Comparing surface water supply index and streamflow drought index for hydrological drought analysis in Ethiopia

Kassa Abera Tareke a,b,*, Admasu Gebeyehu Awoke b

a Department of Hydraulic Engineering, Wollo University, KioT, Ethiopia
b Addis Ababa University, Addis Ababa Institute of Technology, Ethiopia

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ABSTRACT

Recently, floods and drought have become common natural hydroclimatic hazards in several countries. Consequently, the identification of an appropriate drought index is now a challenging task for researchers. It is obvious that there is not a single best drought index; rather a comparison of indices will give a relative option. The objective of this study was to compare two hydrological drought indices; the modified surface water supply index (M1SWSI) and streamflow drought index (SDI) over eight river basins, in Ethiopia. The M1SWSI and SDI value was computed from 1973 to 2014 using 34 streamflow stations, 42 rainfall gauge stations, and 3 lake-level data. The two indices results showed that the 1980s were the most severe drought years for all river basins. But for the case of Genale Dawa and Wabishebele basins, the drought severity increased from 2000 to 2014. Hydrological drought analysis using SDI has more drought occurrence frequency than M1SWSI. In all river basins from 1973 to 2014, there were a total of 18 severe drought events when using M1SWSI, but there were a total of 39 severe and 12 extreme drought events when using SDI. This implied that M1SWSI reduced the occurrence probability of severe drought by 53.85% and extreme drought by 100%. It is known that Ethiopia is stricken by extreme droughts in the last few decades. But M1SWSI doesn’t detect those invidious drought events. In this study, SDI is found to be a better hydrological drought index. Therefore, policy and strategic planners, master plan developers, and decision-makers can use SDI to analyze historical and future hydrological drought trends to develop effective drought mitigation measures.

1. Introduction

Floods and droughts are natural hydroclimatic hazards affecting several countries in the world. Globally, flood studies have good concern than drought due to their fast impact and short duration [1]. Flood and drought disasters become a bottleneck for the economic development of many countries. However, drought is the most complex and widespread hydrological extreme than flood [2]. Drought has a devastating negative impact on water supply, irrigation, hydropower, and all kinds of water resource projects [3]. As a consequence, recent drought analysis and forecasting studies become more interesting to develop effective drought mitigation measures [4].

The definition of drought is more subjective due to its complex nature and scholars defined it from a different perspective [5]. However, drought can commonly be classified into four types (a) meteorological drought associated with scarcity of precipitation for long periods below normal situations [6, 7, 8], (b) hydrological drought related to the low water level in surface and subsurface water resources such as a lake, reservoir, streamflow and groundwater [6], [9, 10, 11, 12, 13, 14, 15], (c) agricultural drought related to lack of soil moisture to attain the minimum crop water required in the soil and distracts agricultural productivity [16, 17, 18, 19] and (d) the fourth one is socio-economic drought which is the overall welfare crisis of the society caused by severe drought [5, 20, 21, 22, 23]. Meteorological drought highly affects the agricultural systems by aggravating food insecurity, especially in developing countries due to crop failures before harvesting season while hydrological and agricultural drought causes low production of industries because of shortage of water supply to irrigation, municipals, and industries, hydropower generation [24]. The cumulative effects of meteorological and hydrological droughts lead to socioeconomic drought, which disturbs the entire ecosystem and badly affects and even loses the lives of humans and animals [8]. In addition to this extreme hydrological events has high influence on water quality and it needs a wide concern [25].

* Corresponding author.
E-mail address: kassa.abera@aait.edu.et (K.A. Tareke).

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Studies revealed that Ethiopia has faced several severe and extreme drought events in the last few decades as a result of erratic rainfall and climate change [26, 27, 28, 29]. Northern Tigray region, some parts of Amhara region such as South Wollo, North Wollo, South Gondar, and Afar region, most parts of Somalia region, and eastern parts of Oromia region (Borena Zone) have frequently been affected by severe drought in Ethiopia [26, 30, 31, 32, 33, 34]. According to [35], drought in Ethiopia occurs at a recurrence interval of three to ten years. Even though this frequent recurrence is well recognized there still lacks any firmly-established drought mitigation measure for these disasters. In Ethiopia, drought response efforts are provided in the form of food aid when food supplies have decreased significantly due to extended drought for a short-term recovery.

Relatively, meteorological drought analysis gets more focused than other types of drought in Ethiopia [35, 36, 37, 38, 39, 40, 41]. There are few drought indices comparison studies across Ethiopia and specifically Upper Blue Nile in the Abay river basin, respectively [42, 43]. Bayissa (2018) [43] tried to compare six drought indices in Upper Blue Nile; three meteorological indices, two agricultural indices, and one hydrological index. Since the number of input data and the purpose of the index developed affects the selection of the appropriate drought index for a specific study area. Tsige et al. (2019) [42] also compared two indices (meteorological and agricultural indices) in which the finding were relatively good compared to Bayissa’s finding. However, both scholars were focused on meteorological drought indices than hydrological drought indices. Hydrological drought analysis is not well studied in Ethiopia as a national level which has a great influence on national economic development.

Hydrological drought is related to surface and subsurface water shortage in terms of volume from the long-term normal condition. Hydrological drought always lags from meteorological drought and it propagation process from meteorological to hydrological drought is important to develop effective drought early warning system [44]. For long-time drought events, meteorological and agricultural droughts have been propagated to hydrological drought which caused streamflow, reservoir and lake level, and groundwater level reduction. As a result, water supply, irrigation, and hydropower generation have been directly affected. Because the development of hydrological drought is directly related to the transformation of precipitation into effective streamflow generation [45]. Ethiopia has many perennial rivers and lakes, but still, those resources are not well utilized [46]. While hydrological and agricultural drought analysis and monitoring have not been thoroughly explored, meteorological drought analysis has been regularly studied in various parts of the country [47].

Many drought indices are region sensitive and developed in different countries [48]. Most of the indicators are developed for meteorological and agricultural drought analysis. However, there are also drought indicators used for hydrological drought analysis such as the Palmer hydrological drought index (PHDI) [49], streamflow drought index (SDI) [50], and surface water supply index (SWSI) [12]. SDI is simple and required a single input data (streamflow) and is suitable for drought study at the site [47] whereas, SWSI was developed at Colorado University by Shafer and Dezman (1982) and is used for regional or basin-level hydrological drought analysis by considering the available surface water from different sources [12]. It requires all forms of surface water sources such as streamflow, precipitation, reservoir level, and groundwater level. Hydrological drought analysis gives good information for policymakers and serve as crucial input for water management. Because drought related to transboundary rivers has crucial importance for special treatment during drought events and it is important to develop a good water resource management strategy before and after drought has occurred. Many Ethiopian rivers are transboundary rivers and need effective assessment and management. Therefore, this study was aimed to analyze hydrological drought conditions in Ethiopia by comparing two hydrological drought indicators (SWSI and SDI). The severity condition of drought obtained by these indicators was also compared using Pearson’s correlation coefficients.

2. Methods and materials

2.1. Study area

Geographically, Ethiopia is located in the eastern horn of Africa at 3° N to 15° N latitude and 33° E to 48° E longitudes. Approximately the total area of Ethiopia is 1.13 million km² [51]. From this, the study covered about 87.3% of the country. The rate of population growth increases rapidly and causes deforestation and expansion of urban areas which indirectly increases hydroclimatic variability and extremes. Figure 1 shows the major river basins in Ethiopia and the spatial location of hydro-meteorological stations. Of the existing 12 major river basins (Figure 1), three are dry and one river basin has low flow and low recorded data [47]. Therefore, comparing of two hydrological drought indices (SDI and SWSI) was conducted only on eight major river basins.

Ethiopia is the tropical Zone laying between the equator and the tropic of Cancer. It has three different climate zones according to elevation. These are: Kolla (Tropical Zone) below 1830 m in elevation and the annual average temperature and rainfall are 27 °C and 510 mm respectively. The second is Wolna Dega (Subtropical Zone), which is composed of highland regions between 1830 and 2440 m in elevation and has an average annual temperature of nearly 22 °C and 510–1530 mm of rainfall. The third is Dega (Cool zone), which is located above 2440 m in elevation and has an annual rainfall range of 1270–1280 mm with an average yearly temperature of about 16 °C. The country has four major seasons: Summer ‘Kiremet’ (June–August; JJA); autumn ‘Tibe’ (September–November; SON); winter ‘Bega’ (December–February; DJF) and spring ‘Belg’ (March–May; MAM). However, the coldest month is not always in ‘Bega’ and the hottest month is not always in ‘Kiremet’. Ethiopia lies near the equator where maximum heat from the sun is received. The length of days and nights is almost the same in most regions.

Precipitation is the main source of streamflow generation for river basins in Ethiopia. For the eight studied basins, most of them have received high rainfall during the summer season (JJA). But for the case of Genale Dawa and Wabishebele, they receive high rainfall during the spring season (MAM) and low rainfall during summer (JJA), and the variation of streamflow level is also corresponding to the precipitation time variance (Figure 2).

The spatial distribution of rainfall over the country highly varies; Abay, Baro Akobo and Omo Gibe River basins receive high rainfall whereas the remaining five river basins receive medium to low rainfall. As indicated in Figure 3, semi-arid and arid basins such as Genale Dawa, Wabishebele, and Ogaden receives below 1000 mm annually. Tekeze, Awash, and Rift Valley have an annual rainfall range between 770 to 1100 mm.

3. Methods

3.1. Data preparation

Precipitation data were collected from the Ethiopian Meteorology Institute whereas streamflow and lake level data were collected from the Ministry of Water and Energy (MoWE). Based on data record length, quality, and availability; 42, 34, and 3 precipitation gauge stations, streamflow, and lake level stations were collected respectively over eight major river basins in the country. But for all those stations, the data record length is not the same. Especially, streamflow data length is varying from basin to basin. However, the dominant record range was decided from 1973 to 2014. Missing data for precipitation was completed using the areal ratio method and for streamflow, XLSTAT was used. XLSTAT is a statistical analysis tool integrated with Microsoft excel used to fill in missing data, analyze hydrological tests such as consistency and homogeneity, and visualize and plot hydroclimatic data [52].

Hydrometeorological data can be affected by natural hazards or by human intervention. For example, the gauge station may be collapsed,
break, or miss reading and data collectors may collect wrong data. Due to those and other reasons, the information generated from these poor-quality data is affecting the decision of researchers, stakeholders, and planners. Therefore, before any data is used as model input, data quality analysis is mandatory. In any water resource management activities, the hydroclimatic data should be as much as possible stationary, homogeneous, consistent, stable variance and mean [53, 54]. So, in this study, consistency and homogeneity tests were checked using double mass curves and non-dimensional ratio methods, respectively for all selected meteorological stations [55, 56].

3.2. Original surface water supply index

Shafer and Dezman (1982) [57], in Colorado, developed SWSI to supplement the Palmer Drought Severity Index by taking streamflow, reservoir storage, and snowpack into account. The steps to calculate the SWSI for a specific basin are as follows: monthly data are gathered and added for all the reservoir inflow, streamflow monitoring stations, and precipitation stations throughout the basin. A long-term mean is used to normalize each component's sum. Each element is given a weight based on how frequently it contributes to the surface water in
The large portion of available water resources in Ethiopia is surface water (streamflow) which meteorological drought indexes such as SPI, RDI, and PDSI do not explicitly include. The main inputs for SWSI are streamflow, precipitation, reservoir storage, and groundwater level (optional). But reservoir storage is directly related to the inflow stream condition of the basin and groundwater level is important for groundwater drought analysis. Therefore, for this research streamflow, precipitation, and lake level instead of reservoir storage were used as input for SWSI analysis. The equation is given below in Eq. (1):

\[
SWSI = \frac{a \cdot PN_{strm} + b \cdot PN_{prec} + c \cdot PN_{lal} - 50}{12}
\]

where: \( SWSI \) = Surface Water Supply Index, \( PN_{strm}, PN_{prec}, \) and \( PN_{lal} \) are a percentage of non-exceedance (%) of monthly streamflow, precipitation, and lake level respectively, and \( a, b \) and \( c \) = weight for each hydrologic component in which; \( a + b + c = 1 \). Subtracting \( 50 \) centers the SWSI values around zero, and dividing by \( 12 \) compresses the range of values between \(-4.2\) to \( +4.2 \). The non-exceedance probabilities are taken from probability distributions fitted to each hydrologic component.

### 3.3. Modified surface water supply index (M1SWSI)

This method was modified by [48] using forecasted streamflow and reservoir storage volume. But it does not explicitly analyze different hydrological components and this masks important information about the behavior of each hydrologic component. The equation is given by Eq. (2):

\[
SWSI = \frac{(P - 50)}{12}
\]

where: \( P \) = the non-exceedance probability (%) of a long-term mean.

The surface water supply index (SWSI) is one of the hydrological drought indicators which gives a wide range of drought characterization than SDI. It is applicable for basin-level drought analysis and it was developed based on PDSI algorism [58, 59]. For this work without altering the algorism, the equation is modified to make it easy to compare with the SDI value. SWSI was developed to incorporate multiple hydrologic/meteorological components into a single objectively derived index value for each river basin [60].

However, still, SWSI is more subjective, and compared with PSDI which is meteorological drought indices, the hydrological components considered need explicit analysis. So, it is important to modify the equation to make it comparable with a hydrological index such as SDI by reducing the compressed range from \(-4.2\) to \( +4.2 \) into \(-2.1\) to \( +2.1 \). This reduction of the range is done without altering the algorithm of the model and simply reduced the range by increasing the denominator. Now it can be comparable with the SDI value for a given basin and the equation is given by Eq. (3):

\[
M1SWSI = \frac{a \cdot PN_{strm} + b \cdot PN_{prec} + c \cdot PN_{lal} - 50}{24}
\]

where: \( M1SWSI \) is modified SWSI, and all other terms are described in Eq. (1).

The value of weighted factors \( a, b, \) and \( c \) were more subjective in the original SWSI development even though eliminated by the revised one [15]. But it is important to make it objective and give a sense of the art of science. Therefore, the value of these weighted factors is formulated below in Eq. (4).

\[
P_a = P_b = P_c = \frac{X_i}{X_{max}}
\]

where: \( P_a, P_b, \) and \( P_c \) are the proportional value of monthly or annual streamflow, precipitation, and lake level respectively whereas \( X_i \) and \( X_{max} \) are the observed monthly or annual value and maximum values,
respectively for all components. Now the weighted factors can be determined as follow in Eq. (5).

\[
a = \frac{Pa}{Pt}, \quad b = \frac{Pb}{Pt}, \quad c = \frac{Pc}{Pt}
\]  

(5)

where: Pa, Pb, and Pc are as described earlier in Eq. (4) and Pt is the total proportionality of each surface component (Pt = Pa + Pb + Pc); a, b and c are weighted factors of each surface water component (streamflow, precipitation and lake level) respectively.

The probability of non-exceedance for each component was determined using Eq. (6) as shown below developed by Weibull [61].

\[
PN = 1 - \frac{m}{n + 1}
\]

(6)

where: PN is the non-exceedance probability of each component, m is the rank and n is the total number of data considered in the time series.

Table 1 shows the drought criteria originally classified by Shafer and Dezman in 1982 and the modified classification is downscaled by half from the original.

### 3.4. Streamflow drought index analysis

The Streamflow Drought Index (SDI) was developed by Nalbantis and Tsakiris (2009) [62], which is used to characterize the hydrological drought situation of a study area. Since its calculation is similar to SPI’s, it has the same efficiency and simplicity. The SDI gives the advantage of controlling hydrological drought or the availability of water in the short, medium, and long term because it is based on monthly observed streamflow amounts at various time scales. The SDI is defined as follows for each reference period k of the ith hydrological year based on the cumulative streamflow volumes Vi,k:

\[
SDI = \frac{Vi,k - Vkm}{Sk}
\]

(7)

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

Since these are calculated over a long period, Vkm and Sk are the mean and standard deviation of the cumulative streamflow volumes of the reference period k, respectively. The SDI runs from −2 to +2 in terms of wetness and dryness. Below −2 and above +2, respectively, are the values that are exceedingly dry and wet. The SDI criteria for identifying the worst and most intense drought occurrences are shown in Table 2.

SWSI was developed based on the PDSI algorithm. But PDSI is more important for meteorological and agricultural drought analysis than hydrological drought [63]. Therefore, comparing SWSI with PDSI is subjective and it needs some modification of the range of SWSI results and weighted factors. After compressing the value of SWSI from −4.1 to +4.1 into −2.1 and +2.1; it is possible to compare the result with SDI for a given river basin. Based on this, the correlation of the two hydrological drought indices was computed.

### Table 1. Original SWSI (Shafer and Dezman, 1982) and modified M1SWSI values.

| Original SWSI Range | M1SWSI range | Description |
|---------------------|--------------|-------------|
| ≥ 4                 | ≥ −2         | Abundant supply |
| 3.99 to 1.99        | 1.99 to 0.99 | Wet         |
| 2 to −0.99          | −0.5 to −0.99| Normal      |
| −1 to −1.99         | −1 to −1.49  | Incipient drought |
| −2 to −2.99         | −1.5 to −1.99| Moderate drought |
| −3 to −3.99         | −1 to −1.99  | Severe drought |
| ≤ −4               | ≤ −2         | Extreme drought |

Note: M1SWSI is a modified surface water supply index.

### 4. Results and discussion

#### 4.1. Consistency and homogeneity analysis

The analysis of consistency and homogeneity was conducted using the double mass curve method and non-dimensional ratio approach method respectively. For the case of Awash and Omo Gibe River basins, two stations were found inconsistent and non-homogeneous (see Figures 4 and 5). However, the remaining 40-gauge stations within the respective river basins showed good homogeneity and consistency result. As shown in Figure 4, one gauging station from the Awash and Omo Gibe River basins (Melkawer and Bonga), respectively was not consistent with other stations from the basins. Therefore, the Melkawer station from the Awash river basin and the Bonga station from the Omo Gibe River basin was not considered for further drought analysis in this study.

As shown in Figure 5, almost in all river basins the stations are relatively homogeneous. But, in the Awash, Omo Gibe, and Rift Valley River basins, some stations are non-homogeneous. However, the variation is not significant, therefore except for Guder station (Awash River basin) and Bonga station (Omo Gibe River basin) all the stations were considered for further analysis (see Figure 5).

#### 4.2. Analysis of hydrological drought using SWSI

Even though SWSI analysis requires more input data, this analysis was computed using three input data for Abbay and Rift Valley River basins (streamflow, precipitation, and lake level), whereas for the remaining six river basins, two input data were used (streamflow and precipitation) due to data scarcity of lake level. All the input data were summed separately and their non-exceedance probability was computed using Eq. (6). The value of component weights (a, b, c) for each basin is different and it was estimated for seasonal and annual values (Table 3). There are four seasons in Ethiopia, Autumn (Tibe or Meher), Winter (Bega), Spring (Tsekey or Belg), and Summer (Kiremt). The value of component weights was computed for all seasons but the rainiest seasons in Spring and Summer were selected for discussion. The weightings a, b, and c in Table 3 indicated the component potential impact on surface water available in the basin. As observed from Table 3, the most surface water source for all basins in Ethiopia is precipitation. In Abbay and Rift Valley River basins, the lake level was considered and it shows that the seasonal variation of lake level is insignificant when compared to the variation of streamflow and precipitation (Table 3). The one fact is that the value of component weight for each basin is not always constant as stated in Table 3, rather it will change as the number of gauging stations increases or decreases. But the variation is not that significant.

In all river basins, the 1980s were the driest years, according to the hydrological drought analysis produced by M1SWSI and SDI (Tables 4 and 5). But the severe drought has regularly affected the Abbay and Awash River basins (Table 4). M1SWSI gives the drought information...
over a large area; as a result, it compressed the magnitude of hydrological drought impact in a specific area. Previous studies revealed that Ethiopia is recurrently affected by severe and extreme drought events. But here, the result of M1SWSI indicated that there was no extreme drought event in the last three decades (Table 4). As shown in Table 4, the magnitude of M1SWSI is almost near the moderate drought range category except for Awash in 2001, Baro in 1985, and Genale Dawa in 2003. Genale Dawa, Wabishebele, and Rift Valley river basins are located in lower parts of Ethiopia and highly exposed to prolonged drought in the last decades [64, 65]. But the hydrological drought analysis using M1SWSI minimized the frequency and magnitude of severe drought events in those areas. This indicates that hydrological drought analysis using multiple hydroclimate data may hide the information and it will directly affect the water resource management system.

4.3. Analysis of hydrological drought using SDI

To eradicate the flow variation of stations across time and space, the daily streamflow data were compiled monthly and standardized to zero mean and unit standard deviation. Then, SDI was calculated by applying Eq. (7) to the seasonal base for the three-month length (SDI3) and the yearly base for the twelve-month duration (SDI12). The result implies that the 3-month time scale analysis has a high frequency of drought than the long-term time scale, 12-month. But for the long-term time scale, drought duration is maximum and the severity is increased. The result is

![Figure 4. Consistency test for all river basin using double mass curve.](image)
supported by previous studies related to hydrological and meteorological drought analysis [6, 8, 59]. The most intense and severe drought years across many river basins were recognized in this study. Table 5 reveals that during the past three decades, there have been 11 severe and 4 catastrophic droughts that have had an impact on the Rift Valley River Basin. Besides, the Wabishebele and Abbay river basins experienced severe drought in the 1980s and 2000s, respectively. The result of hydrological drought analysis using SDI agrees with previous meteorological drought study findings in Ethiopia [66, 67, 68, 69]. But the result from M1SWSI contrasts with SDI results.
Table 3. MISWSI seasonal and annual component weights summary.

| Basin     | Season | Weights | a (1) | b (2) | c (3) |
|-----------|--------|---------|-------|-------|-------|
| Abbey     | Spring | 0.21    | 0.32  | 0.47  |
|           | Summer | 0.29    | 0.40  | 0.31  |
|           | Annual | 0.29    | 0.40  | 0.31  |
| Awash     | Spring | 0.47    | 0.53  | -     |
|           | Summer | 0.38    | 0.62  | -     |
|           | Annual | 0.42    | 0.58  | -     |
| Baro      | Spring | 0.31    | 0.69  | -     |
|           | Summer | 0.33    | 0.67  | -     |
|           | Annual | 0.45    | 0.55  | -     |
| Genale Dawa | Spring | 0.38    | 0.62  | -     |
|           | Summer | 0.66    | 0.34  | -     |
|           | Annual | 0.44    | 0.56  | -     |
| Omo Gibe  | Spring | 0.36    | 0.64  | -     |
|           | Summer | 0.49    | 0.51  | -     |
|           | Annual | 0.45    | 0.55  | -     |
| Rift Valley | Spring | 0.22    | 0.45  | 0.32  |
|           | Summer | 0.19    | 0.44  | 0.37  |
|           | Annual | 0.27    | 0.38  | 0.35  |
| Tekeze    | Spring | 0.19    | 0.81  | -     |
|           | Summer | 0.45    | 0.55  | -     |
|           | Annual | 0.39    | 0.61  | -     |
|           | Spring | 0.12    | 0.88  | -     |
| Wabishele | Summer | 0.44    | 0.56  | -     |
|           | Annual | 0.27    | 0.73  | -     |

Where 1, 2, and 3 indicate: (1) Streamflow (2) Precipitation (3) Lake level, and (−) implies no data.

Table 4. Summary of Severe drought years and magnitude in each river basin in Ethiopia using MISWSI.

| River Basin | Severe drought years | Magnitude |
|-------------|----------------------|-----------|
| Abbey       | 1982, 1983           | −1.52, −1.58 |
| Awash       | 1979, 1986, 1987, 2001 | −1.56, −1.56, −1.72, −1.91 |
| Baro        | 1985, 2002           | −1.73, −1.71 |
| Genale Dawa | 2003                  | −1.73    |
| Omo Gibe    | 1981, 1994, 2016     | −1.59, −1.56, −1.73 |
| Rift Valley | 1985                  | −1.64    |
| Tekeze      | 1996, 2008           | −1.6, −1.67 |
| Wabishele   | 2011                  | −1.57    |

4.4. Comparing SDI and MISWSI

SDI value indicated that the Rift Valley river basin is recurrently affected by severe and extreme drought events (Table 5). But the MISWSI result indicates Rift Valley river basin is less affected by drought compared to other basins (Table 4). A previous study indicates the Rift Valley river basin is frequently affected by worth drought [70]. The result of this study agreed with recent findings. However, the MISWSI result deviated from the historical trend not only Rift Valley river basin but also in others. As shown in Table 6, except Rift Valley River basin, SDI and MISWSI have a good correlation in all river basins. The reason for the Rift Valley River basin is that the streamflow value is very minimum and directly joined to a lake which increases the lake level regularly. Therefore, the available surface water in the basin is dominated by lakes and precipitation than streamflow. As a result, the cumulative drought analysis technique using MISWSI gives wet season frequently and the overall result of the index can be dominated by the available lake water.

Table 5. Severe and extreme hydrological drought years and magnitude in Ethiopian river basins using SDI.

| River Basin | Severe drought years | Magnitude | Extreme drought years | Magnitude |
|-------------|----------------------|-----------|-----------------------|-----------|
| Abbey       | 1978, 1983, 1984, 1986, 1994, 2010 | −1.84, −1.66, −1.91, −1.69, −1.98 | 1983, 1984 | −2.21, −2.29 |
| Awash       | 1986, 1987, 2001     | −1.57, −1.88, −1.62, −1.81 | 1986, 1987, 2002 | −2.16, −2.4, −2.38 |
| Baro        | 1982, 1984, 1985, 2002 | −1.52, −1.51 | 2002, 2004 | −2.01, −2.09 |
| Genale Dawa | 1996, 2002, 2003, 2010 | −1.76, −1.9 | - | - |
| Omo Gibe    | 1980, 1981, 1986     | −1.64, −1.77, −1.69 | - | - |
| Rift Valley | 1980, 1983, 1984, 1985, 1987, 1990, 1999, 2002, 2004, 2010, 2012 | −1.52, −1.54, −1.5, −1.55, −1.64, −1.74, −1.52, −1.86, −1.91, −1.91, −1.92 | 1984, 1985, 2003, 2011 | −2.2, −2.1, −2.14, −2.21 |
| Tekeze      | 1996                 | −1.51    | - | - |
| Wabishele   | 1990, 2001, 2002, 2004, 2005, 2011 | −1.9, −1.86, −1.76, −1.69, −1.7 | 2002, 2003 | −2.34 |

Table 6. SDI and MISWSI correlations.

| Basin | Correlation | Basin | Correlation |
|-------|-------------|-------|-------------|
| Abbey | 0.79        | Omo Gibe | 0.64 |
| Awash | 0.51        | Rift Valley | 0.19 |
| Baro  | 0.72        | Tekeze  | 0.68 |
| Genale Dawa | 0.53 | Wabishele | 0.62 |

Table 7 shows that the occurrence of severe and extreme drought frequency is higher for SDI than for MISWSI. This is because SDI gives a site or point drought condition of a single river from the basin but SWSI results are based on the cumulative contribution of different surface water sources such as streamflow, precipitation, and lake level. It is also understood that the probability of occurrence of extreme drought using MISWSI was insignificant (Table 7). Except for the Awash and Tekeze river basins, the frequency of severe drought in all basins has reduced when drought is analyzed by SWSI. The average occurrence of severe and extreme drought using SWSI was reduced by 53.85% and 100% respectively when compared with SDI. This implies that SWSI will hide the impact of local drought and affects the drought management program by reducing the severity of drought over the region. Therefore, for water

Table 7. Number of droughts that occurred in Ethiopia from 1973-2014 using SDI and MISWSI.

| Basin     | Number of Severe Drought Occurred | SDI | SWSI | % of reduction | Number of Extreme Drought Occurred | SDI | SWSI | % of reduction |
|-----------|----------------------------------|-----|------|---------------|-----------------------------------|-----|------|---------------|
| Abbey     | 6                                | 34  | 33.33 | 2              | 2                                 | 2   | 100     |
| Awash     | 4                                | 25  | 62.5  | 2              | 4                                 | 4   | 100     |
| Baro      | 4                                | 50  | 100   | 2              | 0                                 | 0   | 100     |
| Genale Dawa | 4                              | 75  | 100   | 0              | 0                                 | 0   | 100     |
| Omo Gibe  | 3                                | 3   | 100   | 0              | 0                                 | 0   | 100     |
| Rift Valley | 13                             | 92.3| 100   | 4              | 0                                 | 0   | 100     |
| Tekeze    | 1                                | 5   | 80    | 1              | 0                                 | 0   | 100     |
| Wabishele | 5                                | 80  | 100   | 1              | 0                                 | 0   | 100     |
resource planning and infrastructure development in a river, SDI gives good information about the historical frequency of drought conditions than M1SWSI.

The annual time series of SDI and M1SWSI for all river basins in Ethiopia is shown below in Figures 6, 7, 8, 9, 10, 11, 12, and 13. All Figures from 6 to 13 imply that the probability of severe and extreme drought occurrence was high for SDI than M1SWSI. Because M1SWSI has been obtained from a combination of many hydroclimate variables and the result is more dominated by wet events than dry events. This is due to the combination of different hydrological components for a single basin drought analysis. However, the two indexes have good correlations for all river basins except the Rift Valley River basin.

In the case of the Abbay river basin, the hydrological drought frequency was high for SDI from 1973 to 2000. But from 2000 to 2014, the frequency of drought was obtained high by M1SWSI (Figure 6). The result revealed by some researchers such as [71] indicates that the basin was under severe drought from 1980 to 1990.

SDI and M1SWSI in Awash River have less correlation compared to Abbay and Baro river basins (Table 6). Similarly, SDI has a high frequency from 1973 to 2000 but it becomes wetter from 2001 to 2014 compared to M1SWSI. The more severe probability of the basin is obtained by SDI than M1SWSI (Figure 7) [72, 73]. also stated that the Awash river is frequently affected by drought during the last five decades.

A drought study is not conducted in the Baro river basin before. The analysis of this study shows, the two hydrological drought indices (SDI and M1SWSI) have a good correlation for the Baro river basin (Table 6). Baro river is the wettest river basin compared to all basins and the occurrence of drought frequency is less. However, the basin was severely affected by drought between 1985 and 2002 (Figure 8).

In Genale Dawa, the two indices have high variation and from 1984 to 2007 moderate to severe droughts were more frequent for M1SWSI than SDI. It is because the Genale Dawa river basin is located in arid and semiarid areas in which the contribution of rainfall for surface water is minimal [74]. But the source of streamflow is from the highlands of the central parts of the country and depends mainly on a good climate zone. As a result, SDI is relatively wetter than M1SWSI during the analysis time (Figure 9). The severe drought event occurred in the basin period in 2003 for both SDI and M1SWSI. Seven moderate drought events occurred in the Genale Dawa river basin from 1984 to 2012. 43% of the drought occurred during 1990, 1996, and 2007 (M1SWSI), 43% were in 1998, 1999, and 2001 (by SDI and M1SWSI), and 14% is during 2008 (SDI). This result is the same as previous drought studies in the basin by [5, 55, 56, 57, 75, 58].

Omo Gibe River basin is located in a good climate zone, which received high rainfall in two seasons (Spring and summer). As a result, the analysis of drought by different indices (SDI and M1SWSI) relatively gives the same result. Figure 10 shows that from 1980 to 1993, SDI results in moderate to severe drought whereas from 1994 to 2016 the moderate and severe drought events were dominated by M1SWSI.

The Rift Valley River basin is highly dominated by lakes and received minimum rainfall. Many streamflows join into different small lakes and

![Figure 6. Comparison between SDI and M1SWSI in the Abbay river basin.](image)

![Figure 7. Comparison between SDI and M1SWSI in the Awash river basin.](image)

![Figure 8. Comparison between SDI and M1SWSI in the Baro river basin.](image)
the rivers flow restricted from flowing a distance. The basin is located in a depression area and the precipitation variation is insignificant [76]. The fluctuation of lake level in this river basin is constant as stated by [36]. The drought analysis for this basin considered three input parameters such as streamflow, precipitation, and lake level. The result shows that, M1SWSI is influenced by lake level and which results in the basin being in normal to wetter conditions (Figure 11). But SDI result implied that the area is highly affected by frequent drought and the correlation between SDI and M1SWSI is poor (Table 6). This implies that SDI is more suitable for hydrological drought analysis in this basin than M1SWSI. Because other studies also show that [36, 77] the area is frequently affected by severe drought but M1SWSI minimized the impact of drought in the area due to the combination of different surface water sources.

SDI and M1SWSI in the Tekeze river basin have a good correlation (Table 6). As shown in Figure 12, the drought time series of the two indices have a similar fashion. But relatively, M1SWSI results in more drought frequency compared to SDI. Due to the construction of the Tekeze dam, the variation of streamflow in the Tekeze river is balanced [78]. SDI value is dependent on streamflow data; therefore, the result also depends on the fluctuation of flow. However, historical drought studies imply that the area is frequently affected by the severe drought [31, 79]. But in this study, the annual SDI12 value of the Tekeze river basin is in the reverses of previous studies. Therefore, the future drought condition of the Tekeze basin needs a detailed study using different additional streamflow stations located in the tributaries of the Tekeze river.
Wabishebele River basin is one of the arid basins and is commonly affected by severe drought compared to other river basins (Awass., 2009). 1990 and 2011 are the most severe drought years whereas 2002 was the extreme drought year in this river basin. From those drought events, only 2011 was the same for SDI and M1SWSI and the remaining drought events were obtained by SDI (Figure 13).

5. Conclusion

This study has compared two hydrological drought indices (SDI and M1SWSI) and the result showed that the 1980s were the most prolonged hydrological drought event years in Ethiopia. SDI resulted in more frequently severe and extreme drought events occurrence over the country than the M1SWSI. M1SWSI uses multi-hydrological components cumulatively as input and which results in a small magnitude of drought severity and its occurrence frequency was decreased due to the aggregation of components. The number of severe drought events obtained using M1SWSI in all basins was less than 53.85% of the SDI result. Because some hydrological components were dominating the scarce data and which will affect the overall analysis. The result of SDI values agreed with previous historical drought events. Therefore, SDI is the best hydrological drought index compared to M1SWSI for all basins in Ethiopia and this index gives good information for a single river as well as basin-level drought conditions. So, water resource managers and infrastructure development sectors can use this index for decision-making for the best utilization of the available water resource within the basin. Water supply, irrigation, and hydropower projects are more dependent on streamflow and need hydrological drought monitoring system development. Therefore, decision-makers, policy, and strategic planners, and master plan developers can use SDI for historical and future hydrological drought analysis to develop effective drought mitigation measures in Ethiopia.

Declarations

Author contribution statement

Kassa Abera Tareke, Msc; Admassu Gebeeyehu Awoke: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data will be made available on request.

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The authors declare no competing interests.

Additional information

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