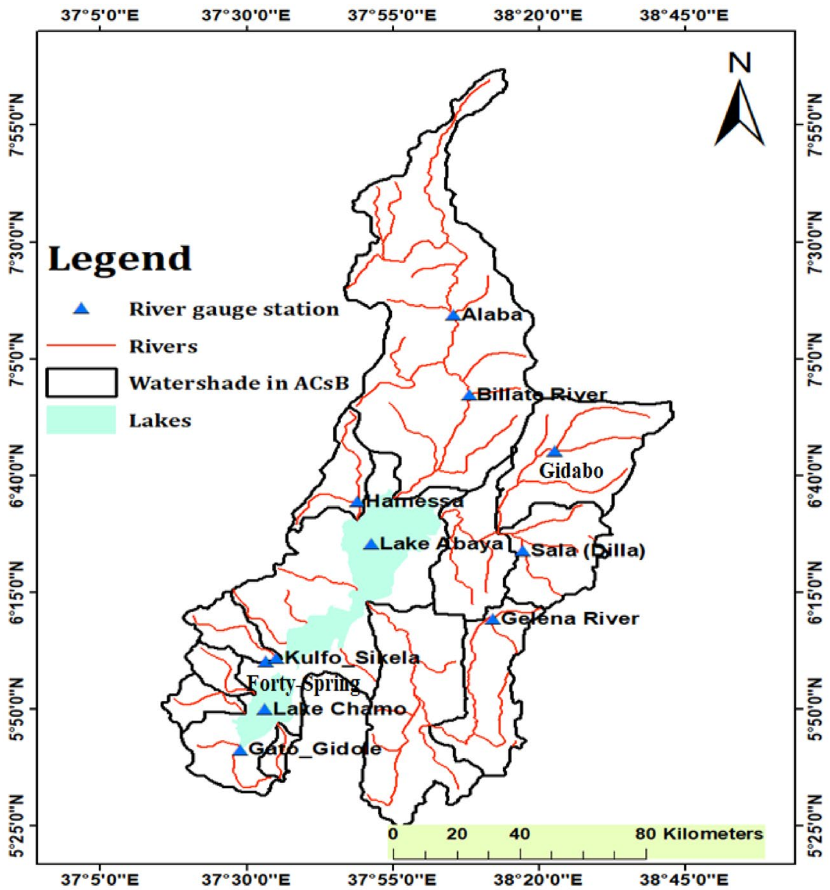

Fig. 2. Location of stream flow gauging stations in the Abaya Chamo sub basin.

Criteria	Drought description
SPEI/SSI/SSMI ≥ 2.0	Extreme wet
2.0 ≥ SPEI/SSI/SSMI ≥ 1.5	Very wet
1.5 ≥ SPEI/SSI/SSMI ≥ 1.0	Moderate wet
−1 ≥ SPEI/SSI/SSMI ≤ 1.0	Normal
−1.5 < SPEI/SSI/SSMI ≤ −1.0	Moderate drought
−2 < SPEI/SSI/SSMI ≤ −1.5	Severe drought
SPEI/SSI/SSMI ≤ −2.0	Extreme drought

Table 2. Drought classification used for SPI, SSI, and SSMI. Adopted from[34,44].

and categorize the drought event. The classification changes depending on how the drought affects specific systems and characteristics unique to each application, such as study aims and location. The indices used in drought analysis are classified as presented in Table 2. In this study correlation analysis was conducted using Pearson's correlation coefficient to assess the relationships between SPEI at 1-, 3-, 6-, and 12-month timescales, representing meteorological, agricultural, and hydrological drought responses. The analysis used monthly SPEI values from 1981 to 2021.

The standardized precipitation evapotranspiration index (SPEI)

The SPEI, which is now widely used to assess drought characteristics was developed by Vicente-Serrano, Beguería[30]. The SPEI computation procedure is based on the calculation of the Standardized Precipitation Index (SPI)[34], where the variable of cumulative precipitation is replaced by the accumulation of water deficit (D) of cumulative precipitation (P) and cumulative potential evapotranspiration (PET), (D = P - PET) at different time scales.

Equation 1 presents the results of the Hargreaves approach, which was proposed by[36] and used in this study to compute the potential evapotranspiration (PET). The FAO recommends this approach, which is the most widely used temperature-based method, as a backup technique for PET estimation in the event that observed meteorological data are not available. This method takes the minimum and maximum temperatures as input[37].

$$PET = 0.0023\,(R_a/\lambda\,)\,(T_{max} - T_{min})^{0.5}\left(\left(\frac{T_{max} - T_{min}}{2}\right) + 17.8\right) \tag{1}$$

where PET signifies the Hargreaves potential evapotranspiration (mm/day); Ra indicates extraterrestrial radiation (mm/day) based on latitude, daylight hours, and solar constant; λ is the latent heat of vaporization (MJ/Kg); and T_{min} and T_{max} are the minimum and maximum temperatures (°C).

Then, using Eqs. 2 and 3, D was normalized into a log-logistic probability distribution to calculate SPEI. The log-logistic distribution was illustrated as:

$$f\,(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)\left(1 + \left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)^{-2} \tag{2}$$

where α, β and γ are coefficients to describe the scale and shape of this distribution.

The SPEI was calculated as follows:

$$\text{SPEI} \ = \ \sqrt{-2\,ln\,(P)} - \frac{\text{C}_0 + \text{C}_1\text{t} + \text{C}_2\text{t}^2}{1 + \text{d}_1\text{t} + \text{d}_2 t^2 + \text{d}_3\text{t}^3} \tag{3}$$

where P is the probability of exceeding a determined D value, given as $P = 1 - f(x)$. The constants expressed above were as follows: $C_0 = 2.515517$, $d_1 = 1.432788$; $C_1 = 0.802853$, $d_2 = 0.189269$; $c_2 = 0.010328$ and $d_3 = 0.001308$.

Standard stream flow index (SSI)

The SSI proposed by Nalbantis[31] is computed based on the cumulative stream discharge data at various timescales using SPI[34] to investigate the distribution and variations in drought severity. The SSI is calculated in similar approach to the SPI, but instead of precipitation, it measures stream flow to quantify hydrological drought. On the other hand, as Gu, Chen[38] noted, the computation method of SSI was similar to that of SPEI, and the stream flow was more consistent with the log-normal distribution.

The difference in the calculation process between SSI and SPEI is that the stream flow time-series data were entered into SSI to fit the log normal distribution. The SSI values were calculated and categorized to determine the SSI range for different drought intensities. Table 2 shows the classification of the indices used in this study, as suggested by[39].

The standardized soil moisture index (SSMI)

Soil moisture is the amount of water in the soil. It's an important element in hydrology, agriculture, and climate research since it affects plant growth, runoff generation, groundwater recharge, and evaporation. Soil moisture is often assessed using volumetric water content (VWC), either as a percentage (%) or cubic meters per cubic meter (m^3/m^3). The study utilized the unit cubic meters per cubic meter (m^3/m^3).

The standardized soil moisture index (SSMI) determines the difference between soil moisture at field capacity, residual soil moisture, and the permanent wilting point. The soil moisture index was calculated using an empirical model of the relationship between land surface temperature (LST) and normalized difference vegetation index (NDVI). Using this assumption, Eq. 4 can be used to calculate the Soil Moisture Index (SSMI) for each pixel[32,33].

$$SSMI_i = \frac{T_{\max(i)} - T_{s(i)}}{T_{\max(i)} - T_{\min(i)}} \tag{4}$$

where i indicates pixel number, Ts(i) is the LST for i^{th} pixel, Tmin(i) and Tmax(i) are minimum and maximum values of observed LST. The spatial variability of soil moisture in the study area is indicated in Fig. 3.

Soil moisture parameters in the Abaya Chamo sub basin are being studied in order to determine hydroclimatic problems. Figure 3 shows the average monthly surface soil moisture levels. The soil moisture map was created using raster data and spatial analytic tools. The approach begins with getting gridded soil moisture data in NetCDF format from 1981 to 2021. Then, using ArcGIS, we calculated the mean monthly soil moisture by averaging the data from each month over the whole period. This generates a sequence of raster datasets, one for each month. To construct a single map representing the spatial average, we compute the mean of monthly rasters. The generated raster was then shown using a color ramp to visually represent the difference in soil moisture measurements, with different colors representing different moisture levels. The map was clipped to the extent of the Abaya Chamo sub-basin.

From January to March, moisture content ranges from 0.54 to 0.59 m^3/m^3 in the northern and northeastern of the sub basin, while the central and southern regions have lower levels of 0.24 to 0.29 m^3/m^3. From April to June, its moisture content rise to 0.68 to 0.79 m^3/m^3 in much of the basin, with the exception of the southwest. Figure 3 shows that from July to December, the northern, eastern, and southeastern regions have greater moisture levels (0.69 to 0.91 m^3/m^3), whereas the southern and southwestern areas have lower moisture levels (0.29 to 0.43 m^3/m^3).

Equations 5–7 for SPEI illustrate how droughts are classified by drought duration (D_d), drought magnitude (DM), and drought intensity (DI). SSI and SSMI are comparable. The sum of the SPEI, SSI, and/or SSMI negative deviations during a drought episode is known as the drought magnitude (DM). The average is calculated by

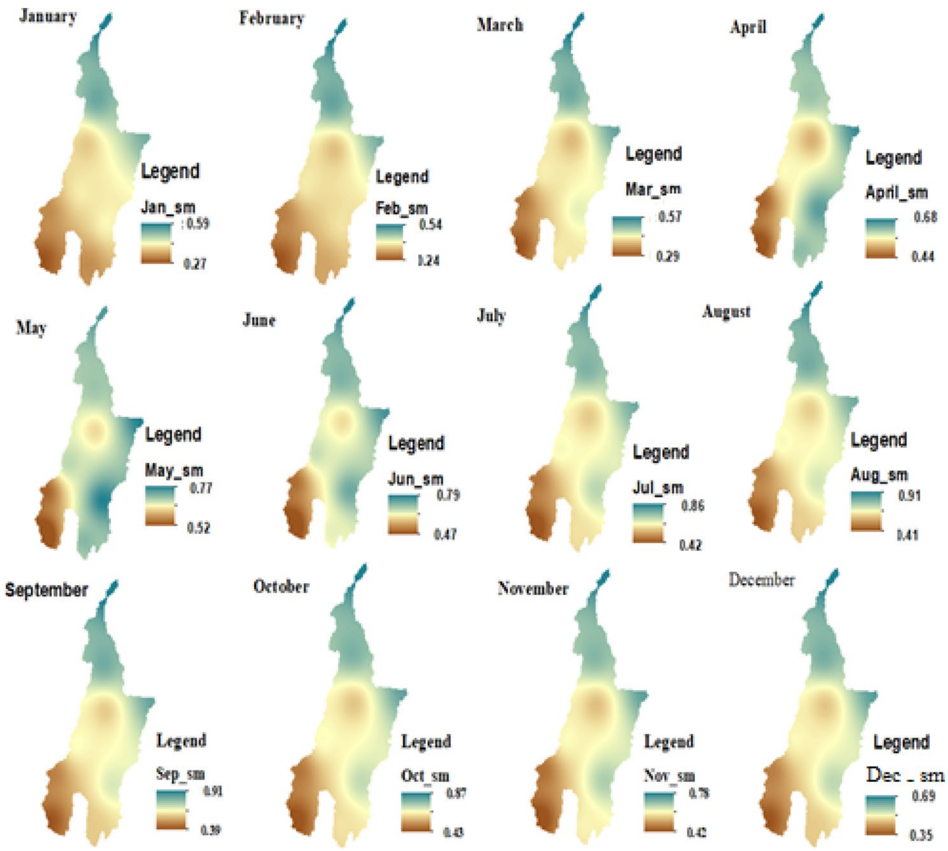

Fig. 3. Spatial mean monthly soil moisture (m^3/m^3) in Abaya Chamo sub basin (1981–2021).

dividing the total number of drought episodes throughout the study period[40]. According to[34,41], DM calculates the total water deficit throughout the dry period, which is stated as follows:

$$DM = \sum_{i=1}^{n} \mathrm{SPEI}_i \tag{5}$$

where n is the number of consecutive months per drought episode, and DM is the drought magnitude. Similar calculations are used to get the SSI and SSMI magnitudes According to[42], the drought intensity (DI) is the ratio of the drought magnitude to the drought length of the drought index (SPEI, SDI, or SSMI).

$$DI = \frac{DM}{D_d} \tag{6}$$

where D_d is the average duration of the drought.

The average drought duration is calculated as the mean duration of all drought events as represented in Eq. 7[43].

$$D_d = \frac{\sum_i^n d_i}{n} \tag{7}$$

where d_i is the duration of the ith drought event in an area, and n is the total number of drought events.

Results

Meteorological drought

SPEI-1 details in the Bilate catchment from 1981 to 2021 revealed − 127 drought magnitude and 89 dry months (Tables 3 and 4). Among these, 1.8% is classified as extremely dry for nine months, with SPEI values ranging from − 2.46 to −2.04. Furthermore, a severe dry period lasted 20 months, accounting for 2% of the total dry months, with SPEI values ranging from − 1.93 to −1.51 is observed. Moderate drought events are observed for 60 months, accounting for 12.1% of the total drought period, with SPEI values ranging from − 1.48 to −1.01. These extreme, severe, and moderate droughts, which occurred in May 2004, June 2005, and August 2005, coincided with the agricultural season in the Bilate watershed[45] resulting in water shortages and affecting crop production in the watershed.

Accumulation period	Mild drought		Moderate drought		Severe drought		Extreme drought	
	N	Probability	*N*	Probability	*N*	Probability	*N*	Probability
SPEI-1	163	1 in 3.2 yrs.	60	1 in 7 yrs.	21	1 in 21 yrs.	8	1 in 40 yrs.
SPEI-3	166	1 in 3.2 yrs.	42	1 in 14 yrs.	31	1 in 14 yrs.	9	1 in 41 yrs.
SPEI-6	161	1 in 3.2 yrs.	53	1 in 7 yrs.	40	1 in 14 yrs.	6	1 in 41 yrs.
SPEI-12	159	1 in 3.2 yrs.	44	1 in 14 yrs.	41	1 in 14 yrs.	5	1 in 41 yrs.

Table 3. Probability of drought events in the Northern part/Bilate catchment of Abaya Chamo sub basin. N represents number of months observed with respective droughts severity classes.

Accumulation period	Drought event in Bilate catchment				Wet event in Bilate catchment			
	Number of dry months	Frequency (%)	Magnitude	Average intensity	Number of wet months	Frequency (%)	Magnitude	Average intensity
SPEI-1	89	18.1	– 127	−1.4	74	15.0	112	1.5
SPEI-3	82	16.7	– 122	−1.5	82	16.7	122	1.5
SPEI-6	94	19.1	– 135	−1.4	72	14.6	109	1.5
SPEI-12	86	17.5	– 128	−1.5	78	15.9	114	1.5

Table 4. Extreme drought and wet events in the Northern part/Bilate catchment of Abaya Chamo sub basin. Where N represents number.

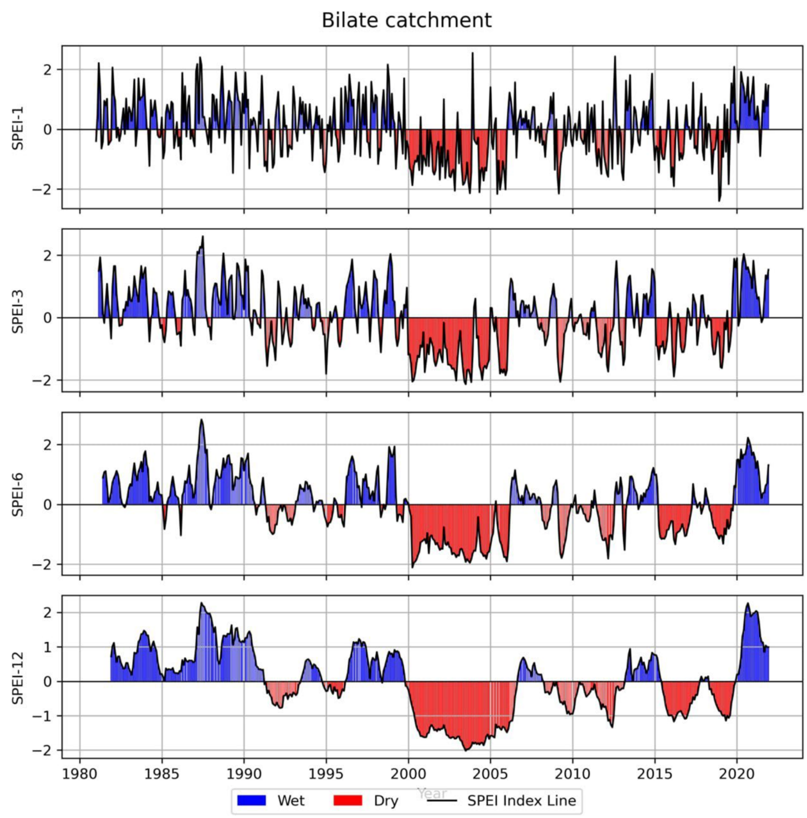

Fig. 4. Monthly SPEI at one to twelve time scales in the northern part of the sub basin from 1981–2021.

On the other hand, as shown in Fig. 4, the Bilate catchment experienced 74 wet months, with 2% of these events being extremely wet, lasting 10 consecutive months and SPEI values range from 2.08 to 2.60. In addition, 4.6% of the catchment's events were very wet, with 8.3% being moderate wet.

The SPEI-3 analysis result designated a drought of magnitude – 122. It also shows a total of 82 drought months, accounting for 16.6% of the study period. Figure 4 indicates that among the dry months, extreme, severe, and moderate drought occurred for seven, 36, and 39 months, respectively. Table 3 also provides a

Accumulation period	Mild drought		Moderate drought		Severe drought		Extreme drought	
	N	Probability	*N*	Probability	*N*	Probability	*N*	Probability
SPEI_1	164	1 in 3.2 yrs.	55	1 in 10 yrs.	28	1 in 20 yrs.	5	1 in 41 yrs.
SPEI_3	169	1 in 3.2 yrs.	53	1 in 10 yrs.	38	1 in 20 yrs.	6	1 in 41 yrs.
SPEI_6	159	1 in 3.2 yrs.	53	1 in 10 yrs.	35	1 in 20 yrs.	7	1 in 41 yrs.
SPEI_12	151	1 in 3.2 yrs.	64	1 in 10 yrs.	28	1 in 20 yrs.	5	1 in 41 yrs.

Table 5. Probability of drought events in the Southwestern part/lakes catchment of Abaya Chamo sub basin. N represents number of months observed with respective droughts severity classes.

Accumulation period	Drought event in lakes catchment				Wet event in lakes catchment			
	Number of dry months	Frequency (%)	Magnitude	Average intensity	Number of wet months	Frequency (%)	Magnitude	Average intensity
SPEI-1	85	17.3	– 123	– 1.5	84	17.1	124	1.5
SPEI-3	83	17.3	– 123	– 1.4	84	17.1	123	1.5
SPEI-6	89	18.1	– 128	– 1.4	81	16.5	118	1.5
SPEI-12	93	18.9	– 130	– 1.4	87	17.7	121	1.4

Table 6. Extreme drought and wet events in the Southwestern part/lakes catchment of Abaya Chamo sub basin. Where N represents number.

detailed overview of the extreme, severe, and moderate events classified into strong and low-index intervals, as well as the corresponding months for each assessment in the Bilate catchment of the basin.

Extreme and severely dry incidents were observed at SPEI_3 over nine and twenty months, with drought index values of −2.5 and − 1.9, respectively. Extreme dry events were observed in May 2004, June and August 2005, and March 2009, while severely dry events were detected in April 2000, August 2001, July 2002, July 2003, and August 2004. These droughts may have an impact on the seedling period in agricultural land because they occurred during the watershed's cropping season.

In addition to analysis for 1 and 3 months the SPEI was employed to evaluate drought and wet event characteristics for 6, and 12 months' time scales within the Bilate catchment. The 6-month (SPEI-6) and 12-month (SPEI-12) indices exhibited drought magnitudes of −135 and − 128, respectively, comparable to those observed for SPEI-1 and SPEI-3. These indices recorded 94 and 86 drought months for SPEI-6 and SPEI-12. The mean drought intensity was calculated as −1.4 for SPEI-6 and − 1.5 for SPEI-12.

Conversely, wet events demonstrated magnitudes of 109 for SPEI-6 and 114 for SPEI-12, with 72 and 78 wet months recorded, respectively. The average intensity of wet events was consistent across all time scales, with a value of 1.5 for both SPEI-6 and SPEI-12, mirroring the results for SPEI-1 and SPEI-3.

Analysis across all time scales revealed that the most persistent droughts occurred between 2000 and 2005, relative to other periods. Additionally, drought frequency was higher from 2001 to 2020 compared to 1981 to 2000 as shown in Fig. 4. At longer time scales (6 and 12 months), droughts were less frequent but exhibited greater persistence compared to shorter time scales (1 and 3 months). The 12-month SPEI, recognized as a hydrological drought index, is particularly suited for monitoring surface water resources, such as river flows[46,47]. On these longer time scales, both drought and wet events were less frequent, resulting in fewer recorded dry or humid periods.

SPEI-1 showed that exceptional drought occurrences with index values between − 2.1 and − 2.0, which accounted for 2% of the research period and had a magnitude of −123, occurred in 10 months in the southwestern portion of the sub-basin/Lake catchment (Table 5). Additionally, the results showed that the average intensity of the drought is −1.5 (Table 6). These extreme dry periods coincided with cereal crop harvesting months: April 1992, July 2010, August 2016, June 2018, July 2019, and March 2020. Besides, severe dry events occurred in 22 months (4.4%), while moderate dry events occurred in 53 months (10.7%) during the same period. Similarly, SPEI-3 revealed the occurrence of extreme, severe, and moderate droughts, accounting for seven months (1.4%), 28 months (5.6%), and 48 months (9.7%) of drought months and − 123 drought magnitudes during the study period.

In contrast, the SPEI-1 analysis identified 84 wet months during the study period. These included eight extreme wet months with index values ranging from 2.0 to 2.6; three of these were climatologically dry months of the study area, namely January 1994, and October to November 1998. These showed the variability of rainfall in the area. Furthermore, there were 24 very wet months (1.6%) and 52 moderately wet months (10.5%) in the catchment. Similarly, SPEI-3 results revealed that there were seven extremely wet months (1.4%), 24 very wet months (4.8%), and 53 moderately wet months (10.7%) during the study period, as illustrated in Fig. 5. The study also discovered that the majority of droughts in the studied area have been mild droughts over the last 41 years (Table 5).

The SPEI-6 and SPEI-12 months' time scale were utilized to assess drought and wet conditions across the Lakes catchment in addition to the 1 and 3 months' time scales, over the study period. The 6-month (SPEI-6) and 12-month (SPEI-12) indices revealed drought magnitudes of −128 and − 130, respectively, aligning closely with

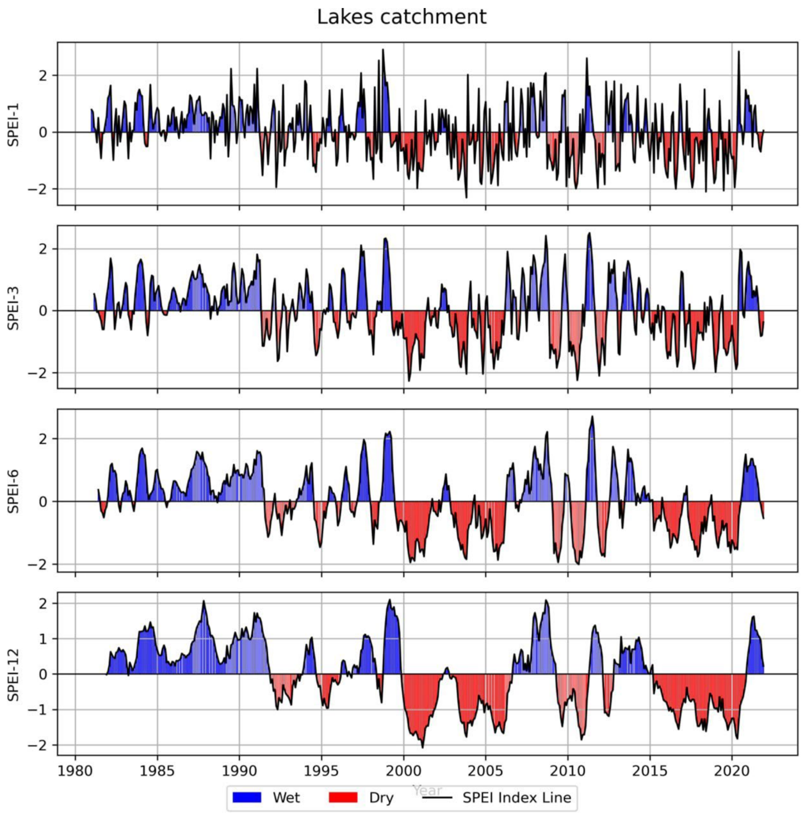

Fig. 5. 1981–2021 monthly SPEI at one to twelve time scales time scales in the southwestern part of the Abaya Chamo sub basin.

	Mild drought		Moderate drought		Severe drought		Extreme drought	
Accumulation period	***N***	**Probability**	***N***	**Probability**	***N***	**Probability**	***N***	**Probability**
SPEI-1	147	1 in 3.2 yrs.	61	1 in 7 yrs.	18	1 in 20 yrs.	5	1 in 41 yrs.
SPEI-3	164	1 in 3.2 yrs.	39	1 in 10 yrs.	34	1 in 13 yrs.	4	1 in 41 yrs.
SPEI-6	163	1 in 3.2 yrs.	36	1 in 10 yrs.	35	1 in 13 yrs.	4	1 in 41 yrs.
SPEI-12	159	1 in 3.2 yrs.	39	1 in 10 yrs.	40	1 in 10 yrs.	3	1 in 41 yrs.

Table 7. The probability of drought events in the Eastern part/Gidabo catchment of Abaya Chamo sub basin. N represents number of months observed with respective droughts severity classes.

the values observed for SPEI-1 and SPEI-3. These indices corresponded to 89 and 93 drought months for SPEI-6 and SPEI-12, respectively. The average drought severity was consistent at −1.4 for both SPEI-6 and SPEI-12.

In contrast, wet periods exhibited magnitudes of 118 for SPEI-6 and 121 for SPEI-12, with 81 and 87 wet months recorded, respectively. The mean intensity of wet events was calculated as 1.5 for SPEI-6 and 1.4 for SPEI-12. At shorter time scales (1 and 3 months), the SPEI indicated a higher frequency of drought events. However, at longer time scales (6 and 12 months), both the frequency of droughts and the variability between dry and wet periods decreased significantly as illustrated in Fig. 5.

Tables 7 and 8 shows that drought occurred in the Gidabo watershed with a magnitude of −123 and 85 drought months for SPEI-1 over the study period, including 10 months (2%) of extreme drought with a maximum index value of −2.5. In addition, the results show 22 months (4.4%) of extreme drought and 53 months (10.7%) of moderate drought. The study also attests that extreme drought periods tended to coincide with crop production seasons, which could affect the productivity of agricultural activities in the study area[48]. Nonetheless, during the study period, there were eight extremely wet months (1.6%), twenty-four very wet months (4.8%), and fifty-three moderately wet months (10.7%). Additionally, the results of the study showed that the catchment had a lower chance of experiencing severe drought (Table 7).

Moving on to the SPEI-3, there was a drought of magnitude – 126, with 83 drought months. This included 7 months (1.4%) of extreme drought, with a maximum index value of −2.24, 28 months (5.6%) of severe drought, and 48 months (9.7%) of moderate drought, as illustrated in Fig. 6. Overall, the trend line in all of the analyses

Accumulation period	Drought event in Gidabo catchment				Wet event in Gidabo catchment			
	Number of dry months	Frequency (%)	Magnitude	Average intensity	Number of wet months	Frequency (%)	Magnitude	Average intensity
SPEI-1	85	17.7	− 123	− 1.4	87	17.7	126	1.4
SPEI-3	83	17.9	− 126	− 1.4	82	16.7	120	1.5
SPEI-6	75	15.2	− 114	− 1.5	75	15.2	112	1.5
SPEI-12	82	16.7	− 124	− 1.5	70	14.2	102	1.5

Table 8. Extreme drought and wet events in the Eastern part/Gidabo catchment of Abaya Chamo sub basin. Where N represents Number.

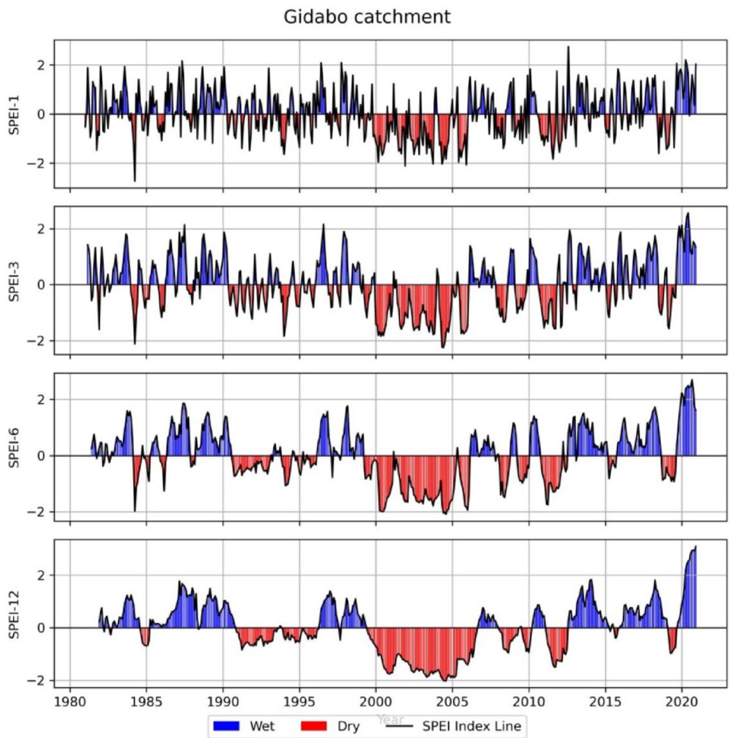

Fig. 6. Monthly SPEI at one to twelve time scales in Eastern part of the Abaya Chamo sub basin from 1981–2021.

indicated a decrease in rainfall accumulation and an increase in droughts. This suggests that the catchment, like others in the Abaya Chamo sub basin, experienced hydroclimatic variability between 1981 and 2021.

The analysis of drought and wet spells in the Gidabo catchment using the SPEI at various timescales revealed distinct patterns. Similar to the shorter timescales (SPEI-1 and SPEI-3), the longer-term (SPEI-6 and SPEI-12) indices also captured significant drought events. For the entire study period, the cumulative drought magnitudes for SPEI-6 and SPEI-12 were − 114 and − 124, respectively. These values correspond to a total of 75 drought months for SPEI-6 and 82 drought months for SPEI-12. The average drought severity was calculated to be −1.5 for both timescales. Conversely, wet events exhibited cumulative magnitudes of 112 for SPEI-6 and 102 for SPEI-12. The number of wet months was 75 for SPEI-6 and 70 for SPEI-12, with an average wet event intensity of 1.5 for both indices.

As shown in Fig. 6, an important finding of this study is the relationship between timescale and event frequency. Shorter timescales (SPEI-1 and SPEI-3) showed a higher frequency and greater variability of both dry and wet events. In contrast, longer timescales (SPEI-6 and SPEI-12) were characterized by less frequent, but often more prolonged, drying and wetting periods. This suggests that the SPEI effectively captures both short-term meteorological fluctuations and long-term climate trends, providing a more robust understanding of hydro-climatic variability in the region.

As shown in Tables 9 and 10, for the Gelena catchment, SPEI-1 and SPEI-3 were 95 and 88 dry months, respectively, and 87 and 82 wet months. The magnitude of drought in the Gelana catchment for SPEI-1 is −130, while SPEI-3 is −126. As shown in Fig. 7, we investigated that severe drought occurred in November 2003, with an index value of −2.0 for SPEI-1 and − 2.3 for SPEI-3. In addition, there were 32 severe dry months (6.5%) and 62 moderate dry months (12.6%). Furthermore, the results showed that no extreme drought occurred in the watershed during the study period (Table 9).

Accumulation period	Mild drought		Moderate drought		Severe drought		Extreme drought	
	N	Probability	*N*	Probability	*N*	Probability	*N*	Probability
SPEI-1	148	1 in 3.2 yrs.	55	1 in 7 yrs.	17	1 in 14 yrs.	7	1 in 41 yrs.
SPEI-3	148	1 in 3.2 yrs.	50	1 in 10 yrs.	27	1 in 14 yrs.	4	1 in 41 yrs.
SPEI-6	154	1 in 3.2 yrs.	52	1 in 7 yrs.	22	1 in 14 yrs.	6	1 in 41 yrs.
SPEI-12	159	1 in 3.2 yrs.	45	1 in 10 yrs.	31	1 in 13 yrs.	5	1 in 41 yrs.

Table 9. The probability of drought events in the Southern part of Abaya Chamo sub basin. N represents number of months observed with respective droughts severity classes.

Accumulation period	Drought event in Gelana catchment				Wet event in Gelana catchment			
	Number of dry months	Frequency (%)	Magnitude	Average intensity	Number of wet months	Frequency (%)	Magnitude	Average intensity
SPEI_1	95	19.3	– 130	– 1.4	87	18.1	128	1.4
SPEI_3	88	17.9	– 126	– 1.4	82	16.7	120	1.5
SPEI_6	80	16.3	– 114	– 1.4	88	17.9	126	1.4
SPEI_12	78	15.9	– 113	– 1.5	73	14.8	107	1.5

Table 10. Extreme drought and wet events in the Southern part/Gelana catchment of Abaya Chamo sub-basin. Where N represents Number.

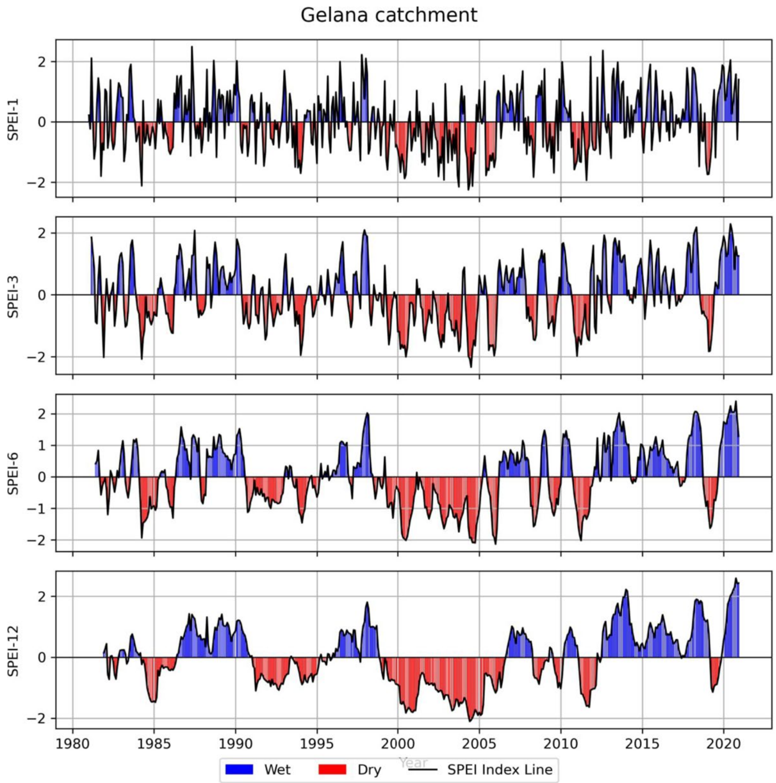

Fig. 7. Monthly SPEI at one to twelve time scales in the Southern part/Gelana catchment of the sub basin from 1981–2021.

In terms of wet events, five extreme wet months (1%) overlapped with the cultivation season, while 28 months (5.6%) were very wet. Similarly, there were 56 months with moderate rainfall (11.3%). Overall, the analysis revealed fluctuations between dry and wet periods in the catchment, with more dry months than wet months, indicating complex hydroclimatic pattern dynamics.

This study analyzed drought and wet spell characteristics using the SPEI at 6 and 12 months timescales besides 1 and 3 months. While all timescales captured both dry and wet periods, differences in frequency and magnitude were observed between short- and long-term indices. For the longer timescales (6- and 12-month), the cumulative drought magnitudes were recorded at −114 for SPEI-6 and − 113 for SPEI-12. These periods spanned 80 and 78 months, respectively, with average drought intensities of −1.4 and − 1.5. On the other hand, wet events showed cumulative magnitudes of 126 (SPEI-6) and 107 (SPEI-12) over 88 and 73 months, with average intensities of 1.4 and 1.5. These results highlight that longer-term SPEI values tend to reflect more persistent, though less frequent, climatic events.

As illustrated in Fig. 7, there is inverse relationship between SPEI timescale and the frequency of events. The shorter timescales (SPEI-1 and SPEI-3) were characterized by a higher frequency and greater variability of both dry and wet event occurrences. In contrast, the longer-term (SPEI-6 and SPEI-12) indices demonstrated a reduction in the frequency and variability of these events. This indicates that while short-term indices are sensitive to rapid meteorological fluctuations, longer-term indices effectively smooth out these variations to highlight prolonged periods of moisture deficit or surplus. This comparative analysis demonstrates the utility of using a multi-scalar approach to understand the full spectrum of hydro-climatic variability in the region.

Hydrological drought

To assess hydrological drought or compute streamflow deficits in the sub-basin, we used the standardized streamflow index (SSI). Streamflow deficit months are shown in Table 11 with their corresponding years. The lowest five flow years for each gauging station are presented in Table 11. Extreme to severe droughts with SSI values ranging from − 2.0 to −1.8 are observed in the northern part of the basin at the Bilate gauging station in March 1997, March 2000, December 2001, July 2002, and February 2003.

These extreme flow deficits impacted the water flow of the Bilate River, resulting in high scarcity of water from 1990 to 2015, demonstrating that the probability of an extreme deficit in Bilate river flow is high. The largest recorded SSI in the southwestern part of the basin (Lakes Catchment) of the Kulfo River was − 2.7 to −2.2 in November 1991, May 1991, July 1991, October 1993, and July 2014, showing deficiency of water in the catchment during 1990–2020.

The largest recorded drought index in the eastern part of the Abaya Chamo sub-basin (Gidabo catchment) was − 2.3 to −1.8 in July 2002, October 2003, February 2003, January 2006, and April 2011, indicating an extreme hydrological drought of 13 years within the 26 years from 1990 to 2015. In the southern part of the basin (Gelana catchment), the extreme drought index value ranges from − 2.8 to −1.7, as recorded in July 1991, February 2003, October 2009, January 2009, and April 2011. This designated that the water deficiency lasted 11.6 years out of 26 years.

Agricultural drought

sAs shown in Fig. 1, the sub-basin is divided into four regions: the northern Bilate catchment, the southwestern Lake Catchment, the eastern Gidabo catchment, and the southern Gelena catchment. Gridded soil moisture was averaged over these four regions before applying the standardized soil moisture index for each region.

The result shows that the northern part of the basin had a 34.2% soil moisture deficit (Table 12). The soil moisture deficit of 1.8% indicates extreme drought, with an index value of −2.3. Similarly, 19.1% and 13.3% account for severe and moderate droughts, respectively, in SSMI_1. The results for SSMI_3 illustrate that 33% of the months were in soil deficit, with 20.4% showing severe deficit and 11.8% designating moderate deficit of soil moisture. While the catchment's wet period accounted for 32.6% of moderate to excessive soil moisture, SSMI_1 had 15.4% moderately logged soil moisture and 16.8% highly logged soil moisture, respectively. Similarly, SSMI_3 findings revealed that 32.2% of the months during the study period had sufficient soil moisture in the catchment, 1.4% had excessive soil moisture, and 17.8% and 12.9% had moderately and highly logged soil moisture, respectively.

In the southwestern region/Lake catchment, the dry period for SSMI_1 analysis was 35.8%, signifying a lack of soil moisture in the region. Among these months, the results showed that 1.6% had extreme soil moisture deficiency with an index value of −2.0. The findings also revealed that 19.7% of the time was spent in extremely drought conditions, while 14.5% was in moderate drought. On the other hand, the findings revealed that the catchment experienced 32.5% of adequate soil moisture, with 1.2% of excessive soil moisture, while the watershed experienced 17.0% and 14.3% of extremely and severely logged soil moisture, respectively.

Station name	Extreme deficit value	The lowest five flow years	TY	Year interval	NY	Recurrence of deficit year
Forty-spring	− 2.3 to − 2.0	Jan 1988, Oct 2003, Dec 2005, Mar 2000, Feb 2003	35	1981–2015	12.4	Every 2.8 years
Bilate	− 2.0 to − 1.8	Mar 1997, Mar 2000, Dec 2001, Jul 2002, Feb 2003	26	1990–2015	13.8	Every 1.9 years
Gato	− 2.4 to − 2.0	Feb 1994, Feb 1996, Jun 1999, Aug 1999, Jun 2000	21	1985–2005	10.3	Every 2 years
Gelana	− 2.8 to − 1.7	Jul 1991, Feb 2003, Oct 2009, Jan 2009, Apr 2011	26	1990–2015	11.6	Every 2.2 years
Gidabo	− 2.3 to − 1.8	Jul 2002, Oct 2003, Feb 2003, Jan 2006, Apr 2011	26	1990–2015	13.0	Every 2 years
Hamessa	− 2.3to − 1.8	Mar 2000, Oct 2002, Feb 2003, Apr 2011, Feb 2013	26	1990–2015	13.4	Every 1.9 years
Kulfo	− 2.7 to − 2.2	Nov 1991, May, 1991, Jul 1991, Oct 1993, Jul 2014	31	1984–2014	12.5	Every 2.5 years
Sala (Dilla)	− 2.4 to − 1.6	Jan 2006, May 2008, Dec 2009, Aug 2009, Jan 2010	27	1985–2012	6.8	Every 4 years
Lake Abaya	− 2.1 to − 1.9	Mar 2003, Oct 2003, Apr 2005, Jan 2006, Feb 2010	40	1981–2020	12.8	Every 3 years
Lake Chamo	− 2.7 to − 2.3	May 1984, Oct 2003, Nov 2003, Jan 2004, Jan 2006	40	1981–2020	20.5	Every 2 years

Table 11. Extreme points of SSI and their probability of deficit period in rivers and lakes in the Abaya Chamo sub basin. TY-Time length in year, NY - Number of deficit year.

Severity	Bilate catchment				Lakes catchment			
	SSMI_1		SSMI_3		SSMI_1		SSMI_3	
	Nm	%	Nm	%	Nm	%	Nm	%
Extremely deficit soil moisture	9	1.8	4	0.8	8	1.6	4	0.8
Severely deficit soil moisture	92	19.1	98	20.4	95	19.7	98	20.4
Moderately deficit soil moisture	64	13.3	57	11.8	70	14.5	69	14.3
Normal soil moisture	158	32.9	164	34.1	150	31.2	146	30.4
Moderately logged soil moisture	74	15.4	86	17.9	69	14.3	73	15.2
Highly logged soil moisture	81	16.8	62	12.9	82	17.0	86	17.9
Excessive soil moisture	2	0.4	7	1.4	6	1.2	2	0.4

Table 12. The soil moisture deficit and logging period of northern/Bilate catchment and Southwestern region/Lakes catchment in Abaya Chamo sub basin for the period from 1982 to 2021. Nm represents Number of months observed with deficit or logged water content of soil moisture.

Severity	Gidabo catchment				Gelana catchment			
	SSMI_1		SSMI_3		SSMI_1		SSMI_3	
	Nm	%	Nm	%	Nm	%	Nm	%
Extremely deficit soil moisture	10	2.0	7	1.4	6	1.2	7	1.4
Severely deficit soil moisture	87	18.1	91	18.1	94	19.5	91	18.9
Moderately deficit soil moisture	65	14.1	61	12.5	76	15.8	74	15.4
Normal soil moisture	165	34.3	171	35.6	141	29.3	155	32.2
Moderately logged soil moisture	65	13.5	75	15.6	77	16.0	65	13.5
Highly logged soil moisture	83	17.2	67	13.9	81	16.8	81	16.8
Excessive soil moisture	2	0.4	6	1.2	5	1.0	5	1.0

Table 13. The soil moisture deficit and logging period of eastern/Gidabo catchment and Southern regions/Gelana catchment in Abaya Chamo sub basin for the period from 1982 to 2021. Nm represents number of months observed with deficit or logged water content of soil moisture.

The SSMI_3 additionally demonstrated deficient and excessive soil moisture in the catchment. According to the findings, 35.5% of the period was experienced as deficient in soil moisture, with 20.4% severely and 14.3% moderately deficient in soil moisture. The results also showed that 33.5% of the months during the study period had moderate to excessive soil moisture in the watershed. From these months, 17.9% and 15.2% reported highly and moderately logged soil moisture, respectively.

As shown in Table 13, the SSMI_1 analysis in the eastern region/Gidabo catchment identified that the region experienced a dry period of 34.2%. The region will experience 2% of extreme drought months, with an index of −2.4. In addition, the area experienced severe and moderate soil moisture droughts at 18.1% and 14.1%, respectively. Similarly, the SMI_3 indicated that 32% of the months in the period under consideration were dry, with 1.4% experiencing extreme drought. The findings also reveal that 18.1% of the total study time was spent in severe drought, with 12.5% experiencing moderate drought. During this study, we found wet periods in the catchment using both SSMI_1 and SSMI_3.

The study also found that 31.1% of the study time was spent in moderate to excessive soil moisture. Moreover, we discovered that 17.2% was heavily logged, 13.5% was moderately logged, and only 0.4% had excessive soil moisture. Similarly, the SSMI_3 findings demonstrated 30.7% of the study time was spent with sufficient soil moisture, with 13.9% highly logged, 15.6% moderately logged, and 1.2% with excessive soil moisture.

In the southern region/Gelena catchment, the SSMI_1 result indicated that the deficit moisture period covered 36.5% of the area, with 1.2% experiencing extreme drought (index of −1.8). In addition, the area experienced 19.5% severe drought and 15.8% moderate drought months during the time period studied. Similarly, the SSMI_3 indicated that 35.7% of the time was during a drought. The results also showed 1.4%, 18.9%, and 15.4% of extreme, severe, and moderate soil moisture deficit periods. In contrast, the SSMI_1 findings showed 33.8% of the study time was spent with moderate to excessive soil moisture. Furthermore, we discovered that 16.8% was heavily logged, 16.0% was moderately logged, and only 1% had excessive soil moisture. The SSMI_3 results designated 31.3% of the soil was sufficiently moist, with 16.8% being highly logged, 13.5% being moderately logged, and only 1% having excessive moisture.

Discussions

Characterization of meteorological drought

Understanding the relationship between droughts caused by a lack of rainfall, streamflow, and soil moisture is important for water resource management and agricultural productivity. We examined the meteorological, hydrological, and agricultural droughts in the Abaya Chamo sub-basin of the Rift Valley Lakes basin, as well as their relationships. We applied three drought indices (SPEI, SSI, and SSMI) to evaluate meteorological, hydrological and agricultural. The current investigation considered mainly two timescales: one month and three months of aggregation. The time series value of SSI was calculated using observed river flow data from gauging stations. SPEI and SSMI were calculated using the areal average values. The results were presented and compared across catchments based on maximum drought intensity and percentage of months with drought events.

As shown in the results section, the extreme meteorological, hydrological, and agricultural drought index values of SPEI, SSI, and SSMI in the Bilate catchment can reach − 2.46, −2.0, and − 2.3, respectively. The extreme drought index values for the Lake catchment were − 2.1, −2.7, and − 2.0 for SPEI, SSI, and SSMI. Similarly, extreme meteorological, hydrological, and agricultural droughts were observed in the Gidabo catchment, with index values of −2.5, −2.3, and − 2.4, respectively. In the Gelana catchment, the SPEI, SSI, and SSMI values were − 2.0, −2.8, and − 1.8. These findings indicated the presence of severe to extreme meteorological, hydrological, and agricultural droughts in the sub-basin. A previous study also indicated that the sub-basin was experiencing extreme drought, with index values reaching − 3.27[49]. We also observed the existence of association between the three drought types and this implies that the hydroclimatic variable, streamflow, is sensitive to rainfall and soil moisture conditions in the sub-basin.

In addition, the analysis showed that the meteorological drought in the Bilate and Gidabo catchments is more severe than the agricultural and hydrological droughts. A study by Wen and Ying[50] in Yangtze River also observed that meteorological drought was more severe than agricultural and hydrological droughts in terms of degree. This could be related to less rainfall and higher temperatures in arid and semi-arid areas, where rainfall is the only source of soil moisture. The higher temperature may result in increased evapotranspiration, which will quickly evaporate and could be one of the causes of increased meteorological drought. In addition, SSMI considers more variables than SPEI, including evapotranspiration, soil properties, and root depth[51]. Furthermore, because some land and hydrological processes in the catchments delay rainfall, agricultural and hydrological droughts are less severe than meteorological droughts[52].

The results revealed that in the sub basin, extreme to severe hydrological droughtwere occured in the study area with drought index values ranging from − 2.8 to −1.7. For example, in the Kulfo catchment the SSI values were − 2.7 to −2.2. Similarly[53],) stated that the Rift Valley lakes basin, which includes the Abaya Chamo sub basin, is one of Ethiopia's most hydrological drought susceptible places. They also noted that the hydrological drought-vulnerable zones are related with crop growth seasons in the country's southwest. This could be due to the river's available surface water, which is susceptible to high temperatures and evaporates quickly. Warmer temperatures, which increase plant water uptake, may exacerbate the amplifying effect of catchments[54]. In addition, more variable rainfall associated with a warmer climate is expected to result in more variable river flows, posing a significant challenge to river transportation, ecosystem sustainability, and water supply reliability[55]. Another study indicated that runoff and soil moisture drying are more widespread and severe than precipitation drying, indicating that other temperature-sensitive drought processes, such as evapotranspiration and surface water, play an important role[56]. Furthermore[57], studied on hydrological drought forecasting using the stream flow drought index (SDI) predicted extreme drought years in most Ethiopian river basins, including the Abaya Chamo sub basin of the Rift Valley Lakes basin, in the future.

Considering the number of drought and wet events in the sub-basin in terms of percentage of months for the one and three months accumulations (SSMI_1 and SSMI_3), the deficit soil moisture period covered 33.0% to 34.2% in the northern, 35.5% to 35.8% in the southwestern, 32.0% to 34.2% in the eastern, and 35.7% to 36.5% in the southern region of the basin.

In contrast, the wet soil moisture condition ranged from 32.2% to 32.6% in the north, 32.5% to 33.5% in the southwest, 30.7% to 31.1% in the eastern, and 31.3% to 33.8% in the southern part of the sub-basin. According to these findings, the Abaya Chamo sub-basin experienced more soil moisture deficit than wet periods during agricultural drought, as measured by one-month and three-month accumulation periods. The study findings are consistent with previous research on the occurrence of agricultural droughts in the Ethiopian Rift Valley's Upper Awash sub-basin. There was a 35% probability of severe drought and a 50% of moderate drought during the study area's Belg (March to April) season. Similarly, during the Kiremt (June to September) season, there was a 30% and 80% chance of severe and moderate drought, respectively[58].

The study also discovered that meteorological drought has a similar pattern to agricultural drought, with more drought than wet periods. For example, drought months ranged from 15.9% to 16.6% in the Bilate, 16.6% to 17.1% in the Lakes and Gidabo catchments, and 17.7 to 19.1% in the Gelana catchment. In addition, the researchers discovered that agricultural drought months outnumber meteorological drought months.

Agricultural droughts may be exacerbated as temperatures rise, resulting in high evapotranspiration rates that allow crops to transpire even in dry conditions. These droughts have a greater long-term impact than meteorological droughts because crop roots rely heavily on stored soil moisture. Furthermore, soil types and properties, such as differences in moisture retention capacities between regions, can contribute to more severe agricultural drought conditions in some areas[59].

On the other hand, this study found that the number of less wet months in the sub-basin compared to drought months varied from 14.9% to 16.6% in the Bilate, 12.7% to 16.6% in the lakes, 17.1% in the Gidabo, and 16.9% in the Gelana catchments. Droughts in the sub basin's four catchments were found to be more severe in the Gelana catchment, which is located in the south of the basin. Similarly, a prior study in the neighboring sub basin found that the southern region where the sub basin found and South-eastern Ethiopia experienced the most severe drought, with a peak negative SPEI-3 score of −4.4. Besides, the study also noted that the drought was very severe and affected 10.2 million people in southern and south-eastern lowland areas of the country[60].

In contrast, the northern Bilate catchment experienced less severe drought. The probability of occurrence indicated that drought occurs more frequently in the Bilate catchment compared to other catchments in the sub basin. This finding indicated that drought in the Abaya Chamo sub-basin is a more frequent event than in the

	SPEI_1	SPEI_3	SPEI_6	SPEI_12
SPEI_1	1			
SPEI_3	0.72	1		
SPEI_6	0.59	0.82	1	
SPEI_12	0.53	0.69	0.85	1

Table 14. The pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for bilate catchment.

	SPEI_1	SPEI_3	SPEI_6	SPEI_12
SPEI_1	1			
SPEI_3	0.70	1		
SPEI_6	0.52	0.78	1	
SPEI_12	0.36	0.53	0.75	1

Table 15. The pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for lakes catchment.

	SPEI_1	SPEI_3	SPEI_6	SPEI_12
SPEI_1	1			
SPEI_3	0.69	1		
SPEI_6	0.56	0.80	1	
SPEI_12	0.40	0.59	0.79	1

Table 16. The pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for Gelana catchment.

	SPEI_1	SPEI_3	SPEI_6	SPEI_12
SPEI_1	1			
SPEI_3	0.70	1		
SPEI_6	0.57	0.80	1	
SPEI_12	0.47	0.63	0.82	1

Table 17. The pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for Gidabo catchment.

Rift Valley Basin in general, which experienced an average drought occurrence within every 1.76 in the Kiremt and 1.68 in the Belg seasons from 1981 to 2017, which could be due to higher climate variability in the study area[61].

The variation in drought severity across the sub-basin catchments could be attributed to topographic complexity, which influences Ethiopia's annual temperature and rainfall cycle[62]. Furthermore, spatial variability in hydro-climatic elements in the sub-basin may affect available water and exacerbate the region's drought[6]. As a result, evaluating all meteorological, agricultural, and hydrological droughts is critical for identifying severe droughts and their impact on available water for agricultural production in the study region.

Propagation of droughts

The findings of this study indicated that there is a lag between different types of droughts. These could be attributed to a variety of factors generating a meteorological drought, in which a decrease in rainfall gradually depletes soil moisture, potentially limiting crop development. A recent study in the upper Gelana catchment stated that agricultural drought occurs when meteorological drought persists, reducing soil water content and significantly impacting agricultural productivity[63].

To demonstrate drought propagation and for discussion, this work determined correlations between meteorological, agricultural, and hydrological droughts using SPEI correlation analysis over multiple timescales (1, 3, 6, and 12 months), as shown in Tables 14, 15, 16 and 17. This reflects the progression of drought impacts, from short-term meteorological deficiencies to long-term agricultural and hydrological effects.

For example the correlation matrix for Bilate catchment reveals a substantial positive correlation ($r = 0.72$) between SPEI_1 and SPEI_3, demonstrating that short-term meteorological drought (SPEI_1) affects soil moisture deficits (important to agricultural drought) over a three-month period. The correlation declines gradually with longer durations, with SPEI_1 vs. SPEI_6 ($r = 0.59$) and SPEI_1 vs. SPEI_12 ($r = 0.53$), implying a delayed and weakened reaction in hydrological systems, such as stream flow or groundwater, which correspond to SPEI 12.

Similarly, SPEI-3 correlates highly with SPEI-6 ($r = 0.82$) and SPEI_12 ($r = 0.69$), whereas SPEI_6 and SPEI_12 have the strongest correlation ($r = 0.85$), indicating the cumulative and lagged propagation of drought signals from agricultural to hydrological systems (Table 14). These results suggest that meteorological drought (SPEI_1) drives agricultural drought (SPEI_3 to SPEI_6) with a lag of 3–6 months, whereas hydrological drought (SPEI-12) emerges with delays of 6–12 months, corresponding with the later reaction of groundwater and stream flow to precipitation deficiencies[64–66].

Drought impacts and adaptation strategies

The results of this study designated that the majority of extreme droughts frequently occur during the rainy season (March-September) in the Abaya Chamo sub-basin, a key agricultural area in Ethiopia's Rift Valley. This timing severely impacts availability of water for crop and livestock production in the watersheds. Similarly, prior studies in the Bilate watershed in the Abaya Chamo sub-basin showed that drought is severe throughout the watershed's crop growing seasons, and it might disrupt crop growth and growing period, resulting in devastating impacts on society[48]. Besides, Mohammed and Yimam[67] confirmed the occurrence of recurring drought over an extended period of time that would have an impact on crop yields in subsequent years.

The region's reliance on rain-fed agriculture makes it highly vulnerable to these events. The synchronization of drought with crop growing seasons has significant agricultural and economic consequences. While specific yield loss data for Abaya Chamo is limited, similar studies in the rift valley during the 1984 drought showed significant declines in Teff (61%) and Sorghum (94%) yields[68]. Such losses cause household food shortages, income reduction, and asset depletion, particularly for smallholder farmers.

The economic impact is substantial, with the Federal Democratic Republic of Ethiopia (FDRE) estimating GDP losses of 1 to 4% due to climate variability[69]. Drought also affects livestock health and production by reducing pasture and water availability, which directly impacts agro-pastoralist livelihoods. Population pressure and recurrent droughts contribute to unsustainable land practices, such as expanding farming into marginal areas, leading to increased soil erosion and degradation. The Abaya Chamo Basin saw a 59.15% increase in agricultural land from 1985 to 2010 due to these pressures[70].

To cope with drought, farmers in the Abaya Chamo sub-basin employ various indigenous and introduced adaptation strategies. They use crop diversification, planting drought-tolerant and short-duration varieties like teff, sorghum, and millet[71]. Adjusting planting schedules to align with rainfall patterns is another tactic, though it is increasingly difficult due to erratic rainfall[72]. To conserve soil moisture and reduce erosion, farmers implement soil and water conservation practices, including terracing, contour plowing, mulching, and constructing water harvesting structures[71]. Small-scale irrigation from rivers or wells is used to mitigate critical dry spells[73]. Additionally, they integrate trees with crops and livestock (agroforestry) to improve soil fertility and water retention, with home gardens being a notable practice in the Gedeo Zone, eastern part of the sub basin[74].

Limitation of the study

This study provides a comprehensive analysis of meteorological, hydrological, and agricultural droughts using relevant datasets, including rainfall and temperature data to identify meteorological drought stream flow to evaluate hydrological drought, and soil moisture to assess agricultural drought. However, some limitations should be acknowledged. A primary limitation is the temporal misalignment between the meteorological and the stream flow data. This discrepancy constrains the historical scope of the hydrological drought analysis, which could affect the generalizability of the findings, particularly regarding long-term drought patterns.

Another limitation is the lack of a comprehensive spatial analysis. Due to the limited number of hydrological gauging stations and the unavailability of high-resolution spatial data for the sub-basin, the study focused on temporal analysis across four catchments separately. Consequently, the analysis of relationships between drought types relied on temporal statistical correlations, which, while providing valuable insights, do not fully capture the complex spatial dynamics of drought propagation.

These limitations underscore the need for future research to address the gaps in spatial analysis and quantitative drought propagation. Subsequent studies should prioritize acquiring high-resolution spatial datasets to enable integrated spatiotemporal analyses. The incorporation of robust spatial datasets and advanced methodologies, such as geospatial modeling, could enhance the understanding of drought dynamics and improve the predictive accuracy of hydrological models in the region. By transparently acknowledging these constraints, this study aims to inform and motivate future investigations to advance drought characterization and management in this critical area.

Conclusions

The main objective of this study was to investigate the impact of prevailing drought conditions in Ethiopia's Abaya Chamo sub-basin. Drought characteristics were analyzed using the Standardized Precipitation-Evapotranspiration Index (SPEI), Stream flow Index (SSI), and Standardized Soil Moisture Index (SSMI). The research revealed that the sub basin had the maximum drought intensity, as measured by the SPEI, SSI, and SSMI, with index values of −2.5, −2.8, and − 2.4, respectively. The Gelana catchment had the highest average drought magnitude, measuring − 130 for SPEI-3 and − 126 for SPEI-1. The majority of drought occurrences occurred between March and September, which corresponded to the crop growing season in the study area. This shows that drought has a major impact on water resource availability and agricultural productivity in the sub basin. The Gelana catchment experienced more severe drought conditions than the other three catchments, although the Bilate catchment experienced less severe drought.

These findings have important implications for future study on drought features in the Abaya Chamo sub basin. As a result, the study advises that stakeholders use adaptive water resource management techniques as well as comprehensive drought risk management strategies to improve regional food security. In addition, authorities should prioritize expenditures in monitoring systems and early warning methods to ensure successful drought mitigation planning. Future research should also prioritize the collection of high-resolution spatial data to allow for comprehensive spatial mapping and propagation analysis of drought types in the sub basin, as well as the use of geospatial tools to improve drought management and gain a better understanding of drought dynamics in various catchments in the Abaya Chamo sub basin. Overall, these findings highlight the critical need for proactive initiatives to mitigate the effects of drought on agricultural and water resources in the region.

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

Received: 15 February 2025; Accepted: 1 October 2025
Published online: 06 November 2025

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Acknowledgements
We are grateful to the Ethiopian Meteorological Institute (EMI) for providing the meteorological data. The same gratitude goes to the Department of Water, Irrigation, and Electricity (MoWIE) for providing the hydrological data. Besides, we acknowledge Arba Minch university for arranging facilities in the campus.

Author contributions
Mr. Tamirat Tessema Gillo collected analyzed and wrote the first text. Dr. Tadesse Tujuba Kenea, Dr. Yoseph Arba Orke, and Mr. Yared Godeine Demeke offered conceptual guidance, technical support, and suggestions for improvement. Additionally, all authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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