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Abstract: The Upper Blue Nile (UBN) basin is less-explored in terms of drought studies as compared to other parts of Ethiopia and lacks a basin-specific drought monitoring system. This study compares six drought indices: Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index (SPEI), Evapotranspiration Deficit Index (ETDI), Soil Moisture Deficit Index (SMDI), Aggregate Drought Index (ADI), and Standardized Runoff-discharge Index (SRI), and evaluates their performance with respect to identifying historic drought events in the UBN basin. The indices were calculated using monthly time series of observed precipitation, average temperature, river discharge, and modeled evapotranspiration and soil moisture from 1970 to 2010. The Pearson's correlation coefficients between the six drought indices were analyzed. SPI and SPEI at 3-month aggregate period showed high correlation with ETDI and SMDI ($r > 0.62$), while SPI and SPEI at 12-month aggregate period correlate better with SRI. The performance of the six drought indices in identifying historic droughts: 1973–1974, 1983–1984, 1994–1995, and 2003–2004 was analyzed using data obtained from Emergency Events Database (EM-DAT) and previous studies. When drought onset dates indicated by the six drought indices are compared with that in the EM-DAT. SPI, and SPEI showed early onsets of drought events, except 2003–2004 drought for which the onset date was unavailable in EM-DAT. Similarly, ETDI, SMDI and SRI-3 showed early onset for two drought events and late onsets in one-drought event. In contrast, ADI showed late onsets for two drought events and early onset for one drought event. None of the six drought indices could individually identify the onsets of all the selected historic drought events; however, they may identify the onsets when combined by considering several input variables at different aggregate periods.

Keywords: drought assessment; drought indices; Upper Blue Nile; comparison of indices

1. Introduction

Drought is abnormally dry condition sustained for a prolonged period. Unlike other natural disasters, such as floods and tornadoes, drought's impacts do not manifest immediately. However, in its aftermath, crops wilt, livestock dies, rivers and reservoirs dry up, and socioeconomic sectors are affected [1,2]. Drought can be characterized by its severity, duration, and areal extent. In the past few decades, a number of devastating drought events have been occurred. For example, in 2009, severe drought affected different parts of the globe, but more people were affected in eastern Africa than anywhere else. About 20 million people were estimated to have been suffering from food insecurity in eastern Africa [3]. The year 2009 was also recorded as a severe drought year in Ethiopia; six million people were affected and needed food aid from international emergency services [3]. Other historic drought events have also occurred in Ethiopia in the past few decades, most notably 2003/2004 and 1984/1985 [4]. These drought years were recorded as the worst in the history of the country, in which millions of people lost their lives and many more people were forced into further destitution [5]. Natural drought events cannot be prevented, but through monitoring, forecasting, and early warning, drought mitigation can be better managed, and impacts can be reduced.

Drought is mainly categorized into four major types: meteorological, agricultural, hydrological, and socioeconomic [1,2]. Meteorological drought is characterized by a prolonged deficit of precipitation from its long-term average [1]. Agricultural drought is characterized by deficits of total soil moisture and results mainly from the shortage of precipitation. Hydrological drought is related to the impacts of persistent shortage of precipitation on surface and/or subsurface water supply (i.e., streamflow, reservoir and lake levels, and groundwater) [1,6–10]. Socioeconomic drought is associated with the impacts of meteorological, agricultural, and hydrological droughts on the socioeconomic sectors. Drought monitoring employs widely used drought indices, such as the Palmer Drought Severity Index (PDSI) [11,12], Standardized Precipitation Index (SPI) [12–15], Standardized Precipitation Evapotranspiration Index (SPEI) [16], Standardized Runoff Index (SRI) [17], Surface Water Supply Index [18], Decile Index [19], and Vegetation Drought Response Index [20]. Detailed reviews of drought indices can be found in Zargar et al. [21], and regional specific drought studies can be found in Keyantash and Dracup [22], Ntale and Gan [23], Morid et al. [24], Barua et al. [25], Dogan et al. [26], and Trambauer et al. [27].

Because of the inherent complexity of the drought phenomenon and variation in the available good quality data, the performance of drought indices in characterizing historic drought events may vary from place to place [28]. Identifying an appropriate drought index for a specific region is crucial for mitigating and preparing for drought-related disasters. Comparative studies of drought indices have been carried out in many regions or river basins. Jain et al. [28] compared the suitability of six drought indices in the Ken River basin, India, and indicated that the Effective Drought Index (EDI) is a more suitable drought index for the study basin. Morid et al. [24] compared the performances of seven drought indices and recommended using the EDI and SPI for drought monitoring in the basin. Their study also indicated that the EDI was more responsive to drought and performed better than the SPI. Okpara and Tarhule [29] evaluated the performance of three drought indices in the Upper Niger basin based on six decision criteria. They reported that the SPI ranked first among meteorological drought indices. Barua et al. [25] evaluated the performance of five drought indices for the Yarra river catchment in Australia using five subjective decision criteria (robustness, tractability, sophistication, transparency, and extendibility). They found that the Aggregate Drought Index (ADI) was superior and preferable to other indices for the study catchment. Many similar studies have been conducted in other basins [30–33]. In addition, drought related studies in Ethiopia have been reported in the literature, especially focusing on areas in the northern and eastern parts of the country [4,34,35], including the Upper Blue Nile (UBN) basin [5,34,36]. However, the UBN lacks a basin-specific drought monitoring system.

The main objective of this study is to evaluate and compare the performance of multiple drought indices for indicating the onset, severity, and duration of historical drought events in the Upper Blue Nile (UBN) basin. The six drought indices used are the Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index (SPEI), Evapotranspiration Deficit Index (ETDI), Soil Moisture Deficit Index (SMDI), Aggregate Drought Index (ADI), and Standardized Runoff-discharge

Index (SRI). These drought indices were calculated using observation data and hydrological model results. This study is expected to help in establishing basin-specific drought monitoring by advancing the understanding of how different drought indices perform in identifying historical drought events.

2. Study Area and Data

2.1. Study Area: Upper Blue Nile Basin (UBN)

The UBN basin is located in the north-western region of Ethiopia between 7°40′ N and 12°51′ N latitudes and 34°25′ E and 39°49′ E longitudes (Figure 1), and covers a total area of 176,000 km^2 upstream of the Ethiopia-Sudan border [37]. The topography of the basin signifies two distinct features: the highlands with rugged mountainous areas in the central and eastern part of the basin, and the lowlands in the western part of the basin. The altitude in the basin ranges from 490 to 4260 m. While the highlands are the main source of water, the lowlands have expanses of flat lands through which the river flow travels from the highlands to the lower riparian countries (Sudan and Egypt). Tekleab et al. [38] reported that the mean annual temperature (data years 1995–2004) ranges from 13 °C in south-eastern parts to 26 °C in the south-western part near the Ethiopia-Sudan border. The annual rainfall ranges from 780 to 2200 mm, with the highlands having the highest rainfall (ranging from 1500 to 2200 mm) and the lowlands receiving less than 1500 mm [37,39,40]. Following the seasonality of the rainfall, 82% of the annual flow occurs during the main rainy season in June to September [41].

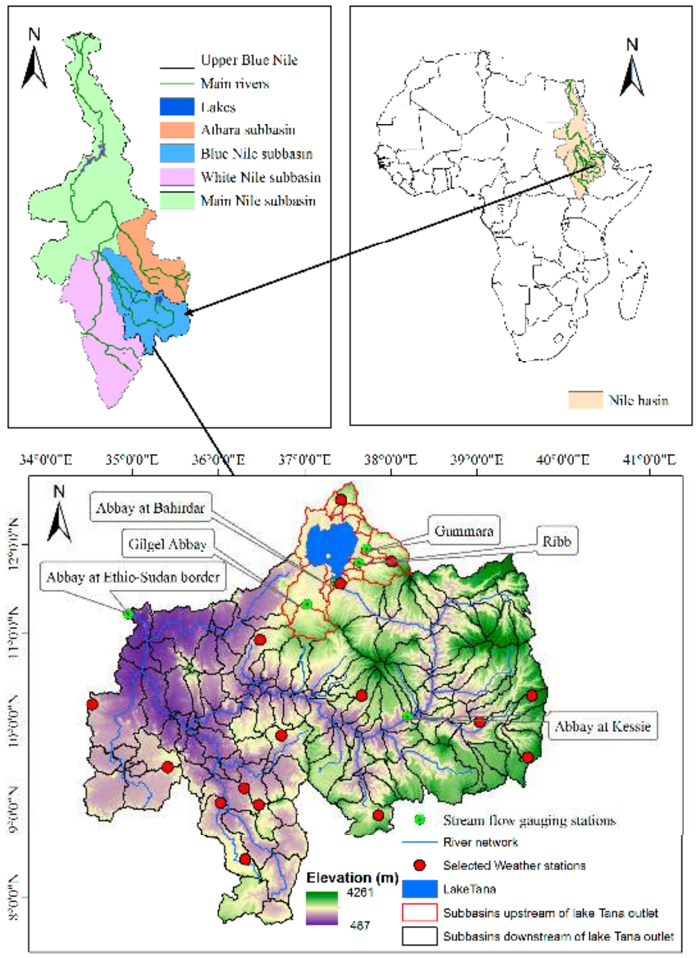


Figure 1. Upper Blue Nile basin with river network, gauging stations, and the sub-basin discretisation used by the Soil and Water Assessment Tool (SWAT) model to estimate soil moisture and actual evapotranspiration (Section 2.2.2), upstream and downstream of the Lake Tana outlet.

The land cover in the basin is dominated by dry-land crops, pastures, savannah, grassland, woodland, water bodies, and sparsely vegetated plants [42]. Volcanic rock and Precambrian basement rock are the most widely available geological formations in the basin, and small areas are covered by sedimentary rock [36]. The dominant soil types are Leptosols and Alisols (21%), Nitosols (16%), Vertisols (15%), and Cambisols (9%) [43].

Administratively, 47% of the area of the UBN basin is in the region of Amhara, 31% in the region of Oromia, and 23% in the region of Benishangul Gumuz. In the earlier division of the country (before 1992), the basin covers substantial parts of Gondar, Wollo, Gojjam, Welega, and Shoa provinces of Ethiopia. The drought onset and number of affected population data in the basin prior to 1992 are associated with the former political administrative provinces (Note: Ethiopia was divided into provinces until they were replaced by regions ("Kililoch") and chartered cities in 1992).

2.2. Data Used

2.2.1. Historical Drought Events

The history of drought in the basin is poorly documented. However, major historical drought events within the study period (1970–2010) were identified from previous studies and Emergency Events Database (EM-DAT), the international disaster database (http://www.emdat.be/database) [5,33,44]. According to previous studies, 1973–1974, 1983–1984, 1994–1995, and 2003–2004 were reported as the major drought years in Ethiopia [5,33]. EM-DAT (Table 1) includes these drought events as well, but reports the 1973 and 1994 events as part of longer drought periods from 1973 to 1978 and from 1989 to 1994, respectively. This possibly reflects the occurrence of multiple drought events during these years in different parts of the country. For evaluating the six drought indices (Section 4.2), the EM-DAT drought periods are taken as a reference, while keeping in mind their reporting of prolonged droughts. The EM-DAT database is compiled from various sources, including UN agencies, non-governmental organizations, insurance companies, research institutes, and press agencies. The available information for the selected drought events is presented in Table 1. A previous report shows that the quality and reliability of the EM-DAT is complementary with other disasters data reporting organizations (e.g., NatCat and Sigma) since the EM-DAT data are derived mainly from humanitarian agencies and development organizations [45]. Its main limitation is a lack of data at a finer spatial resolutions (e.g., at county, or district level) so that the particular drought start date (Table 1) is assumed to be the same for all of the provinces. The year 1983–1984 stands out as the drought year with the highest percentage (22%) of the population affected. For other drought events, this percentage is 16% or less. The provinces indicated in bold (Table 1) are situated (partly) within the UBN basin. For example, according to the previous division of provinces (before 1992), Gondar includes the northern part of the basin, whereas Wollo and Shoa include eastern and northeast, and southeast parts of the basin, respectively. According to the current regional classification, Amhara covers the central, northern, northeastern, and northwest parts, and Oromia covers the southern, southeast, and southwest parts of the UBN basin. The eastern and some of the central parts of the basin have not been reported drought affected area in EM-DAT. Both the start and end dates of the historic drought events are shown in Table 1, but the months of the end dates are not indicated. Hence, the evaluation of the drought indices in identifying drought events focuses on the onset of the drought events.

2.2.2. Actual Evapotranspiration (ET) and Soil Moisture Data

We used a process based semi-distributed hydrological model (Soil and Water Assessment Tool; SWAT) to simulate the actual evapotranspiration and soil moisture time series data. The SWAT model was setup using mainly daily rainfall, and temperature; and calibrated and validated using river discharge data from 1970 to 2010. The monthly calibration results in terms of coefficient of determination (r^2) and Nash-Sutcliffe efficiency (NSE) between observed and simulated river discharge in five stations vary from 0.83 to 0.93 (for r^2) and 0.84 to 0.91 (for NSE). The Hargreaves method [46] was used for potential ET in SWAT. Weather data of relative humidity, solar radiation, wind speed, and sunshine hour available from 10 stations are used for updating the SWAT database. Other input data (Digital Elevation Model (DEM), land use, and soil maps) were collected from difference sources. The 90 m spatial resolution DEM data were obtained from the Shuttle Radar Topography Mission (SRTM) (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1). Land use classification data of the year 2000 at a spatial resolution of 5 km by 5 km were acquired from the Ministry of Agriculture and Rural Development (MARD) [47] of Ethiopia. The basin is classified into 32 land use classes. Cultivated land is the dominant land cover in the basin. The soil map and physical and chemical properties at different soil layers were obtained from the Ministry of Water, Irrigation, and Electricity of Ethiopia [48]. Actual evapotranspiration and soil moisture from the model output were used to calculate evapotranspiration deficit index (ETDI) and soil moisture deficit index (SMDI), respectively. Previous studies have shown the capability of SWAT to model the hydrological processes in the UBN basin (e.g., [42,49–53]).

Table 1. The start and end date of the historic drought events and the total number of people affected during the years 1970–2010. The provinces indicated in bold are situated (partly) within the UBN basin.

Start Date	End Date	Location	Total Affected Population (10^6)	Total Number of Population in Ethiopia (10^6)	Ratio b/n Column 4 and 5 (%)
December 1973	1978	Wollo, North Shoa, Tigray, Kangra province	3	32.57	9
May 1983	1984	Wollo, Gondar, Gore, Tigray, Shoa, Harerge, Sidamo	7.75	35.24	22
June 1987	1987	Ogaden, Tigray, Wollo, Shewa, Gamo Gofa, Sidama, Gondar, Bale	7	48.06	15
October 1989	1994	Northern Ethiopia, Tigray, Wollo, Gondar, Harerge	6.5	48.06	14
2003	2004	Tigray, Oromia, Amhara, Somali, Afar province	12.6	76.61	16
May 2008	October 2009	Oromia, Somali, Amhara, Afar, Tigray, SNNPR province	6.4	87.56	7

Source: EM-DAT International Disaster Database. Centre for Research on the Epidemiology of Disasters-CRED; http://www.emdat.be/database (last access: 17 July 2016); http://www.worldometers.info/world-population/ethiopia-population/. The provinces indicated in bold are situated (partly) within the UBN basin.

2.2.3. Rainfall and Temperature Data

Weather data, such as precipitation, and maximum and minimum temperature, were collected from the National Meteorological Agency (NMA) of Ethiopia. Data from 34 stations with records from 1970 to 2010 were used in this study. According to the NMA's classification, the majority of the stations are class three, which only record precipitation and temperature data. In this study, ten "class I" stations that have additional observations of relative humidity, wind speed, and sunshine hour, were also included for updating the SWAT model database. The data were on daily time step and the location of the stations is shown in Figure 1. The quality of the rainfall data has been checked in the previous study [5] and the same stations were used in this study. The rainfall and temperature data were used to calculate the SPI and SPEI indices as well as to run the SWAT model.

2.2.4. River Discharge Data

The river discharge data measured at five selected gauging stations (Gilgel Abay, Ribb, Gumara, Abbay at Kessie, and Ethiopia-Sudan border) were obtained from the Ministry of Water, Irrigation, and Electricity of Ethiopia (Figure 1). The data are on a daily time step (except at the Ethiopia-Sudan border, where only monthly data were available). The river discharge data at these selected stations were used to calculate the time series values of SRI, and to calibrate and validate the SWAT model. The data length for the period from 1989 to 1996, and 1997 to 2002 were used to calibrate and validate the model respectively.

Table 2 summarizes the input data used in this study. The details about the data can be referred in Sections 2.2.1–2.2.4.

Table 2. Summary of the input data used in this study.

Variables	Data Length	Resolutions		Source
		Temporal	Spatial	
Actual Evapotranspiration	1970–2010	Monthly	HRU	SWAT based
soil moisture data	1970–2010	Monthly	HRU	SWAT based
Rainfall	1970–2010	Daily	Point	NMA Ethiopia
Temperature	1970–2010	Daily	Point	NMA Ethiopia
Relative Humidity	1970–2010	Daily	Point	NMA Ethiopia
Solar Radiation	1970–2010	Daily	Point	NMA Ethiopia
Wind Speed	1970–2010	Daily	Point	NMA Ethiopia
River discharge	1970–2010	Daily/monthly	Point	NMA Ethiopia
DEM			90 m	SRTM
Land Use	2000		5 km	MARD

3. Drought Indicators

The drought indices used in this study collectively characterizes meteorological, agricultural, and hydrological drought types. The SPI (based on precipitation) and SPEI based on precipitation and temperature) characterize primarily meteorological drought. The ETDI (based on evapotranspiration) and SMDI (based on soil moisture) characterize agricultural drought. Similarly, the SRI, which is based on discharge, characterizes the occurrence of hydrological drought. ADI aggregates multiple input data sets that represent meteorological, agricultural and hydrological variables. These drought indices have been selected because of their less data intense, potential for characterizing drought at different aggregate period, and describe the dry and wet periods. These drought indices are described below.

3.1. Meteorological Drought Indicator

Standardized Precipitation Index (SPI): The SPI utilizes monthly time series of rainfall data preferably (30 years or more) to compute its value. SPI measures the standardized departure that the observed precipitation on a given time scale deviates from the long-term average precipitation [22]. The computation fits a probability density function to the frequency distribution of precipitation summed over the period of interest then transfers to a normal distribution [53,54]. The details about the calculation procedure of the SPI can be found in Bayissa et al. [5]. Based on SPI values, meteorological droughts are classified into different levels of severity, as shown in Table 3.

Standardized Precipitation Evaporation Index (SPEI): The SPEI differ from SPI in that it incorporates the effect of potential evaporation (calculated based on temperature) in addition to precipitation [16,27,55]. The calculation procedure of the SPEI is also similar to that of the SPI, except that it uses the difference between precipitation and potential evaporation instead of precipitation alone. Like the SPI, the SPEI is calculated at different time scales (e.g., 1-, 2-, and 3-month). In this study, a log-logistic distribution is applied because it fitted the best in the majority of rainfall stations that were used [5]. Negative SPEI values indicate dry condition due to less precipitation and/or higher potential evaporation (dry conditions) as compared to the historical mean. Unlike the SPI, the SPEI has not been widely applied and tested in the UBN basin [5].

Table 3. SPI values that show different categories of drought severity (McKee et al. [13]).

SPI Value	Drought Category
−2.00 and less	Extreme
−1.50 to −1.99	Severe
−1.00 to −1.49	Moderate
0 to −0.99	Near normal or mild
Above 0	No drought

3.2. Agricultural Drought Indicators

Evapotranspiration Deficit Index (ETDI): The ETDI is based on the anomaly of water stress to its long-term average [9], in which monthly water stress is defined using potential and actual evapotranspiration (Equation (1)).

$$WS = \frac{PET - AET}{PET}, \quad (1)$$

The WS ranges from 1 (no evapotranspiration) to 0 (evapotranspiration occurring at the same rate as PET). Next, monthly water stress anomaly (WSA) is calculated as:

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{MWS_j - minWS_j} \times 100, \text{ if } WS_{i,j} \leq MWS_j, \quad (2)$$

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{maxWS_j - MWS_j} \times 100, \text{ if } WS_{i,j} > MWS_j, \quad (3)$$

where MWS_j is the long-term median of water stress of month j, $maxMWS_j$ is the long-term maximum water stress of month j, $minWS_j$ is the long-term minimum water stress of month j, and WS is the monthly water stress. The subscripts i and j are used for years and months, respectively. The water stress anomaly ranges from −100 to +100 for each month, indicating very dry to very wet conditions [9].

Finally, ETDI is calculated using Equation (4). In the original formula developed by Narasimhan and Srinivasan [9], WSAj is divided by 50 to scale the ETDI between −4 and 4 to compare with PDSI values. Here, as suggested by Trambauer et al. [27], the WSAj values are divided by 100 to scale the ETDI between −2 and 2 to compare with SPI, SPEI, and SRI values.

$$ETDI_j = 0.5ETDI_{j-1} + \frac{WSA_j}{100}, \quad (4)$$

Soil Moisture Deficit Index (SMDI): The SMDI is calculated in the same way as ETDI, but with the available soil water content in the soil profile [9]. First, the median, maximum, and minimum values for each month were extracted using soil moisture time series. The median was chosen instead of the mean because it is less affected by the outliers. The SMDI values (deficit or excess) for the 39 years (1970–2010) were calculated using Equations (5)–(7).

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{MSW_j - minSW_j} \times 100, \text{ if } SW_{i,j} \leq MSW_j, \quad (5)$$

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{maxSW_j - MSW_j} \times 100, \text{ if } SW_{i,j} > MSW_j, \quad (6)$$

where $SD_{i,j}$ is the soil water deficit (%) ranging from −100 (very dry condition) to +100 (very wet condition); $SW_{i,j}$ is monthly soil water available in the soil profile (mm); and, MSW_j, $maxSW_j$, and $minSW_j$ are long-term median, maximum, and minimum available soil water in the soil profile (mm), respectively.

Thus, the SMDI in any given month is determined by:

$$SMDI_j = 0.5SMDI_{j-1} + \frac{SD_j}{100}, \quad (7)$$

SMDI ranges from −2 to +2, with negative values indicating drought.

3.3. Hydrological Drought Indicator

Standardized Runoff-discharge Index (SRI): The SRI is based on river discharge and its computation procedure is similar to that of SPI [17]. The gamma distribution is also used here to fit the river discharge data. The SRI and SPI drought categories are similarly calculated. We used river discharge data at the five selected gauging stations from the study area.

3.4. Aggregate Drought Index (ADI)

The ADI [22] is a multivariate drought index that aggregates the three types of drought (meteorological, agricultural, and hydrological) through considering several input variables representing these three drought types (e.g., rainfall, evapotranspiration, soil moisture, and stream flow). In this study, rainfall, evapotranspiration, and soil moisture are used to derive a single (aggregated) index, ADI, using Principal Components Analysis (PCA). The z-score values (1-month time scale) of these three input variables were calculated to avoid inconsistency as a result of different units of measurement. PCA constructs a symmetric correlation matrix ($p \times p$, where p is the number of variables) between the z-score values of the input variables. PCA transform the original p-variables data set to a number of uncorrelated (principal) components z_j ($1 < j \leq p$) [25] using Equation (8).

$$Z = XE, \quad (8)$$

where Z is the ($n \times p$) matrix of PCs (i.e., uncorrelated components), in which n is the number of observations, X is the ($n \times p$) matrix of the observation data, and E is the ($p \times p$) matrix of eigenvectors of the correlation matrix.

The ADI was calculated for the first PC (PC1) normalized by the standard deviation. PC1 described more than 65% of the variation in the input data.

$$ADI_{i,k} = Z_{i,1,k} / \sigma_k, \quad (9)$$

where $ADI_{i,k}$ is the ADI value for month k in year i, $Z_{i,1,k}$ is the first PC for month k in year i, and σk is the sample standard deviation of $Z_{i,1,k}$ for all years I and months k. The ADI was calculated for each of the station locations and each month. The threshold of ADI was determined based on McKee classifications of SPI drought categories (Table 3), which were developed for stations across Colorado in the United States. According to McKee, mild drought occurs 24% of the time, moderate drought occurs 9.2% of the time, severe drought occurs 4.4% of the time, and extreme drought occurs 2.3% of the time. In this study, we determine the ADI drought category through constructing cumulative distribution of the time series of ADI across the UBN basin. The drought categories of ADI at the corresponding percentile are shown in Table 4.ADI values of −0.96 or lower indicate a drought at a different severity level (Table 4).

Table 4. Aggregate drought index (ADI) drought category classification.

above 0.92	Wet
−0.95 to 0.92	Near normal
−1.40 to −0.96	Moderate drought
−1.69 to −1.41	Severe drought
−1.70 or less	Extreme drought

The summary of the drought indices used in this study is shown in Table 5.

Table 5. Summary of the drought indices used in this study.

Drought Index	Variable	Distribution Fitted
SPI	Precipitation	Gamma
SPEI	Precipitation, PET	Log-logistic
SRI	Runoff	CDF standardized to Gaussian values
ETDI	Actual evapotranspiration	
SMDI	Soil moisture	
ADI	Precipitation, actual evapotranspiration, and soil moisture	

4. Methods

4.1. Correlation between Drought Indices

First, we derived monthly time series of drought indices that are defined in the previous section. The drought indices were calculated at the corresponding locations of each meteorological station. The spatial extent of SWAT based evapotranspiration and soil moisture were in hydrologic response units (HRUs). The HRUs are the smallest spatial units of the model defined based on lamping similar land uses, soils, and slopes [56]. In SWAT modelling, the basin was divided into two major parts: upstream and downstream of the Lake outlet. This division has been made to exclude the Lake Tana from the modelling processes of the basin due to the lack of appropriate data to characterize the lake. The upstream and downstream parts are further divided into 14 and 139 sub-basins and 104 and 1027 HRUs, respectively. The HRUs were defined based on percentage combinations of land use, soil, and slope. In this study, 10% land use, 20% soil, and 10% slope threshold combinations were adopted, based on the findings of Setegn et al. [50]. The HRUs values of evapotranspiration, and soil moisture at the locations of each meteorological station were extracted and used to calculate ETDI and SMDI drought indices. For all indices, data from 1970 to 2010 are used. For SPI, SPEI, and SRI indices were derived for five different aggregation periods, namely 1-, 3-, 6-, 9-, and 12-months. Thus we have a total of 18 indices; five each from SPI, SPEI, and SRI and one each from ETDI, SMDI, and ADI. Next, Pearson correlation coefficients were derived for paired time series values of drought indices. Each drought index is paired with every other drought indices, resulting in 18 by 18 correlation coefficient matrix.

4.2. Comparison of Drought Indices Based on Drought Onset, Duration, and Severity

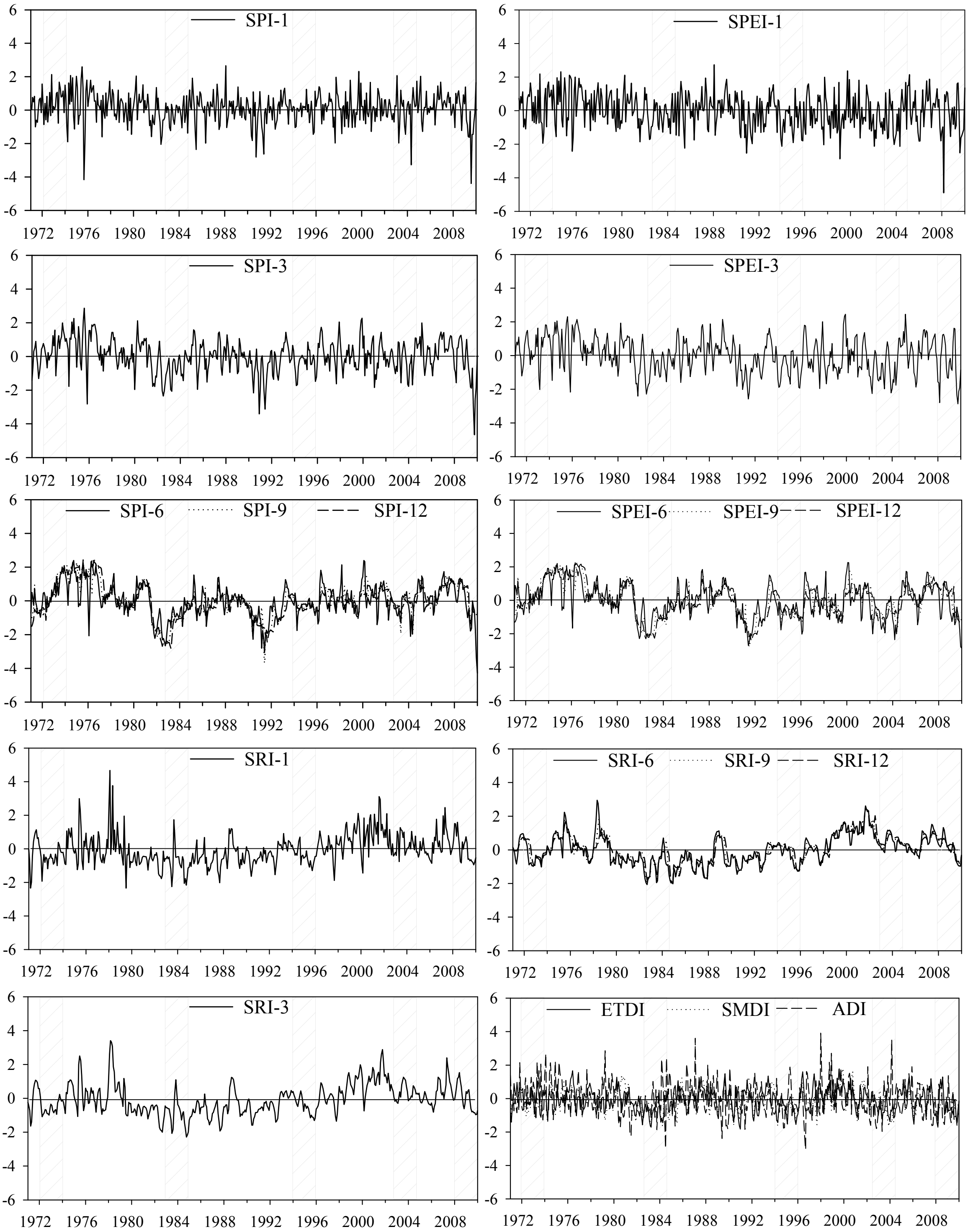
The comparison of the drought indices based on the drought characteristics, such as percentage of drought months, maximum drought intensity, and drought duration was analyzed for the selected 16 stations that are representing majority of the study area. The percentage of drought months was calculated by taking the percentage of the ratio of the total number of months that show drought condition (including mild, moderate, severe, and extreme drought) with the total events in the study period. The maximum drought intensity represents the smallest value of the drought index within the study period (1970–2010). The average value of the maximum intensity of the different aggregate periods (1-, 3-, 6-, 9-, and 12-month) was considered for SPI, SPEI, and SRI, and was compared with the self-defined single time scale indices (i.e., ETDI, SMDI, and ADI). The drought duration is defined as the consecutive months that show the drought condition (below normal conditions). Drought duration is also considered as one of the evaluation criteria to compare the drought indices for the selected stations.

Other drought indices comparison criteria (i.e., drought onset, duration, and severity) have been used by dividing the UBN basin into upper, middle, and lower parts, representing the areas upstream of the river gauging stations Abbay at Bahirdar, Kessie, and Ethiopia-Sudan border, respectively. The drought indices were calculated using areal averages of the variables, namely rainfall, temperature, soil moisture, and actual ET based on the simple arithmetic mean technique. The drought severity, duration, and onset values were extracted for the known historic drought year (1973–1978, 1983–1984, 1989–1994, and 2003–2004). The time series values of the drought indices for these selected drought events were analyzed to calculate the drought severity. The consecutive negative values of each drought index were considered to quantify the different drought characteristics. For example, mean intensity (M) and maximum intensity (Mmax) of drought are the average and maximum values within the consecutive negative drought index values, respectively. Drought duration (D) represents the time span of the consecutive negative index values. Drought severity is defined as the product of drought duration (D) and the mean intensity (M) [1,8,9]. The severity is interpreted as near normal, moderate, severe, and extreme drought based on the drought category classification of each drought index, as described in Section 3. Based on drought severity and duration, each drought index was compared whether they characterize and indicate the severity and persistency of drought years in the basin. Moreover, the drought onset (starting month) that was estimated by each index was compared with similar data obtained from EM-DAT (Section 2.2.1).

5. Results and Discussion

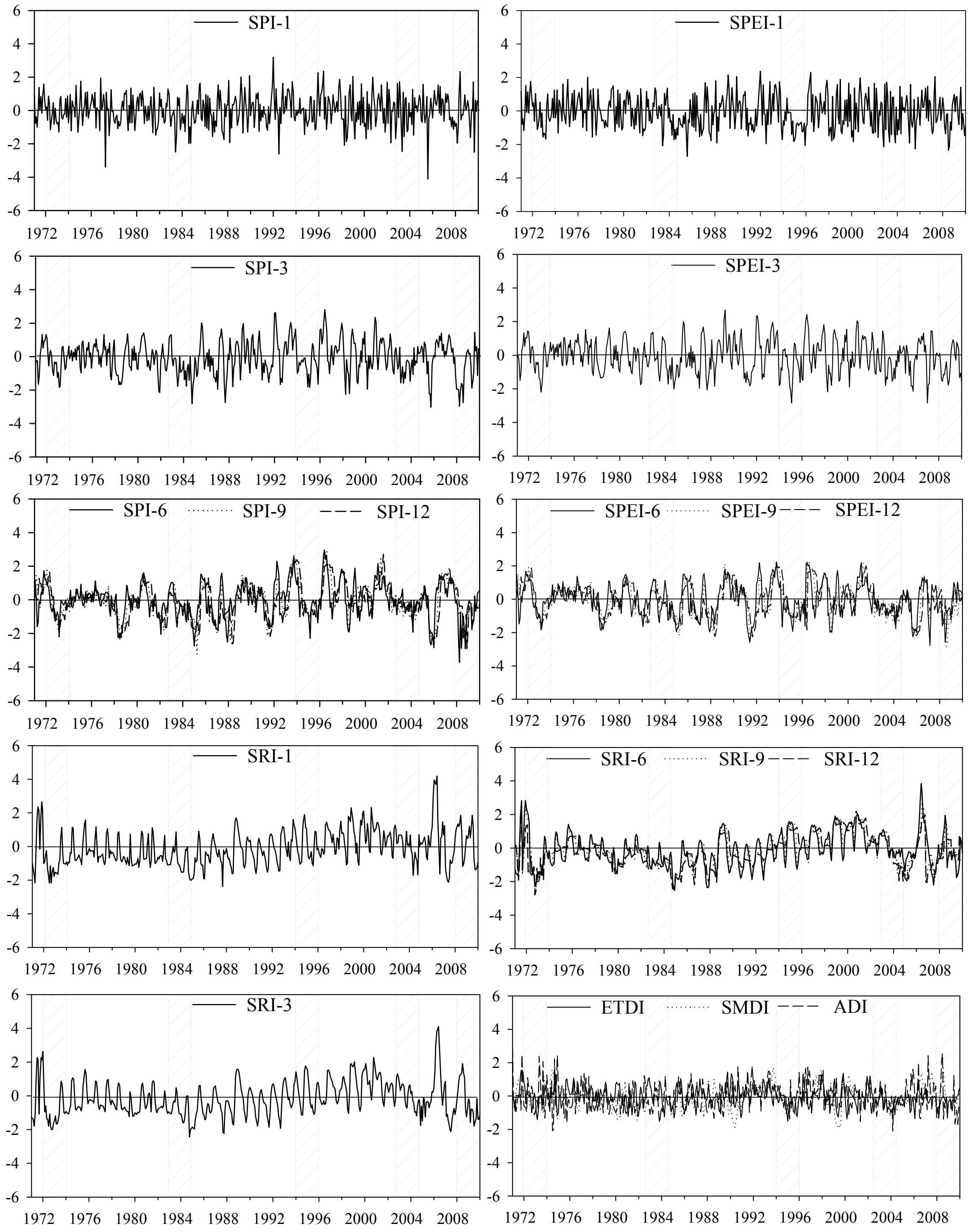
5.1. Time Series of the Drought Indices

The time series (1970–2010) of the drought indices were produced for all the stations considered. Only the result obtained at Gondar, and Debremarkos stations were shown in Figure 2 for further discussion in this section. These two stations are representative of the upstream and downstream parts of the study basin. Figure 2 depicts the performance of the drought indicators on indicating the historic drought events. In general, the majority of the drought indices indicated the historic drought years (1973–1974, 1983–1984, 1994–1995, 2003–2004, 2008–2009), except observing a frequent jump between the drought and normal condition at a lower time scale (1- and 3-month). The persistency of the historic drought years was indicated at a larger time scales (e.g., 6-, 9-, 12-month). The meteorological drought indices showed severe drought conditions in the year 1991–1992 in the majority of the stations; however, the severity of this drought condition has not been reflected by other drought indices. The agricultural drought indices showed a similar patter with the meteorological drought indices of smaller time scales (1- and 3-month). Moreover, the agricultural drought indices showed smaller magnitude of the drought severity in some of the stations (e.g., Gondar) as compared to other drought indices. The hydrological drought indices indicated the persistency of the drought condition even at lower time scale as compared to the other indices. The possible reason is perhaps the fluctuation of river flow is very gradual as compared to the other input variables, such as rainfall, evapotranspiration, etc. The majority of the drought indices indicated the severity of the historic drought condition at different severity level that ranges from mild to extreme drought condition. Thus, each drought index could potentially be used to assess some of the historic drought conditions in the UBN basin.



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. The time series plots of the drought indices for Gondar (**a**) and Debremarkos (**b**) stations. The plots for Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Runoff Index (SRI) at 6-, 9-, and 12-month time scales are shown in the single panel since it is easier to visualize the trend. Similar approach was considered for Evapotranspiration Deficit Index (ETDI), Soil Moisture Deficit Index (SMDI), and Aggregate Drought Index (ADI).

5.2. Correlation between Drought Indices

The Pearson's correlation coefficient matrix was developed for the six drought indices for each meteorological station. The results obtained at Gondar (Table 6a) and Debremarkos (Table 6b) stations are presented as an example. A correlation matrix of 18 rows by 18 columns was created to investigate the relationship between the drought indices (Table 6). SPI-3 showed a relatively high correlation coefficient with a majority of other indices, except SPI among itself at other aggregation periods. For example, SPI-6 correlates better with SPI-9 (0.77) and SPI-12 (0.72) than SPI-3 does with SPI-9 (0.73) and SPI-12 (0.68) at Gondar station. However, SPI-3 correlated better with SPI-1 (0.65) than SPI-6 (0.53), SPI-9 (0.48), and SPI-12 (0.45). Table 6 shows that the correlation coefficients between SPI and SRI or SPEI and SRI consistently increase as the aggregation period for SPI and SPEI increases. For example, SPI-12 and SPEI-12 correlated better with the SRI than the SPI and SPEI at shorter aggregation periods. In general, longer aggregation periods of SPI and SPEI better correlate with SRI. The highest correlation for SRI was reached when both indices are aggregated over 12 months (correlation of about 0.55). Compared to correlations between other pairs of indices, correlations involving SRI are generally low. SRI is based on river flow, which is a combination of surface flow, interflow and base flow (or ground water flow), and is expected to have certain lag time with meteorological and agricultural droughts. This might be one of the possible reasons why the SRI is not correlated well with other drought indices. Table 6a,b, first five columns, show that there is a strong correlation between drought indices of the same aggregation period. SMDI and ETDI (agricultural drought indices based on monthly data) have a higher correlation with SPI-3 and SPEI-3 (meteorological drought indices based on 3-month aggregated data) than with the other indices or aggregate periods. This indicates that in the UBN basin the meteorological drought indices at 3-month aggregate period explains best the agricultural drought indices and perhaps the occurrence of an agricultural drought. Similar results were obtained for Debremarkos (Table 6b), and other meteorological stations (can be referred from the Supplementary Material Table S1).

The statistical significance of the correlation coefficient values of each station was tested using t-test distribution. The result of the test is shown in Table 7 for each drought index. The result shows that, for the majority of the drought indices, the p-values are less than or equal to 0.01 (shown in green in Table 7), meaning they are statistically significant at 99% or higher confident level. Few other correlation values (e.g., SPEI-1 and SPEI-12 with SRI at different aggregation periods, and ADI with all SPEIs) are significant at 90% or higher confidence level (i.e., $p \leq 0.1$) (shown in yellow in Table 7). However, the correlation values of ADI with the majority of the other drought indices (e.g., with SPI-6, SRI-9, ETDI, and SMDI) are statistical insignificant at 90% confident level (i.e., $p > 0.10$), and needs further investigation for future studies.

Table 6. The Pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for (a) Gondar station and (b) Debremarkos station. The SRI used in the cases are calculated using flow records at Bahirdar station and Debremarkos station respectively.

(a)

SPI-1	1																
SPI-3	0.65	1															
SPI-6	0.53	0.77	1														
SPI-9	0.48	0.73	0.77	1													
SPI-12	0.45	0.68	0.72	0.96	1												
SPEI-1	0.85	0.55	0.36	0.28	0.26	1											
SPEI-3	0.49	0.89	0.61	0.48	0.45	0.63	1										
SPEI-6	0.35	0.59	0.93	0.72	0.65	0.42	0.69	1									
SPEI-9	0.32	0.53	0.75	0.94	0.83	0.33	0.55	0.79	1								
SPEI-12	0.30	0.51	0.69	0.83	0.94	0.31	0.52	0.72	0.89	1							
SRI-1	0.20	0.28	0.33	0.40	0.41	0.16	0.23	0.16	0.21	0.25	1						
SRI-3	0.22	0.31	0.31	0.44	0.48	0.11	0.26	0.25	0.26	0.30	0.81	1					
SRI-6	0.20	0.24	0.37	0.49	0.52	0.07	0.19	0.31	0.31	0.33	0.70	0.88	1				
SRI-9	0.24	0.32	0.43	0.51	0.53	0.08	0.16	0.26	0.33	0.34	0.63	0.80	0.93	1			
SRI-12	0.21	0.31	0.41	0.52	0.55	0.04	0.15	0.24	0.30	0.36	0.57	0.74	0.87	0.95	1		
ETDI	0.53	0.67	0.59	0.43	0.45	0.59	0.49	0.34	0.28	0.28	0.23	0.21	0.22	0.28	0.27	1	
SMDI	0.44	0.65	0.45	0.38	0.29	0.43	0.55	0.37	0.32	0.32	0.25	0.28	0.21	0.18	0.17	0.68	1
ADI	0.75	0.59	0.40	0.32	0.30	0.78	0.59	0.39	0.38	0.36	0.33	0.23	0.15	0.12	0.13	0.68	0.63	1

Table 6. *Cont.*

(b)																		
SPI-1	1																	
SPI-3	0.55	1																
SPI-6	0.35	0.65	1															
SPI-9	0.27	0.48	0.74	1														
SPI-12	0.20	0.39	0.61	0.81	1													
SPEI-1	0.87	0.54	0.33	0.26	0.20	1												
SPEI-3	0.48	0.89	0.59	0.43	0.34	0.59	1											
SPEI-6	0.30	0.58	0.91	0.66	0.53	0.36	0.66	1										
SPEI-9	0.24	0.44	0.69	0.92	0.73	0.29	0.49	0.74	1									
SPEI-12	0.18	0.35	0.56	0.75	0.91	0.22	0.39	0.60	0.81	1								
SRI-1	0.10	0.18	0.17	0.14	0.16	0.07	0.15	0.15	0.08	0.07	1							
SRI-3	0.10	0.19	0.23	0.17	0.18	0.05	0.14	0.20	0.12	0.08	0.86	1						
SRI-6	0.08	0.20	0.28	0.26	0.23	0.05	0.13	0.21	0.20	0.13	0.63	0.83	1					
SRI-9	0.06	0.19	0.29	0.32	0.30	0.05	0.14	0.22	0.24	0.21	0.49	0.67	0.87	1				
SRI-12	0.05	0.16	0.27	0.32	0.36	0.03	0.12	0.21	0.23	0.24	0.48	0.56	0.71	0.84	1			
ETDI	0.27	0.51	0.39	0.25	0.22	0.29	0.49	0.37	0.27	0.26	0.01	0.00	0.03	0.04	0.09	1		
SMDI	0.24	0.42	0.35	0.30	0.28	0.23	0.37	0.28	0.23	0.22	0.14	0.13	0.12	0.13	0.08	0.38	1	
ADI	0.07	0.10	0.08	0.06	0.03	0.09	0.06	0.05	0.01	0.03	0.16	0.14	0.09	0.02	0.08	0.04	0.00	1

Table 7. The summary of the significant test for the selected 16 stations.

	SPI-1	SPI-3	SPI-6	SPI-9	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-9	SPEI-12	SRI-1	SRI-3	SRI-6	SRI-9	SRI-12	ETDI	SMDI
SPI-3	$p<0.01$																
SPI-6	$p<0.01$	$p<0.01$															
SPI-9	$p<0.01$	$p<0.01$	$p<0.01$														
SPI-12	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$													
SPEI-1	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$												
SPEI-3	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$											
SPEI-6	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$										
SPEI-9	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$									
SPEI-12	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$								
SRI-1	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$							
SRI-3	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$						
SRI-6	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$					
SRI-9	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$				
SRI-12	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$			
ETDI	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$		
SMDI	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.1$	$p<0.01$	
ADI	$p<0.1$	$p<0.1$	$p>0.1$	$p<0.1$	$p<0.1$	$p<0.1$	$p<0.1$	$p<0.1$	$p<0.1$	$p<0.1$	$p<0.01$	$p<0.01$	$p<0.1$	$p>0.1$	$p<0.1$	$p>0.1$	$p>0.1$

(green) $p < 0.01$, (yellow) $p < 0.1$, (red) $p > 0.1$.

5.3. Comparison of Drought Indices Based on Drought Characteristics

The comparison of the drought indices based on drought characteristics, such as the percentage of drought months, maximum drought intensity, and drought duration was analyzed and used as additional comparison criteria for each index. The results obtained at the selected 16 stations that are representing the majority of the study area were discussed in this section. The percentage of the drought months represents the proportion of the total number of drought months (including mild, moderate, severe, and extreme droughts) within the study periods (1970–2010) of each station. The resulting graph is shown in Figure 3 and each spider web represents the value of each drought index across the selected stations. In general, the percentages of the drought months of the hydrological (SRI), agricultural (ETDI and SMDI), and ADI depict relatively larger values as compared to the meteorological drought indices (i.e., SPI, and SPEI) in majority of the stations for 1-month, 3-month, 6-month, and 12-month temporal scales. However, meteorological indices showed a smaller improvement (increase) of the percentage of drought months as the time scale increases in majority of the stations. The comparative analysis of the percentage of the drought months was extended separately for each drought severity categories, such as mild, moderate, severe, and extreme drought. Only the result obtained for severe and extreme drought categories are shown in Figure 4. Interestingly, a similar result (as above) was observed only for mild and moderate drought conditions (not shown). However, an opposite result that shows a relatively larger percentage of drought months was observed by meteorological drought indices (Figure 4) for severe and extreme drought condition as compared to other drought indices in the majority of the stations. This perhaps shows meteorological drought indices are influenced by the variability of the amount of rainfall during drought event. ADI also showed large percentage of the drought months, which may indicate the dominance of the rainfall in ADI index than the other two input variables (evapotranspiration and soil moisture).

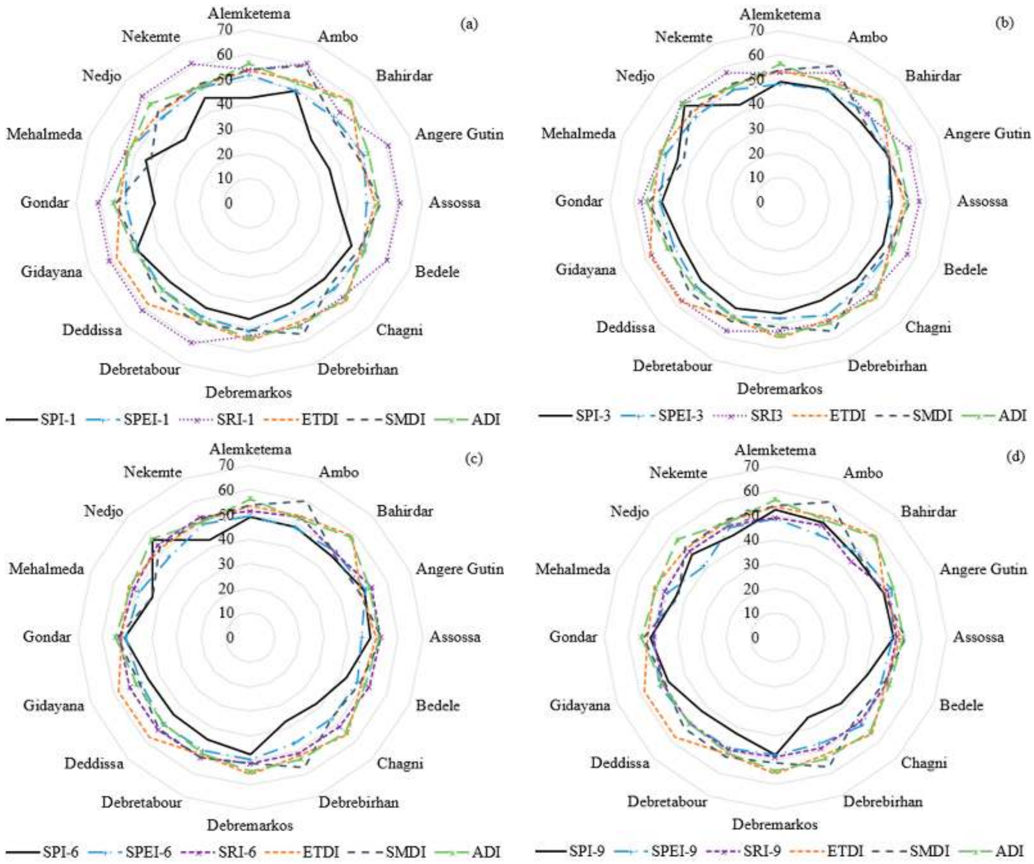


Figure 3. *Cont.*

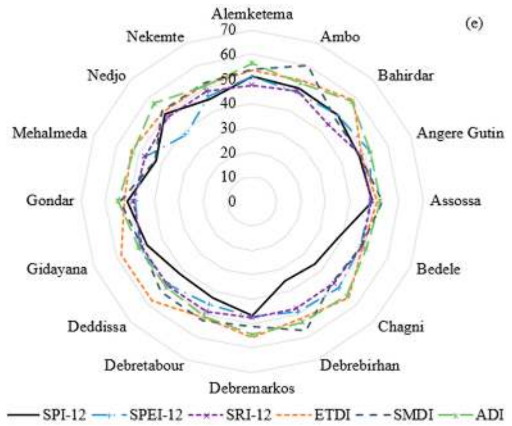


Figure 3. Comparison of SPI, SPEI, and SRI with ETDI, SMDI, and ADI at 1-month (**a**), 3-month (**b**), 6-month (**c**), 9-month (**d**), and 12-month (**e**) time scales based on percentage of drought months at the locations of the selected meteorological stations. A line is used to connect values of the same variable at distinct locations to increase the visibility of the points in this figure. .

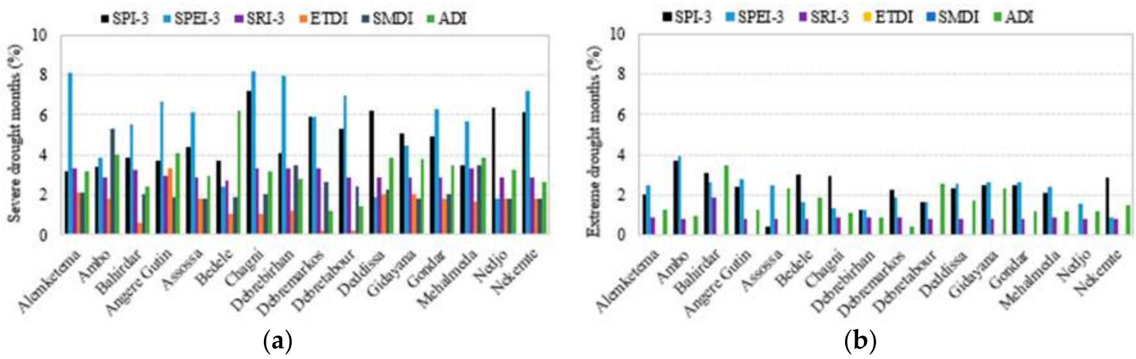


Figure 4. Percentage of severe (**a**), and extreme (**b**) droughts months observed for the drought indices within the study period (1970–2010) for the selected meteorological stations.

The maximum duration of drought was also considered as another comparison criteria of drought indices for all time scales (Figure 5). The number of consecutive drought months that shows drought severity values of -1 and less (representing moderate, severe, and extreme) were counted for the study period. Evaluating drought indices based on the maximum duration of drought helps to evaluate their performance on indicating the persistency of historic drought events. In general, the result shows an increase in the maximum drought duration as the time scale increases for SPI, SPEI, and SRI in the majority of the stations. This shows persistent drought is indicated at larger time scales (e.g., 12-month) than small time scales (e.g., 1-month). ETDI, SMDI, and ADI shows less persistent drought in the majority of the stations and the result corresponds with the persistency indicated by SPI and SPEI at lower time scales (1-, and 3-month). This shows the comparability of the agricultural drought with the meteorological drought indices at lower temporal scales. The comparison of maximum duration of drought of SPI, SPEI, and SRI at the same time scales (e.g., 3-month) shows the performance of SRI on indicated relatively a large drought duration month than SPI, and SPEI. The time series of SRI is derived based on river flow (resulted from the catchment process) so that SRI is less affected by the extreme wet event in between a particular historic drought years. Interestingly, SPEI also showed relatively larger drought duration months as compared to SPI at the same time scale. The possible reason might be the use of additional input variables (e.g., potential evaporation, in the case of SPEI) could help to show the persistency of drought. The maximum duration of drought indicated by ETDI, SMDI, and ADI is relatively less in the majority of the stations. For several aggregate periods and for several locations, SPI, SPEI, and SRI showed maximum consecutive drought duration of more than 12-months. It may, therefore, be of interest to analyze drought indices at higher time scales (>12-months) in future studies.

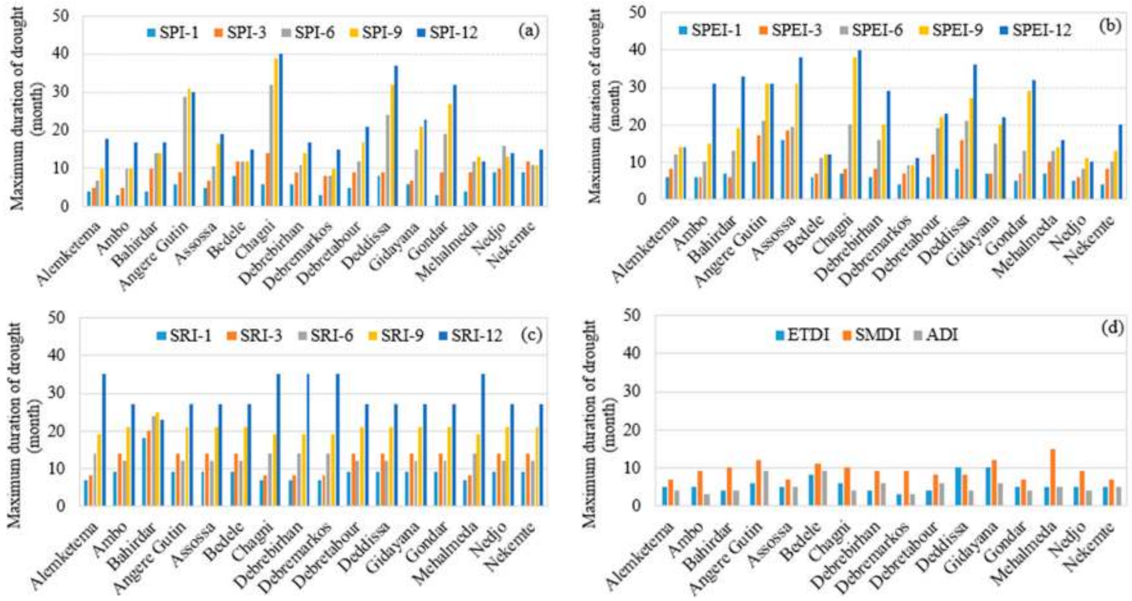


Figure 5. The maximum duration of consecutive drought indicated by SPI (**a**), SPEI (**b**), SRI (**c**) and other indices (**d**) such as ETDI, SMDI, and ADI. Five temporal scales (i.e., 1-, 3-, 6-, 9-, and 12-months) were considered for SPI, SPEI, and SRI.

Similar approach/method that was followed in this study was also tested in other watershed to compare drought indices [28,30]. In general, the results of these studies showed the capability of the method to identify the drought indices that can better characterize the drought condition in a specific location.

5.4. Comparison of Drought Indices through Characterizing the Hhistoric Drought Events

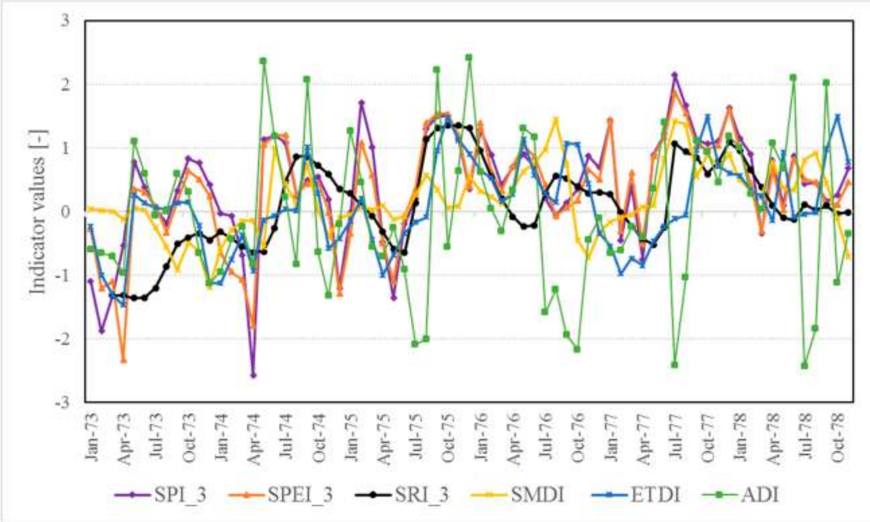
Comparison of the drought indices was carried out at three river gauging stations: Abbay at Bahirdar, Kessie, and Ethiopia-Sudan border (their locations are shown in Figure 1). These stations represent the upper, middle, and lower parts of the UBN basin, respectively. The time series values of the SRI-3 were calculated using the river flow data measured at these three gauging stations, whereas the areal average values were considered for the SPI-3, SPEI-3, ETDI, SMDI, and ADI. The result that was obtained for the upper part of the basin is presented for further discussion. Table 8 shows for the historic drought events, the characteristics resulting from each of the six indices. Based on the severity of the drought, the majority of the drought indices indicated 2003–2004 and 1983–1984 as the most severe drought years in the basin, except the SPEI, which showed 1989–1994 as the most severe drought year. The result further reveals that persistent droughts were observed in 2003–2004 and 1983–1984. Based on the mean (M) and maximum (Mmax) intensities, the SRI indicated the severity of 2003–2004 and 1984–1985 to have been higher than the other drought indices, except the SPEI (Mmax = −2.63). The SRI indicated the persistence of the 1983–1984 drought, which extended beyond the start and end year as provided by EM-DAT. The SPI ranks 1973–1974 as the most severe drought year based on mean intensity (M = −1.21) and maximum intensity (Mmax = −2.57). However, the drought durations of the SPI and SPEI for the same year are relatively small, most likely resulting from the earlier start of the drought in 1972. The onset month of each drought year is used as the other comparison criteria, and the result is shown in Table 8. According to EM-DAT, the 1973–1978 drought started in December 1973 and lasted until 1978. The ETDI showed the closest onset (November

1973) for this year. The SMDI showed a slightly earlier onset (July 1973) of the 1973–1978 drought, whereas the SPI and SPEI (January 1973) and SRI (March 1973) indicated an early start of this drought. The ADI showed the latest onset (July 1976) of this particular drought event. According to EM-DAT, the 1983–1984 drought started in May 1983, but all indices except the ETDI and ADI showed an early start (January 1983) of this drought event. The ETDI and ADI show a late start (December 1983 and September 1983, respectively) of the 1983–1984 drought. The 1989–1994 drought started in October 1989; the SPI and SPEI showed an August 1989 start, the SRI showed a December 1989, and the ETDI and SMDI indicated drought earlier than all the other indices. The drought start month indicated by ADI is December 1993. While this does not correspond with EM-DAT, it corresponds to the historic drought 1993–1994 reported in other studies (see Section 2.2.1). Note that it is likely that the 1993–1994 has been included in the EM-DAT database as part of the prolonged drought period from 1989 to 1994. For 2003–2004, there is no reference onset from EM-DAT to compare with the six drought indices. However, all of the indices indicated the onset of the drought in January and February 2003, except the SRI, which indicated the onset of drought in July 2003. Overall, the meteorological drought indices (SPI and SPEI) indicate the start date of four or more months before the reported start month, whereas agriculture drought indices onset often lagged by three or more months than the reported starting date of a historic drought. The aggregate drought index (ADI) most often lagged by some months. It can be noted from this result that no single drought index consistently indicates the exact onset of the drought. Similar results are obtained for the middle, and lower parts of the UBN basin.

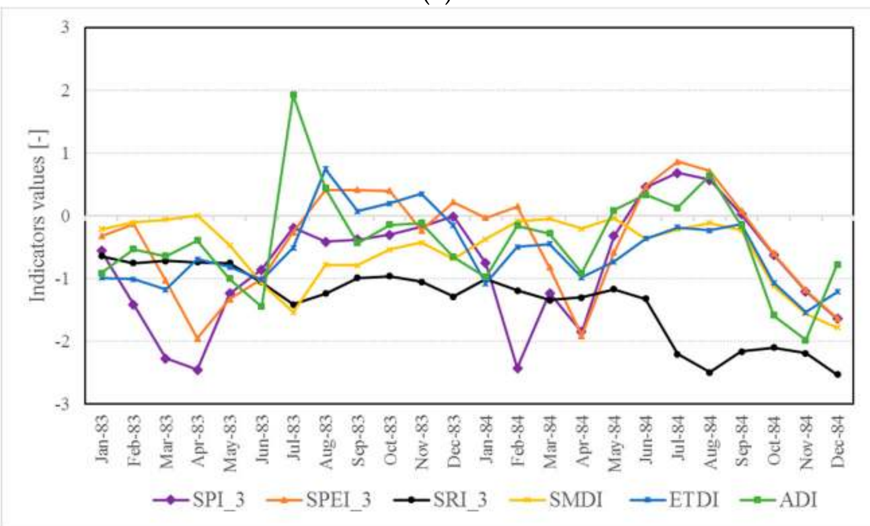
Figure 6 compares the time series patterns of the six drought indices for the historic drought years 1973–1978, 1983–1984, 1989–1994, and 2003–2004. In the 1973–1978 drought (Figure 6a), the majority of the drought indices showed the occurrence of moderate to severe drought condition in several months between 1973 and 1975 (index value <-1.0 and lower), whereas mild drought and wet conditions were observed from 1976 to 1978 except for the ADI, which showed severe drought for ten months. Relatively persistent drought was indicated by the SRI and ETDI in 1973–1974, whereas other indices show a frequent jump between drought and non-drought conditions. In this study, persistent drought is defined if consecutive months (>10 months) showed below average values (zero). The majority of drought indices indicated mild to severe drought condition for several months (>6) in the year 1983/1984 (Figure 6b). The SRI showed the severity and persistency of the 1983–1984 drought and indicated drought conditions throughout 1983/1984. The SPI also showed mild to severe drought conditions for several months, except for non-drought conditions in mid-1984. The 1989–1994 drought is not well defined except for 1990, 1991, and 1994; the majority of the indices showed the occurrence of moderate to severe drought condition during these years. Like the 1983/1984 drought, the majority of the drought indices showed mild to extreme in 2003–2004, although the SRI, SPEI, and ADI showed non-drought conditions for some months. SRI showed severe to extreme drought condition, whereas SMDI showed mild to moderate drought conditions for several months in 1983–1984. SPI-3, SPEI-3, ETDI, and ADI showed out of drought condition for the period of 4 to 10 months. However, SPI-3, SMDI, and ETDI indicated the drought condition in the year 2003–2004, whereas SRI showed an opposite pattern than other indices. In general, SPI and SPEI showed similar patterns in most cases while ADI showed a frequent jump between drought and non-drought conditions. Moreover, ADI showed relatively higher positive and negative values perhaps because of a direct consideration of the eigenvector as weights/coefficients in combining the input variables. Other approach, such as the percentage of contribution, could be considered for future studies. SRI showed the persistency of the drought and non-drought condition for several months possibly because of less fluctuation of the river flow with time as compared to the rainfall.

Table 8. Characteristics of the historic drought events as identified by the six drought indices for the Upper Blue Nile basin upstream of Bahirdar. Note that if the index indicated the onset to be before January of the reported calendar year of the historic drought, this is presented in the table with "before" and if, according to the index, a drought extended beyond December of the reported calendar year, this is presented with "after". The drought duration in these cases is based on a start in January and an end in December of the reported drought year.

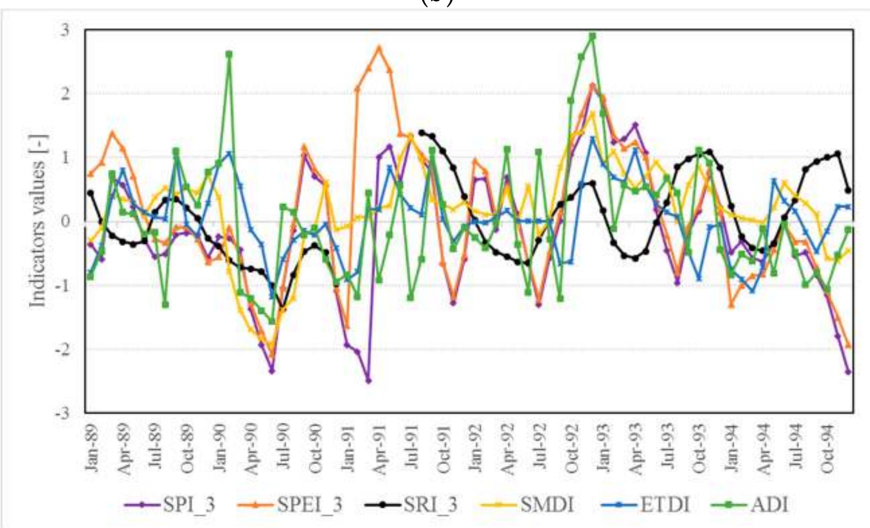
Drought Index	SPI-3	SPEI-3	SRI-3	ETDI	SMDI	ADI
1973–1978 drought (Onset on December according to EM-DAT)						
Starting date	Before 01/1973	Before 01/1973	03/1973	11/1973	07/1973	07/1976
Ending date	04/1973	04/1973	06/1974	06/1974	05/1974	04/1977
Mean Intensity, M	−1.21	−1.23	−0.75	−0.48	−0.42	−0.94
Maximum intensity, Mmax	−2.57	−2.33	−1.36	−1.47	−1.19	−2.43
Duration, D (months)	4	4	16	8	11	10
Severity, S	−4.84	−4.91	−11.94	−3.85	−4.57	−9.38
1983–1984 drought (Onset on May according to EM-DAT)						
Starting date	Before 01/1983	Before 01/1983	Before 01/1983	12/1983	Before 01/1983	09/1983
Ending date	05/1984	07/1983	After 12/1984	After 12/1984	After 12/1984	04/1984
Mean Intensity, M	−0.99	−0.86	−1.36	−-0.66	−0.53	−0.46
Maximum intensity, Mmax	−2.45	−1.95	−2.53	−1.53	−1.78	−1.98
Duration, D (months)	17	7	24	13	24	8
Severity, S	−16.82	−6.02	−32.59	−8.62	−12.79	−3.68
1989–1994 drought (Onset on October according to EM-DAT)						
Starting date	06/1989	07/1989	12/1989	04/1990	02/1990	12/1993
Ending date	08/1990	08/1990	12/1990	02/1991	01/1991	After 12/1994
Mean Intensity, M	−0.69	−0.65	−0.70	−0.85	−0.46	−0.57
Maximum intensity, Mmax	−2.49	−2.09	−1.38	−1.92	−1.18	−1.57
Duration, D (months)	15	14	13	9	11	13
Severity, S	−10.30	−9.13	−-9.06	−7.62	−5.08	−7.38
2003–2004 drought (Onset not defined according to EM-DAT)						
Starting date	Before 01/2003	02/2004	07/2004	Before 01/2003	Before 01/2003	Before 01/2003
Ending date	10/2004	12/2004	12/2004	After 12/2004	After 12/2004	12/2003
Mean Intensity, M	−0.59	−0.71	−1.61	−0.51	−0.45	−0.92
Maximum intensity, Mmax	−1.95	−2.63	−2.13	−1.23	−1.36	−2.27
Duration, D (months)	22	11	6	24	24	12
Severity, S	−12.95	−7.79	−9.64	−12.26	−10.85	−11.09



(**a**)

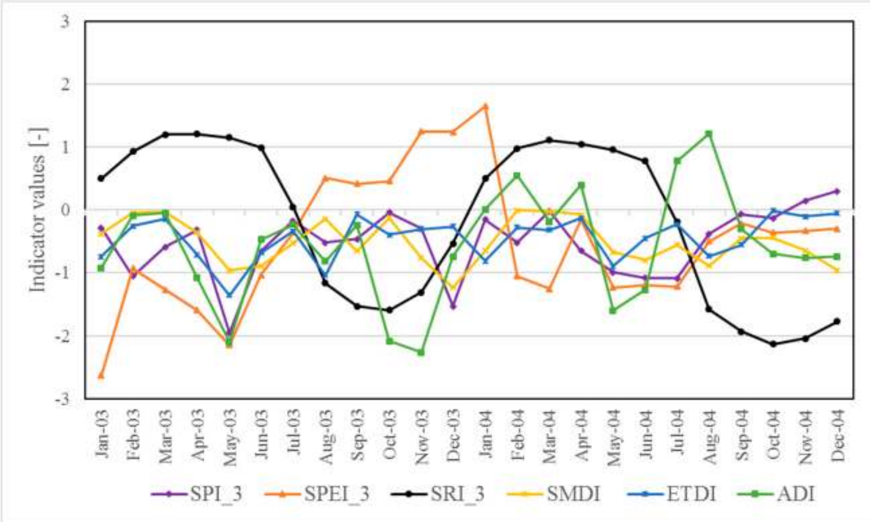


(**b**)



(**c**)

Figure 6. *Cont.*



(**d**)

Figure 6. The time series plot of the six drought indices for 1973/1978 (**a**), 1983/1984 (**b**), 1989/1994 (**c**), and 2003/2004 (**d**) historic drought years in the UBN basin.

6. Conclusions

In this study, we compared six drought indices—SPI and SPEI (meteorological indices), ETDI and SMDI (agricultural indices), SRI (hydrological index), and ADI (aggregate index)—to investigate how well characteristics of historic drought events in the Upper Blue Nile basin are identified by these indicators. Observed data were used for the precipitation, temperature, and streamflow inputs. Soil moisture and actual evapotranspiration data were estimated using the SWAT hydrological model.

In general, meteorological drought indices SPI-3 and SPEI-3 show a higher correlation with the agricultural drought indices SMDI and ETDI than with the hydrological drought index (SRI), whereas hydrological drought index (SRI) correlates better with meteorological drought indices at a 12-month aggregate period (SPI-12 and SPEI-12). This indicates that there exist some interconnection between drought indices in the sense that one drought index can explain more than one specific drought category to a certain degree. Moreover, each index has the potential to characterize and explain at least one recorded (historical) drought condition. It seems that a combination of more than one drought indices, appropriately selected for the specific region, is usually required for drought monitoring.

When comparing the drought onset dates indicated by the six indices for the historical (recorded) droughts, the meteorological drought indices (SPI and SPEI) showed early onsets when compared to the other drought indices except the 2003–2004 drought where SPEI showed a late onset. The agricultural (ETDI, SMDI, and ADI) and hydrological (SRI) drought indices showed late onsets, particularly the ADI, which lagged by several months for all events, except 2003–2004. When the onset dates indicated by the six drought indices are compared with the EM-DAT onset dates, meteorological drought indices (SPI-3, and SPEI-3) showed earlier onsets except for 2003–2004 drought where EM-DAT onset was unavailable. Similarly, the agricultural (ETDI and SMDI) and hydrological (SRI-3) drought indices showed earlier onsets of drought for two drought events and a late onset for one drought event. In contrast, ADI showed late onsets for two drought events and an early onset for 1983–1984. The comparison showed that none of the six drought indices could individually identify the onset of the four selected historic events. They could identify all events if all six indices (including different aggregation periods) were combined. Note that the ADI index tested in this study considers only three input variables at a 1-month aggregate period. The years 2003/2004 and 1983/1984 were indicated as the most severe drought years in the basin. An effective drought monitoring and planning is essential to mitigate drought impacts in the basin. For future drought monitoring for the Upper Blue Nile basin, developing a method that makes optimal use of multiple drought indices is recommended.

Supplementary Materials: The following are available online at www.mdpi.com/2076-3263/8/3/81/s1, Table S1: The Pearson's correlation coefficient matrix computed between the paired values of the drought indices at multiple time scales for the selected stations.

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