Hindawi
Advances in Meteorology
Volume 2022, Article ID 2048077, 18 pages
https://doi.org/10.1155/2022/2048077

Research Article

Hydrological and Meteorological Drought Monitoring and Trend Analysis in Abbay River Basin, Ethiopia

Kassa Abera Tareke [1,2] and Admasu Gebeyehu Awoke [2]

[1] *Wollo University, Kombolcha Institute of Technology, Kombolcha, Ethiopia*
[2] *Addis Ababa University, Addis Ababa Institute of Technology, Addis Ababa 1000, Ethiopia*

Correspondence should be addressed to Kassa Abera Tareke; kassa.abera@aait.edu.et

Received 16 June 2022; Revised 7 November 2022; Accepted 15 November 2022; Published 28 November 2022

Academic Editor: Roberto Coscarelli

The definition of drought is very controversial due to its multi-dimensional impact and slow propagation in onset and end. Predicting the accurate occurrence of drought remains a challenging task for researchers. The study focused on hydrological and meteorological drought monitoring and trend analysis in the Abbay river basin, using the streamflow drought index (SDI), standardized precipitation index (SPI), and reconnaissance drought index (RDI), respectively, to fill this research gap. The study also looked into the interrelationships between the two drought indicators. The SDI, SPI, and RDI were calculated using long-term streamflow, precipitation, and temperature data collected from 1973 to 2014. The data were collected from eight streamflow stations and fifteen meteorological gauge stations. DrinC software (Drought Indices Calculator) was used to calculate the SDI, SPI, and RDI values. The result from meteorological drought using SPI12 and RDI12 shows that 1975, 1981, 1984, 1986, 1991, 1994, and 2010 were extreme drought years, whereas 1983, 1984, 2001, and 2010 were the most extreme hydrological drought years based on the SDI12 result. Except for Bahir Dar and Gondar, a severe drought occurs at least once a decade in all stations considered in this study. In general, the SPI, RDI, and SDI results indicated that the study area was exposed to the most prolonged severe and extreme drought from 1981 to 1991. The findings of this study also demonstrated that the occurrence of hydro-meteorological droughts in the Abbay river basin has a positive correlation at long time scales of 6 and 12 months. The trend analysis using the Mann–Kendall test implied that there was a significant meteorological drought trend in two stations (Debre Berhan and Fiche) at SPI12 and RDI12 time scale, but for the remaining thirteen stations, there is no trend in all time scales. The hydrological drought trend analysis in the basin on a seasonal (SDI3) and yearly (SDI12) time scale also revealed that three streamflow stations have a positive trend (Kessie, Gummera, and Border). This implies that water resource management is still a vital tool for the sustainable development of the Abbay river basin in the future.

1. Introduction

Drought is a series of problem everywhere in the world, and it aggravates food insecurity, causes shortage of water supply, and reduces irrigation and hydropower production for a prolonged period [1]. Contrasting to other natural hazards, such as floods, hurricanes, and tornados; droughts developed slowly in their onset and impacts. Therefore, the definition of drought is very controversial due to its multi-dimensional impact. However, based on the duration of the lack of different forms of water (precipitation, moisture, streamflow, etc.) and the development of drought impact, drought can be categorized into four. These are (i) meteorological drought, related to deficiency of precipitation, (ii) agricultural drought, which is a lack of soil moisture, (iii) hydrological drought, which is associated with a deficiency in surface and sub-surface water, and (iv) socio-economical drought, causing supply and demand imbalance [1–6]. Shortage of precipitation is the primary cause of meteorological drought and gradually propagates to agricultural and hydrological drought related to loss of soil moisture and decrease in surface and groundwater availability, respectively [7–10]. The overall aggregated drought impact develops into a socio-economic drought, in which the demand for water via different groups increases and may cause conflicts among the community [3, 11].

Most African countries are dependent on rainfed agriculture and highly vulnerable to climate change-induced hazards like floods and droughts [12]. In the last six decades, Africa was frequently affected by severe, intense, and widespread drought [13, 14]. In Africa, continentally the most unique extreme droughts were recorded during 1972/73, 1983/84, and 1991/92. Recent studies show that the African continent is expected to face widespread severe and extreme droughts in the coming years [13].

Ethiopia has an ample amount of water resources and serves as a source of surface water for other downstream countries like Sudan and Egypt. However, studies revealed that Ethiopia is under water stress due to a recurrence of drought [15]. The recurrence of catastrophe floods and droughts in Ethiopia leads to more economical loss [16]. Therefore, this drought phenomenon has increased the water stress in the eastern part of the country due to low surface water potential and unlimited demand for irrigation practices such as the Awash river basin. Even though the water stress problem is more common in these areas, water supply practice is concentrated in the western part due to the availability of excess surface and sub-surface water potential such as the Abbay river basin. To improve the imbalance in supply and demand as well as to mitigate drought impact, the construction of dams and reservoirs plays a great role [17].

Drought is still not well studied in Ethiopia both at the national and basin level. Relatively, meteorological drought analysis is studied in different basins of the country due to the easy accessibility of observed and satellite-recorded precipitation data [18–22]. However, the hydrological drought is still needing investigation to balance the available water potential for supply and demand. The Abbay river basin's hydrological and meteorological droughts were studied by Bayissa et al. [23], utilizing a standardized precipitation index (SPI) and standardized runoff-discharge index (SRI). However, for the hydrological drought analysis of the entire river basin, the researcher employed a single streamflow data at the Abbay border (Ethiopian-Sudan border), the outflow locations of the Abbay river basin. Since the standardized runoff-discharge index only provides a point value, it is challenging to see how the drought is varying spatially across the basin using just one streamflow station. Therefore, investigation of drought condition by considering additional streamflow stations which at least represent some sub-basins of Abbay river basin will give good information about spatiotemporal variability of drought over the entire basin.

The goal of this research is (i) to analyze the historical hydrometeorological droughts using SPI, RDI, and SDI, respectively, (ii) to determine long-term drought trends through the Mann–Kendall test, and (iii) to investigate the relationship between hydrological and meteorological droughts over the study period in Abbay river basin. Historically, droughts have frequently occurred in the Abbay river basin in the past four decades [23]. As a result, there is an obvious need for improved and integrated drought mitigation strategies developed in the Abbay river basin to minimize the adverse impact of future droughts. Therefore, this study has good information for researchers, planners, stakeholders, and Abbay basin authorities for future drought preparedness based on the historical drought trend findings.

2. Materials and Methods

2.1. Study Area Description. There are twelve major river basins in Ethiopia. Abbay river basin has an annual runoff of 54.5 BM^3 and covers an area of approximately 176, 000 km^2 which is the second largest basin in the country [20]. Spatially, Abbay basin is located at 7° 40′ N and 12° 51′ N latitude and 34° 06′ E and 40° 00′ E longitude [23] (see Figure 1). In the Abbay river basin, there are sixteen sub-basins from the major tributaries. This basin has crucial importance to Sudan and Egypt because it contributes 62% of the Nile River flow without considering the Baro Akobo and Tekeze river basins [24]. Topographically, the basin elevation ranges from 350 m near Ethiopia-Sudan border to 4230 m above sea level in the central part of the basin, lowest to highest, respectively [24, 25].

Depending on the topographical variation, the basin has high climate variation. The mean annual rainfall ranges from 780 mm to 2250 mm; in some parts of the basin such as Beshilo, Guder, Muger, and Weleka, the annual rainfall is less than 1000 mm. The minimum and maximum average temperature of the basin is 15°C and 28°C, respectively [24–27]. However, in the highland parts of the basin, the temperature is sometimes lower up to −1°C, and the maximum temperature for the northwestern part increases up to 38°C, respectively [26].

2.2. Data Collection and Preparation. The daily precipitation and temperature data were collected from fifteen stations in the Ethiopian Meteorology Institute (EMI). For the case of drought and climate change study, at least a minimum of 30 years of data is required [28]. Therefore, for this study, from 1973 to 2014 (42 years), precipitation and streamflow data were collected from different representative stations for hydrometeorological drought trend analysis. The streamflow data were collected from the Ministry of Water and Energy of Ethiopia (MoWE). Relatively, there are many gauging stations in the basin. The selection of rainfall and streamflow stations was focused on the length of available data, quality, and coverage area. The spatial location of all stations is indicated in Table 1. As shown in Figure 1, eight streamflow stations were selected; Gummera and Bahir Dar represent the upper Abbay basin in the north part, Kessie, Chemoga, and Guder represent the middle part of the basin, Gilgel Beles, the Ethiopia-Sudan border, represents the downstream part of the basin, and Robigumera represents the northeast part of the basin in Jema sub-basin. In this research, the analysis was conducted at monthly (SPI1, RDI1, and SDI1), seasonal (SPI3, RDI1, and SDI3), biannual (SPI6, RDI6, and SDI6), and annual (SPI12, RDI12, and SDI12) time scales. In the case of the 1-month, 3-month, and 6-month SPI, RDI, and SDI analyses, the wettest month

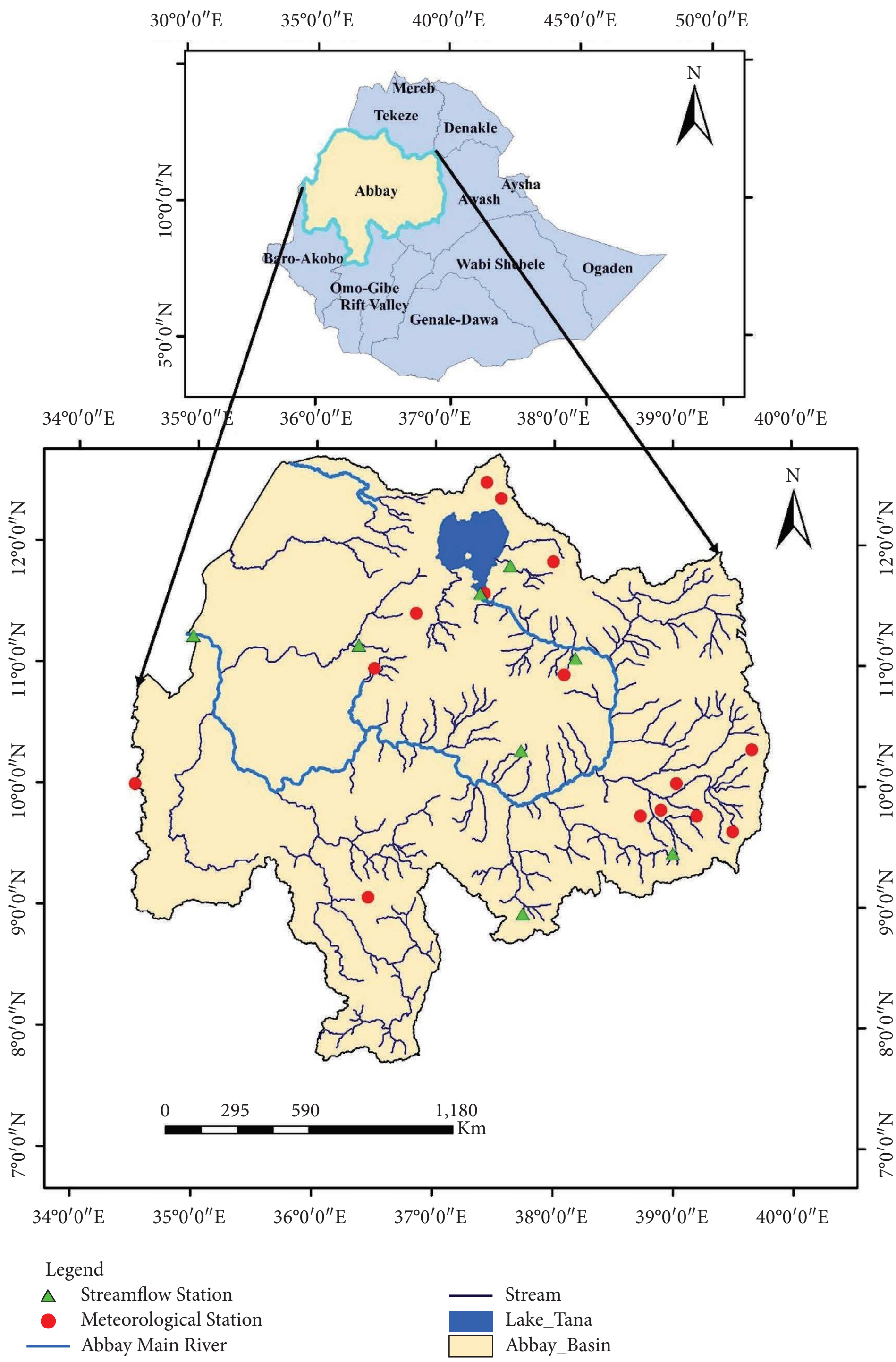

Figure 1: Location of hydrometeorological stations in Abbay river basin.

(August), the summer season (locally Kiremt, June to August), and six months (February to August), respectively, were taken into consideration. Because Ethiopia receives high rainfall during these months and seasons correspondingly, streamflow is also increased. To calculate these drought conditions, the observed precipitation, temperature, and streamflow data were prepared in a monthly manner and used as input for DrinC software (Drought Indices Calculator); recently, it is widely used in different countries to determine three drought indicators such as SPI, RDI, and SDI [29]. The minimum recorded data length in this study is 27 years at the Robigumera streamflow station and the maximum is 42 years in most streamflow stations and precipitation stations (see Table 1).

2.2.1. Filling Missing Data. After collecting the required data from their sources, the next step is preparing the data based

Table 1: Selected hydrometeorological station location in Abbay river basin.

Hydrological stations						
Station name	Latitude	Longitude	Area (km^2)	Annual flow (m^3/s)	Record year	Data length (year)
Border	11.28	37.23	17254	22348.4	1973–2014	42
Bahir Dar	11.6	37.38	15319	1386.02	1973–2014	42
Chemoga	10.3	37.73	364	61.12	1973–2008	36
Gilgele Beles	11.17	36.37	675	213.74	1973–2014	42
Guder	8.95	37.75	524	143.41	1973–2008	36
Gummera	11.83	37.63	1394	413.61	1973–2014	42
Kessie	11.06	38.18	65784	6280.65	1973–2014	42
Robigumera	9.45	39	887	106.94	1983–2009	27
Meteorological stations						
Station name	Latitude	Longitude	Elevation (m)	Mean annual rainfall (mm)	Record year	Data length (year)
Bahir Dar	11.6	37.42	1770	1423.88	1973–2014	42
Chagni	10.97	36.49	1614	1718.27	1973–2014	42
Gondar	12.52	37.43	1973	1161.29	1973–2014	42
Makisegnit	12.39	37.55	1912	1003.89	1973–2014	42
Gundewoin	10.93	38.09	2052	1569.47	1973–2014	42
Debre Tabor	11.87	37.99	2612	1535.97	1973–2014	42
Dangila	11.43	36.85	2116	1609.95	1973–2014	42
Mehalmeda	10.31	39.66	3084	865.42	1985–2016	32
Debre Berhan	9.63	39.5	2750	928.56	1985–2016	32
Alem Ketema	10.03	39.03	2280	1104.35	1985–2016	32
Deneba	9.76	39.2	2600	969.47	1985–2016	32
Lemi	9.81	38.9	2500	1311.75	1985–2016	32
Fiche	9.76	38.73	2784	1143.11	1985–2016	32
Assosa	10	34.51	1600	1079.02	1985–2016	32
Nekemt	9.08	36.46	2080	2065.86	1985–2016	32

on the models required and in line with the objective of the task. But the raw data may have been missing in different cases. Therefore, it is important to fill in the missing data using appropriate techniques. The most common missing data-filling techniques for meteorological data are the arithmetic mean method, normal ratio method, and inverse distance method [30, 31]. In this study, both arithmetic mean method and normal ratio methods were applied for some meteorological stations based on the percentage of the normal annual rainfall of missing data from normal annual rainfall (below 10%, arithmetic, and above 10%, normal ratio method) of the surrounding stations. The equations of the arithmetic mean method and normal ratio method are given below by equations (1) and (2), respectively.

$$P_x = \frac{1}{m}\left[P_1 + P_2 + P_3 + \ldots P_m\right], \qquad (1)$$

where P_x is rainfall at the missing station, $P_1, P_2, P_3, \ldots P_m$ represent rainfall at different stations, and m is the number of known stations considered.

$$P_x = \frac{N_x}{m}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \ldots \frac{P_m}{N_m}\right], \qquad (2)$$

where P_x and N_x are the required missed rainfall and normal annual rainfall; P_1, P_2, P_3, and P_m represent rainfall at different stations; and m is the number of known stations.

Table 2 describes the total number of missing data days from a period of 1973 to 2014 for seven meteorological stations and from 1985 to 2016 for eight stations. As indicated from the table, Assosa and Deneba stations have relatively more missing data. The analysis showed that the normal annual rainfall of Bahir Dar, Makisegnit, Gundewoin, Fiche, and Debre Berhan stations was found below 10% of the surrounding station's normal annual rainfall, whereas ten stations (Chagni, Dangila, Debre Tabor, Gondar, Lemi, Assosa, Nekemt, Mehalmeda, Alem Ketema, and Deneba) have a variation of above 10% of normal annual rainfall value compared to the surrounding stations. Therefore, the missing data for the former five stations were filled by using the arithmetic mean method and the latter ten stations were estimated using the normal ratio method. After filling in all the missing data, finally, the data were prepared in a monthly manner to check the homogeneity and consistency test. Besides, the streamflow missing data were filled using the regression method and the area ratio (AR) method to transfer the streamflow information in the near by station [32].

2.2.2. Data Quality Test

(1) Consistency Test. Water resource management and planning studies require long-term hydrological and meteorological data; therefore, a test must be conducted to check the homogeneity or self-consistency of the recorded data. This is necessary because, over some time, it may happen that there will be some obstructions like trees, buildings, and so on, which may have emerged after the installation of the gauge, or its location might have changed or observational procedure might have changed. The inconsistency of recorded data can be checked by graphical or statistical methods including double mass curve, the Von

Table 2: Percentage of missing rainfall data for selected gauge station in the Abbay river basin.

Station	Number of recorded data	Number of missing data	Missing (%)
Bahir Dar	15362	391	2.54
Chagni	15320	1915	12.46
Dangila	15320	2132	13.87
Debre Tabor	15320	1375	8.95
Gondar	15320	363	2.36
Gundewoin	15320	1852	12.05
Makisegnit	15320	173	1.12
Mehalmeda	8248	900	10.91
Debre Berhan	8248	360	4.36
Alem Ketema	8248	750	9.09
Deneba	8248	1580	19.15
Lemi	8248	1020	12.36
Fiche	8248	180	2.18
Assosa	8248	1540	18.67
Nekemt	8248	480	5.82

Neumann ratio test, cumulative deviation, run test, and specific flow test. However, the double mass curve method is one of the most common and widely accepted methods for checking the consistency of rainfall and streamflow records [33–35]. This method is based on the assumption that the mean accumulated precipitation for a large group of stations is not significantly affected by a change or changes in individual stations.

(2) Homogeneity Test. Homogeneous rainfall records are often required in hydrologic design. However, it is frequently occurring that rainfall data over different periods are not comparable since the measured amount of rainfall depends on factors such as the type, height, and exposure of the rain gauge, which have not always been the same. Therefore, many meteorological institutes maintain an archive with information on the rain gauge sites and the instruments used. Unfortunately, it is often not possible to specify the nature of changes in the mean amount of rainfall from the station documentation. This is partly because it is not always known how a change in the instrument or the rain gauge site may influence the measured amount of rainfall and partly because it is highly questionable whether the station information gives a complete picture of the rain gauge site during the period that the station has been in operation. Therefore, a homogeneity test is used to check the homogeneous and non-homogeneous stations for a specific study area and also used to determine the trend availability. The homogeneity test was obtained by determining the monthly non-dimensional value of each station within the basin [36, 37]. It is given by

$$P_i = \frac{P_{\text{av.}m}}{P_{\text{av.an}}} * 100, \qquad (3)$$

where P_i is the non-dimensional percentage (%) and $P_{\text{av.}m}$ and $P_{\text{av.an}}$ represent the long-term monthly average and annual rainfall, respectively.

2.3. Drought Analysis Methods. Drought indices are considered a powerful statistical value used to monitor drought conditions and to develop an early warning system for a region. Many drought indices have been developed in the last few decades, and most of them are region specific and have some limitations in different climate regions [38, 39]. Therefore, the selection of drought indices for a specific study area depends on many factors. The most common selection criteria are the number of input data required, data availability, the objective of the study, climate condition, novelty of the index, and validity which are the factors that determine the selection of indicators [38, 40].

There are several types of drought indicators used for meteorological and hydrological drought monitoring. It is difficult to prioritize the effectiveness of one index from others due to the complex nature of drought [38]. However, based on the literature recommendation and the objective of the index developed, it is possible to select the appropriate drought index related to the aim of the specific study. Meteorological drought can be monitored by simple to complex indices such as percentage decile (%), standardized precipitation index (SPI), Palmer drought severity index (PDSI), reconnaissance drought index (RDI), standardized precipitation-evapotranspiration index (SPEI), and so on [41–44]. Recently, the World Meteorological Organization (WMO) presents SPI as a universal meteorological drought index. It is due to its ability to monitor drought for multiple time scales, and it is comparable between different regions or watershed drought events [45, 46]. RDI and SPEI are the most important meteorological drought indices by incorporating the effect of potential evapotranspiration in addition to precipitation variability [43]. Especially in a climate region highly dominated by glaciers and ice, the variation of temperature plays a great role and RDI and SPEI are very important to monitor drought trends. Even though the variability of precipitation has more impact on the development of drought phenomenon than temperature variation in Ethiopia, both SPI and RDI were selected in this study to monitor the meteorological drought variability in the Abbay river basin. Commonly, deviation of precipitation from the long mean value is an indicator of drought onset. However, its impact is dependent on the duration of no rain times as well as the rate of evapotranspiration during the drought season. Therefore, RDI plays a great role to analyze meteorological drought by considering the impact of temperature variability in addition to precipitation variability [47, 48].

Agricultural and hydrological drought analysis indicators are more limited because of extensive input data requirements. Some of the most common agricultural drought indices are PDSI and soil moisture deficit index (SMDI) [21], whereas hydrological drought indices are streamflow drought index (SDI), Palmer hydrology drought index (PHDI), and surface water supply index (SWSI) [4, 49, 50]. PHDI and SWSI need more data related to soil moisture and groundwater level and reservoir water level. But in developing countries such as Ethiopia, it is difficult to access all the required input data. So, the simplest and most common streamflow-based drought index (SDI) was used to characterize the hydrological drought phenomena in this study [9, 51–53].

Therefore, in this study, the historical meteorological and hydrological droughts in the Abbay river basin in Ethiopia were analyzed by using SPI, RDI, and SDI, respectively. This analysis was considered for four time scales: monthly (SPI1, RDI1, and SDI1), seasonal (SPI3, RDI3, and SDI3), biannual (SPI6, RDI6, and SDI6), and annual (SPI12, RDI12, and SDI12). In Ethiopia, there are four seasons, Autumn (September to November), Winter (December to February), Spring (March to May), and Summer (June to August). In the Abbay river basin, the precipitation and streamflow volume are high during the summer season. Therefore, in this study, the monthly, seasonal, and biannual meteorological and hydrological drought analysis was focused on the summer season for August, June to August, and March to August.

2.3.1. Standardized Precipitation Indices. For the first time, McKee et al. (1993)[54] developed the standardized precipitation index (SPI) at the University of Colorado State [55]. It is the most popular meteorological drought monitoring index. Its popularity is due to its low data requirement, statistical analysis approach, and ease of calculation, and it can also describe drought in spatial and temporal extent [56]. SPI is widely used for meteorological drought analysis. But for the long-term time scale (12, 24, and 48 months), it is also used for hydrological drought analysis in case of a lack of streamflow data [57]. But the input data only include precipitation and do not consider the influence of temperature [48].

A probability distribution function of SPI should fit the accumulated precipitation data for each time scale. Finally, the precipitation data were transferred to a standard normal distribution with a standard deviation of one and a mean of zero, respectively. The objective of transformation is to make SPI comparable in time and space (temporal and spatial variability). Gamma distribution is the most common fitted function to precipitation data in SPI calculation [56]. Accordingly, SPI can be determined using the following equation:

$$\mathrm{SPI} = \frac{X_i - X_m}{\sigma}, \tag{4}$$

where X_i is the value of precipitation at i^{th} month or season and year, X_m is the mean monthly, seasonal, or annual precipitation, and σ is the standard deviation of recorded precipitation.

2.3.2. Reconnaissance Drought Index. RDI is a recent drought analysis indicator which considers the effect of temperature in drought monitoring [43]. SPI only uses precipitation data, whereas RDI uses both precipitation and temperature as input data to overcome the limitation of SPI to understand the effect of temperature on water balance [47]. RDI computation is based on the ratio of total precipitation and potential evapotranspiration. Potential evapotranspiration is estimated using maximum and minimum temperature values. The procedure of RDI value classification and analysis is the same as SPI. The classification of drought conditions is the same as SPI which ranges from −2 to 2, extreme drought to extreme wet, respectively (see Table 3). The calculation of RDI is given by

$$\mathrm{RDI} = \sum_{n=1}^{12} \left(\frac{P_{ij}}{\mathrm{PET}_{ij}} \right), \tag{5}$$

where P_{ij} is seasonal precipitation at i^{th} rain gauge station and j^{th} observation and PET_{ij} is seasonal potential evapotranspiration at i^{th} rain gauge station and j^{th} observation.

2.3.3. Streamflow Drought Indices. Hydrological drought analysis is not an easy task like meteorological drought analysis. It requires many input data in the hydrologic cycle. However, Nalbantis and Tsakiris (2009) [59] developed the streamflow drought index (SDI) which is a simple hydrological drought indicator using a single kind of hydrological data, streamflow [60]. The calculation of SDI is similar to SPI and it has the same efficiency and simplified characters as SPI. SDI is estimated using monthly streamflow volume to control hydrological drought and water supply shortage at different time scales such as short, medium, and long term. Using aggregated streamflow volumes V_{nq}, the SDI can be determined at different reference times q of the n-th hydrological year as given by the following equation:

$$\mathrm{SDI} = \frac{V_{n,q} - V_{qm}}{S_q}, \tag{6}$$

where $n = 1, 2; \ldots$ and $q = 1, 2, 3, 4$.

V_{qm} and s_q are the mean and the standard deviation of cumulative streamflow volumes of the reference period q as these are estimated over a long period, respectively. According to McKee (1993) and Tsakiris et al., (2009), the wetness and dryness value of SPI and SDI is between −2 and 2.

Table 3 shows different drought categories, and the extremely dry and wet values are below or equal to −2 and above 2, respectively. The number of drought classification using SPI, RDI, and SDI varies from seven to nine, in which

Table 3: Hydrometeorological drought category based on SPI, RDI, and SDI values [58].

SPI, RDI, and SDI ranges	Drought categories
>2	Extremely wet
1.5–1.99	Severely wet
1.0–1.49	Moderately wet
−0.99–0.99	Near normal
−1.0–−1.49	Moderate drought
−1.5–−1.99	Severe drought
<−2	Extreme drought

some classification merges slightly wet and normal values (0.5–0.99 and −0.5–0.49) into −0.5–0.99 as a normal range [23, 42].

2.4. Drought Trend Analysis Using Mann–Kendall Test. Many historical studies indicated that climate variability is the main threat in different regions of the globe in the future [61]. There are several methods to detect drought trends in terms of streamflow and rainfall such as statistical approaches and rank-based tests [62]. Statistical methods include slope-based tests, least squares linear regression (LR), Sen's slope estimator (SS), and rank-based tests based on the Mann–Kendall (MK) test and Spearman rank correlation (SRC) test [63]. Pre-whitening, trend free pre-whitening, and variance correction with the Mann–Kendall test are considered in the serial correlation effect by statistical approaches [64]. In this study, the Mann–Kendall test is used to detect hydrological and meteorological drought trends at a 5% significance level based on the value of SDI and SPI time sequences in the Abbay river basin by using the AUTO_MK_Sen.exe software.

The Mann–Kendall (MK) test is determined using two sequential time series (X_j and X_i) from n data points in a series [64]. Each subsequent data value in a given time series is compared with other data of the series. The value of statistics S can be increased or decreased by 1 based on the rearrangement of the data sequence of earlier and later data values. Then, the statistics S value is calculated using the two incremental and decrement data values' net result. Therefore, the Mann–Kendall (MK) test statistic S is estimated using the following equations:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Sign}\left(X_j - X_i\right),$$
$$\mathrm{Sign}\left(X_j - X_i\right) = \left\{ \begin{array}{l} 1; if\ H_j - XI > 0 \\ 0; if\ X_j - X_i = 0 \\ -1; if\ X_j - X_i < 0 \end{array} \right\}, \tag{7}$$

where x_j and x_i are the data values in years j and i, respectively. If the number of data points in the time series is less than 10, then the value of $|S|$ is compared directly to the distribution S; in other cases, if the number of data points in the time series is greater than 10, then the value of statistic S is distributed by the mean and variance shown in equation (8), respectively.

$$E(S) = 0,$$
$$\mathrm{Var}(S) = \frac{m(-1)(2m+5) - \sum_{k=1}^{n} k1(k1-1)(2k1+5)}{18}, \tag{8}$$

where m and k_i represent the number of SPI and SDI time series and the ties of the sample time series, respectively.

The performance of the Mann–Kendall test was computed by AUTO_MK_Sen.exe, and the calculated statistics Z_c test is given by

$$Zc = \left\{ \begin{array}{c} \frac{S-1}{\sigma};\ if\ S > 0 \\ \\ 0;\ if\ S = 0 \\ \\ \frac{S+1}{\sigma};\ if\ S < 0 \end{array} \right\}. \tag{9}$$

The calculated Z_c statistics follow a normal distribution and positive and negative Z_c values indicate an increasing and decreasing trend for a given time series period, respectively.

2.5. Spatial Distribution Analysis of Drought. The spatial distribution of drought analysis is important for appropriate drought preparedness and early warning system development [27, 65–67]. There are several interpolation techniques to display drought-affected areas in ArcGIS software. Among those, the inverse distance weighted (IDW) interpolation technique is suitable for heterogeneous topography like Ethiopia [68, 69]. The inverse distance weighted (IDW) spatial analysis tool in ArcGIS software is used to analyze the drought-prone area and its extension over the basin at a specific drought year after the temporal drought has been properly determined using SPI, RDI, and SDI. The value of selected severe and extreme drought events by SPI, RDI, and SDI is used as input for the IDW tool. This geographical analysis tool is intended to pinpoint places that are extremely prone to drought and to display the size of the coverage areas that are affected by it.

3. Results and Discussion

3.1. Consistency and Homogeneity Checking of Rainfall Data. The consistency of all selected rainfall stations was checked using the double mass curve analysis method. As shown in Figure 2, one gauging station, Nekemt, is slightly deviated from a straight line compared to the remaining 14 stations. But the variation is not that exaggerated. Most stations are located in the upstream part of the river basin in the northern and northeast direction (see Figure 1) in which the area relatively received less rainfall compared to the middle and western parts of the basin. Even though the gauge stations were taken from different sub-basins of the Abbay river basin, it can be seen that all stations have a straight line relation with the mean cumulative rainfall value of all stations in the study area. Therefore, all fifteen stations are considered for further meteorological drought analysis in the basin.

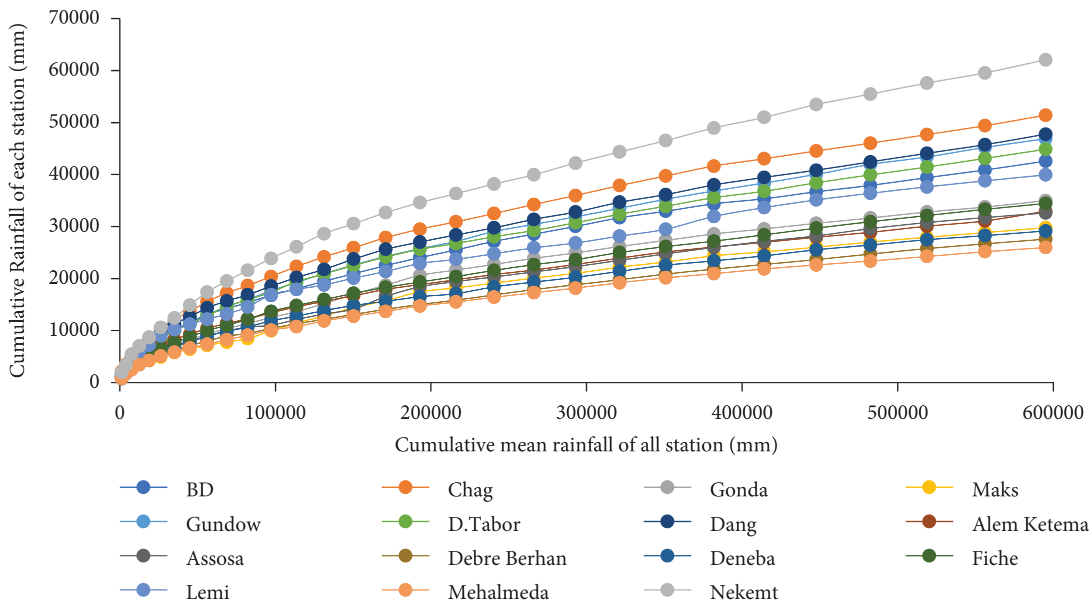

Figure 2: Consistency test of rainfall data in Abbay river basin using double mass curve.

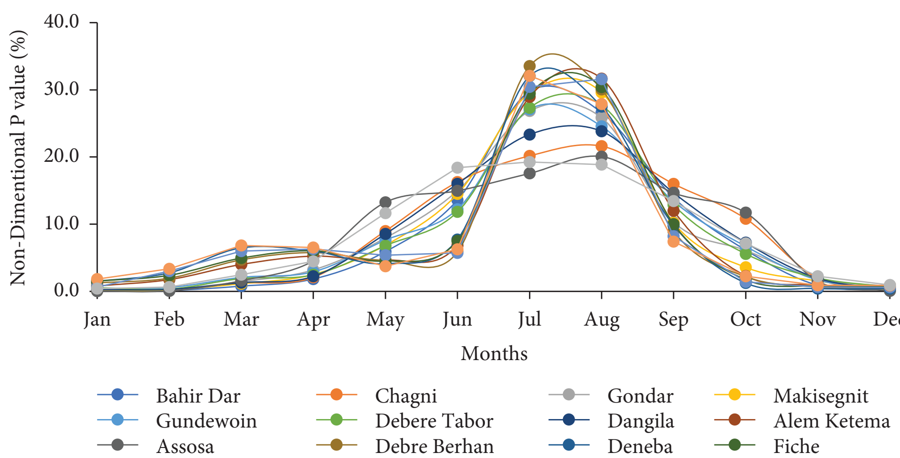

Figure 3: Rainfall data homogeneity test in the Abbay river basin.

Following the consistency test, it is important to check the homogeneity of rainfall gauge stations' time series. The homogeneity of fifteen rainfall stations was checked using a non-parametric ratio method in the Abbay river basin, Ethiopia. The result indicates that almost all selected stations are relatively homogeneous. But as shown in Figure 3, Chagni, Nekemt, Assosa, and Dangila stations are non-homogeneous during July and August months. Since the representative rainfall stations were collected from different sub-basins of the Abbay river basin in which there are high spatial variations, a slight change in inhomogeneity can be expected. However, the variation is not significant; therefore, all the stations were considered for this study.

3.2. Meteorological Drought Characteristics Using SPI and RDI. A meteorological drought analysis was conducted in the Abbay river basin using SPI and RDI from fifteen meteorological stations from 1973 to 2014 and 1981 to 2016, respectively. Meteorological drought analysis via SPI is mostly considered for a short time scale, one to six months (SPI1, SPI3, and SPI6). However, for areas lacking hydrological data (streamflow), SPI12 and above are used for hydrological drought analysis [18, 20, 23]. But in this study, SPI1, SPI3, SPI6, and SPI12 were computed for meteorological drought monitoring, and the result indicated that drought severity increased as the time scale increased from SPI1 to SPI12, but the frequency of occurrence decreased over a long time scale analysis. Figure 4 shows that the period 1981 to 1996 was the longest drought season and frequent moderate to severe droughts occurred for all time scales. Commonly, the periods 1981–1996, 2001–2004, and 2008–2010 experienced moderate to extreme drought while the period 1997–2000 was the wet period in the Abbay river basin. Bayissa et al. [20] stated that the Abbay river basin was in severe drought in the years 1978/1979, 1984/1985, 1994/1995, and 2003/2004. The result of this study also agreed with this finding, but there were some additional severe

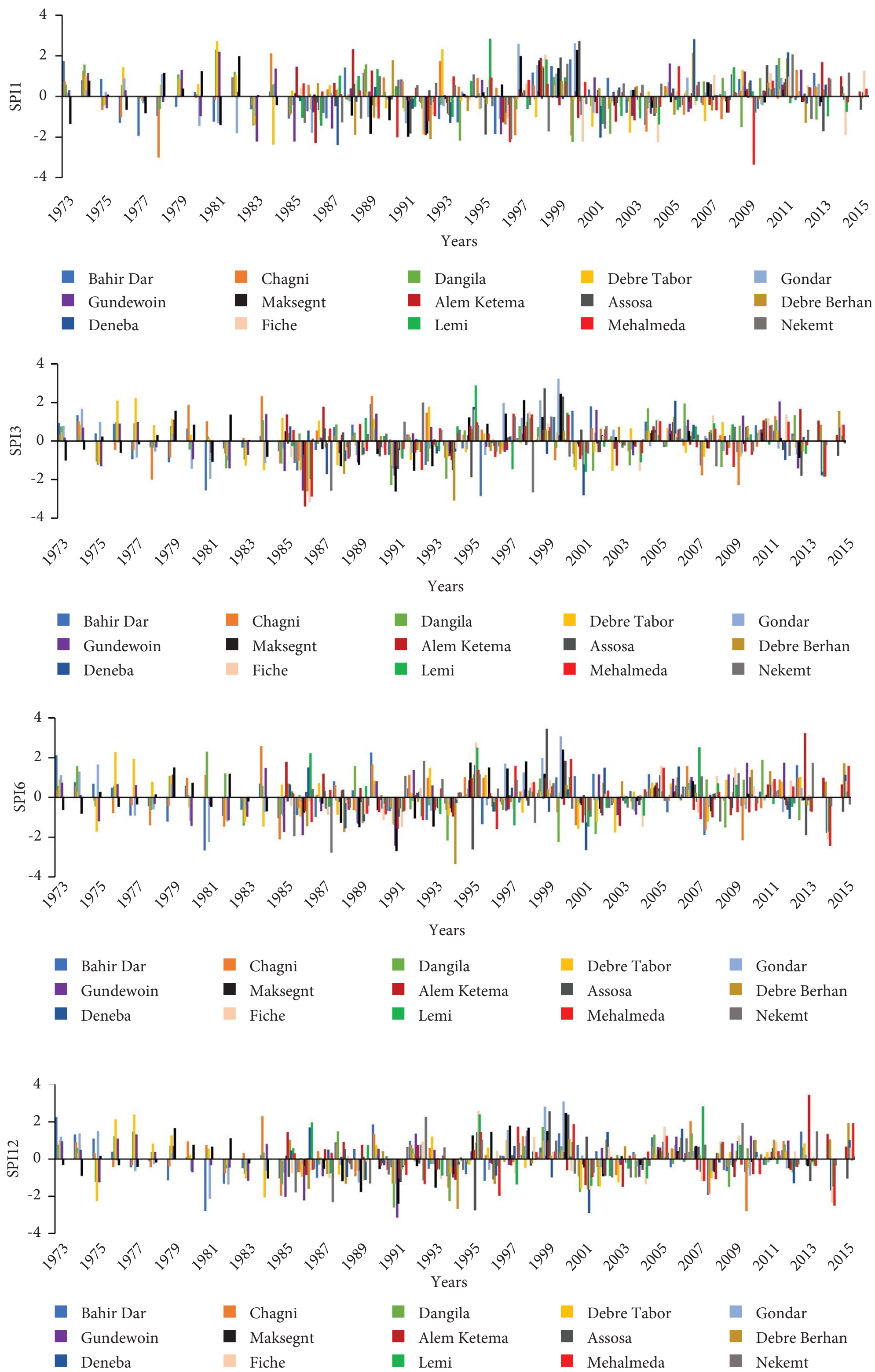

FIGURE 4: Meteorological drought time series in Abbay river basin using SPI.

drought years such as 1989, 1991, 1993, 2001, 2008, and 2010 (see Figure 4). In this river basin, extreme droughts in most gauge stations occurred in 1975, 1981, 1984, 1986, and 1991 (see Table 4).

Table 4 shows that the Abbay river basin was regularly hit by severe and extreme meteorological droughts from 1975 to 2008. The result also indicates that the 1980s was the most hazardous decade compared to other decades. Spatially, the

Table 4: Severe and extreme drought years in the Abbay river basin during 1973–2014 in SPI12.

Station	Drought year	Magnitude	Frequency (%)	Drought category
Bahir Dar	1981	−2.77	2.44	Extreme
	2008	−1.89	2.44	Severe
Chagni	1985	−1.94	7.32	Severe
	1994	−1.51		Severe
	2008	−1.82		Severe
	2010	−2.76	2.44	Extreme
Dangila	1991	−2.57	4.88	Extreme
	1994	−2.23		Extreme
	2001	−1.73	2.44	Severe
Debre Tabor	1975	−2.22	4.88	Extreme
	1984	−2.03		Extreme
	2001	−1.54	2.44	Severe
Gondar	1981	−2.10	2.44	Extreme
Gundewoin	1985	−1.98	2.44	Severe
	1986	−2.2	4.88	Extreme
	1991	−3.12		Extreme
Makisegnit	1989	−1.74	4.88	Severe
	1991	−2.37	2.44	Extreme
	1993	−1.51		Severe
Assosa	1995	−2.72	3.23	Extreme
Debre Berhan	1986	−1.56	6.42	Severe
	1994	−2.64	3.23	Extreme
Deneba	2001	−2.88	3.23	Extreme
	2014	−1.66	3.23	Severe
Fiche	2001	−1.62	3.23	Severe
	2014	−2.32	3.23	Extreme
Mehalmeda	1996	−1.94	3.23	Severe
	2014	−2.46	3.23	Extreme
Nekemt	1985	−1.76	3.23	Severe
	1987	−2.29	3.23	Extreme

drought frequently occurred in the northern parts of the basin (Gondar, Makisegnit, and Debre Tabor) compared to other stations in the western and east south parts (see Table 4).

RDI was computed from 1981 to 2015 for fifteen meteorological stations. As shown in Figure 5, the frequency of severe and extreme drought decreases from RDI1 to RDI12, but its severity and duration are increased. 1984, 1991, 1994, and 2001 were found to be the common severe drought events in most stations in the Abbay river basin. The longest duration was found from 2000 to 2004. The result of RDI highly agrees with the result of SPI in all time scales. In the northern and northeastern parts of the basin (Makisegnit, Gondar, Debre Tabor, Deneba, and Mehalmeda), severe droughts occur more frequently than in the western part (Assosa and Nekemt).

3.3. Hydrological Drought Characterization Using SDI. The hydrological drought analysis was computed using SDI by considering eight streamflow stations (Bahir Dar, Border, Gilgel Beles, Gummera, Kessie, Chemoga, Robigumera, and Guder) from 1973 to 2014 for five consecutive stations, from 1973 to 2009 for two stations, Chemoga and Guder, and from 1983 to 2009 for Robigumera station (see Table 1 and Figure 6). Similar to SPI and RDI, the SDI was computed for four time scales depending on different season variations (SDI1, SDI3, SDI6, and SDI12). The result showed that the SDI1 value for Border and Kessie lies under extreme drought during 1983 and 1986, whereas Chemoga and Bahir Dar stations were under extreme drought during 2001 and 2009 for SDI1 and SDI3, respectively (see Figure 6).

In Figure 6, SDI3, SDI6, and SDI12 commonly showed that from 1978 to 1987, the Abbay river basin was highly affected by hydrological drought for ten consecutive years. In the year 1989, the central and the lower parts of the basin (Kessie and Border) were under a moderate drought, but the upper part of the basin was in normal to mild drought conditions (Gummera and Bahir Dar), whereas Guder and Gilgel Beles were under wet condition, respectively. Gilgel Beles and Bahir Dar stations experienced moderate to severe drought from 2007 to 2011, whereas Gummera, Kessie, and Border stations were under wet conditions from 2005 to 2013. Generally, after 1988, the hydrological drought severity in most stations of the basin decreased. Seven streamflow stations were collected from the head to the lower parts of the river basin and nearer and to the main Abbay river basin. But Robigumera is taken from the Jema sub-basin in the east-southern part of the basin, and the result shows that the sub-basin was under severe drought during 1983, 1988,

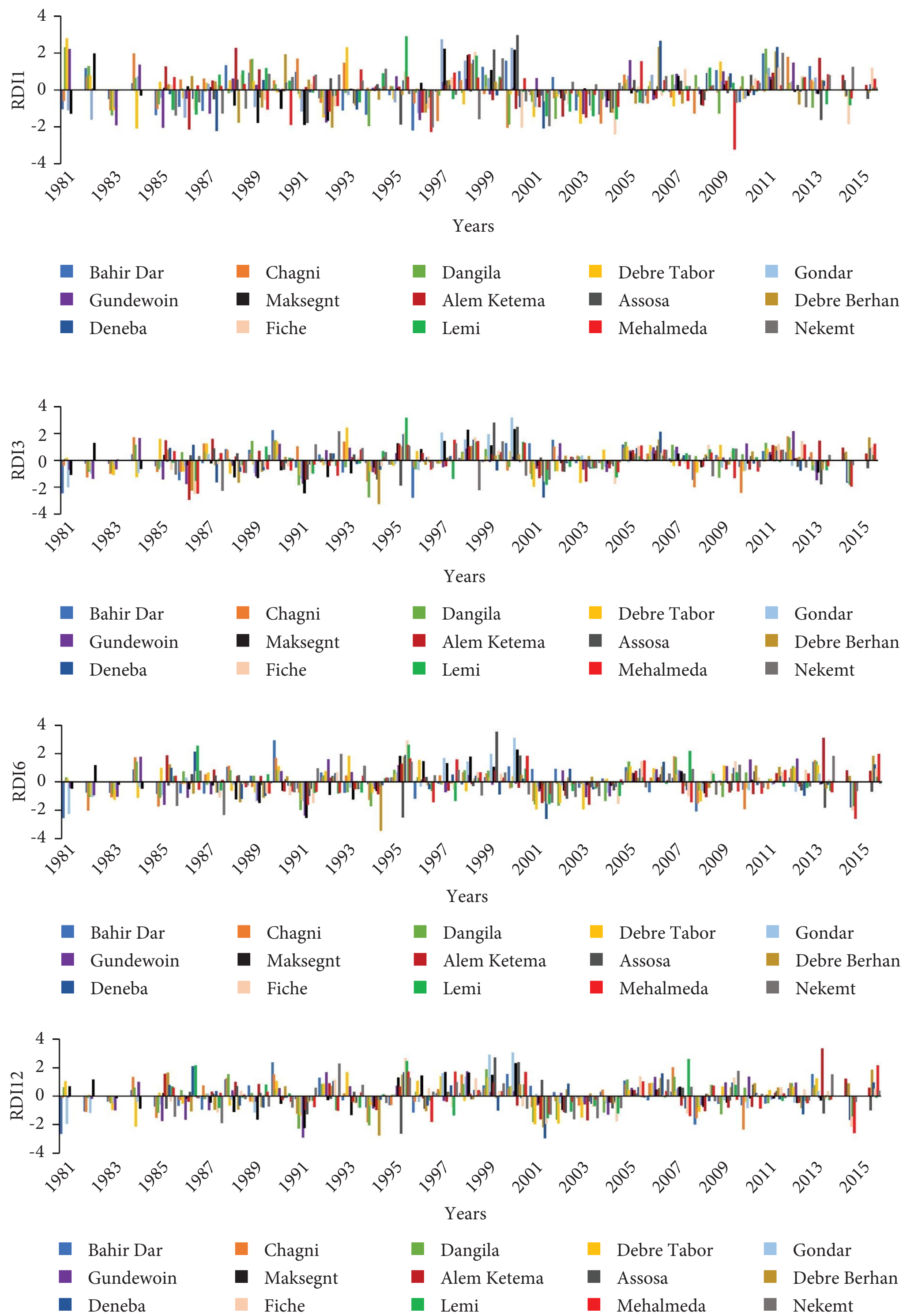

Figure 5: Meteorological drought time series in Abbay river basin using RDI.

and 1991. The overall result of SDI1, SDI3, SDI6, and SDI12 indicated that the Jema sub-basin is relatively wet and the effect of drought is minimal compared to the Tan sub-basin (upper) and Kessie sub-basin (middle). The result from SPI and RDI also supports the result of SDI in the Jema sub-basin.

As shown in Table 5, four severe drought events and one extreme drought event occurred in Kessie station from a period of 1979 to 1986. Next to Kessie station, Border and Gilgel Beles stations were also highly affected by severe drought. The frequency of severe drought is minimum at Bahir Dar, Gummera, Chemoga, and Guder stations.

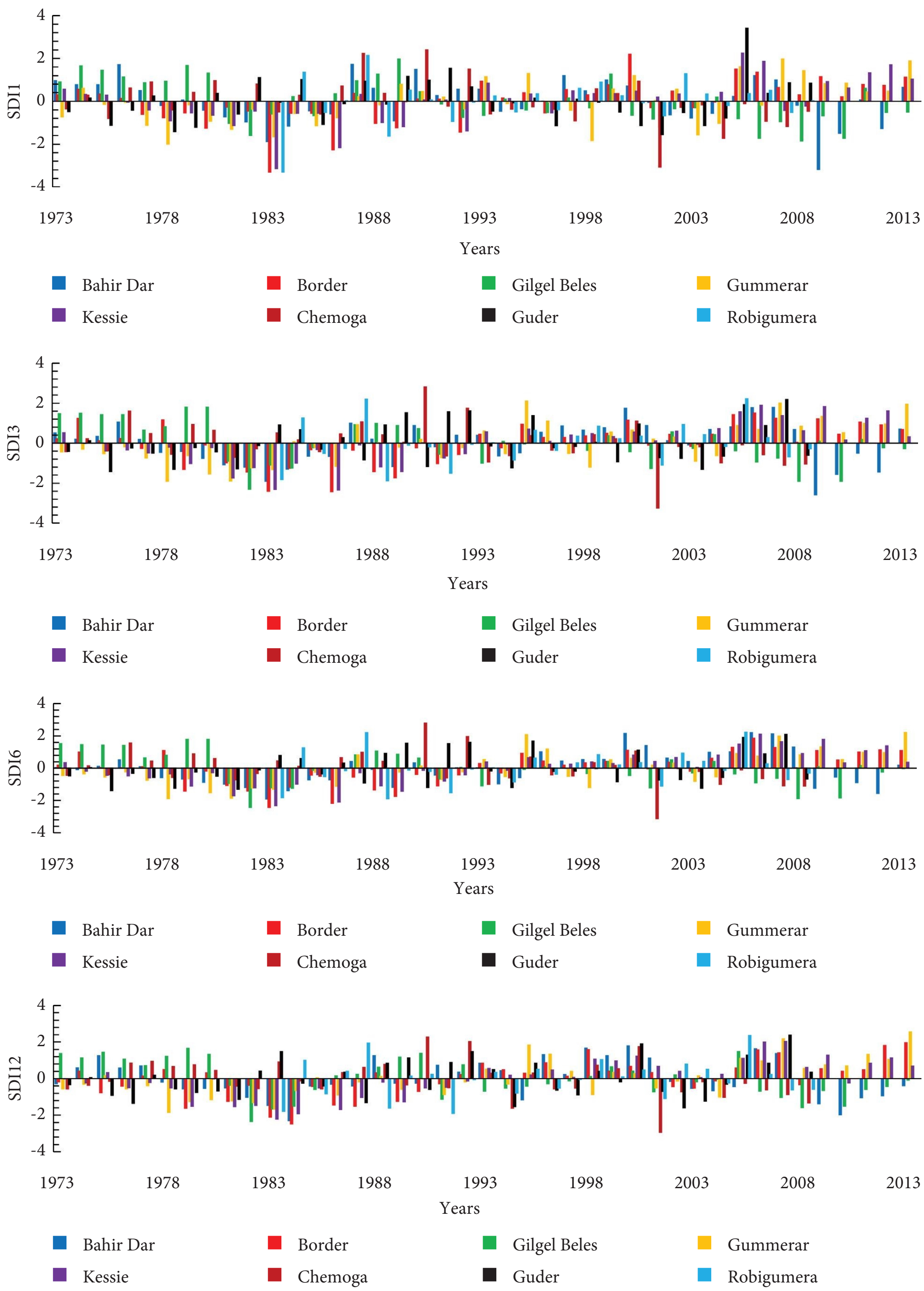

Figure 6: Hydrological drought (SDI) time series in Abbay river basin.

3.4. Meteorological and Hydrological Drought Trend Analysis. Meteorological and hydrological drought trend in the Abbay river basin was computed using the Mann–Kendall (MK) test integrated with AUT_MK_Sen.exe software. The result indicated that at the seasonal time scale (SDI3), there is a significant increasing drought trend in two streamflow stations (Gummera and Kessie), upper and middle parts of the basin, respectively, and in the remaining five stations, there is no significant hydrological drought trend. For the annual time scale (SDI12), three stations (Border, Gummera, and Kessie) have a significant hydrological drought trend at a 5% significant level (see Table 6). Severe and extreme

Table 5: Severe and extreme drought years in the Abbay river basin during 1973–2014 in SDI12.

Station	Drought year	Magnitude	Frequency (%)	Drought category
Bahir Dar	1984	−2.29	2.44	Extreme
	2010	−1.98	2.44	Severe
Border	1979	−1.62	4.88	Severe
	1983	−2.11		Extreme
	1984	−2.47	4.88	Extreme
	1987	−1.5		Severe
Gilgel Beles	1982	−2.35	2.44	Extreme
	1983	−1.66		Severe
	1984	−1.5	9.76	Severe
	2008	−1.59		Severe
Gummera	1978	−1.84	4.88	Severe
	1983	−1.66		Severe
Kessie	1979	−1.52	9.76	Severe
	1981	−1.53		Severe
	1983	−2.21	2.44	Extreme
	1984	−1.91		Severe
	1986	−1.69		Severe
Chemoga	1994	−1.63	2.78	Severe
	2001	−2.94	2.78	Extreme
Guder	1994	−1.52	5.56	Severe
	2002	−1.6		Severe
Robigumera	1983	−1.79	11.54	Severe
	1988	−1.61		Severe
	1991	−1.89		Severe

Table 6: Results of Mann–Kendall (MK) test for SDI3 and SDI12.

Stations	Bahir Dar	Border	Chemoga	Gilgel Beles	Guder	Gummera	Kessie	Robigumera
				SDI3				
$Z_{\text{calculated}}$	1.48	1.85	−2.08	−1.88	1.28	2.64	2.37	1.26
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	No trend	Decrease	No trend	No trend	Increase	Increase	No trend
				SDI12				
$Z_{\text{calculated}}$	−0.1	2.13	−2.22	−1.13	1.38	2.09	2.13	0.62
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	Increase	Decrease	No trend	No trend	Increase	Increase	No trend

drought events occurred from 1979 to 1986 for Border, Gummera, and Kessie streamflow stations. The trend analysis is shown in Table 6.

However, as shown in Table 7, in seasonal (SPI3) and annual (SPI12) meteorological drought trend analysis, there is no significant trend at a 5% significance level in most stations except Debre Berhan and Fiche stations. The analysis of the meteorological drought trend using RDI also shows almost the same result as SPI, in which only Debre Berhan and Fiche have an increasing trend, but other stations have no trend. Tables 6 and 7 imply that considering temperature and streamflow data in drought analysis will give good information about the drought trend than using a single precipitation variable. From this result, it is understood that monitoring hydrological drought is important in the future to manage the available water resource effectively during drought periods.

3.5. Comparing Meteorological and Hydrological Drought. The distribution of rainfall in Ethiopia is highly varying from time to time and from place to place. SPI follows the variability series of rainfall in time and space. As a result, the meteorological drought trend of the Abbay river basin does not show a significant trend from 1973 to 2014 for most stations. But in two stations, Debre Berhan and Fiche have increasing trends both in SPI and RDI indices. On the other hand, streamflow measurement is taken at the outlet of the concentrated flow location of a basin. Therefore, the flow has followed an increasing or decreasing trend depending on the seasonal variation of rainfall over the basin. Therefore, the hydrological drought trend directly follows the trend of streamflow in the river, i.e., if the streamflow increases, the drought phenomenon decreased and vice versa. The result of this study reveals that the hydrological drought condition of some streamflow stations increased from 1973 to 2014 (see Table 6). The correlation of the SPI, RDI, and SDI values was

Table 7: Result of Mann–Kendall (MK) test for SPI3, SPI12, RDI3, and RDI12.

Stations	Bahir Dar	Chagni	Dangila	Debre Tabor	Gondar	Gundewoin	Makisegnit	
				SPI3				
$Z_{\text{calculated}}$	0.53	−0.33	−0.07	−0.72	0.55	1.47	0.2	
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	
Trend (MK)	No trend	No trend	No trend	No trend	No trend	No trend	No trend	
				SPI12				
$Z_{\text{calculated}}$	0.85	−0.37	−0.64	−0.52	0.52	0.88	−0.03	
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	
Trend (MK)	No trend	No trend	No trend	No trend	No trend	No trend	No trend	
Stations	Mehalmeda	Debre Berhan	Alem Ketema	Deneba	Lemi	Fiche	Assosa	Nekemt
				SPI3				
$Z_{\text{calculated}}$	0.82	2.99	0.51	1.37	0.27	2.70	-0.11	0.17
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	Increase	No trend	No trend	No trend	Increase	No trend	No trend
				SPI12				
$Z_{\text{calculated}}$	0.37	2.87	−0.34	−0.07	−0.83	0.93	−0.04	1.65
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	Increase	No trend	No trend	No trend	No trend	No trend	No trend
Stations	Bahir Dar	Chagni	Dangila	Debre Tabor	Gondar	Gundewoin	Makisegnit	
				RDI3				
$Z_{\text{calculated}}$	1.58	0.37	0.9	0.9	-0.5	2.03	0.63	
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	
Trend (MK)	No trend	No trend	No trend	No trend	No trend	Increase	No trend	
				RDI12				
$Z_{\text{calculated}}$	0.63	0.6	0.5	0.87	0.11	1.69	−0.24	
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	
Trend (MK)	No trend	No trend	No trend	No trend	No trend	No trend	No trend	
Stations	Mehalmeda	Debre Berhan	Alem Ketema	Deneba	Lemi	Fiche	Assosa	Nekemt
				RDI3				
$Z_{\text{calculated}}$	0.56	2.52	0.2	0.36	0.27	2.28	−0.71	0.5
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	Increase	No trend	No trend	No trend	Increase	No trend	
				RDI12				
$Z_{\text{calculated}}$	−0.89	2.02	−0.78	−0.71	−0.99	0.59	0.09	0.99
$Z_{\text{critical}(a=0.05)}$	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96	±1.96
Trend (MK)	No trend	Increase	No trend	No trend	No trend	No trend	No trend	

Table 8: Hydrometeorological drought index correlation.

Correlation	SPI1	SPI3	SPI6	SPI12	RDI1	RDI3	RDI6	RDI12
SDI1	**0.54**	0.63	0.49	0.51	**0.58**	0.66	0.43	0.46
SDI3	0.35	**0.83**	0.82	0.78	0.34	**0.84**	0.72	0.68
SDI6	0.29	0.81	**0.84**	0.78	0.26	0.80	**0.72**	0.66
SDI12	0.45	0.75	0.81	**0.87**	0.47	0.79	0.78	**0.83**
SPI1	1	**0.66**	0.49	0.55	**0.95**	0.65	0.41	0.54
SPI3	0.66	1.00	**0.83**	0.83	0.56	**0.95**	0.68	0.71
SPI6	0.49	0.83	1.00	**0.95**	0.43	0.85	**0.95**	0.89
SPI12	0.55	0.83	**0.95**	1.00	0.51	0.87	0.91	**0.95**

computed for short, medium, and long time scale (1 month, 3 months, 6 months, and 12 months). Table 8 indicates that the relationship between SPI, RDI, and SDI in the Abbay river basin was increased from a short time scale (1 month to 3 months) to a long-term time scale (6 months to 12 months) with a value of 0.54, 0.83, 0.84, and 0.87, respectively, for SDI and SPI correlation. In the same manner, the correlation of RDI and SDI also increased from short-term to long-term time scale, except that RDI6 to SDI6 is 0.72, but RDI3 to SDI3 is found to be 0.84. On the other hand, the correlation of SPI and RDI is excellent for all time scales with a value of 0.95. This indicates that meteorological drought analyses using SPI and RDI in this basin will be relatively the same. This result is also supported by Bayissa et al. [23] in which the correlation of SPI and RDI for Kiremt (3 months) is 0.5 and that for annual (12 months) is 0.85, respectively. However, the correlation of SPI and RDI in this study has high strength than Bayissa's finding. The analysis of the

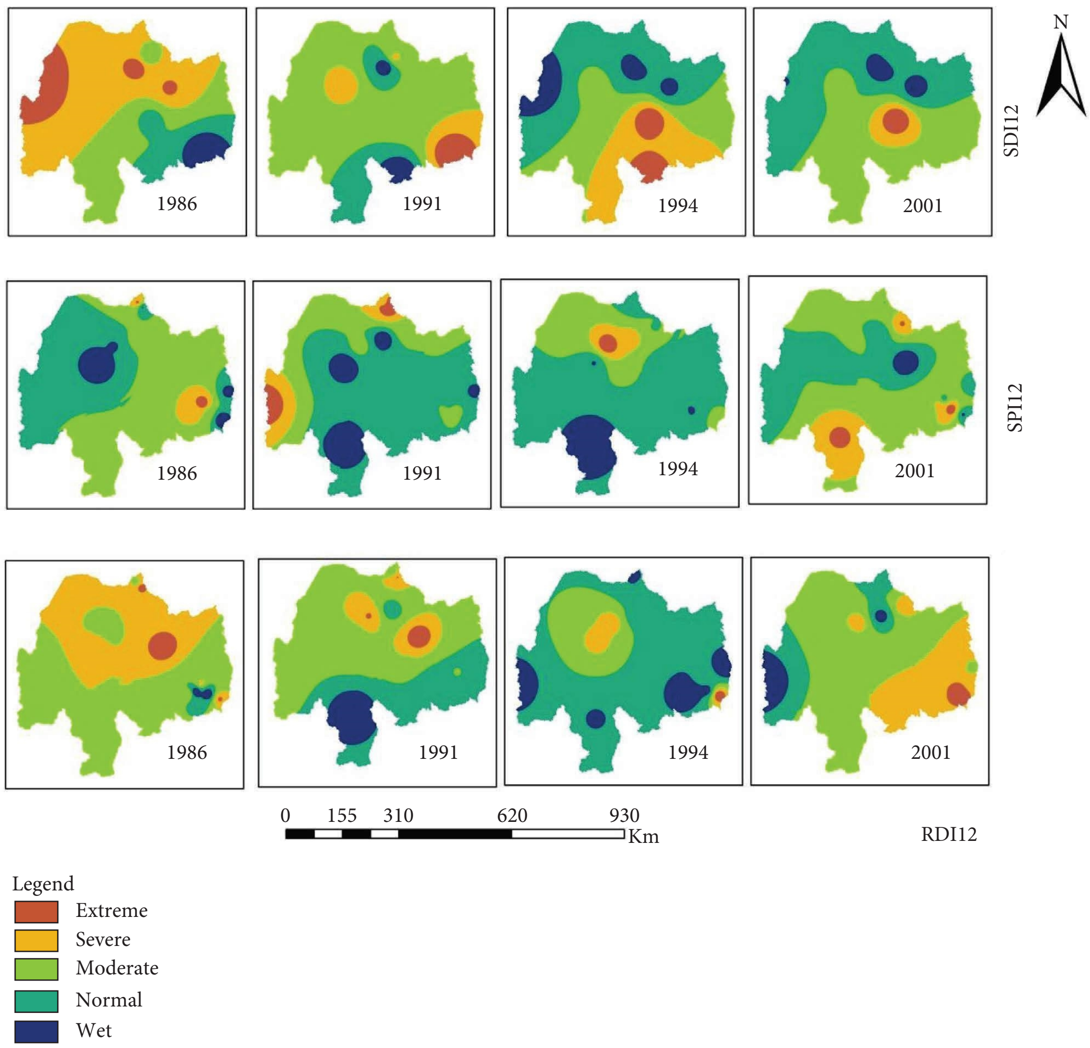

Figure 7: Spatial distribution of hydrometeorological drought in the Abbay river basin.

correlation between two meteorological drought indices and one hydrological drought index was considered from 1985 to 2014, which is the common data availability period for all indicators. The overall result shows that SDI has a relatively strong correlation with SPI than RDI.

3.6. Spatial Distribution of Drought in Abbay River Basin. In this study, the temporal variability of hydrometeorological drought variability was assessed from fifteen meteorological stations and eight hydrological stations (streamflow stations) in the Abbay river basin. But the temporal result gives information only about the magnitude of the drought event corresponding to the analysis time scale and it hides the spatial distribution of drought. Spatial distribution analysis has a vital role in drought early warning system development and appropriate drought mitigation measure planning. Figure 7 indicates the spatial variability of hydrometeorological drought in the Abbay river basin for selected drought events. 1986, 1991, 1994, and 2001 were found to have common moderate to extreme drought conditions for SDI, SPI, and RDI indices in most stations. In 1986, SDI12 and RDI 12 value shows that most of the Abbay river basin was under severe to extreme drought (see Figure 7). On the other hand, in 1994 and 2001, the basin was affected by severe drought based on SDI 12 and RDI 12 results, respectively. However, the SPI 12 spatial variability is minimal compared to SDI and RDI indices in all selected drought years. In the case of 1991, the basin was predominantly affected by moderate drought in both meteorological and hydrological drought indices. The meteorological drought spatial distribution analysis using SPI shows the minimum drought-prone area coverage compared to RDI. However, the hydrological drought severity is highly visible compared to meteorological drought results as indicated in Figure 7. This implies that investigation of hydrological drought is important to prepare good water resource management policy and drought early warning system development and mitigation measures in the Abbay river basin.

4. Conclusion

In this study, the temporal-based assessment of the historical hydrometeorological drought in the Abbay river basin, Ethiopia, is presented. The analysis was conducted using 42 years of data (1973–2014) from fifteen meteorological stations and eight streamflow stations. The hydrological and meteorological drought time series was performed using two meteorological drought indices (SPI and RDI) and one hydrological drought index (SDI), respectively. The trend analysis was computed using the Mann–Kendall (MK) test, and the result indicates that there was a positive increment of hydrological drought trend at Gummera, Kessie, and Border stations (upper-middle-lower parts of the basin), respectively, for a long time scale (SDI12). But for the case of meteorological drought, there is no significant drought trends at a 5% significant level for most stations in all time scales except Debre Berhan and Fiche which have increasing trend at SPI12 and RDI12. The most common severe hydrological drought years of the Abbay river basin were 1978, 1979, 1986, 1987, and 2010, whereas the extreme drought years were 1982, 1983, 1984, and 2001. For the meteorological drought condition, 1985, 2001, and 2008 were severe drought years, and 1975, 1981, 1984, 1986, 1991, 1994, and 2010 were extreme drought years. Commonly, 186, 1991, 1994, and 2001 were selected for spatial distribution analysis for SDI12, SPI12, and RDI12 time scales. Generally, in the 1980s, frequent drought events occurred in both meteorological and hydrological droughts. The relationship between meteorological and hydrological drought was increased as the time scale increased from 1 month to 12 months. SPI and RDI have a high correlation, and this implies that both indices are suitable for meteorological drought analysis in the Abbay river basin. The spatiotemporal drought variability of hydrological drought results shows that more attention is needed for water resource management in the Abbay river basin. Recently, the Ethiopian government has planned many water resource-related projects to reduce the impact of poverty. However, hydrological drought studies are still limited in the country. Hydrological drought investigation will show the historical drought severity condition and trend of a specific area, and it is possible to forecast the future hydrometeorological constraints in water resource management and infrastructure development. Therefore, this study has a vital role for decision makers, researchers, water resource managers, and policymakers as a primary source for drought preparedness and mitigation measure development in the Abbay river basin.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request, and it is possible to access them from the Ethiopian Meteorology Institute (EMI) and Ministry of Water and Energy (MoWE), Ethiopia.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] H. V. Lanen, N. Wanders, L. M. Tallaksen, and A. V. Loon, “Hydrological Drought across the World: Impact of Climate and Physical Catchment Structure,” *Hydrology and Earth System Sciences*, vol. 17, no. 5, pp. 1715–1732, 2013.

[2] A. F. Van Loon, “Hydrological Drought Explained,” *Wiley interdisciplinary reviews*, vol. 2, no. 4, 2018.

[3] B. Bąk and K. Kubiak-wójcicka, “Assessment of meteorological and hydrological drought in Torun (central Poland town) in 1971–2010 based on standardized indicators,” in *Proceedings of the 3rd International Conference - Water resources and wetlands*, pp. 164–170, Toruń,Poland, September 2014.

[4] X. Liu, X. Xu, M. Yu, and J. Lu, “Hydrological drought forecasting and assessment based on the standardized stream index in the Southwest China,” *Procedia Engineering*, vol. 154, pp. 733–737, 2016.

[5] H. Kwon and S. Kim, “Assessment of Distributed Hydrological Drought Based on Hydrological Unit Map Using SWSI Drought Index in South Korea,” *KSCE Journal of Civil Engineering*, vol. 14, pp. 923–929, 2010.

[6] S. Barua, A. W. M. Ng, and B. J. C. Perera, “Drought assessment and forecasting: a case study on the Yarra river catchment in Victoria, Australia,” *Australasian Journal of Water Resources*, vol. 15, no. 2, pp. 95–108, 2005.

[7] M. E. Keskin, T. Ouml zlem, D. T. E, and K. Derya, “Meteorological drought analysis using artificial neural networks,” *Scientific Research and Essays*, vol. 6, no. 21, pp. 4469–4477, 2011.

[8] G. Sarailidis, “Analysis of Streamflow Droughts Using Fixed and Variable Thresholds,” *Hydrological processes*, vol. 33, no. 3, pp. 414–431, 2019.

[9] P. Alegre, E. T. De Jesus, R. Junqueira, and M. R. Viola, “Meteorological and hydrological drought from 1987 to 2017 in doce River Basin , southeastern Brazil,” *Scientific/Technical Article*, vol. 25, pp. 1–10, 2020.

[10] J. Nasir, E. Assefa, T. Zeleke, and E. Gidey, “Meteorological drought in northwestern escarpment of Ethiopian rift valley: detection seasonal and spatial trends,” *Environ. Syst. Res.*vol. 10, no. 1, p. 16, 2021.

[11] J. Juana, “Socioeconomic Impact of Drought in Botswana the Socio-Economic Impact of Drought in Botswana,” *Journal of Environment and Sustainable Development*, vol. 11, no. 1, pp. 43–60, 2014.

[12] L. Mwadzingeni and R. Mugandani, “Risks of climate change on future water supply in smallholder irrigation schemes in Zimbabwe,” *Water*, vol. 14, no. 11, pp. 1–20, 2022.

[13] I. Masih, S. Maskey, and P. Trambauer, “A Review of Droughts on the African Continent: A Geospatial and Long-Term Perspective,” *Hydrology and Earth System Sciences*, vol. 18, no. 9, pp. 3635–3649, 2014.

[14] B. R. A. Yugi, E. M. O. L. E. Resanya, A. U. O. M. O. Nyango, F. A. K. A. O. Gou, E. U. C. H. O. Koro, and C. H. O. B. O. Koye, “Review of meteorological drought in Africa: historical trends,” *Impacts, Mitigation Measures, and Prospects*, vol. 179, pp. 1365–1386, 2022.

[15] Y. Bayissa, S. Moges, A. Melesse, T. Tadesse, and A. Z. Abiy, “Multi-Dimensional Drought Assessment in Abbay/Upper Blue Nile Basin: The Multi-Dimensional Drought Assessment in Abbay/Upper Blue Nile Basin: The Importance of Shared Management and Regional Coordination Efforts for Mitigation,” *Drought -- National Drought Mitigation Center*, vol. 177, 2021.

[16] A. Teshome, “Increase of Extreme Drought over Ethiopia under Climate Warming,” *Advances in Meteorology*, vol. 2019, Article ID 5235429, 18 pages, 2019.

[17] D. D. C. D. Melo, B. R. Scanlon, Z. Zhang, E. Wendland, and L. Yin, “Reservoir storage and hydrologic responses to droughts in the Paraná River basin, south-eastern Brazil,” *Hydrology and Earth System Sciences*, vol. 20, no. 11, pp. 4673–4688, 2016.

[18] E. Lemma, S. Upadhyaya, and R. Ramsankaran, “Meteorological drought monitoring across the main river basins of Ethiopia using satellite rainfall product,” *Environ. Syst. Res.*vol. 11, no. 1, p. 7, 2022.

[19] Y. Mohammed, F. Yimer, M. Tadesse, and K. Tesfaye, “Meteorological Drought Assessment in north east highlands of Ethiopia,” *International Journal of Climate Change Strategies and Article Information*, vol. 10, no. 1, 2017.

[20] Y. A. Bayissa, S. A. Moges, Y. Xuan et al., “Spatio-temporal assessment of meteorological drought under the influence of varying record length: the case of Upper Blue Nile Basin, Ethiopia,” *Hydrological Sciences Journal*, vol. 60, no. 11, pp. 1–16, 2015.

[21] Y. Bayissa, S. Maskey, T. T. Id, and S. J. Van Andel, “Comparison of the performance of six drought indices in characterizing historical drought for the upper Blue Nile Basin, Ethiopia,” *Geosciences*, vol. 8, 2018.

[22] Y. Mohammed, “Meteorological Drought Assessment in north east highlands of Ethiopia,” *International Journal of Climate Change Strategies and Management*, vol. 10, no. 1, 2018.

[23] Y. Bayissa, S. Moges, A. Melesse, T. Tadesse, A. Z. Abiy, and A. Worqlul, “Multi-dimensional drought assessment in Abbay/upper blue Nile Basin: the importance of shared management and regional coordination efforts for mitigation,” *Remote Sens*, vol. 13, p. 1835, 2021.

[24] D. Mengistu, W. Bewket, A. Dosio, and H. J. Panitz, “Climate change impacts on water resources in the upper blue nile (abay) River Basin, Ethiopia,” *Journal of Hydrology*, vol. 592, Article ID 125614, 2021.

[25] V. Roth, T. Lemann, G. Zeleke, and A. Teklay, “Effects of Climate Change on Water Resources in the Upper Blue Nile Basin of Ethiopia,” *Heliyon*, vol. 4, no. 9, 2018.

[26] A. Yimere and E. Assefa, “Beyond the implications of Grand Ethiopian Renaissance Dam filling policies,” *AIMS Geosciences*, vol. 7, no. 3, pp. 313–330, 2021.

[27] W. M. Khairy, “Spatial Analysis of Base Flow and Stream Flow from the Abbay River Basin after Watershed Management Interventions,” *International journal of enivronmental science and development*, vol. 1211 pages, 2021.

[28] E. Comission, *Standardized Precipitation Index (SPI)*, , pp. 1–5, Copernicus Eur. Drought Obs, 2020.

[29] H. Vangelis, “Incorporating aSPI and eRDI in drought indices calculator (DrinC) software for agricultural drought characterisation and monitoring,” *Hydrology*, vol. 9, no. 6, 2022.

[30] N. Adilah and H. Hannani, “Comparison of methods to estimate missing rainfall data for short term period at UMP gambang,” in *Proceedings of the IOP Conference Series Earth and Environmental Science*, February 2021.

[31] M. T. Sattari, A. R. Joudi, and A. Kusiak, “Assessment of different methods for estimation of missing data in precipitation studies,” *Hydrology Research*, vol. 48, pp. 1032–1044, 2017.

[32] Q. Li, Y. Peng, G. Wang, H. Wang, B. Xue, and X. Hu, “A combined method for estimating continuous runoff by parameter transfer and drainage area ratio method in ungauged catchments,” *Water*, vol. 11, p. 1104, 2019.

[33] M. A. Kohler, “On the Use of Double-Mass Analysis for Testing the Consistency of Meteorological Records and for Making Required Adjustments,” *Bulletin of the American Meteorological Society*, vol. 30, no. 5, pp. 471–476, 1937.

[34] K. Van Eerdenbrugh, S. Van Hoey, G. Coxon, J. Freer, and N. E. C. Verhoest, “Consistency Assessment of Rating Curve Data in Various Locations Using Bidirectional Reach,” *Hydrology and Earth System Sciences*, vol. 21, no. 10, 2017.

[35] M. Amjadi, P. Mostafapoor, and P. Chegin, “Statistical analysis of rainfall data (case study: TRNC),” *Free and accessible knowledge*, vol. 2, pp. 1–8, 2021.

[36] T. Kocsis, “Homogeneity Tests and Non-parametric Analyses of Tendencies in Precipitation Time Series in Keszthely Western Hungary,” *Theoretical and Applied Climatology*, vol. 139, pp. 849–859, 2020.

[37] A. Khalil, “Inhomogeneity detection in the rainfall series for the mae klong River Basin , Thailand,” *Applied Water Science*, vol. 11, no. 9, p. 147, 2021.

[38] S. Kchouk, L. Melsen, D. Walker, and P. van Oel, “A review of drought indices: predominance of drivers over impacts and the importance of local context,” *Natural hazards and earth system sciences*, pp. 1–28, 2021.

[39] A. Zargar, R. Sadiq, B. Naser, and F. I. Khan, “A review of drought indices,” *Environmental Reviews*, vol. 19, pp. 333–349, 2011.

[40] H. Aladaileh, M. Al Qinna, B. Karoly, E. Al-Karablieh, and J. Rakonczai, “An investigation into the spatial and temporal variability of the meteorological drought in Jordan,” *Climate*, vol. 7, no. 6, pp. 82–25, 2019.

[41] E. E. Moreira, D. S. Martins, and L. S. Pereira, “Assessing Drought Cycles in SPI Time Series Using a Fourier Analysis,” *Natural Hazards and Earth System Sciences*, vol. 15, pp. 571–585, 2015.

[42] V. Mercedes, S. Garc, V. Ruiz-ortiz, and S. Zazo, “Precipitation Variability and Drought Assessment Using the SPI: Application to Long-Term Series in the Strait of Gibraltar Area,” *Water*, vol. 14, no. 6, 2022.

[43] D. Tigkas, H. Vangelis, N. Proutsos, and G. Tsakiris, “Incorporating aSPI and eRDI in drought indices calculator (DrinC) software for agricultural drought characterisation and monitoring,” *Hydrology*, vol. 9, pp. 100–106, 2022.

[44] V. K. Jain, R. P. Pandey, M. K. Jain, and H. R. Byun, “Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin,” *Weather and Climate Extremes*, vol. 8, pp. 1–11, 2015.

[45] R. Ortiz-gómez, “Characterization of droughts by comparing three multiscale indices in Zacatecas , Mexico Caracterización de las sequías mediante la comparación de tres índices multiescalares en Zacatecas , México,” *Tecnología y Ciencias del Agua*, vol. 9, pp. 47–88, 2018.

[46] H. Jamshidi, I. Researcher, and D. Khalili, “Assessment and Comparison of SPI and RDI Meteorological Drought Indices in Selected Synoptic Stations of Iran,” in *Proceedings of the World Environmental and Water Resources*, May 2011.

[47] M. A. Asadi Zarch, H. Malekinezhad, M. H. Mobin, M. T. Dastorani, and M. R. Kousari, “Drought monitoring by reconnaissance drought index (RDI) in Iran,” *Water Resources Management*, vol. 25, no. 13, pp. 3485–3504, 2011.

[48] S. Pashiardis and S. Michaelides, “Implementation of the standardized precipitation index (SPI) and the reconnaissance drought index (RDI) for regional drought assessment: a case study for Cyprus,” *European Water*, vol. 23, pp. 57–65, 2009.

[49] L. Zalokar, M. Kobold, and M. Šraj, “Investigation of spatial and temporal variability of hydrological drought in Slovenia using the standardised streamflow index (Ssi),” *Water (Switzerland)*, vol. 13, pp. 3197–3222, 2021.

[50] S. Giri, A. Mishra, Z. Zhang, R. G. Lathrop, and A. O. Alnahit, "Meteorological and hydrological drought analysis and its impact on water quality and stream integrity," *Sustainability*, pp. 1–24, 2021.

[51] A. F. Van Loon and G. Laaha, "Hydrological drought severity explained by climate and catchment characteristics," *Journal of Hydrology*, vol. 526, pp. 3–14, 2015.

[52] L. J. Barker, J. Hannaford, S. Parry, K. A. Smith, M. Tanguy, and C. Prudhomme, "Historic Hydrological Droughts 1891–2015: Systematic Characterisation for a Diverse Set of Catchments across the UK," *Hydrology and Earth System Sciences*, vol. 23, pp. 4583–4602, 2019.

[53] S. Ansarifard and S. A. Shamsnia, "Monitoring drought by reconnaissance drought index (RDI) and standardized precipitation index (SPI) using DrinC software," pp. 29–35, 2018.

[54] T. B. McKee, N. J. Doesken, and J. Kleist, "The relationship of drought frequency and duration to time scales," in *Proceedings of the 8th Conference on Applied Climatology*, vol. 17-22, pp. 179–184, Anaheim, CA, USA, January 1993.

[55] S. F. V. Arash Asadi, "The efficiency of meteorological drought indices for drought \nMonitoring and evaluating in kohgilouye and boyerahmad \nProvince, Iran," *Ijmer*, vol. 3, no. 4, pp. 2407–2411, 2013, http://www.ijmer.com/papers/Vol3_Issue4/DP3424072411.pdf.

[56] L. J. Barker, J. Hannaford, A. Chiverton, and C. Svensson, "From meteorological to hydrological drought using standardised indicators," *Hydrology and Earth System Sciences*, vol. 20, no. 6, pp. 2483–2505, 2016.

[57] Y. Ilmaz, "Analysis of Hydrological Drought Trends in the GAP Region (southeastern Turkey) by Mann-Kendall Test and Innovative Sen Method," *Applied Ecology and Environmental Research*, vol. 17, no. 2, 2019.

[58] A. Ceglar, *Drought indices ppt*, Biotechnical faculty, University of Ljubljana, Ljubljana, Slovenia, 1999, http://www.dmcsee.org/uploads/file/70_drought_indices_a_ceglar.pdf [Online]. Available:.

[59] I. Nalbantis and G. Tsakiris, "Assessment of hydrological drought revisited," *Water Resources Management*, vol. 23, pp. 881–897, 2009.

[60] D. Tigkas, H. Vangelis, and G. Tsakiris, "DrinC: a software for drought analysis based on drought indices," *Earth Science Informatics*, vol. 8, no. 3, pp. 697–709, 2015.

[61] D. J. Mehta and S. M. Yadav, "Long-term trend analysis of climate variables for arid and semi-arid regions of an Indian State Rajasthan," *International Journal of Horticultural Science and Technology*, vol. 13, no. 2, pp. 191–214, 2022.

[62] S. M. Pingale, D. Khare, M. K. Jat, and J. Adamowski, "Trend analysis of climatic variables in an arid and semi-arid region of the Ajmer District, Rajasthan, India," *Journal of Water and Land Development*, vol. 28, no. 1, pp. 3–18, 2016.

[63] D. Mehta and S. M Yadav, "Temporal analysis of rainfall and drought characteristics over Jalore District of S-W Rajasthan," *Water Practice and Technology*, vol. 17, no. 1, pp. 254–267, 2022.

[64] S. K. Jain, V. Kumar, and M. Saharia, "Analysis of rainfall and temperature trends in northeast India," *International Journal of Climatology*, vol. 33, no. 4, pp. 968–978, 2013.

[65] S. Mathbout, J. A. Lopez-Bustins, J. Martin-Vide, J. Bech, and F. S. Rodrigo, "Spatial and temporal analysis of drought variability at several time scales in Syria during 1961–2012," *Atmospheric Research*, vol. 200, pp. 153–168, 2018.

[66] B. Bonaccorso, I. Bordi, A. Cancelliere, G. Rossi, and A. Sutera, "Spatial Variability of Drought: An Analysis of the SPI in Sicily," *Water Resources Management*, vol. 17, pp. 273–296, 2003.

[67] F. A. Anose, K. T. Beketie, T. T. Zeleke, D. Y. Ayal, G. L. Feyisa, and B. T. Haile, "Spatiotemporal analysis of droughts characteristics and drivers in the Omo - gibe River basin , Ethiopia," *Environ. Syst. Res.*vol. 11, no. 1, p. 3, 2022.

[68] G. Achilleos, "Mechanism – Creating a DEM from an Analogue Topographical Map the Inverse Distance Weighted Interpolation Method and Error Propagation Mechanism – Creating a DEM from an Analogue Topographical Map," *Journal of Spatial Science*, vol. 56, no. 11, 2011.

[69] I. Khouni, G. Louhichi, and A. Ghrabi, "Use of GIS based inverse distance weighted interpolation to assess surface water quality: case of wadi el bey, Tunisia," *Environmental Technology & Innovation*, vol. 24, Article ID 101892, 2021.