Hindawi
Advances in Meteorology
Volume 2022, Article ID 7067951, 19 pages
https://doi.org/10.1155/2022/7067951

Research Article

Hydrological Drought Analysis using Streamflow Drought Index (SDI) in Ethiopia

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Received 5 February 2022; Revised 16 March 2022; Accepted 4 April 2022; Published 22 April 2022

Academic Editor: Upaka Rathnayake

Drought is a natural disaster that has impacts on society, the environment, and the ecosystem. Ethiopia faced many horrible severe drought events in the last few decades. Even though there are some drought-related studies in the country, most of the investigations were focused on meteorological drought analysis. This study was focused on hydrological drought analysis in Ethiopia using the streamflow drought index (SDI). The main objective was to identify drought-prone areas and severe drought events years. Streamflow data were collected from 34 stations to analyze SDI in seasonal (3-month) and annual (12-month) timescales. The analysis implies that seasonal time scale (3-month) hydrological drought has a high frequency of occurrence but short duration, whereas annual (12-month) analysis has a low frequency with a large magnitude. The overall result shows that 1984/85, 1986/87, 2002/03, and 2010/11 were the most severe and extreme drought years in all river basins. The 1980s were found severe and extreme drought years in which most hydrological drought events occurred in the country. The spatial analysis shows that Tekeze, Abbay, and Baro river basins have similar characters; Awash and Rift Valley River basins show relatively the same character, and Genale Dawa and Wabishebele river basins have a similar character. But Omo Gibe River basin has a unique character in which the severe drought occurred in a different year of other river basins.

1. Introduction

Drought is a worldwide natural hazard and has a severe impact on the social, environmental, and economic aspects [1]. Hydrological extreme events both flood (high flow) and drought (low flow) are the most concerning issues in the world [2]. However, drought is one of the most common natural disasters that have a great negative impact on agriculture and water resources projects in a wide range [3]. But researchers are highly focused on flood disasters than drought.

Drought is a complex phenomenon, and due to its notorious nature, there is no universal definition for it [4]. Albeit it has no universal definition, droughts can be (1) meteorological, which is a scarcity of precipitation [5–7], (2) hydrological drought, which is the scarcity of streamflow water, reduction of reservoir and Lake water level [8–10], (3) agricultural drought related to deficit of soil moisture [11, 12], and (4) socioeconomic drought which is the imbalance between supply and demand [13, 14] and each drought is a cause of the other [15]. Meteorological and agricultural droughts are mainly causing the failure of crops, while hydrological drought is a deficiency of water supply, a decrease in reservoir water level and groundwater level, and a decrease in irrigation and hydropower production [16]. The aggregated impact of meteorological, agricultural, and hydrological drought and the contradiction between water supply and demand results in socioeconomic drought [17, 18], in which the overall ecosystem of the drought region is disturbed, and there is a loss of life [19]. The overall

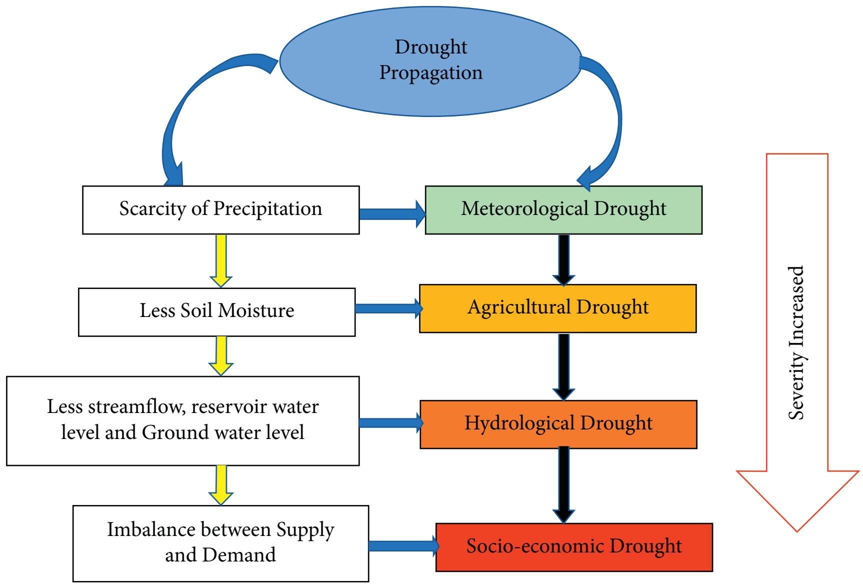

Figure 1: Relationship and propagation of different types of droughts.

propagation of each drought development is summarized in Figure 1.

The scientific analysis of the recurrence and persistence of drought seeks to establish an estimate of probabilities that will contribute to the planning of strategies for mobilization and management of water resources [19]. Due to climate change, the global vulnerability to floods and drought has been increasing [20]. The assessment of droughts affecting agricultural areas in Africa is highly relevant. Many African countries strongly rely on rain-fed agriculture. Since rainfall is commonly the limiting factor for rain-fed agricultural systems, droughts can lead to severe socioeconomic consequences like crop failure, food shortages, and even humanitarian crises [21]. For example, drought events have caused more than 800,000 deaths and affected about 262 million people in Africa from 1900 to 2013 [22].

Ethiopia has also experienced severe drought in the past centuries. Researchers have thought that severe drought has occurred once in three to ten years' recurrence interval [23]. Even though this recurrence time is quite short, no permanent drought mitigation measures have been established effectively. Measures are more localized and usually come in the form of food aid during the drought period.

Large-scale drought analysis studies have been recently conducted globally or continental level for present and future climate change [24]. But in the case of Ethiopia, drought studies were focused on catchment level and they do not give good information about the drought condition of the country. Few drought studies were conducted in the northern and eastern parts of Ethiopia, which are mainly focused on meteorological drought analysis [25]. Finally, the researchers try summarizing the effect of drought events throughout the country. But drought events are inconsistent across all of Ethiopia. The variability of the temporal, spatial, and magnitude characteristics of drought events requires in-depth analysis to determine different approaches for mitigation. The government of Ethiopia develops and planned different water resource infrastructures to reduce poverty. Yet, hydrological drought analysis is not well studied. Therefore, to develop permanent and effective drought mitigation measures, it is important to analyze the historical hydrological drought over the nation. So, the main objective of this study is to analyze and characterize historical hydrological drought in Ethiopia using the streamflow drought index (SDI) for a better understanding of its impact on water resource infrastructure development.

2. Methods

2.1. Description of the Study Area. Ethiopia is located in the eastern horn of Africa, which locates in 3°N and 15°N latitude and 33°E and 48°E longitude. The area of the country is about 1.13 million km^2 and this study covers 87.3% of the country. Of 12 major river basins, 4 are not included in this study due to a lack of data (Figure 2). The population of the country rapidly increases from decade to decade causing deforestation and expansion of urban areas. As a result, variability in climate conditions also increased. There are twelve major river basins, yet the development of water resources is still low. Of the existing 12 major river basins, three (3) are dry and one river basin has low flow and low recorded data as presented in Figure 2 northeast part. Due to this reason, this study was focused only on eight (8) major river basins. The drought phenomenon is a common natural hazard throughout the country, especially since the severity is high in the northern and eastern parts. The country receives high rainfall during the summer (June, July, and August). The mean annual rainfall and a temperature range from 510 to 1300 mm and 16°c to 27°c, respectively.

The topography of Ethiopia and the respective major river basins are described by the Digital Elevation Model (DEM), which was collected from the Ministry of Water, Irrigation and Electricity, GIS division with a spatial resolution of 30 m × 30 m. The river network and basin boundary

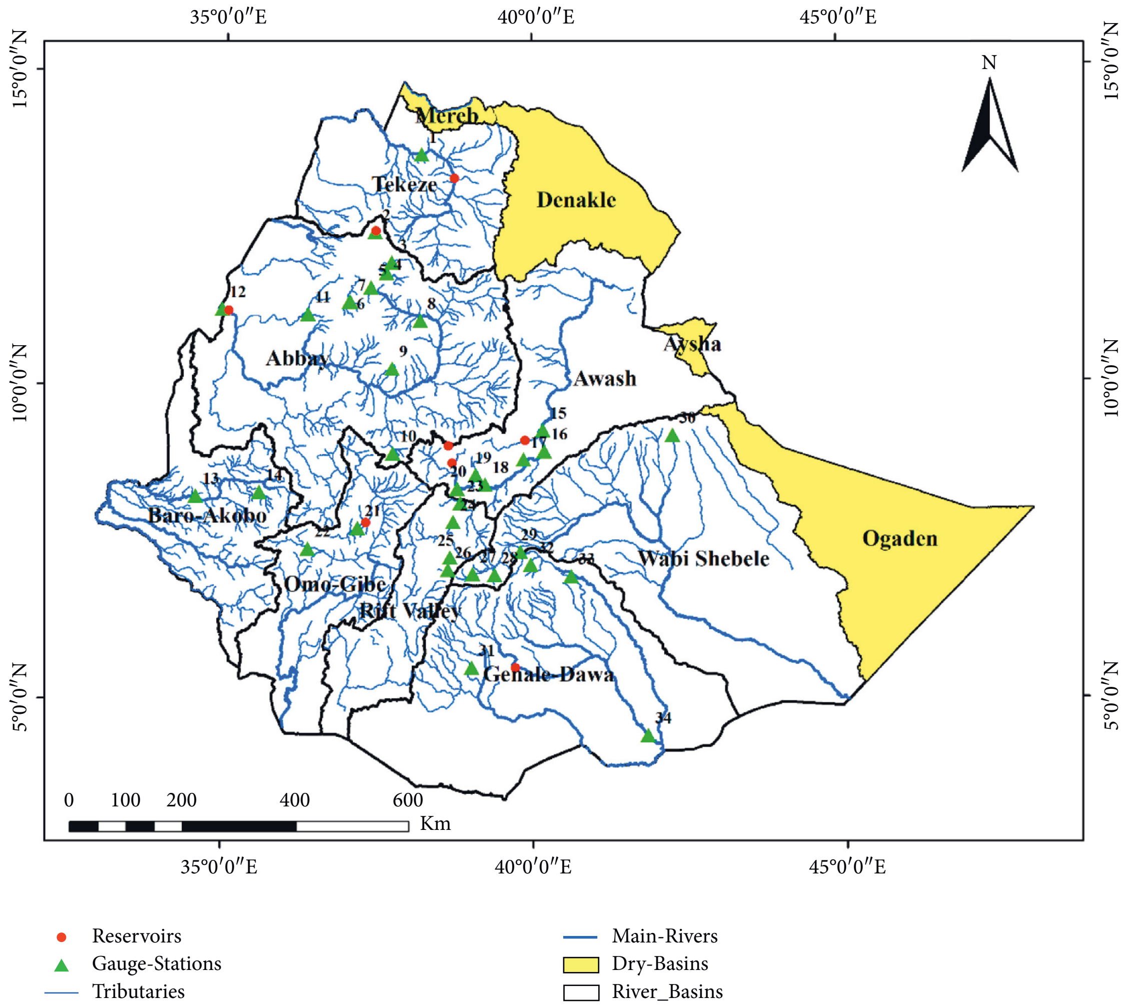

FIGURE 2: Location of streamflow stations.

are automatically extracted from the DEM itself by performing the ArcGIS software and the spatial location of 34 streamflow gauge stations and some major reservoirs are indicated in Figure 2.

2.2. Data Collection and Preparation. Streamflow data were collected from the Ministry of Water, Irrigation, and Electricity (MoWIE). The stations were selected based on data quality, recorded length, and area coverage. The data were collected from 34 streamflow stations with a length of 35–41 years, except for the Tekeze basin, which has only 21 years' record length (Table 1). The streamflow stations in the Tekeze basin have more missing data and it is difficult to analyze drought trends with minimum data availability. Therefore, for this basin, only one streamflow station is considered, which has 21 years of recorded data from 1994 to 2014. But, the other seven basins fulfill the minimum data length required (30 years) for drought analysis. Table 1 summarizes the spatial location of the gauge station and its corresponding data record length.

The annual flow in each basin varies from season to season. Abbay, Baro Akob, and Omo Gibe River basins (northwest, western, and southern parts) have a high flow than other basins, 52.6, 23.6, and 17.9 BM^3 annual runoff, respectively, whereas Tekeze Genale Dawa, Rift Valley, Awash, and Wabishebele (northern, central and eastern parts) have a relatively moderate flow, 7.6, 5.8, 5.6, 4.6, and 4.6 BM^3 annual runoff, respectively. Figure 3 illustrates the mean monthly flow rate (m^3/s) of all river basins. As shown in Figure 3, Abbay has a high flow rate followed by the Omo Gibe River basin.

2.3. Hydrological Drought Indicators Selection. There is no single drought indicator for all types of drought in a specific region [26] because all available drought indicators have their limitation during development and application [27]. Therefore, drought indicator selection requires a thorough investigation related to the type of drought and the respective drought indicator based on the availability of data, ease of communication, result implication, strength and limitations of the indices, and the objective of the investigation [26]. Of many drought indices, the most common are discussed in Table 2.

From the water resources development and management perspective, it is important to define the reference flow levels and indicators of drought severity (what drought duration

Table 1: Streamflow stations location and a corresponding record year in each river basin.

No	Station name	Basin	Latitude (°)	Longitude (°)	Area (km^2)	Recorded year
1	Embamadre	Tekeze	13.73	38.20	45694	1994–2014
2	Megech	Abbay	12.48	37.45	462	1980–2014
3	Rib	Abbay	12.00	37.72	1592	1972–2012
4	Gummera	Abbay	11.83	37.63	1394	1973–2014
5	Bahir Dar	Abbay	11.60	37.38	15319	1973–2014
6	Gilgel Abbay	Abbay	11.37	37.03	1664	1972–2012
7	Koga	Abbay	11.37	37.05	244	1972–2012
8	Kessie	Abbay	11.07	38.18	65784	1973–2014
9	Chemoga	Abbay	10.30	37.73	364	1973–2009
10	Gilgel Beles	Abbay	11.17	36.37	675	1973–2014
11	Guder	Abbay	8.95	37.75	524	1973–2009
12	Abbay border	Abbay	11.23	34.98	17254	1973–2014
13	Gambela	Baro	8.25	34.58	23461	1973–2014
14	Sorie	Baro	8.32	35.60	1622	1973–2014
15	Melkawerer	Awash	9.32	40.17	31183	1973–2010
16	Awash7 killo	Awash	8.98	40.18	19110.75	1973–2013
17	Metehara	Awash	8.85	39.85	16416.8	1982–2014
18	Wonj	Awash	8.45	39.23	11690	1973–2014
19	Mojo	Awash	8.60	39.08	1264.4	1973–2014
20	Hombel	Awash	8.38	38.78	7656	1973–2014
21	Assendabo	Omo Gibe	7.75	37.18	2966	1980–2018
22	Gojeb	Omo Gibe	7.42	36.38	3577	1980–2018
23	Meki	Rift valley	8.15	38.83	2433	1973–2014
24	Kekersitu	Rift valley	7.85	38.72	7488	1980–2014
25	Dedeba	Rift valley	7.28	38.67	156	1980–2014
26	Wosha	Rift valley	7.08	38.63	20	1980–2014
27	Wabi bridge	Wabishebele	7.02	39.03	1035	1976–2014
28	Leliso	Wabishebele	7.00	39.38	135	1976–2014
29	Weiyb	Wabishebele	7.37	39.80	7719	1983–2014
30	Erer	Wabishebele	9.23	42.25	469	1983–2014
31	Chenemasa	Genale Dawa	5.52	39.02	10574	1983–2014
32	Shaya	Genale Dawa	7.17	39.97	4338	1981–2014
33	Weib	Genale Dawa	6.98	40.62	3576.9	1984–2014
34	Halewe	Genale Dawa	4.43	41.83	54093	1984–2014

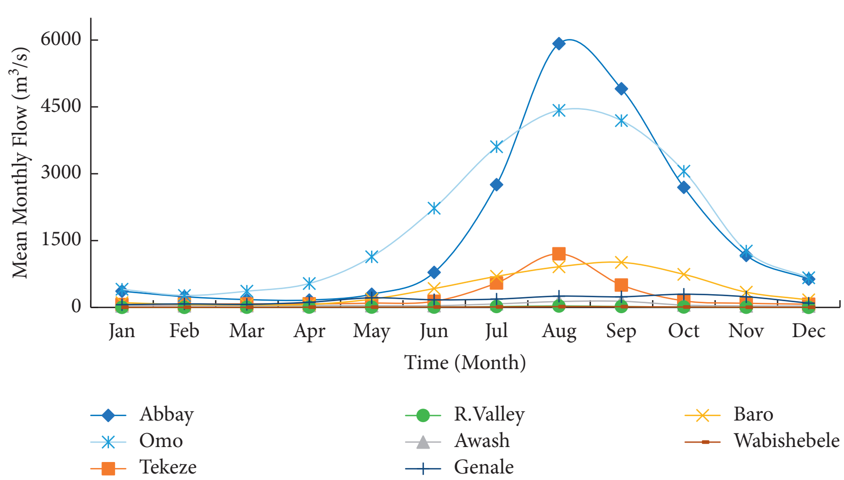

Figure 3: Seasonal variation of mean monthly streamflow over Ethiopian River Basins.

and/or flow deficit constitutes mild or severe drought). Several indices measure how much streamflow for a given period has deviated from historically established norms. Most water supply planners find it useful to consult one or more indices before making a decision [28, 29].

Hydrological drought can be defined in terms of the differences between the water supply and water demand time series. The supply time series is characterized by a river flow and the demand time series-by the demand of a particular user (e.g., irrigation) or by the total demand for all

Table 2: Summary of drought indicator's strengths and weakness.

No	Indicator	Strength	Weakness
1	Decile	Easy for analysis and used for all types of droughts at a different time scale	Uses only precipitation and does not consider temperature and other hydrological variables
2	Palmer drought severity index (PDSI)	Widely used, good for agricultural drought	The need for serially complete data cause problems
3	Palmer hydrology drought index (PHDI)	Its water balance approach allows the total water system to be considered	Frequencies will vary by region and time of year
4	Standardized precipitation index (SPI)	Easy to calculate, applicable in all climate regimes	The temperature effect is not considered
5	Standardized precipitation evapotranspiration index (SPEI)	Account for the impact of temperature on a drought situation, the output applies to all climate regimes	The requirement for a serially complete dataset for both temperature and precipitation limits its use due to insufficient data
6	Reconnaissance drought index (RDI)	Easy to use, precipitation and temperature as input, consider the water balance of the region	Comparing RDI for different climate regions may be subject to error
7	Streamflow drought index (SDI)	The program is widely available and easy to use. Missing data are allowed	A single input (streamflow) does not consider management decision
8	Surface water supply index (SWSI)	Considering the full water resources of a basin provides a good indication of the overall hydrological health of a particular basin or region	As data sources change or additional data are included, the entire index must undergo recalculation

Source: Handbook of Drought Indicators and Indices; Integrate Drought Management Program (IDMP); World Meteorological Organization WMO—No. 1173 (2016).

users. When demand exceeds supply, water shortages occur, which represents that the start of a such as storage is also a useful indicator of water shortages, due to data availability on a daily or weekly basis. Simultaneously, these data are strongly influenced by the reservoir operation rules [30].

The hydrological drought indices (HDIs) depend on the purpose of hydrologic monitoring and prediction, such as reservoir operation and water allocation for hydroelectric generation, irrigation, and domestic or industrial water supply. Most hydrological drought indices are largely based on stream flows. Streamflow deficit regarding normal conditions is not always the true representative, particularly in the river systems with diversion of virgin flows. Therefore, hydrological drought is characterized by more factors than just low flows. The preparation of streamflow data for drought management or any purpose is hampered by the lack of adequate data because shorter record lengths and artificial influences (such as abstraction) and even the longer recorded station have high missing values in developing countries such as Ethiopia.

Drought indices and definitions based solely on flow or reservoir storage are normally designed for reservoir operation and are seldom (if at all) used as triggers for drought relief, or drought monitoring over vast territories. Although none of the major indices is inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses [31].

In Ethiopia, there is a high scarcity of data for streamflow analysis of both flood and drought. Most reservoirs in the country have no gauge staff and groundwater level is not well known in all basins, which makes it difficult to use more data-intensive drought indicators for hydrological drought analysis. Therefore, in such circumstances, SDI is the best alternative for hydrological drought analysis due to its less input requirement and simplicity for analysis and interpretation [32]. Streamflow is the most crucial variable in the quantity of water that expresses the availability of surface water resources. Therefore, in terms of normal conditions, a hydrological drought occurrence is linked to the streamflow deficit [20, 24]. Therefore, due to the following reasons, SDI is selected for this study: (i) the areal extent of a drought event is very useful for meteorological drought, but it is not of interest for hydrological droughts since water managers are interested in streamflow only as a small number of points in space (Basin outlets, Reservoir inlets, and outlets); (ii) streamflow at these points provides an integrated measure of spatially distributed runoff; (iii) furthermore, the river basin can be proposed as the unit for applying measures for water resource protection and management; (iv) in Ethiopia, there is a scarcity of data availability especially Lake level, reservoir level, soil moisture, and groundwater level. Relatively, precipitation and streamflow data are available from the 1970s to date.

2.3.1. Streamflow Drought Index. The streamflow drought index (SDI) was developed by [33], which is used to characterize the streamflow drought conditions. Its calculation is similar to SPI and therefore has the same characteristics of simplicity and efficiency. The SDI is based on monthly observed streamflow volumes at different time scales and thus offers the advantage of controlling streamflow drought or the supply of water in the short, medium, and long term. The calculation is given by

$$V_{i,j} = \sum_{j=1}^{k} Q_{i,j}\, i = 1, 2, \ldots,\ j = 1, 2, \ldots, 12,\ k = 1, 2, 3, 4, \quad (1)$$

where $V_{\mathrm{i,j}}$ is the cumulative streamflow volume for the i-th streamflow year and the k-th reference period, and K is a seasonal value (four-season, Ethiopia case). $Q_{\mathrm{i,j}}$ is monthly streamflow volume at i^{th} streamflow year and j^{th} month within that year.

Based on the cumulative streamflow volumes $V_{i,k}$, the streamflow drought index (SDI) is defined for each reference period k of the i-th streamflow year as follows:

$$SDI = \frac{Vi, k - Vkm}{Sk}, \quad (2)$$

where i = 1, 2; . . ., and k = 1, 2, 3, 4.

Vkm and *sk* are, respectively, the mean and the standard deviation of cumulative streamflow volumes of the reference period k as these are estimated over a long period. The range of wetness and dryness of SDI ranges between −2 and +2. The extremely dry and wet values are below −2 and above +2, respectively. According to Nalbantis and Tsakiris, 2009, hydrological drought classification using SDI is shown in Table 3.

2.4. Hydrological Drought Characterization. The drought index plays a great role in order to evaluate the consequences of drought impact and to decide various drought characterization, such as duration (D), severity (S), magnitude (M), and relative frequency (RF) [34, 35]. Drought duration is the time taken between consecutive drought events (onset and end of drought). The duration is from starting with a negative SDI value and turns to a positive SDI value. Drought severity is the summation of negative SDI values from onset to end of a drought event as defined by Equation (3). The magnitude of drought is the ratio between drought severity and drought duration which is defined by equation (4):

$$Si = -\sum_{i=1}^{D} S\ DI\ i, \quad (3)$$

$$M = \frac{S}{D}. \quad (4)$$

The relative drought frequency is the ratio between the number of droughts (n) with negative SDI in drought duration and the total number of drought years in the analysis (N) [36] and RF is defined as

$$RF = \frac{n}{N} * 100. \quad (5)$$

3. Results and Discussion

3.1. Hydrological Drought Analysis using Drought Indices. Indices are important to give quantitative information about drought events in terms of duration, intensity, frequency, and recurrence interval for readers and scientists. Such information is extremely important for planning and water resource management [37]. There are many hydrological drought indices such as SDI, SWSI, PHDI, and ADI. But except for SDI, all indices are more data-intensive [32, 38]. Therefore, in this study, the historical hydrological drought trend in Ethiopia was analyzed using SDI. SDI is a point or site drought indicator that gives information about the river's temporal and special variation. The analysis was computed using the DrinC model (Drought Indicator Calculator), which is developed to determine SPI, RDI, and SDI using monthly input data [39, 40].

Table 3: Drought classification according to the SDI values (Nalbantis and Tsakiris, 2009).

SDI value	Category
≥2	Extremely wet
1.5–1.99	Severely wet
1–1.49	Moderately wet
0.5–0.99	Slightly wet
−0.49–+0.49	Normal
−0.5–−0.99	Mild drought
−1–−1.49	Moderately drought
−1.5–−1.99	Severely drought
≤−2	Extremely drought

3.1.1. Hydrological Drought Analysis using SDI. The daily streamflow data were prepared monthly and normalized to zero mean and unit standard deviation to illuminate the flow variation of stations in time and space. Then, SDI was estimated using Equation (2) for short and long-time scales (SDI3 and SDI12), the seasonal base for the three-month duration (SDI3), and the annual base for the twelve-month duration (SDI 12). In Ethiopia, the summer covers from June to August (JJA); during this season nearly all river basins receive high rainfall and streamflow volume increased. Hydrological drought is developed gradually due to the scarcity of precipitation in the region when there is no rainfall for some consecutive months or a year. Therefore, this study focuses on the summer season (SDI3) and annually based (SDI12) hydrological drought analysis because the remaining three seasons, autumn (SON), winter (DJF), and spring (MAM) follow the summer season drought condition and it can be summarized by the annual drought conditions. The analysis result indicates that the 3-month time scale (SDI3) analysis frequency of drought occurrence was high compared to the long-term time scale, the 12-month (SDI12). This finding is agreed with previous studies such as [6, 19, 38, 41, 42]. But for the long-term time scale, drought duration is maximum and the SDI value is minimum as shown in Figure 4. In this study, the temporal and spatial variation of streamflow drought in Ethiopia was analyzed using SDI. Therefore, the most severe and extreme drought years over different river basins were identified. As shown in Table 4, the Rift Valley River basin was highly affected by 13 severe and 4 extreme droughts followed by the Abbay river basin for the last four decades.

In the Abbay river basin, 11 streamflow stations were considered for hydrological drought analysis using SDI. Since SDI is a point or site drought indicator, the discussion here considers all gauging stations within the basin and the result of each station is shown in Figure 4. The correlation of each station implies that the Abbay Border station correlates well with Kessie, Ribb, Megech, Gummera, Bahir Dar (0.85, 0.61, 0.61, 0.6, and 0.44), respectively. This 42-year drought analysis shows that the lower and central parts of the basin have similar drought occurrence seasons (Abbay border, Chemoga, Kessie, Guder, Gilgel Abbay, and Gilgel Beles),

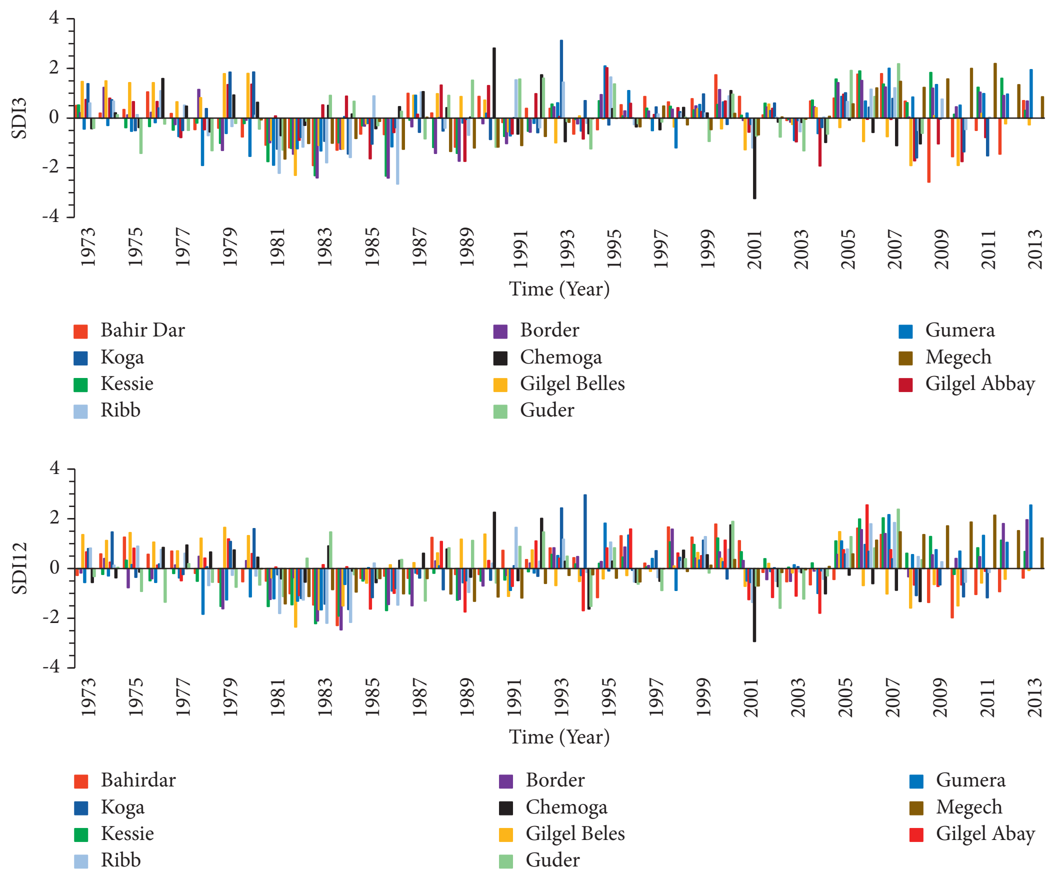

Figure 4: Temporal variation in seasonal (SDI3) and annual (SDI12) for Abbay river basin.

Table 4: Hydrological drought years in different river basins in Ethiopia from 1973 to 2014.

River basin	Severe drought years	Extreme drought year
Abbay	1979, 1981, 1983, 1984, 1986, 1994, 2010	1983/1984, 1984/1985
Awash	1979, 1996, 1997, 2001	1986/1987, 1987/1988, 2002/2003
Baro	1982, 1984, 1985, 2002	2002/2003, 2004/2005
Genale Dawa	1996, 2002, 2003, 2010	
Omo Gibe	1980, 1981, 1986	
Rift valley	1980, 1983, 1984, 1985, 1987, 1990, 1999, 2001, 2002, 2004, 2010, 2011, 2012	1984, 1985, 2003, 2012
Tekeze	1996	
Wabishebele	2001, 2002, 2004, 2005, 2007	2002

and the upper part of the basin is affected by drought differently (Megech, Bahir Dar, Ribb, and Koga). Commonly, the most severe streamflow drought year of all gauging stations in the Abbay basin was obtained in 1979, 1980, 1981, 1982, 1983, 1986, 1987, and 2010. This implies that for seven consecutive years (1980–1987), most parts of the basin were affected by severe drought (Figure 4). Besides these drought events, the period of 2001 to 2004 was dominated by moderate and severe drought conditions in most stations. But Chemoga station has been specifically affected by extreme drought in both seasonal (SDI3) and annual (SDI12) timescale during 2001 (Figure 4). In this basin, an extreme drought occurred in 1983/1984, and 1984/1985 in the upper, middle, and lower parts of the basin. The result is supported by [18, 43]; however, these studies were focused on the upper parts of the basin only but the lower and middle parts of the basin have not yet been studied before.

The Awash river basin is country-locked and it is extensively used for different purposes such as water supply, irrigation, and hydropower generation compared to other river basins in the country. However, according to [44], the basin is frequently affected by severe drought in the last few decades. In this study, six streamflow stations were considered to analyze hydrological drought over the whole basin, and the result indicated that the most severe drought years were found in 1979, 1996, 1997, and 2001, whereas extreme droughts occurred in 1986, 1987, and 2002 as shown in Figure 5. In addition to [44], the result is supported by other previous studies, such as [45]. According to this researcher, 2002, 1965, and 1984 were the worst drought years;

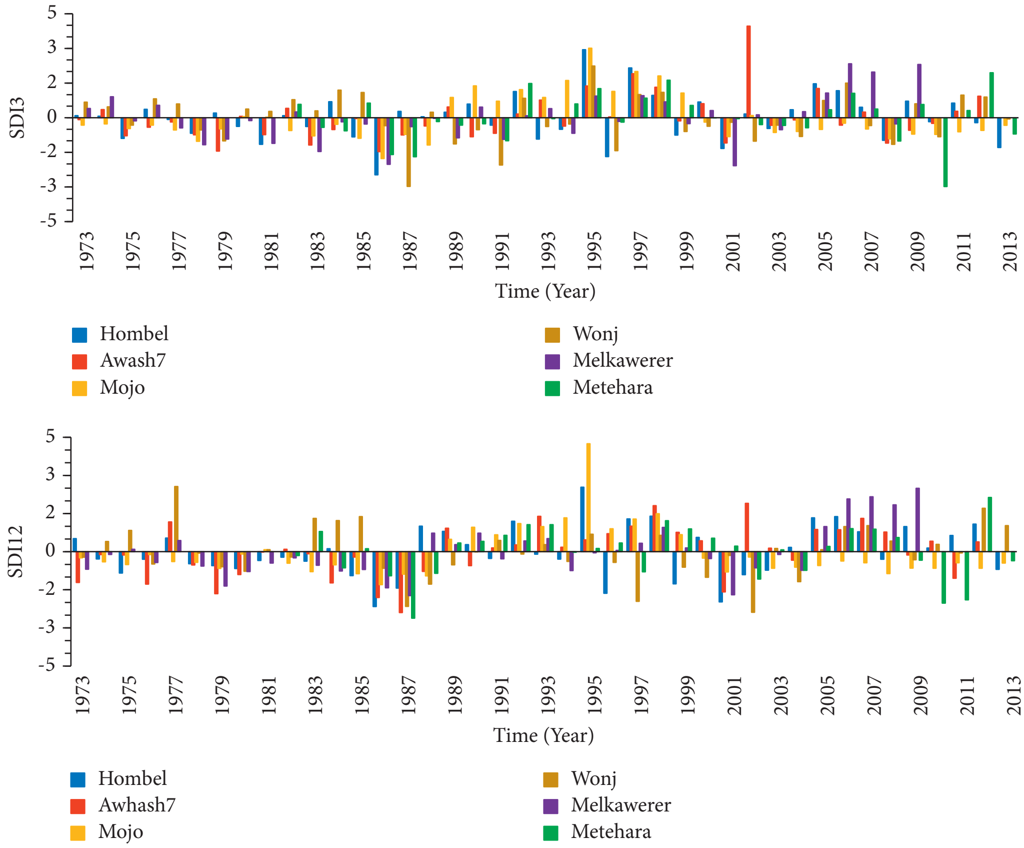

Figure 5: Temporal variation in seasonal (SDI3) and annual (SDI12) for Awash river basin.

99%, 97%, and 95% of the total basin area were affected by severe drought during the listed year, respectively. But during this analysis 1984/1985 is a moderate drought year and its magnitude is less relative to the Abbay river basin, but other drought years agreed with the previous studies.

Two streamflow stations (Gambela and Sore) were considered in the case of the Baro Akobo River basin drought analysis. This basin is received rainfall in two seasons, spring (MAM) and summer (JJA). So, the frequency of severe and extreme drought occurrence is less compared to other river basins in the country. In the Baro Akobo river basin, a drought analysis study is not conducted before this study. Results of this study show that the Baro Akobo basin was under moderate to severe drought conditions in the periods from 1980 to 1986 and 2001 to 2005 (seasonal and annual timescale analysis), and the most severe drought years of this basin occurred during the period of 1982/1983 and 1984/1985 and extreme drought years were 2002/2003 and 2004/2005, respectively, as shown in Figure 6.

Genale Dawa river basin is one of the drought-prone areas and receives less annual rainfall [46]. For the last few decades, drought analysis studies are not conducted in this basin, particularly hydrological drought analysis. Four streamflow stations were considered to identify the historical hydrological drought conditions of the basin during the period from 1981 to 2014 (34 years). As shown in Figure 7, SDI3 has high frequency and magnitude than the annual timescale (SDI12) in this basin. From 1981 to 1988, the basin was under mild-to-moderate drought conditions, whereas 1996 and 1999 were moderate drought years, and from 2001 to 2004, the basin was under moderate to severe drought. Previous meteorological studies concluded that the eastern and southeastern part of the country is frequently affected by the drought in which this basin is located [47–52]. However, meteorological drought results cannot be a good indicator of hydrological drought because the source of surface water for Genale and Wabishebele river basins is from the central part of the country, in which the flow travels a long distance in the arid area. Besides, the hydrological drought of this basin has been low if the central part of the country received good rainfall during the summer. The selected streamflow stations are from the upper part of the basin near the source. Therefore, in this study, the result generally shows that the basin highly experienced moderate to severe drought from the period of 1981to 2012.

Omo Gibe and Baro Akobo river basins are the wettest basins compared to other basins in the country. These basins received rainfall in two seasons (spring and summer). Assendabo and Gojeb streamflow stations were selected for Omo Gibe River basin hydrological drought analysis for the period from 1980 to 2017 (38 years). Results indicated that 1980–1981 and 2001 were severe drought years for Asseendabo station whereas 1986, 2002, and 2016 were for Gojeb station. Generally, this basin was under severe-moderate-mild drought conditions from 1980 to 1989 and 2001 to 2004, respectively, in the order of the years. Figure 8

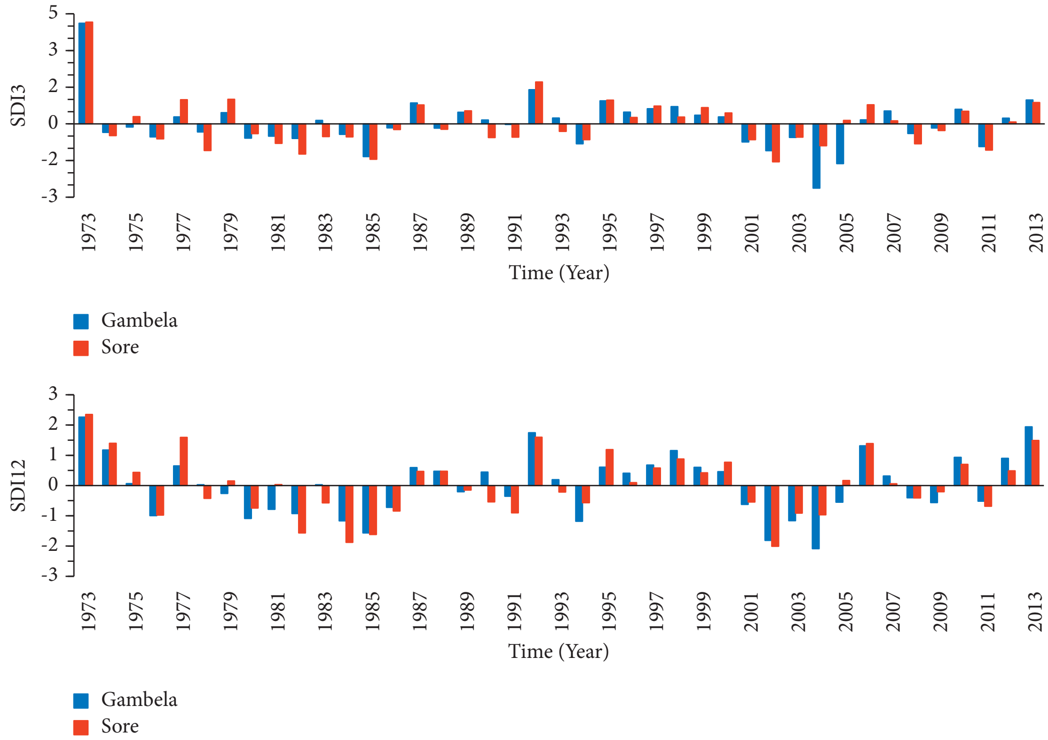

Figure 6: Temporal variation in seasonal (SDI3) and annual (SDI12) for Baro river basin.

Figure 7: Temporal variation in seasonal (SDI3) and annual (SDI12) for Genale Dawa river basin.

indicated that 1980–1987 and 2001 to 2004 were the most drought event year in the basin. But its severity is less than compared to Abbay river basins in the same drought event such as 1980 to 1987.

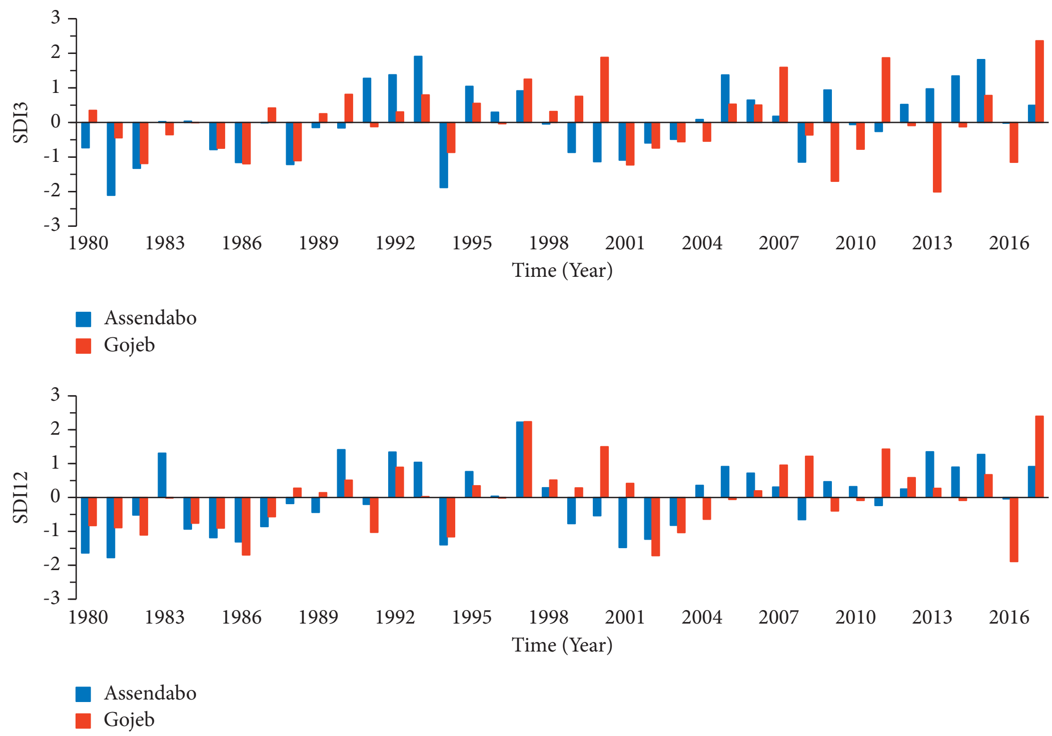

Figure 8: Temporal variation in seasonal (SDI3) and annual (SDI12) for Omo Gibe River basin.

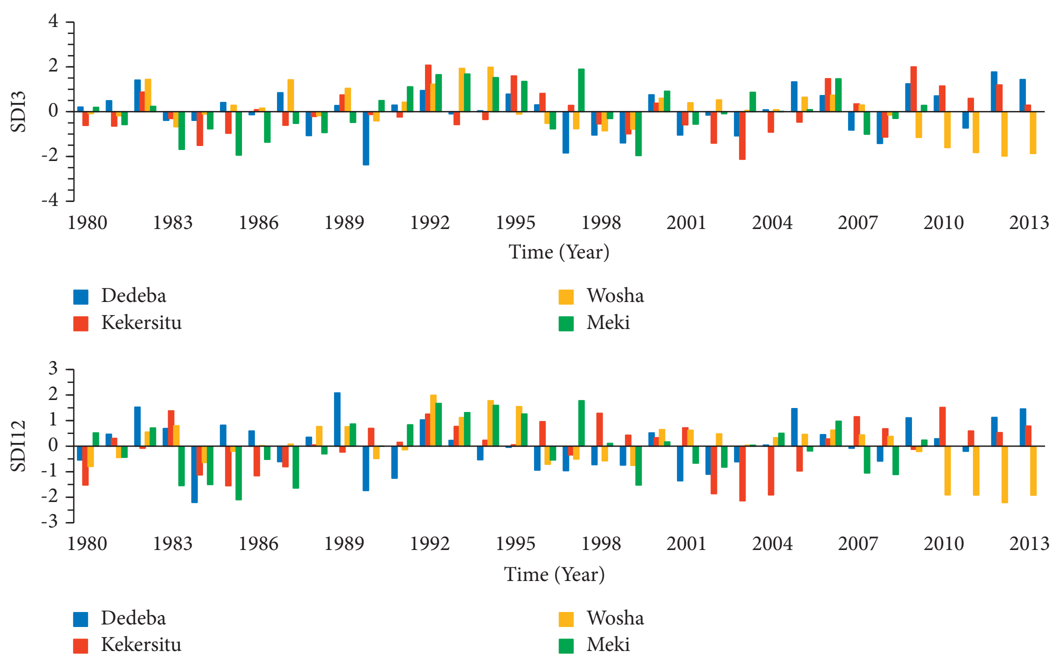

Figure 9: Temporal variation in seasonal (SDI3) and annual (SDI12) for Rift Valley River basin.

Relatively Rift Valley River basins have been frequently affected by severe drought compared to other basins in the last three decades (Figure 9). This result is agreed with [53] in which the basin is hit by moderate to severe droughts in more than 13 events in the last three decades. Particularly in this basin, the severity of drought increases from decade to decade. Figure 9 indicates that both seasonal and annual timescale analyses imply the occurrence of severe and extreme droughts over the three continuous decades (the 1980s, 1990s, and 2000s) increased. In particular, after 2010, the severity of drought at Wosha station increased because Wosha station is the most downstream station of the four considered stations in the basin for this study and which is nearer to arid and semiarid river basins such as Genale Dawa

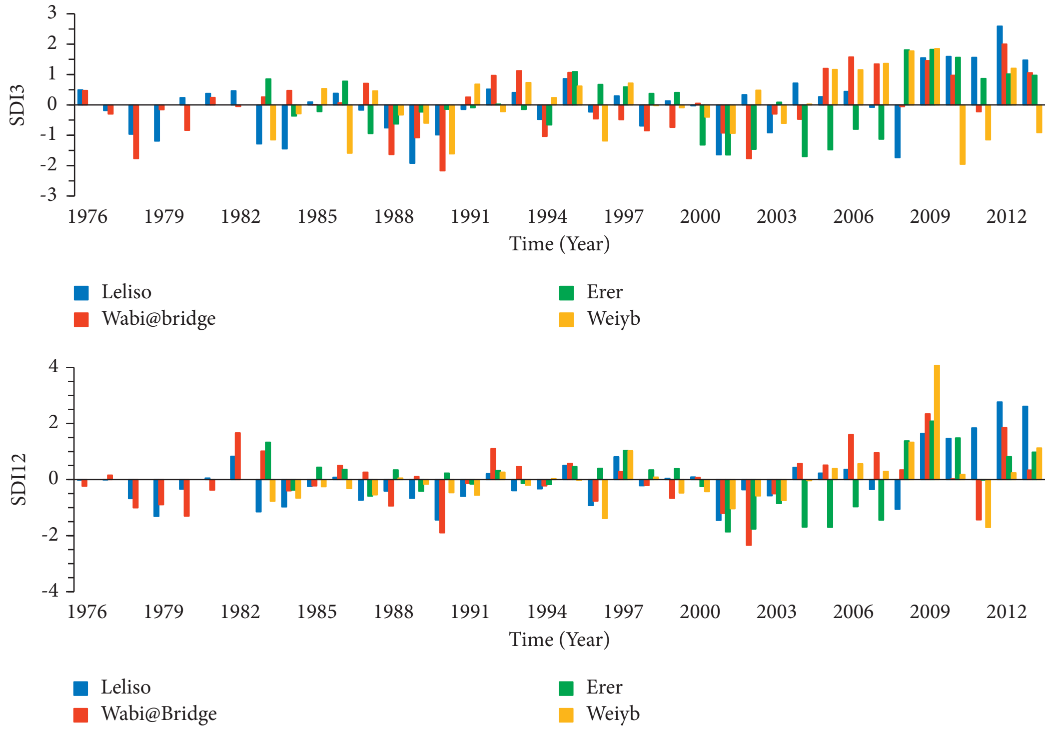

Figure 10: Temporal variation in seasonal (SDI3) and annual (SDI12) for the Wabishebele river basin.

and Wabishebele. Two stations from Genale Dawa river basin (Weib and Halewe) and two stations from Wabishebele river basin (Wabi@bridge and Weiyb) have also indicated the same drought condition after 2010 as Wosha (see Figures 7 and 10).

Drought analysis for the Tekeze basin was considered from 1994 to 2014 (21 years). Most flow stations located above Tekeze dam have no good data for drought analysis purposes. So, the Embamadre station, which is located below the dam, was considered for this study. After the completion of the Tekeze dam, the downstream flow is regulated starting from 2008 [54]. Therefore, for the last decade, the streamflow was increasing due to the conservation of flow by the Tekeze reservoir. As a result, the occurrence of severe as well as extreme drought is dramatically decreased. Figure 11 shows that the annual timescale has severe drought in 1996 whereas the seasonal timescale implies that a severe drought occurred in 2008 and 2009. But from 2001 to 2014, the result indicates wet years. Different studies reveal that the northern part of Ethiopia is frequently affected by drought [23, 47–49, 52, 55]. Therefore, this station is not a good representation for Tekeze basin hydrological drought analysis and it needs further investigation.

The Wabishebele river basin is one of the water-scarce basins in the country. While having the largest area coverage, its annual runoff and water availability are one of the lowest among the major river basins [56]. Before a decade, one drought study was conducted by Awass, 2009, in this river basin. His result shows that the most severe drought years of the basin were 1984/85, 1991/92, and 1998. However, in this study, the most severe and extreme drought events were 1986, 1988, 1989, 1990, 1991, 2001, 2002, 2004, 2005, and 2011. Figure 10 indicated that the magnitude of SDI3 was maximum compared to SDI12 for the above-listed drought years.

In arid and semiarid areas, the variation of streamflow is not significant because the low flow is the common characteristic of these areas. Therefore, moderate drought is more dominant than severe and extreme drought conditions for Genale Dawa and Wabishebele river basins, respectively (Figures 7 and 10).

In all river basins, the occurrence of extreme drought is decreased starting from 1990. For the case of Abbay, Awash, and Baro river basins, the analysis was considered for the long term (1974–2014) which results in different drought conditions, especially since the 1980s was the major drought event decade at the national level.

3.2. Hydrological Drought Characteristics. The hydrological drought characteristics of the 12-month (SDI12) timescale are shown in Tables 5–13. The result implies that the differences in duration (D), severity (S), magnitude (M), and relative frequency (RF) have high variation at different gauge stations within a basin (see Tables 6–13) but the average value of each drought characteristics has the relatively same value for all river basins (see Table 5). The maximum drought duration, severity, magnitude, and relative frequency are observed in the Abbay river basin at a period of 1980–1998 (19 years) at Megech station with 55.88% relative frequency. The hydrological drought condition of the Rift Valley River basin is agreed with Yisehak et.al. (2020); he was investigating drought characteristics at the Kulfo river and the result is almost the same as this finding [53].

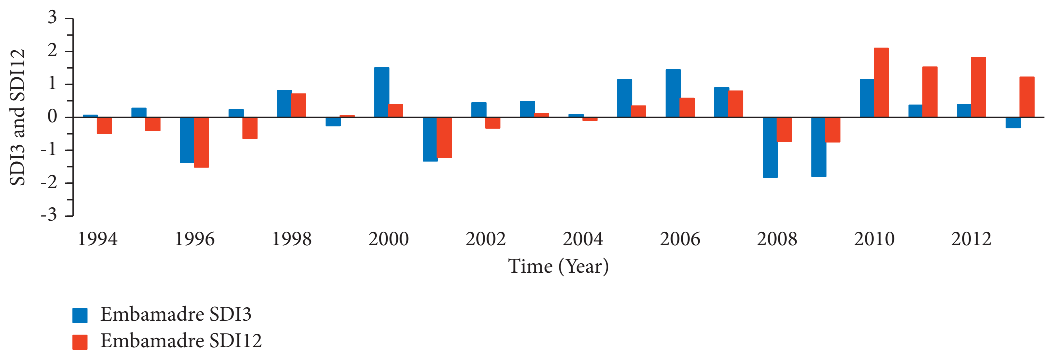

Figure 11: Temporal variation in seasonal (SDI3) and annual (SDI12) for the Tekeze river basin.

Table 5: Recapitulation of hydrological drought characteristics.

Basin	D (year)			S			M			RF (%)		
	Max	Min	Aver	Max	Min	Aver	Max	Min	Aver	Max	Min	Aver
Abbay	19	1	3.2	15.6	0.16	2.48	2.12	0.09	0.72	55.88	2.44	8.25
Awash	14	1	3.03	8.54	0.15	2.33	1.64	0.15	0.79	34.15	2.44	7.55
Baro	5	1	2.17	6.48	0.21	1.87	1.30	0.21	0.74	12.2	2.44	5.28
Genale Dawa	7	1	2.54	5.52	0.43	1.87	1.56	0.22	0.83	21.21	3.03	8.25
Omo Gibe	8	1	2.69	6.77	0.2	2.35	1.89	0.2	0.89	21.05	2.63	7.09
Rift valley	6	1	2.33	8.16	0.2	2.29	2.2	0.2	0.89	20	2.94	7.08
Tekeze	3	2	2.33	2.4	1.47	1.80	0.8	0.74	0.77	15.00	10.00	11.67
Wabishebele	8	1	2.43	10.52	0.22	1.82	1.7	0.16	0.70	25.81	2.63	7.03

Table 6: Hydrological drought characterization in Ethiopian major river basins, Tekeze river basin.

Station	Event	D (year)	S	M	RF (%)
	1994–1996	3	2.4	0.80	15.00
Embamadre	2001–2002	2	1.54	0.77	10.00
	2008–2009	2	1.47	0.74	10.00

3.3. Spatiotemporal Variability Analysis. The main important point in drought analysis and monitoring development is identifying the spatial extent of a drought over the river basin [36]. The drought-prone area identification was accomplished using ArcGIS software by applying a spatial analysis interpolation tool called inverse distance weighted (IDW). The result of SDI for the selected severe drought years was used as input for IDW in ArcGIS. The four severe and extreme drought years were selected to identify drought-prone areas over the region. Relatively, the common severe drought years for most river basins of the country were 1984/85, 1986/87, 2002/3, and 2010/11. The spatial variability of those identified drought years is shown in Figure 12. In 1984, the north and northwest parts of the country were affected by severe droughts (Tekeze, Abbay, and Baro) and some parts of the south and northeast parts were under moderate drought conditions (Rift Valley and Awash) (Figure 12(a)). In 1986, the central and south parts (Awash and Baro) of the country were affected by severe drought (Figure 12(b)). Severe drought was extended in the western part (Baro) and eastern part (Genale Dawa and Wabishebele) in 2002 (Figure 12(c)). But, in 2010, the drought was high in the Abbay basin and occurred in Genale Dawa and Rift Valley basins (Figure 12(d)).

Table 7: Hydrological drought characterization in Ethiopian major river basins, Omo Gibe River basin.

Station	Event	D (year)	S	M	RF (%)
	1980–1982	3	3.93	1.31	7.89
	1984–1989	6	4.9	0.82	15.79
	1991	1	0.2	0.20	2.63
Assendabo	1994	1	1.4	1.40	2.63
	1999–2003	5	4.48	0.90	13.16
	2008	1	0.66	0.66	2.63
	2011	1	0.23	0.23	2.63
	1980–1987	8	6.77	0.85	21.05
	1991	1	1.03	1.03	2.63
	1994	1	1.16	1.16	2.63
Gojeb	2002–2005	4	3.45	0.86	10.53
	2009–2010	2	0.49	0.25	5.26
	2016	1	1.89	1.89	2.63

Table 8: Hydrological drought characterization in Ethiopian major river basins, Abbay river basin.

Station	Event	D (year)	S	M	RF (%)
Bahir Dar	1973	1	0.28	0.28	2.44
	1978–1987	10	7.66	0.77	24.39
	1989–1990	2	0.48	0.24	4.88
	1995	1	1.17	1.17	2.44
	2002–2005	4	1.78	0.45	9.76
	2009	5	5.7	1.14	12.20
Border	1973	1	0.18	0.18	2.44
	1975–1976	2	1.18	0.59	4.88
	1979	1	1.62	1.62	2.44
	1981–1991	11	11.46	1.04	26.83
	2002–2004	3	1.05	0.35	7.32
	2008	1	0.33	0.33	2.44
G. Beles	1981–1985	5	6.47	1.29	12.20
	1991	1	2.12	2.12	2.44
	1993–1997	5	2.01	0.40	12.20
	2001	1	0.72	0.72	2.44
	2003–2004	2	0.2	0.10	4.88
	2006–2013	8	6.53	0.82	19.51
Gummera	1973–1984	12	10.7	0.89	29.27
	1986–1987	2	1.08	0.54	4.88
	1989–1992	4	1.63	0.41	9.76
	1994	1	0.28	0.28	2.44
	1998	1	0.88	0.88	2.44
	2001–2002	2	0.62	0.31	4.88
	2004	1	1	1.00	2.44
Guder	1973	1	0.32	0.32	2.78
	1975–1976	2	2.27	1.14	5.56
	1978–1981	4	3.1	0.78	11.11
	1984–1985	2	0.65	0.33	5.56
	1987	1	1.31	1.31	2.78
	1990	1	0.58	0.58	2.78
	1994	1	1.52	1.52	2.78
	1996–1997	2	1.51	0.76	5.56
	1999	1	0.18	0.18	2.78
	2001–2004	4	3.82	0.96	11.11
G. Abbay	1977	1	0.49	0.49	2.56
	1982	1	1.09	1.09	2.56
	1985–1987	3	2.85	0.95	7.69
	1989	1	1.75	1.75	2.56
	1991	1	0.72	0.72	2.56
	1994	1	1.69	1.69	2.56
	2001–2004	5	5.32	1.06	12.82
	2008–2011	4	2.15	0.54	10.26
Koga	1975	1	0.35	0.35	2.56
	1977	1	0.24	0.24	2.56
	1981–1990	10	8.69	0.87	25.64
	1992	1	0.31	0.31	2.56
	1995–1996	2	0.17	0.09	5.13
	2000–2001	2	0.98	0.49	5.13
	2008–2001	4	4.08	1.02	10.26
Ribb	1978–1984	7	8.7	1.24	17.95
	1986	1	1.47	1.47	2.56
	1989	1	0.96	0.96	2.56
	1994	1	0.16	0.16	2.56
	1996–1997	2	0.9	0.45	5.13
	2001–2004	4	2.46	0.62	10.26
	2010–2011	2	0.71	0.36	5.13

Table 8: Continued.

Station	Event	D (year)	S	M	RF (%)
Chemoga	1973–1975	3	1.7	0.57	8.33
	1981–1982	2	0.97	0.49	5.56
	1984–1985	2	0.66	0.33	5.56
	1989	1	0.34	0.34	2.78
	1991	1	0.49	0.49	2.78
	1994	1	1.63	1.63	2.78
	1996–1997	2	1.06	0.53	5.56
	2001–2008	8	7.92	0.99	22.22
Megech	1980–1998	19	13.01	0.68	55.88
	2001–2003	3	0.91	0.30	8.82
Kessie	1973–1974	2	0.25	0.13	4.88
	1976–1992	17	15.6	0.92	41.46
	2010	1	0.23	0.23	2.44

Table 9: Hydrological drought characterization in Ethiopian major river basins, Baro Akobo river basin.

Station	Event	D (year)	S	M	RF (%)
Gambela	1976	1	0.99	0.99	2.44
	1979–1982	4	3.06	0.77	9.76
	1984–1986	3	3.46	1.15	7.32
	1989	1	0.21	0.21	2.44
	1991	1	0.35	0.35	2.44
	1994	1	1.18	1.18	2.44
	2001–2005	5	6.23	1.25	12.20
	2008–2009	2	0.96	0.48	4.88
	2011	1	0.52	0.52	2.44
Sorie	1976	1	0.98	0.98	2.44
	1978	1	0.43	0.43	2.44
	1980	1	0.74	0.74	2.44
	1982–1986	5	6.48	1.30	12.20
	1989–1991	3	1.59	0.53	7.32
	1993–1994	2	0.78	0.39	4.88
	2001–2004	4	4.43	1.11	9.76
	2008–2009	2	0.62	0.31	4.88
	2011	1	0.69	0.69	2.44

Table 10: Hydrological drought characterization in Ethiopian major river basins, Awash river basin.

Station	Event	D (year)	S	M	RF (%)
Awash7	1973–1976	4	2.74	0.685	10
	1978–1981	4	3.1	0.775	10
	1984–1988	5	6.42	1.284	12.5
	1990	1	0.55	0.55	2.5
	2001	1	1.58	1.58	2.5
	2011	1	1.05	1.05	2.5
Hombel	1974–1976	3	1.43	0.48	7.32
	1978–1983	6	2.64	0.44	14.63
	1985–1987	3	4.53	1.51	7.32
	1993–1994	2	0.39	0.195	4.88
	1996	1	1.64	1.64	2.44
	1999	1	1.27	1.27	2.44
	2001–2003	3	3.62	1.21	7.32
Melka	1973–1974	2	0.8	0.40	5.41
	1976	1	0.43	0.43	2.70
	1978–1987	10	8.54	0.85	27.03
	1991	1	0.28	0.28	2.70
	1994–1995	2	0.8	0.40	5.41
	2000–2004	5	3.44	0.69	13.51
Wonj	1973	1	0.22	0.22	2.44
	1976	1	0.48	0.48	2.44
	1978–1980	3	1.43	0.48	7.32
	1986–1990	5	4.61	0.92	12.20
	1996–1997	2	2.37	1.19	4.88
	1999–2002	4	4.15	1.04	9.76
	2004	1	1.18	1.18	2.44
	2009	1	0.32	0.32	2.44
Metehara	1982	1	0.15	0.15	2.44
	1984	1	0.63	0.63	2.44
	1986–1988	3	4.47	1.49	7.32
	1997	1	0.79	0.79	2.44
	2002	1	1.08	1.08	2.44
	2004	1	0.73	0.73	2.44
	2009–2011	3	4.27	1.42	7.32
	2013	1	0.36	0.36	2.44
Mojo	1973–1980	8	2.83	0.35	19.51
	1982–1988	7	5.77	0.82	17.07
	2000–2013	14	7.59	0.54	34.15

4. Discussion

This study assessed the historical hydrological drought conditions in Ethiopia from 1973 to 2014. The analysis was computed using the streamflow drought index (SDI) on a 3-month and 12-month timescale for 34 streamflow stations in all basins. The results indicate that the occurrence of severe and extreme drought events declined from decade to decade, especially in the last two decades the 2000s and 2010s compared to earlier decades (1970s, 1980s, and 1990s). However, less severe and extreme drought events occurred from 2001 to 2004 in some river basins, particularly, Baro, Rift Valley, Genale Dawa, and Wabishebele river basins. Even though there is a limitation to hydrological drought analysis at a national level, some previous meteorological drought studies supported this finding such as [55].

This study also suggests that all river basins in Ethiopia experienced some degree of drought at both seasonal (3 months) and annual (12 months) timescales. The most severe and extreme drought events occurred in the period from 1981 to 1987 and 2002 to 2004. This result is also

Table 11: Hydrological drought characterization in Ethiopian major river basins, Genale Dawa river basin.

Station	Event	D (year)	S	M	RF (%)
Halawel	1984–1985	2	0.81	0.41	6.90
	1987	1	0.64	0.64	3.45
	1990–1991	2	1.68	0.84	6.90
	1993–1994	2	0.83	0.42	6.90
	1998–1999	2	1.56	0.78	6.90
	2001–2005	5	3.91	0.78	17.24
	2007–2008	2	1.46	0.73	6.90
	2012	1	0.8	0.80	3.45
Shaya	1981–1987	7	4.12	0.59	21.21
	1989–1991	3	1.43	0.48	9.09
	1993–1994	2	0.43	0.22	6.06
	1996	1	1.52	1.52	3.03
	1999–2005	7	5.52	0.79	21.21
Weib	1984–1988	5	1.36	0.27	16.67
	1990–1991	2	1.44	0.72	6.67
	1996	1	0.89	0.89	3.33
	1999	1	1.27	1.27	3.33
	2001–2003	3	3	1.00	10.00
	2008	1	1.38	1.38	3.33
	2010–2011	2	3.11	1.56	6.67
Chenemsa	1984–1988	5	2.31	0.46	16.13
	1990–1991	2	1.82	0.91	6.45
	1996	1	1.42	1.42	3.23
	1999	1	1.17	1.17	3.23
	2001–2003	3	3.85	1.28	9.68
	2007–2008	2	0.78	0.39	6.45

Table 12: Hydrological drought characterization in Ethiopian major river basins, Rift Valley River basin.

Station	Event	D (year)	S	M	RF (%)
Dedeba	1980	1	0.54	0.54	2.94
	1984	1	2.2	2.20	2.94
	1987	1	0.61	0.61	2.94
	1990–1991	2	3	1.50	5.88
	1994–1999	6	3.94	0.66	17.65
	2001–2003	3	3.07	1.02	8.82
	2007–2008	2	0.66	0.33	5.88
	2011	1	0.2	0.20	2.94
Kekersitu	1980	1	1.52	1.52	2.94
	1984–1987	4	4.66	1.17	11.76
	1989	1	0.23	0.23	2.94
	1997	1	0.35	0.35	2.94
	2002–2005	4	6.88	1.72	11.76
Meki	1981	1	0.44	0.44	3.33
	1983–1988	6	7.59	1.27	20.00
	1996	1	0.54	0.54	3.33
	1999	1	1.52	1.52	3.33
	2001–2002	2	1.49	0.75	6.67
	2007–2008	2	2.16	1.08	6.67
Wosha	1980–1981	2	1.25	0.63	5.88
	1984–1985	2	0.84	0.42	5.88
	1990–1991	2	0.62	0.31	5.88
	1996–1999	4	2.54	0.64	11.76
	2009–2013	5	8.16	1.63	14.71

assured by [18]. The proportional area affected by mild and moderate drought showed a statically increasing trend over

Table 13: Hydrological drought characterization in Ethiopian major river basins, Wabishebele river basin.

Station	Event	D (year)	S	M	RF (%)
Leliso	1978–1980	3	2.05	0.68	7.89
	1983–1985	3	2.36	0.79	7.89
	1987–1991	5	3.84	0.77	13.16
	1993–1994	2	0.73	0.37	5.26
	1996	1	0.92	0.92	2.63
	1998	1	0.22	0.22	2.63
	2001–2003	3	2.39	0.80	7.89
	2007–2008	2	1.41	0.71	5.26
Erer	1984	1	0.37	0.37	3.23
	1987	1	0.59	0.59	3.23
	1989	1	0.41	0.41	3.23
	1993–1994	2	0.32	0.16	6.45
	2000–2007	8	10.52	1.32	25.81
Wabi	1976	1	0.23	0.23	2.63
	1978–1981	4	3.49	0.87	10.53
	1984–1985	2	0.66	0.33	5.26
	1988	1	0.94	0.94	2.63
	1990–1991	2	2.04	1.02	5.26
	1994	1	0.22	0.22	2.63
	1996	1	0.77	0.77	2.63
	1998–199	2	0.88	0.44	5.26
	2001–2003	3	4.06	1.35	7.89
	2011	1	1.43	1.43	2.63
Weyb	1983–1987	5	2.54	0.51	16.13
	1989–1991	3	1.18	0.39	9.68
	1995–1996	2	1.41	0.71	6.45
	1999–2004	6	3.3	0.55	19.35
	2011	1	1.7	1.70	3.23

the 42 years. The areas subjected to the droughts of high intensity (i.e., severe and extreme) also exhibited a statistically significant decrease with the peak of the decline from the 1990s and 2000s. These findings imply that the decrease in drought frequency in the recent decade is associated more with a decrease in the frequency of intense drought episodes. The overall analysis also indicates anon—synchronous occurrence of drought episodes over the country, whereas some severe drought episodes were witnessed in specific periods, while no droughts were corresponding to these episodes across other regions of the study area.

The spatial variability of hydrological drought occurrence has a wide range from basin to basin. These different drought occurrence patterns are related to diverse geographical areas and are associated with different temporal variations. It is observed that there is a strong relationship between streamflow and drought potential basins in the regions [20], where the most significant pattern of the drought was specifically found over the arid areas, while less significant patterns were observed over the most humid regions.

The 1980s was the driest year in all river basins. At a country level, four severe to extreme drought years were identified, 1984/1985, 1986/1987, 2002/2003, and 2010/2011 from 1973 to 2014. However, only 1984/1985 was nationally as well as globally get attention, but other severe drought years hindered the economic growth of the country in the last three decades.

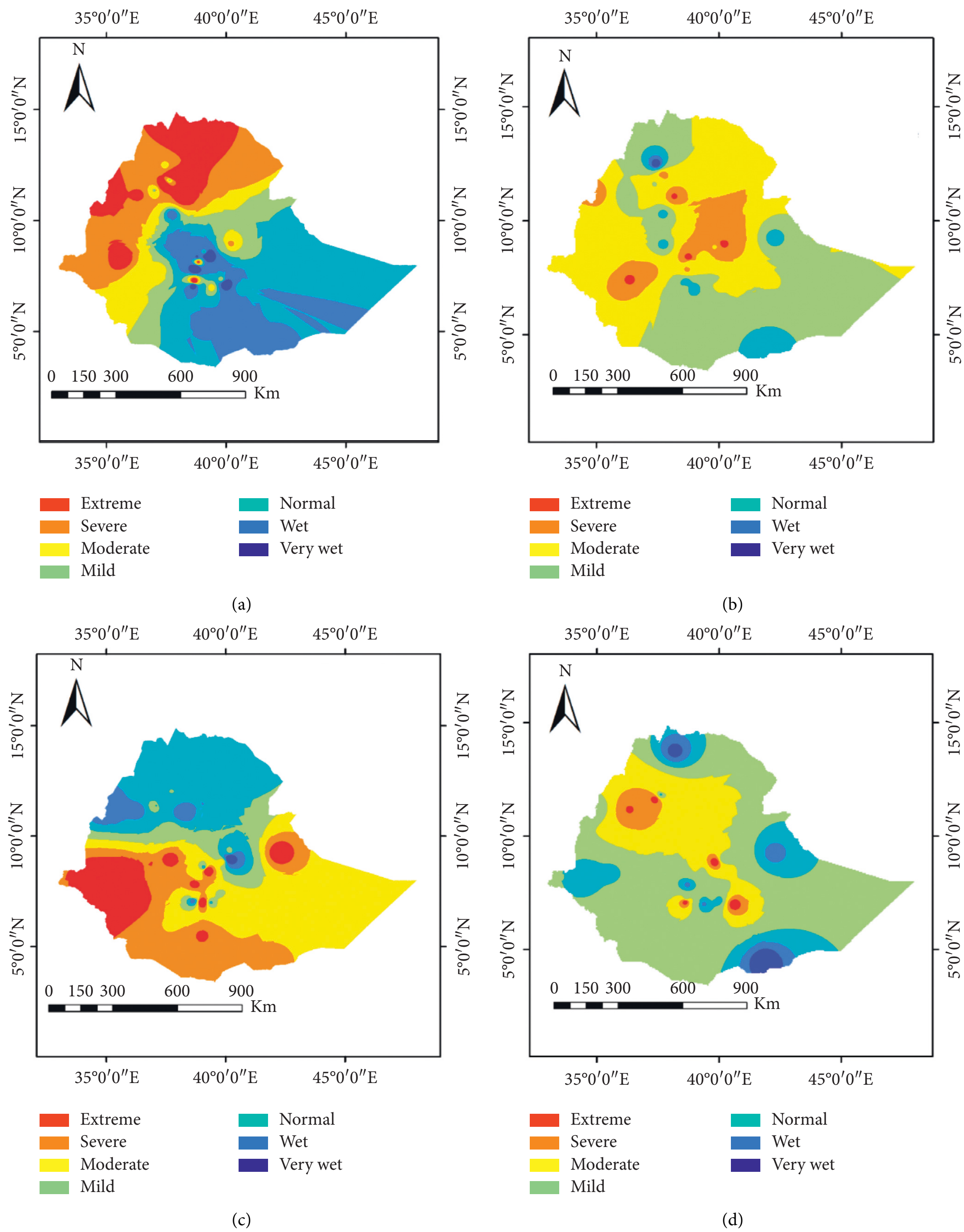

Figure 12: Spatial variation of streamflow drought in Ethiopia in four severe drought years. (a). SDI 1984. (b). SDI 1986. (c). SDI 2002. (d). SDI 2010.

5. Conclusion

In Ethiopia, many sectors such as agriculture, water supply, and hydropower are highly affected by hydrological drought in which most human activities depend on these sectors, but the hydrological drought is not well studied in the country. Particularly, Baro Akobo, Omo Gibe, Genale Dawa, and Rift Valley River basins are not been studied before. Abbay, Awash, Tekeze, and Wabishebele river basins are partially studied, more focused on meteorological drought than other droughts. Therefore, this study analyzed hydrological drought in Ethiopia using SDI to identify the most severe and extreme drought years and drought-prone areas. Accordingly, 1979, 1981, 1983, 1987, 1996, 1997, and 2001 were the most severe drought years, whereas 1984, 1986, 2002, and 2010 were relatively extreme drought years in all river basins in Ethiopia from 1973 to 2014. However, globally, only the 1984 severe drought event was popularly recognized and other drought years were not focused on but affected food security, water supply, and hydropower production system over the country. Abbay, Awash, and Rift Valley River basins were frequently affected by severe streamflow drought, but for the case of Baro Akobo and Omo Gibe River basins, the frequency of severe drought was less. Genale Dawa and Wabishebele river basins were located in arid and semiarid areas in which drought conditions are dominated by their aridity nature and the occurrence of severe and extreme drought events was rare. But mild and moderate drought events frequently occur in these basins. Generally, severe and extreme drought frequency is relatively decreased for all river basins in the 1990s and 2000s compared to the 1970s and 1980s. The source of streamflow for all river basins is from highlands and mountainous areas. Therefore, most of the streamflow stations considered for this study were from the upstream and middle parts of the basins. Therefore, the drought conditions for these stations can represent the downstream parts of the basins. Generally, Abbay and Awash river basins are the most populated basins and cover large investment areas in which the investigation of hydrological drought and development of drought early warning systems is important. Therefore, this study gives good information about hydrological drought conditions for all river basins for decision-makers for good mitigation measurement development.

Data Availability

This research is not completed and the author is working on future forecasting of hydrological drought conditions in Ethiopia using the data used in this article. Therefore, the data will be provided after completing the forecasting analysis. But at this level, the data are not provided due to future extension of the research. So, the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known conflicts of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The corresponding author acknowledges the Ethiopian Ministry of Water and Energy (MoWE) for their support of hydrological data (Streamflow)

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