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Drought Characterization Using Multiple Indices over the Abbay Basin, Ethiopia

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Abstract: Analyzing agricultural and hydrological drought at different timescales is essential for designing adaptation strategies. This study aimed to assess agricultural and hydrological drought in the Abbay Basin of Ethiopia by using multiple indices, namely the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), normalized difference vegetation index (NDVI), vegetation condition index (VCI), and drought severity index (DSI). Climate extremes were assessed over the Abbay Basin between 1981 and 2022. The results indicate that the years 1982

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and 2014 were the most drought-prone, while the year 1988 was the wettest year in the Abbay Basin. The results revealed the presence of extremely dry and severely dry conditions, potentially impacting agricultural output in the region. Agricultural drought was identified during the main crop seasons (June to September). The VCI results indicated the presence of extremely wet and severely wet conditions. In 2012, 65% of the area was affected by extreme drought conditions, while nearly half of the Basin experienced extreme drought in 2013 and 2022. The DSI results indicated the occurrence of agricultural drought, although the spatial coverage of extreme dry conditions was lower than that of the other indices. In 2003, 78.49% of the Basin experienced moderate drought conditions, whereas severe drought affected 20% of the region. In 2010, about 90% of the Basin experienced moderate drought. This study provides valuable insights for agricultural communities, enabling them to mitigate the impact of drought on crop yields by utilizing different adaptation strategies. An adequate knowledge of agricultural and hydrological drought is essential for policymakers to assess the potential effects of drought on socioeconomic activities and to recognize the significance of implementing climate change adaptation measures.

Keywords: Abbay Basin; drought indices; drought severity index; SPI; SPEI; vegetation condition index

1. Introduction

Agricultural and hydrological drought assessments are crucial for providing reliable information for farming communities and decision-makers to design appropriate adaptation and mitigation measures. Both agricultural and hydrological droughts are aggravated by climate change. Climate change remains a pressing issue in the 21st century. It is agreed that climate change is having a greater impact on humanity than ever before. Climate change, particularly weather extremes, has a greater impact on food supply and demand. Accordingly, it significantly affects agricultural outputs, incomes, food quality, and food safety [1,2]. Many studies have confirmed that temperatures are rising almost everywhere in the world [3–6]. On a global scale, between 2001 and 2020, the surface air temperature increased within the range of 0.84 to 1.10 °C, surpassing the increase observed from 1850 to 1900, which was approximately 0.61 °C [7]. The IPCC report highlights the significant impact of the projected increase in the global mean temperature, which ranges from 1.5 °C to 2 °C. While temperatures are increasing worldwide, there is variation in rainfall patterns, with some areas experiencing an increase while others experiencing a decreasing trend [8].

Droughts are categorized into four classes: meteorological, agricultural, hydrological, and socioeconomic droughts [9]. Meteorological drought can be detected by using the SPI at one month timescales [10,11], agricultural drought at thee–six month timescales, while hydrological drought at twelve month timescales [12] and socioeconomic drought is associated with water supply and demand against the minimum requirements [13]. All drought types are interconnected. Meteorological droughts can lead to hydrological and agricultural droughts [14,15]. Meteorological drought refers to the absence of precipitation or rainfall for an extended period, while agricultural drought refers to a water deficiency to sustain plant growth [16]. Hydrological drought occurs when there is a lack of surface and subsurface water, resulting in below-average water availability [17,18]. On the other hand, socioeconomic drought refers to a situation where a watershed fails to meet the demand of various water-use sectors and their socioeconomic benefits [19], leading to water scarcity [20].

Drought and extreme rainfall are common in many countries. They can occur over years or decades and can have a negative impact on sustainable development goals (SDGs), mainly SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 7 (affordable and clean energy). While various factors contribute to the occurrence of extreme weather events, evidence strongly points to human activities as the major causes of floods and droughts [21–23]. The increasing trend of greenhouse gas emissions is the primary cause of global warming. Scientific evidence shows that the concentration of carbon dioxide

has increased by more than 50% (from preindustrial levels, when it was about 280 parts per million (ppm) in the 1700s, reaching more than 420 ppm in 2023 [24]. It is universally agreed that the global community should minimize the increase in global temperature to less than 2 °C above pre-industrial levels [4,25]. As global warming continues to intensify, it becomes evident that climate extremes, such as drought and floods, pose significant challenges to humanity [26–28].

Like other countries, Ethiopia has been exposed to climate extremes for many years [29–31] and will continue to be one of the most vulnerable countries in the future under business as usual. The 1983–1985 Ethiopian famine, driven by prolonged droughts, threatened the lives and livelihoods of millions of people [32]. As climate extremes are expected to increase in the future, the probability of rural food security in Ethiopia is unreliable [33]. The agricultural sector faces significant risks due to the impacts of climate change, which have become more frequent and severe in recent decades. This research highlights the importance of employing multiple drought indices such as SPI, SPEI, DSI, and VCI to accurately assess drought conditions. Based on these findings, specific adaptation strategies are necessary to mitigate the adverse impacts of drought on crop yield and water availability. These strategies include the adoption of drought resistant crop varieties and improved livestock breeds, improved water resource management, changing planting and harvesting dates, crop diversification, crop rotation, and the implementation of more efficient irrigation systems, all of which are critical for ensuring food security and agricultural sustainability under changing climate conditions.

In 2015, Ethiopia also experienced severe droughts [30,34]. Previous studies confirmed that droughts significantly affect the Ethiopian economy, which affects the lives of civilians [8,32,35]. Rainfall shocks are another climate-related disaster that significantly affects agricultural production and can lead to food insecurity and poverty in different parts of Ethiopia. The Lake Tana Basin, a region within the Abbay Basin, has recently experienced extreme and severe meteorological and hydrological drought [36], highlighting the urgent need for research on agricultural drought assessments to support farming communities in designing various adaptation strategies. This problem is also common around the Awash Basin as well in the pastoral communities in the southeastern part of the country.

A decrease in rainfall contributes to a 5% loss of agricultural gross domestic product around the Awash Basin of Ethiopia [37]. A previous study in southwestern Ethiopia found that rainfall during the main crop growing season declined [38]. This decline in rainfall has also had a considerable impact on livestock, which is highly vulnerable to climate change, within pastoral communities [39]. Between 2001 and 2003, the Somalia Regional State of Ethiopia experienced severe drought, which resulted in the loss of approximately 80% of the entire cattle population [40]. This loss of livestock increased the stress levels within communities and further exacerbated internal migration from areas affected by severe drought. Ethiopia, a rain-dependent farming community, is facing a significant challenge in livestock loss. This problem poses a serious threat to most of the population who rely heavily on agriculture, an economic sector highly susceptible to weather conditions [40].

Significant studies have been conducted to indicate the occurrence of drought in Ethiopia [27,29,37,41–48]. Some of these studies have focused on sub-watershed and micro-watershed scales, while others have been conducted at the country level. There is still a lack of drought characterization at the Basin level, especially in developing nations like Ethiopia. In addition to spatial limitations, most previous studies have focused on rainfall and temperature data, neglecting evapotranspiration and other environmental factors such as the normalized difference vegetation index (NDVI) and vegetation condition index (VCI), which could provide valuable information on the severity of agricultural and hydrological drought.

The World Meteorological Organization (WMO) has recommended the use of standardized precipitation index (SPI) for drought characterization [49]. This index utilizes only rainfall or precipitation data to quantify drought, without considering temperature, evaporation, and other environmental factors. The SPI is capable of detecting meteoro-

logical drought, agricultural drought, and hydrological drought at one month, six month, and twelve month timescales, respectively [10]. Another index, known as the standardized precipitation evapotranspiration index (SPEI), was proposed by Vicente-Serrano et al. [50] to address the limitation of SPI. The SPEI considers temperature and potential evapotranspiration to quantify drought. It assesses meteorological drought on a monthly scale, agricultural drought over a period of three to six months, and hydrological drought on a twelve month timescale [49,51,52].

Both SPI and SPEI are capable of identifying meteorological drought on timescales of less than three months, agricultural drought at three to six months, and hydrological drought on a timescale of twelve months. In addition to these indices, the Drought Severity Index (DSI) is widely used to characterize drought in a specific region. Initially proposed by Mu et al. [53] for drought assessment, the DSI was compared to the Palmer Drought Severity Index (PDSI) developed by Palmer [54]. The DSI is better than PDSI for drought monitoring [53]. This is because the PDSI relies solely on precipitation data, while the DSI considers evapotranspiration and vegetation conditions [55]. Vegetation condition index (VCI), developed by Kogan [56], is normalized by NDVI and quantifies the vegetation moisture status, directly indicating drought conditions [57]. Various agricultural crops have different tolerance levels to drought and require a depth investigation by using multi-indices. In the agricultural sector, drought stress indicators are consolidated based on several factors that account for the varying tolerance levels of different crops. These factors include physiological traits such as root depth, stomatal regulation, and water use efficiency. Genetic diversity also plays a role, with certain crops like sorghum and millet demonstrating a higher drought resilience compared to more sensitive crops such as maize. Additionally, mechanisms like osmotic adjustment and early maturation contribute to drought tolerance. The FAO's Crop Water Requirement Index provides a standardized framework for evaluating water-use efficiency across different crops, helping to classify their drought tolerance levels.

Due to a lack of complete rain gauge climate data and high-resolution satellite data, drought monitoring in the Abbay Basin remains poorly studied, hindering the management of its water resources and livelihoods. To overcome these limitations, combinations of various indices and geospatial technologies have been used to characterize agricultural and hydrological drought. There is an increasing need for information on farming and hydrological drought to support effective intervention plans that enhance public resilience to drought events. This study aims to provide a comprehensive analysis of drought conditions using multiple indices, including SPI, SPEI, DSI, and VCI, to capture different dimensions of drought (meteorological, hydrological, agricultural). By utilizing multiple indices, the study enhances the understanding of drought's effects on water resources, agricultural productivity, and broader climatic trends. Furthermore, the application of geospatial techniques to map areas susceptible to drought offers critical insights into spatial distribution of drought occurrences.

2. Materials and Methods

The study was conducted in Ethiopia, situated in the horn of Africa, where the majority of the population heavily relies on rain-fed agriculture. Geographically, the country is located between 30 and 150 north latitude and 330 and 480 east longitude. Ethiopia's topography exhibits a wide range of variations, with elevations ranging from −125 m below sea level at the Danakil Depression in the Afar region to 4620 m above sea level at Ras Dashen. The Abbay Basin, which spans an extensive area of 199,812 square kilometers, covers 20% of Ethiopia's land area. It stretches across three regions: the Amhara, Oromia, and Benishangul-Gumuz regions. In terms of coverage within these regions, the Abbay Basin covers approximately 60% of the Amhara region, 40% of Oromia, and 95% of Benishangul-Gumuz [58]. This basin comprises different sub-basins, including Anger, Beles, Dabus, Dedesa, Fincha, Gilgel Abbay, Gumara, Upper Gudar, Koga, Rib, and Jemma. The topography of the Abbay Basin varies from 493 to 4173 m above sea level (Figure 1).

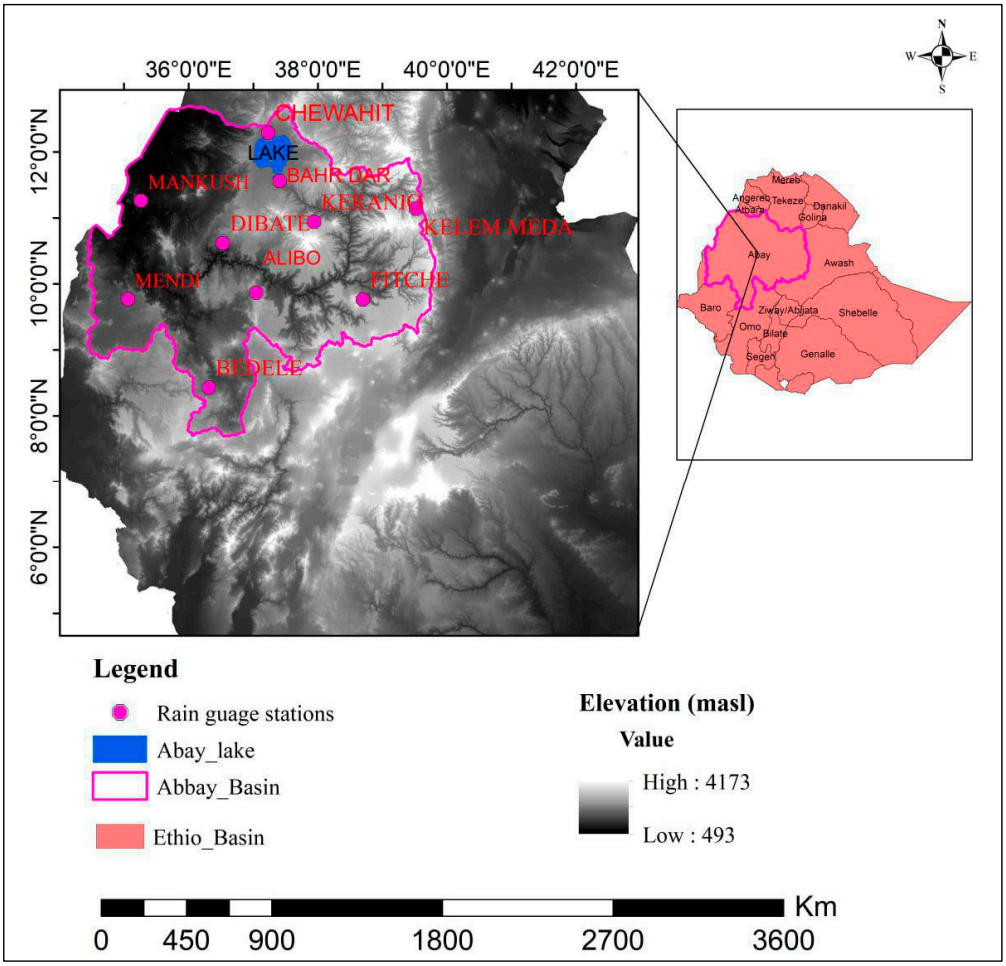


Figure 1. Map of the study area.

This difference in topography may be a significant reason for the variety of climates in the Basin. As a result, the Abbay Basin experiences a semi-desert and desert climate along the border of Sudan and a temperate climate around the high plateau in the northwestern-central part of Ethiopia. This Basin receives maximum rainfall during the primary crop-growing season (June to September).

The annual rainfall in the Basin varies from 400 mm near the Sudan border to 2200 mm in the Didessa sub-basin. The minimum and maximum ranges of air temperatures are between 15–20 °C and 28–38 °C, respectively [59]. A study on hydro-climatic trends in the Abbay Basin by Tekleab et al. [60] highlighted significant temperature increases, while precipitation did not exhibit significant trends. The study area is characterized by rainfed agriculture. Areas receiving less than 500 mm of annual precipitation are generally classified as dry land, whereas regions with more than 500 mm are often considered suitable for rainfed agriculture [61]. The most part of our study area receives high precipitation during the main crop growing season, contributing to diverse agricultural practices that include both rainfed and supplementary irrigation methods.

2.1. Data Sources and Descriptions

In the present study, various data sources, such as Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS), ground observed rainfall (rain gauge), and vegetation cover (eMODIS), were used to characterize agricultural and hydrological drought in the Abbay Basin (Table 1). The CHIRPS with station data version 2 was used for the SPI. The Moderate Resolution Imaging Spectroradiometer-based Normalized Difference Vegetation Index (eMODIS-NDVI) was used to assess the VCI and DSI.

Table 1. Data sources and descriptions.

Data Types	Year	Spatial Resolution	Temporal Resolution	Sources
CHIRPS data	1981–2022	0.05° (5 km)	Monthly	FEWS NET
eMODIS data	2003–2022	250 m	Dekadal	FEWS NET
Temperature data	1981–2022	Point data	Monthly	EMI

Where FEWS NET is the Famine Early Warning Systems Network and EMI is the Ethiopian Metrological Institute.

2.2. Method of Data Analysis

2.2.1. SPI

SPI is widely used to assess and monitor agricultural drought at various timescales [10,62]. For this study, the *SPI* was employed to calculate agricultural drought at 3 to 6 month timescales [12] using the ArcGIS version 10.8, as given in Equation (1). Positive SPI values indicate wetness, while negative values represent dryness. CHRIPS gridded datasets were used to analyze the *SPI* from 1981 to 2022. *SPI* values were categorized into five classes as suggested by McKee et al. [63] extremely wet (*SPI* > 2), very wet (1.5 to 1.99), moderately moist (1 to 1.49), mild drought (0.99 to −0.99), moderate drought (−1 to −1.49), severe drought (−1.5 to −1.99) and extremely dry (>−2). The graph output was drawn using OriginPro 2019 (Northampton, MA 01060, USA, https://www.originlab.com/2019, accessed on 15 March 2024).

$$SPI = \frac{X_i - \mu}{SD} \quad (1)$$

where *SPI* is the standardized precipitation index; X_i is the annual rainfall amount and μ is long term average rainfall, and *SD* is the standard deviation.

2.2.2. eMODIS-NDVI Based Vegetation Indices

The *NDVI* values show changes in vegetation greenness and are used for analyzing vegetation responses to drought [27,43,64,65]. The *NDVI* value ranges from −1 to +1 [66,67]. This study used *MODIS NDVI* data for the *VCI* and *DSI*. The *NDVI* value was derived from *eMODIS* data using ArcGIS, as given in Equation (2).

$$eMODIS\ NDVI = Float\frac{(Smoothed\ eMODIS\ NDVI - 100)}{100} \quad (2)$$

2.2.3. Vegetation Condition Index (VCI)

The *VCI* is derived from the *NDVI* and a robust index for drought monitoring. This index was calculated from the minimum and maximum *NDVI*, and the values ranged from 0 to 100% [27,43]. Equation (4) was used to calculate the *VCI*:

$$VCI = \frac{NDVI - NDVImin}{NDVImax - NDVi} \times 100 \quad (3)$$

where *NDVI*, $NDVI_{min}$, and $NDVI_{max}$ are the mean monthly/seasonal *NDVI* and its absolute long-term minimum and maximum *NDVI* values, respectively, for each pixel. Low percentages of *VCI* indicate poor conditions, while high percentages indicate optimal conditions [68]. According to Kogan et al. [69], a *VCI* ranging from 0 to <20% indicates extreme drought, while a *VCI* ranging between 20% and <35%, 35% and <50%, and >50% indicates severe drought, moderate drought, and no drought, respectively.

2.2.4. Drought Severity Index (DSI)

Using a surface energy balance, the *DSI* was developed to estimate the relative soil water deficit in the root zone [70]. The long-term DSI was computed from composite images of *eMODIS NDVI* during the rainy season by using a raster calculator in the ArcGIS environment using Equation (4). To calculate the *DSI*, the monthly *NDVI* value

and long-term mean *NDVI* for the same month were employed. We classified the *DSI* into five levels of drought severity based on Kogan et al. [69]: extreme drought (<−0.25), severe drought (−0.25 to −0.1), moderate drought (−0.1 to 0.1), mild drought (0.1 to 0.25), and no drought (>0.25).

$$DSI = NDVI_i - NDVImean \quad (4)$$

where $NDVI_i$ is the monthly *NDVI value*, and *NDVImean* is the long-term mean *NDVI* for the same month.

2.2.5. Assessment of Hydrological Drought

The SPI at a 12 month timescale was used to detect the presence of hydrological drought in the Abbay Basin following Vicente-Serrano [12]. The *SPEI* at a 12 month timescale was also employed to characterize hydrological drought in the Basin, as Vicente-Serrano et al. [50]. The *SPEI* is calculated from precipitation and temperature as climatic water balance [71,72]. In this study, we categorized the SPEI values into different categories: extremely wet (>2), very wet (1.50 to 1.99), moderately wet (1 to 1.49), and near normal (0.99 to −0.99). Conversely, moderately dry (−1 to −1.49), severely dry (−1.50 to −1.99), and extremely dry (>−2) following [8,73]. The *SPEI* was computed from the potential evapotranspiration (*PET*) and observed precipitation from 1981 to 2022, as given in Equation (5).

$$SPEI = \frac{P - PET}{\sigma} \quad (5)$$

where P is the observed precipitation, *PET* is the potential evapotranspiration, and σ is the standard deviation of the distribution of *P-PET*. In this study, we employed the L-moments technique [74] to estimate the parameters of the chosen distribution. L-moments are more robust for describing skewed data and outliers compared to traditional moments. This method ensures a better fit for non-normal precipitation distributions, which was a critical factor given the highly variable climate conditions in the study region.

3. Results

3.1. Agricultural Drought Analysis

3.1.1. SPI at 3-Month Timescales

In the present study, we analyzed drought severity classes at three–month timescales from 1981 to 2022. The results showed that 1982 and 2014 were the most drought-prone years throughout the Abbay Basin. Despite variations in drought severity, all ten Basin stations experienced drought conditions (Figure 2). In particular, from 1983 to 1987, drought frequently occurred in the Basin. During the five years (1983–1987), Dibate experienced extremely wet conditions with an SPI value of 3.24 and moderately moist conditions (SPI = 1.23) in 1985. The Dibate station also recorded moderately wet conditions in 1986 (SPI = 1.42). The results of this study will not only support farmers but will also assist different sectors in improving actual climate conditions to use climate change adaptation strategies. The historical Standardized Precipitation Index (SPI) plays a key role in supporting the design of climate change adaptation strategies. By analyzing historical SPI data, we identify drought trends and patterns as SPI helps in assessing long-term precipitation deficits or surpluses, providing valuable insights into historical drought events, their duration, intensity, and frequency. Thus, historical SPI provides a foundation for evidence-based adaptation planning by offering insights into past climate variability and guiding proactive responses to future changes. For instance, in areas experiencing agricultural drought, farmers can implement drought resistant crop varieties, changing or adjusting planting and harvesting dates, and adopt improved livestock breeds. Additionally, all key stakeholders should advocate the importance of soil and water conservation to minimize the impacts of agricultural droughts. Furthermore, the Disaster Preparedness and Emergency Response should focus on boosting

public resilience by providing up-to date information and engaging in drought related disaster and hazardous management strategies. The national meteorological agency is also encouraged to deliver reliable climate information in real or near real time at no cost.

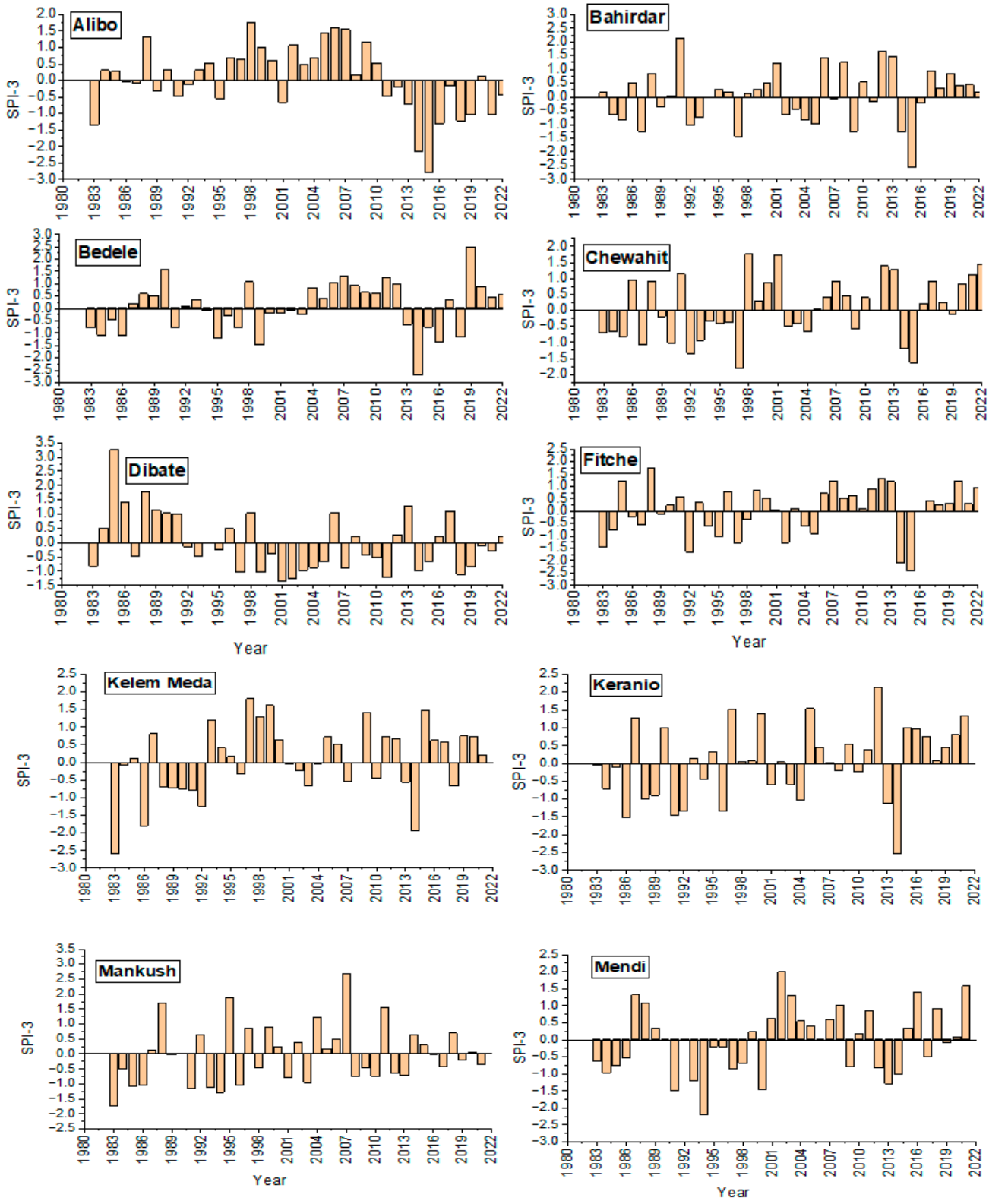


Figure 2. SPI values at three-month timescales at ten stations in the Abbay Basin.

Between 1981 and 2022, the Abbay Basin experienced varying levels of drought and wetness. After several drought years, the year 1988 was the wettest year across the Basin. Four years later, in 1992, with the exception of Bedele, drought was prevalent at all stations. The years 1992 and 1997 were other drought years in the Basin. In these two years, nine out of ten stations recorded mild to severe drought conditions. The year 2006 was the second wettest year, occurring after almost two decades (19 years). Between 2007 and 2013, a significant number of stations experienced no drought conditions. Following the wetter years, the years 2014 and 2015 were affected by a shortage of precipitation, including extremely dry conditions. Specifically, three stations, namely Alibo, Bedele, and Fitche, recorded extremely dry conditions. In 2015, four stations, namely, Alibo, Bahirdar, Fitche, and Keranio, experienced extremely dry, while the Chewahit and Kelem Meda stations experienced severe dry. In 1987, 1992, 1997, and 2015, nine of the ten stations experienced drought. Overall, 1982 and 2014 were the most drought prone years, while 1988 and 2006 were the wettest years in the Abbay Basin at three months timescales.

It is very important to investigate the conditions of rainfall, especially during the primary crop-growing season. Insufficient precipitation during this critical period can significantly impact the region's economy and lead to famine, if not managed well in advance. In the present study, we analyzed the drought categories in the years 1982, 1992, 2009, and 2015, specifically focusing on the main rainy season in the Abbay Basin. Our results revealed that extremely dry and severely dry conditions were observed, highlighting the problem of agricultural drought in the Basin. These extremely dry and severely dry conditions can affect crops' growth, leading to yield loss and low productivity. Except for July 2015, August 1992 and 2009, the remaining months experienced both extremely dry and severely dry conditions, as shown in Figure 3. In September 2009, nearly half of the Basin experienced severe dry conditions. Overall, July and August exhibited lower levels of drought than June and September throughout the study period. Most of the northern, central, southern, and southwestern parts of Ethiopia received maximum rainfall during June and July.

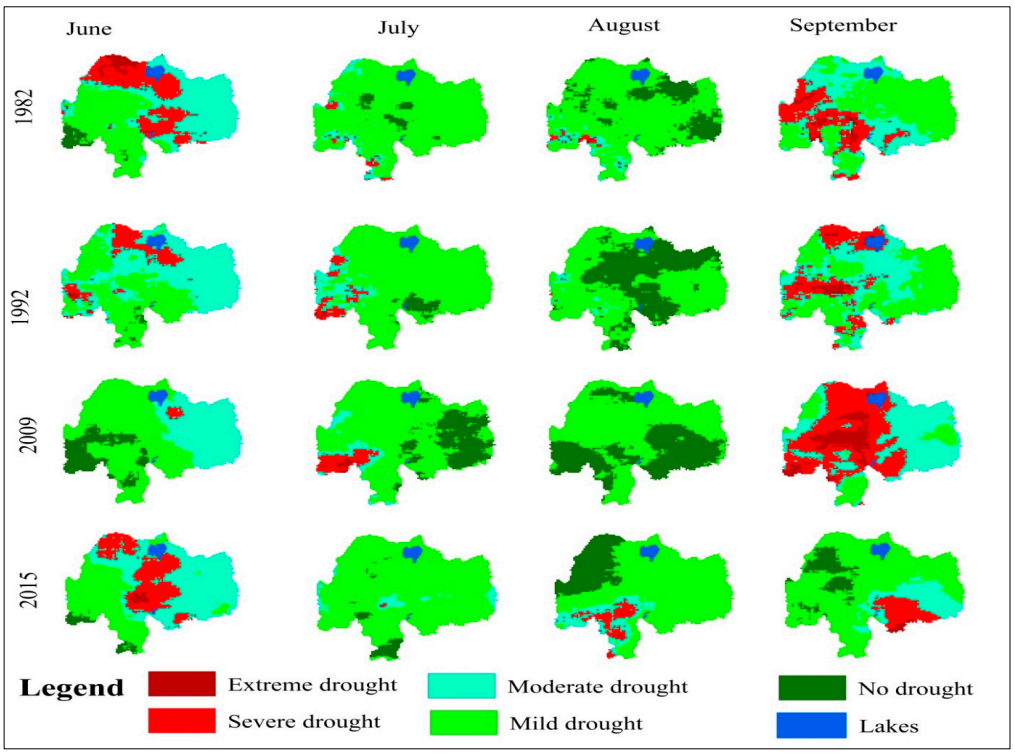


Figure 3. Spatial distribution of drought conditions (1982, 1992, 2009, and 2015) in the Abbay River Basin during the main crop-growing season (June to September).

3.1.2. SPEI at Three-Month Timescales

Agricultural droughts at three month timescales were analyzed using the SPEI. In this study, a low SPEI indicates dry conditions, while a high SPEI represents wet conditions (Supplementary Material (SM), Figure S1). The results revealed that all the Abbay Basin stations experienced extremely dry and extremely wet conditions (Table 2). Extremely dry areas were recorded at Alibo in 2005 and 2015. Additionally, severe dry was frequently recorded at this station in the 1980s, 1990s, and 2020s. In Bahirdar, extremely dry weather was recorded in 2015, while severely dry weather was recorded in the 1980s, 1990s, and 2020s. Bedele was extremely dry in 2003, 2006, and 2014. Additionally, significant numbers of severely dry were recorded at the Bedele station. The Chewahit station faced extremely dry conditions in 1982, 1984, 1990, 1999, and 2005. The Dibate station experienced extreme dryness in 2002 and 2005, while severely dry occurred in 1986, 1990, 2001, 2006, 2009, 2012, and 2013.

Table 2. Drought conditions based on SPEI three-month-timescales.

Station	Extremely Dry	Severely Dry	Extremely Wet	Severely Wet
Alibo	2005, 2015	1982, 1984–1985, 1990, 1994, 2001–2004, 2006, 2009, 2012–2015, 2017, 2018	1990, 1998	1987, 1989, 1993, 1996–1999, 2006, 2010, 2014, 2016, 2019
Bahirdar	2015	1982, 1984, 1987, 1992, 2002, 2005, 2006, 2009, 2012, 2017	1990, 1992, 1994–1995, 1999, 2013	1987, 1996, 1997, 1998, 2000, 2006
Bedele	2003, 2006, 2014	1984, 1991, 1994, 2000, 2002–2005, 2012, 2013	1988, 1990, 2007, 2010, 2014, 2019	1987, 1992, 1996–1997, 2007–2008, 2017, 2020, 2021
Chewahit	1982,1984, 1990, 1999, 2005	1986, 1992, 1995, 1997, 2002–2004, 2009, 2011, 2015, 2017	1987, 1990, 1996, 1997, 1998, 2014	1983, 1985, 1988, 1992, 1999, 2001, 2006, 2012, 2019, 2021
Dibate	2002, 2005	1986, 1990, 2001, 2006, 2009, 2012, 2013	1982, 1985, 1990, 1997, 2000, 2008, 2014, 2020	1981, 1987, 1990, 1991, 1999, 2008, 2016, 2017
Fitche	1984, 1999, 2005, 2006, 2008, 2015	1982, 1988–1989, 1992, 1994, 1997, 2000–2003, 2012–2014	1987, 1988, 1990, 1997, 2016, 2019	1981–1982, 1985, 1993, 1996, 1998, 2007, 2020
Kelem-Meda	1984, 1999, 2008, 2012	1982, 1987, 1992, 2000–2002, 2005, 2009, 2011–2012, 2015, 2017	1990, 1998, 2019	1981–1983, 1987, 1992, 1993, 1997, 2016, 2019, 2020, 2022
Keranio	2002, 2003, 2005, 2006, 2015	1984, 1987, 1988, 1992, 1995, 1999, 2000, 2009, 2012–2013, 2017	1982, 1990, 1996, 1998, 2014	1987, 1988, 1992, 1997–2000, 2013, 2016
Mankush	1982, 1991, 1995, 2001, 2010	1983, 1986, 1987, 1990, 1995, 2002, 2003, 2011, 2015–2016, 2022	1981, 1990–1992, 1998	1995, 1996, 2006, 2015, 2019
Mendi	1995, 1996	1982, 1986, 1990, 1992, 2001, 2005, 2009, 2012–2013	1997, 2016, 2017	1983, 1985, 1988–1989, 1996, 2008, 2014, 2019, 2022

In Fitche, extremely dry conditions were observed in 1984, 1999, 2005–2006, 2008, and 2015. Severely dry conditions also occurred in 1982, 1988, 1989, 1992, 1994, 1997, 2000–2003, and 2012–2014. Kelem Meda was extremely dry in 1984, 1999, 2008, and 2012. Keranio was extremely dry in 2002–2003, 2005–2006, and 2015. At Mankush, extremely dry conditions occurred in 1982, 1991, 1995, 2001, and 2010. Mendi was extremely dry in 1995 and 1996.

Similar to extremely dry and severely dry, extremely wet and severely wet have also been recorded in the Basin. Alibo experienced extremely wet conditions in 1990 and 1998. At Bahirdar extremely wet conditions were recorded in 1990, 1992, 1994–1995, 1999, and 2013. The Bedele station experienced extremely wet conditions in 1988, 1990, 2007, 2010, 2014, and 2019. At Chewahit extremely wet conditions occurred in 1987, 1990, 1996, 1997, 1998, and 2014. At the Dibate station, extremely wet conditions occurred in 1982, 1985, 1990, 1997, 2000, 2008, 2014, and 2020. Fitche station experienced extremely wet conditions in 1987, 1988, 1990, 2016, and 2019. At Kelem Meda, extremely wet conditions occurred in 1990, 1998, and 2019. At Keranio extremely wet occurred in 1982, 1990, 1996, 1998, and 2014. Mankush recorded extremely wet conditions in 1981, 1990–1992, and 1998; the Mendi station experienced extremely wet conditions in 1997, 2016, and 2017.

3.1.3. Vegetation Condition Index

We utilized the VCI, to indicate the presence of agricultural drought in the Abbay Basin. Unlike other remote sensing-based indices, the VCI assessed drought conditions, specifically during the main growing season. The results showed the occurrence of all drought severity classes within the Basin. Spatially, about 130,253.18 km^2 (65%) of the study area was affected by extreme drought conditions in 2012. In 2013 and 2022, approximately half of the Abbay Basin (49%) suffered from extreme drought (Table 3).

Table 3. Spatial coverage of drought severity classes based on VCI values.

Year	Drought Severity Class	Area (km^2)	Area (%)
2003	Extreme drought	70,723.74	35.3
	Severe drought	60,632.54	30.3
	Moderate drought	43,245.98	21.6
	No drought	25,550.62	12.8
	Total	200,152.88	100
2009	Extreme drought	83,098.62	41.5
	Severe drought	62,504.38	31.2
	Moderate drought	31,729.34	15.9
	No drought	22,820.54	11.4
	Total	200,152.88	100
2012	Extreme drought	130,253.18	65.1
	Severe drought	36,114.62	18.0
	Moderate drought	20,772.06	10.4
	No drought	13,013.02	6.5
	Total	200,152.88	100
2013	Extreme drought	98,461.18	49.2
	Severe drought	45,741.82	22.9
	Moderate drought	31,408.7	15.7
	No drought	24,541.18	12.3
	Total	200,152.88	100
2018	Extreme drought	86,708.86	43.3
	Severe drought	48,635.9	24.3
	Moderate drought	34,470.3	17.2
	No drought	30,337.82	15.2
	Total	200,152.88	100
2022	Extreme drought	98,147.1	49.0
	Severe drought	33,209.02	16.6
	Moderate drought	28,849.18	14.4
	No drought	39,947.58	20.0
	Total	200,152.88	100

A significant portion of the Basin experienced extreme and severe drought conditions in 2003, 2009, and 2018. These drought conditions significantly negatively impact crop

growth and agricultural production within the Basin. Based on the spatial distribution map of the VCI, it is evident that 2012 was the year with the most droughts, while 2003 had the least extreme and severe drought occurrences in the Basin (Figure 4). In 2022, the majority of the western and southwestern regions of the Basin were not affected by extreme drought or severe drought, while a considerable portion of the eastern, southeastern, and northern parts of the Basin experienced both extreme drought and severe drought.

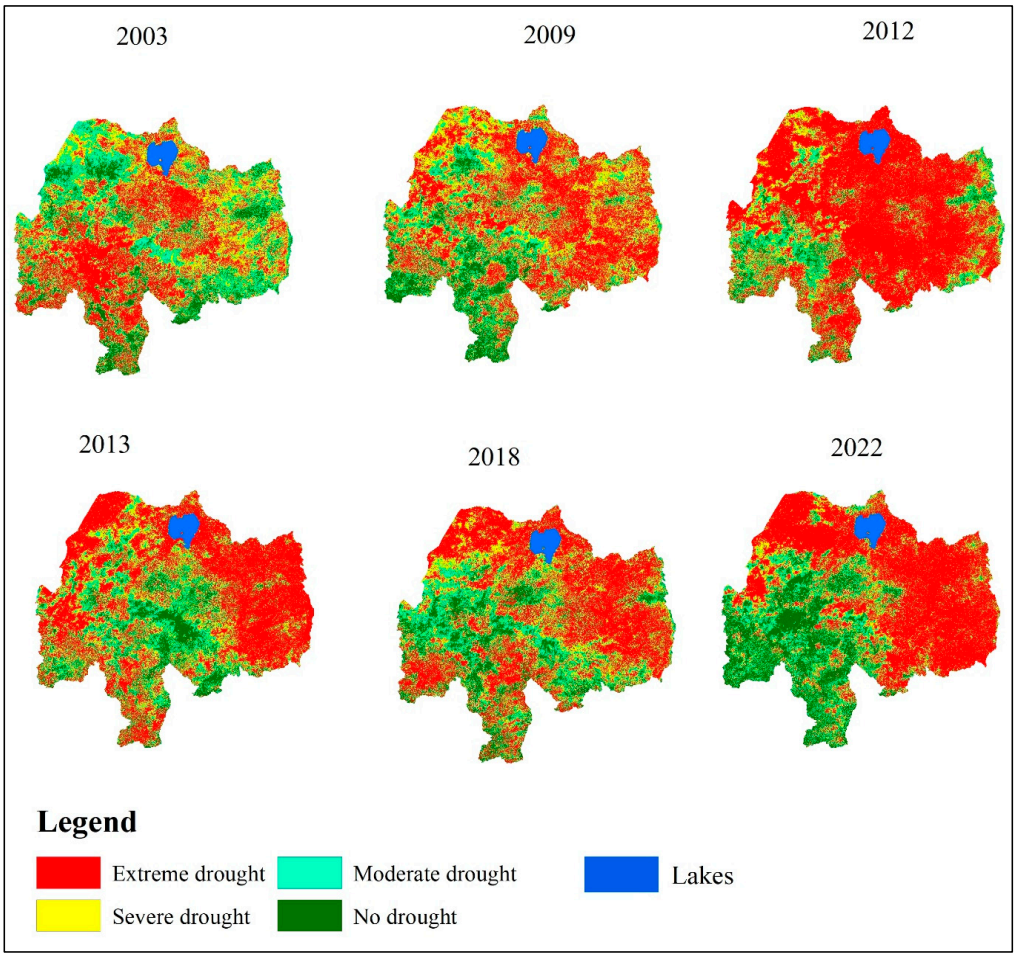


Figure 4. The spatial pattern of the VCI during the main crop growing season.

3.1.4. Drought Severity Index (DSI)

The drought severity index (DSI) is widely used to analyze meteorological and agricultural droughts. In 2003, moderate drought affected 78.49% of the Basin, while severe drought impacted 20% of the area. In 2005, the coverage of severe drought decreased to 5.84%, while the proportion of the Basin affected by moderate drought increased to 88.53%. In 2009, the area affected by severe drought increased compared to previous years. In 2010, more than 90% of the Basin experienced moderate drought conditions. In 2012, about 45.40% of the Basin experienced severe drought, while 51.50% faced moderate drought. The spatial distribution map of the DSI showed that the most extreme drought occurred in 2012, followed by 2022 (Figure 5). A significant portion of the Basin was affected by severe drought. For instance, 45% in 2012, 36% in 2022, and 31.15% in 2013 were affected by severe drought (Supplementary Materials Table S1).

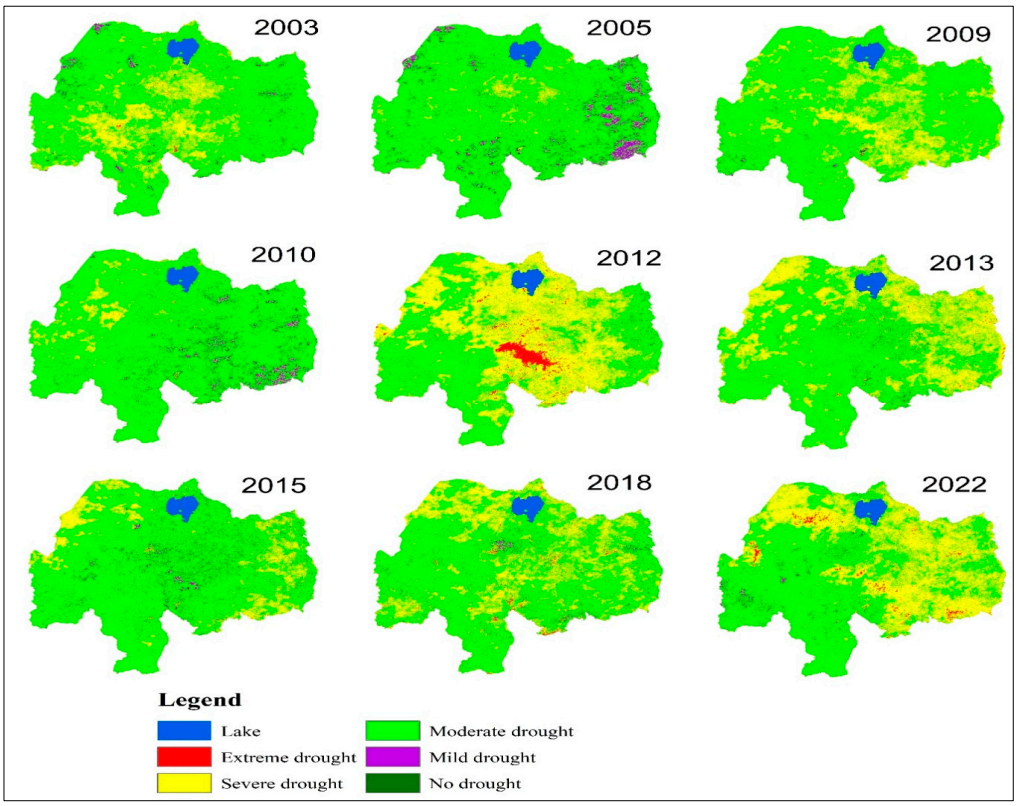


Figure 5. Spatial distribution map of the DSI in the Abbay Basin.

3.2. Hydrological Drought Assessment

3.2.1. SPI at 12-Month Timescales

Analyzing hydrological drought is particularly crucial in regions experiencing water scarcity, such as Ethiopia, where groundwater depletion and limited surface water availability pose significant challenges. Like three-month timescales, drought occurrences across the Abbay Basin have been detected at 12 month timescales (Figure 6). At 12 month timescales, all stations in the Basin experienced drought in 1982–1984, ranging from mild to extremely dry conditions. In 1985, except Dibate and Fitche, other stations in the Basin experienced mild and moderate moisture. In 1986, Chewahit and Kelem Meda were the only ones that did not record drought, while others experienced drought, including extremely dry conditions at Bedele and Mankush.

In 1988, no drought was detected in the Basin, which supports the SPI results at three month timescales. In 1990, all stations, except Fitche, experienced drought with varying degrees. In 1994 and 1995, the majority of the stations in the Basin experienced mild to moderately dry conditions. In 2002, all the stations in the Basin experienced drought, with extremely dry conditions occurring at Dibate. Between 2003 and 2005, most stations recorded mild to severely dry conditions. Conversely, in 2006, no drought was recorded in the Basin. In 2007, all stations, except Bahirdar and Dibate, experienced wetter conditions. Similarly, in 2008, only Fitche and Kelem Meda experienced drought, while the other eight stations received sufficient amounts of precipitation. In 2009, except for Bedele, all the stations experienced drought, including extremely dry conditions at Bairdar, with an SPI value of 2.50 (Supplementary Materials Figure S2). In 2017, no drought was detected at the 12 month timescale. In 2020, only mild drought was recorded at Mankush. The results revealed that all the stations in the Basin experienced mild to extremely dry conditions in 1982, 1983, 1984, and 2002. In contrast, in 1988 and 2017, no drought was detected in the Basin at 12 month timescales.

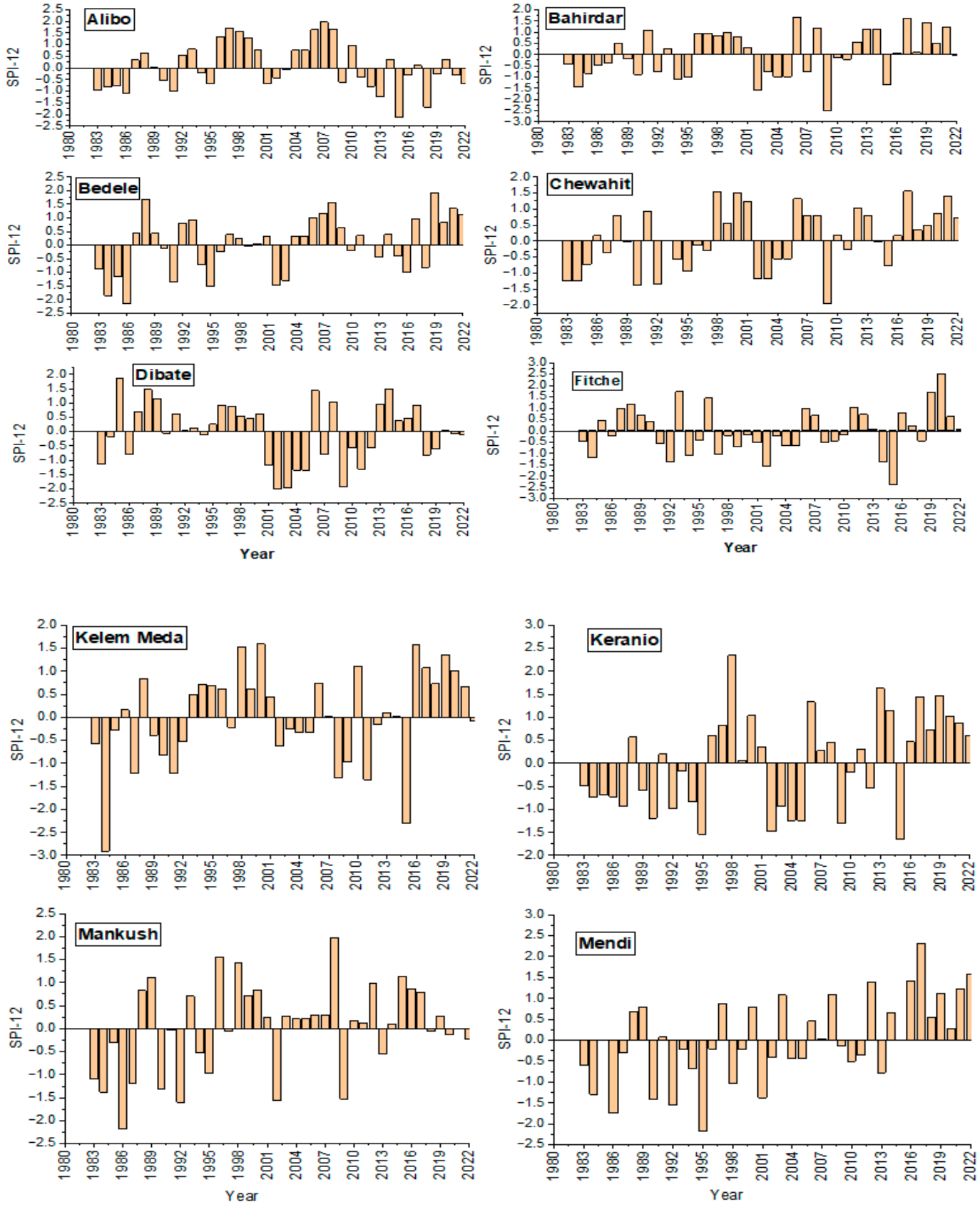


Figure 6. SPI values at 12 month timescales at ten stations in the Abbay Basin.

3.2.2. SPEI at 12 Month Timescales

A long-term drought assessment was performed using the SPEI-12. The analysis of SPEI was carried out at ten stations within the Abbay Basin to understand the severity of the hydrological drought conditions. Over 12 month timescales, except Chewahit, Dibate, and Mendi, other stations experienced extremely dry conditions. However, all the Basin stations experienced severe dry conditions between the 1980s and 2020s (Table 4). In contrast, the Basin also experienced extremely wet and severely wet periods. Except for Mankush, all stations in the Basin recorded highly wet conditions, although the frequency of occurrence was lower that at three month timescale.

Table 4. Drought conditions based on SPEI 12 month timescales.

Station	Extremely Dry	Severely Dry	Extremely Wet	Severely Wet
Alibo	2003, 2015	1986, 2002, 2012, 2018	2007	1996, 1997, 1998, 2008
Bahirdar	2003	2003, 2004, 2009	2014	1993, 1998, 2000, 2006, 2013, 2014, 2017, 2020
Bedele	2003, 2004	1984, 1986, 1995	1998, 2007	1988, 1993, 2009, 2019, 2020, 2021
Chewahit		1982, 2003, 2004, 2009	1998	1987, 1998, 2000, 2001, 2007, 2014, 2017, 2021
Dibate		2002–2005, 2009, 2012	1998, 1985, 1988, 1989, 2014	1991, 1999, 2016
Fitche	2002, 2015	1992,1998, 2004	1989, 2020	1993, 1996
Kelem-Meda	1984	1988, 1991, 2003, 2008, 2015	2016, 2020	1993, 1998, 2001, 2019
Keranio	2003	1998, 1992, 2002, 2003, 2004, 2005	1998, 2014	2020
Mankush	1983	1986, 1992, 1995, 1997, 2002, 2010		1981, 1989, 1991, 1996, 1999, 2008
Mendi		1992, 1995, 2002, 2003, 2006, 2010	2017	1989, 2016, 2020–2022

4. Discussion

4.1. Impacts of Agricultural and Hydrological Droughts

The impacts of drought are very complex and can significantly influence social, political, economic, and environmental outcomes. Drought is a multifaceted natural hazard with substantial impacts on agriculture, industry, ecological environment, and peoples' livelihoods [19]. When water availability for crops falls below the optimal level, it can greatly hinder their growth and overall productivity. Human activities significantly contribute to environmental changes, resulting in extreme climate events like drought and floods. There is ample evidence indicating that drought has a significant impact on the socioeconomics and livelihoods of countries that are heavily dependent on agriculture [1,2,8,32,35].

Our study aimed to assess agricultural and hydrological drought occurrences in the Abbay Basin of Ethiopia by utilizing multiple indices, such as the SPI, SPEI, NDVI, DSI, and VCI. Based on our assessment, all drought categories, namely, extreme drought, severe drought, and moderate drought, were detected in the Basin, which can hurt agricultural crop growth, yield productivity and water resource management. The SPI results over three month timescales indicated that the Abbay Basin experienced agricultural drought, but the severity levels varied across different periods and locations. In the early 1980s, particularly between 1983 and 1987, agricultural drought frequently occurred throughout the country, with high severity in the northern part of Ethiopia. Previous studies documented extreme and severe drought conditions during the 1980s [31,32,75]. Another study also highlights that drought was severe and intense in 1984–1985 over the horn of Africa [45].

This prolonged agricultural drought in the Abbay Basin led to significant losses in crop production and widespread food insecurity. More specifically, drought-driven famine in the early 1980s led to the loss of approximately 400,000 to one million lives [75].

Farmers were forced to abandon their fields or rely on emergency aid to survive. The government implemented various measures to mitigate the effects of the drought, including providing subsidies for farmers and improving irrigation infrastructures [76,77]. Despite these efforts, the impact of the agricultural drought on the local economy and population was devastating, highlighting the urgent need for sustainable water resource management and climate change adaptation strategies in the region. Thus, it is crucial to advise the agricultural communities to utilize drought-resistant crop varieties in order to minimize the risk of agricultural yield loss during the prolonged drought.

The results of the SPI and SPEI at 12 month timescales revealed different levels of drought, ranging from extremely dry to moderately dry. This indicates that the presence of hydrological droughts in the Abbay Basin significantly affects surface and subsurface water quality and availability [18,20]. It is clear that changes in land use and climate change can lead to hydrological reactions that have the potential to harm the entire ecosystems and the environment. The dynamics of land use and land cover can lead to hydrological reactions [78]. It is clear that changes in land use change can significantly impact the hydrological processes. Alterations in land use have played a significant role in the rise in the maximum temperature in the southwestern region of Ethiopia [38].

In 1983, 1984, 2002–2004, and 2015, extreme drought events were detected in the Abbay Basin. These extreme drought events severely impacted agriculture, water resources, and overall ecosystem health in the region. The decrease in surface water availability and the depletion of groundwater reserves during these drought years led to water scarcity and competition among various stakeholders [79]. The impact of hydrological drought extends beyond surface and subsurface water scarcity, as it also exerts and influences the environment and the whole climate system. Hydrological drought refers to negative anomalies in surface or subsurface water resources [17]. Analyzing hydrological drought is essential for understanding drought propagation and retrieval over a given region [80].

Additionally, these extreme drought events highlight the vulnerability of the Abbay Basin to climate variability and the importance of implementing sustainable water management practices to mitigate the impacts of future drought events. The findings of our study align with previous research that emphasizes the devastating consequences of drought events in Ethiopia. The 1980s drought resulted in substantial loss of life and property [32,75]. Another study reported widespread drought frequencies between 2002 and 2004 [81]. Our study also detected extreme drought in 2015. The El Nino-induced drought in 2015 contributed to the loss of agricultural production [34]. In 2015, Ethiopia experienced its worst drought due to El Nino. This El Nino-induced drought affected more than ten million people in 2016 [30,82].

Similar to three month timescales, different severity levels of drought were detected at 12 month timescales in the Basin. With the exception of Chewahit, Dibate, and Mendi, all the stations in the Abbay Basin experienced extreme drought. Different studies have documented the occurrence of extreme drought in various parts of Ethiopia [8,29,37,43,47]. Rainfall shocks have been reported as one of the driving factors of food insecurity in rainfed dependent economies. About 5% of the agricultural gross domestic product in the Awash Basin of Ethiopia was lost due to rainfall shortages [37].

It is clear that there is a direct link between food security and climate change, as the availability of food depends on climate conditions. Thus, climate related disruptions such as agricultural drought can have a significant impact on the livelihoods of smallholder farmers. A previous study by Tofu et al. [83] concluded that climate change-driven problems have played a significant role in contributing to food insecurity and poverty in the northern Ethiopia. The impact of drought is not limited to the northern part of the country, but also severely affects the southeastern part of the country, where numerous livestock have been lost due to shortage of pasture as the result of prolonged drought. Recently, the Borana people in the southeastern part of Ethiopia lost several million cattle due to a prolonged drought. In addition, a study conducted in the Somalia region between 2001 and 2003 resulted in the loss of approximately 80% of cattle in the area [39]. Our results indicate a

shortage of precipitation during the main crop growing season, specifically in June and September, while July and August receive sufficient amounts of rainfall. Consequently, rain-fed dependent farming communities are facing enough challenges regarding crop and livestock losses. This is mainly attributed to the sensitivity of the Ethiopian economy to climate variability and extremes [30,31,42].

Similar to extremely dry and severely dry, this study revealed that the Abbay Basin also experienced excess precipitation, which can have a significant impact on people's livelihoods, infrastructure, and natural environment. A study conducted by Sinore and Wang [84] in Ethiopia through meta-analysis indicates that both drought and flood have adverse effects on agricultural production. Based on the SPI and SPEI results at 3 month and 12 month timescales, extremely wet and severely wet conditions were recorded at different times in the Basin. However, the frequency of extremely wet and severely wet conditions was less frequent at the 12 month timescale than at the 3 month timescale. This study also detected extremely dry and severely dry. Duration and frequency of extremely dry and severely dry conditions, as well as highly wet and severely wet conditions, are significantly lower at the 12 month timescale than at the 3 month timescale [8,85].

In addition to the SPI and SPEI values, the presence of extreme climates was calculated using the VCI and DSI. Both indices are widely used to analyze agricultural drought [86]. The VCI is crucial to identifying agricultural drought during the main crop-growing season. We investigated the area covered by extremely dry and severely dry conditions in the Basin using the VCI. Our results are promising for policymakers since we calculated the area affected by extremely dry and severely wet conditions over the past few decades, specifically in the eastern, central, and northeastern parts of the Basin. In 2012, more than 65% of the Basin was severely dry, while nearly half of the Basin was severely dry in 2013 and 2022. This extreme drought and severe drought can hurt agricultural yields, which can lead to food insecurity in the region, as the main economy of the area is heavily dependent on a weather-sensitive economy. Household well-being was challenged due to food insecurity, driven by drought in Ethiopia [35]. In the present study, we identified drought severity classes, namely extreme drought, severe drought, and moderate drought, by using the DSI, a remote sensing-based drought assessment technique. Unlike other indices, the results of the DSI indicate the occurrence of extreme drought in the Basin is insignificant. However, moderate drought and severe drought were identified by using the DSI. In 2003, 2005, 2009, 2010, 2012, and 2015 significant areas in the Abbay Basin were affected by moderate drought conditions. Significant regions were affected by severe drought in 2012, 2013, and 2022.

The results of the drought assessment indicate a growing risk to agricultural productivity, particularly during critical growing seasons, as reflected in the three month SPI and VCI data. These findings underscore the need for targeted adaptation strategies to enhance resilience. For instance, the implementation of drought-resistant crop varieties, optimized irrigation techniques (such as drip irrigation), and soil moisture conservation practices are essential for maintaining crop productivity. Additionally, improved water management strategies, including rainwater harvesting and better groundwater usage practices, can help mitigate the impact of prolonged dry periods identified through the 12 month SPEI analysis. The integration of these adaptation strategies into local agricultural practices will not only enhance the sector's resilience but also ensure long-term sustainability in the face of increasing climate variability.

4.2. Practical Implications

Assessing agricultural and hydrological drought in rainfed dependent farming communities can support policymakers to design climate change adaptation strategies, including the use of drought resistant crop varieties and improved livestock breeds [40,84], indigenous knowledge application [87], changing planting and harvesting dates [88], use of small-scale irrigation and agroforestry systems [84], and livelihood diversifications. An increasing frequency of agricultural and hydrological droughts is expected due to land

use land cover changes and accelerating global climate change. The existing literature documented that rainfed dependent agricultural practices are one of the most susceptible to the impacts of climate change by significantly affecting crop yield [89,90]. Maintaining agricultural productivity requires the implementation of specific agronomic strategies, such as modifying fertilizer use, enhancing irrigation practices, selecting diverse crop varieties, promoting soil conservation and crop diversification [88]. Our results clearly indicate the occurrences of both agricultural and hydrological drought in the Abbay Basin of Ethiopia with different severity classes.

Contentious climate change assessment and monitoring are helpful to minimize the vulnerabilities of the farming communities from the effects of climate change, particularly extreme climate events such as drought and flood. It is essential to investigate the possible alteration in future water resources and water-related risks at the regional level due to global warming and local socioeconomic advancements [19]. Thus, the concerned stakeholders should provide reliable information, including short-term weather forecasts and longer-term climate change forecasts. Climate information can be connected to agricultural outcomes and management strategies to guarantee its accessibility and practicality for smallholder farmers [90]. Effectively conveying future climate change predictions to farming communities is vital for reducing the risks associated with agricultural yield loss, which can lead to food insecurity and poverty. Additionally, it is important to share information regarding agricultural and hydrological droughts with agricultural communities to support the adoption of diverse adaptation strategies.

5. Conclusions

This study employed multiple indices to assess agricultural and hydrological drought in the Abbay Basin of Ethiopia. The SPI, SPEI, VCI, and DSI indicate the presence of extremely dry and severely dry conditions in the Abbay Basin. In this study, agricultural drought is observed during the main crop-growing season, which can affect crop growth, yield, and quality characteristics. Both extremely dry and extremely wet conditions can significantly and negatively impact agriculture and other socioeconomic activities in the Basin. Like other countries, the problem of drought and excessive rainfall has been observed in the Abbay Basin during the study period (1982–2022). Under s business-as-usual scenario, there is a probability of future food and water insecurity due to extreme climate events in the Abbay Basin. Hydrological drought has the potential to adversely affect water resources in the reservoirs, leading to a reduction in energy potential such as hydroelectric power. The hydrological drought could potentially lead to a lack of water for irrigation and power generation in the neighboring nations. Thus, it is essential that all stakeholders should collaborate to address the underlying causes of both agricultural and hydrological drought. The present study provides valuable information for farmers to implement effective climate change adaptation strategies, thereby reducing the potential risks associated with climate extremes and disasters. The results of this study will not only support farmers but also assist different sectors in enhancing actual climate conditions on the ground for designing scenarios of climate change adaptation strategies. Additionally, further studies are needed to be undertaken to examine the impact of agricultural and hydrological drought on people's livelihoods and the natural environment. The results of this study can provide robust evidence for policymakers to design appropriate adaptation and mitigation strategies to minimize the negative impacts of agricultural and hydrological drought on the region's economy and beyond.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16213143/s1, Figure S1: SPEI at three month timescales in the selected station in the Abbay basin between 1981 and 2022. Table S1: Spatial coverage of drought severity index in the Abbay basin. Figure S2: SPEI at 12-month timescales in the selected station in the Abbay basin between 1981 and 2022.

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