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Drought sensitivity characteristics and relationships between drought indices over Upper Blue Nile basin

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Abstract

Drought is an extreme event that causes great economic and environmental damage. The main objective of this study is to evaluate sensitivity, characterization and propagation of drought in the Upper Blue Nile. Drought indices: standardized precipitation index (*SPI*) and the recently developed standardized reconnaissance drought index (*RDIst*) are applied for five weather stations from 1980 to 2015 to evaluate *RDIst* applicability in the Upper Blue Nile. From our analysis both *SPI* and *RDIst* applied for 3-, 6-, 12 month of time scales follow the same trend, but in some time steps the *RDIst* varies with smaller amplitude than *SPI*. The severity and longer duration of drought compared with others periods of meteorological drought is found in the years 1984, 2002, 2009, 2015 including five weather stations and entire Upper Blue Nile. For drought relationships the correlation analysis is made across the time scales to evaluate the relationship between meteorological drought (*SPI*), soil moisture drought (*SMI*), and hydrological drought (*SRI*). We found that the correlation between three indices (*SPI*, *SMI* and *SRI*) at different time scales the 24-month time scale is dominant and are given by 0.82, 0.63 and 0.56.

Key words: drought, drought indices relationships, soil moisture index (*SMI*), standardized reconnaissance drought index (*RDIst*), standardized precipitation index (*SPI*), surface runoff index (*SRI*)

INTRODUCTION

Drought occurs due to the scarcity of rainfall spatially and temporally [BAYISSA *et al.* 2015; JEMAI *et al.* 2016]. Conventionally droughts are categorized as meteorological, hydrological, agricultural and socio-economic [AMS Council 1997].

Due to its climatic condition, Ethiopia is often severely affected by droughts. The past history of drought events

revealed that frequently occurrence and diversified impacts on human lives and environment. Among 30 major drought episodes, around 13 were severely affected the entire Ethiopia [GEBREHIWOT *et al.* 2011].

Increasing sea surface temperature anomaly, especially in the South-West Indian Ocean, might be an influence for decreasing rainfall over Ethiopia and also tropical storms over the South-West Indian Ocean had a role for the occurrence of drought in 1984 [SHANKO, CAMBERLIN 1998]. El

Niño has a strong impact for Ethiopian rainfall distributions, and subsequently frequent occurrence of drought [FEKADU 2015]. This situation is occurred due to lower pressure in the eastern Pacific and associated to warmer water and weakened easterly trade winds [WARA *et al.* 2005].

Deficiency of rainfall in southern Ethiopia, during two consecutive rainy seasons autumn and summer, and severity of drought was evaluated in different time scales for different regions mostly in 1984 and 2009 [VISTE *et al.* 2013]. Drought occurs for short and long period of time had impact on severity, intensity and duration in spatio-temporal [KHEZAZNA *et al.* 2017]. Mostly drought propagation observed from meteorological droughts to hydrological drought [BAK, KUBIAK-WÓJCIKA 2017; HASLINGER *et al.* 2014].

Meteorological drought is identified by lack of precipitation as the main indicator, while agricultural drought is related to the total soil moisture deficit [HEIM 2002].

The hydrological drought, on the other hand, is characterized due to shortage of stream flow, ground-water supplies [FLEIG *et al.* 2006] and implementing the capacity change of reservoir [YASA *et al.* 2018].

Several indices have been developed for drought monitoring based on different variables, like precipitation, soil moisture, and runoff [MISHRA, SINGH 2010].

Drought is directly related to precipitation, evapotranspiration, blockage of zonal winds, soil moisture, runoff and others meteorological, agricultural and hydrological variables.

The Upper Blue Nile of Ethiopia supply large amount of water to the Nile River; however, drought influences northeastern parts and some pocket portions towards the central part of the basin are historically associated with drought [CONWAY 2000].

Drought characteristics monitored by using drought indices [JAIN *et al.* 2015]. The drought indices are imple-

mented action plans, assessment of early warning for the impact of drought [NGAKA 2012]. The spatial and temporal variation of droughts by using standard drought index (*SPI*) was investigated over Upper Blue Nile basin by BAYISSA *et al.* [2015].

Although *SPI* index can easily be applied for each location, but its main disadvantage is using only precipitation variable.

While recently developed reconnaissance drought index (*RDI*) considering precipitation and potential evapotranspiration is best choice for meteorological and agricultural drought analysis showed by [TSAKIRIS, VANGELIS 2005].

According to ZAROUG *et al.* [2014] drought and floods are evaluated during the period of El Niño and La Niña events. These events exhibiting different patterns and sequences have an influence over Blue Nile catchment droughts and floods [ZAROUG *et al.* 2014]. When an El Niño events beginning in April–June leads to droughts in the upper catchment of the Blue Nile.

The satellite rainfall products (CHIRPS) with high resolution used in this study was validated over Upper Blue Nile [BAYISSA *et al.* 2017]. The CHIRPS rainfall product was implemented evaluation of the spatial and temporal variability of meteorological drought by using Z-score.

In this study, we used the standardized precipitation index (*SPI*), standardized reconnaissance drought index (*RDIst*), soil moisture index (*SMI*) and runoff index (*SRI*). We used CHIRPS precipitation data for *SPI* and soil moisture data for *SMI* and runoff data for *SRI* computation. These indices are used to evaluate meteorological, agricultural and hydrological drought of severity, duration intensity and relationship among each other.

SMI is an indicator of drought for agriculture [HUANG *et al.* 1996] and *RDIst* used for meteorological as well as for agricultural drought analysis [TSAKIRIS *et al.* 2007].

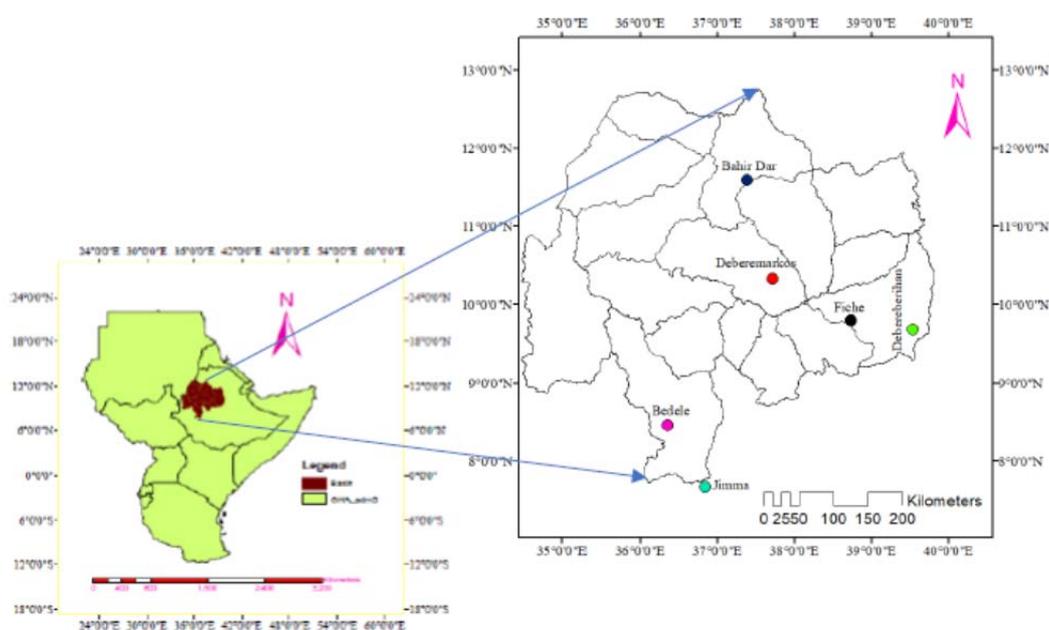


Fig. 1. Study area Upper Blue Nile basin of Ethiopia, Great Horn of Africa; source: own study

DATA AND METHODS

DESCRIPTION OF STUDY AREA

The Upper Blue Nile basin which is located in the north-western part of Ethiopia (Fig. 1) is frequently affected by climate extremes. The topography of the basin is comprised of highlands and hills in the north-eastern part, and is dominated by valleys in the southern and western parts [CONWAY 2000].

The altitude of the Blue Nile basin varies from 350 m a.s.l. close to Sudanese and 4250 m a.s.l. around central part of the Blue Nile basin [AHMED, ISMAIL 2008]. Savannah grass, crop, wood, water body and sparsely vegetated plants predominantly are found in this basin [YIRDAW *et al.* 2017].

The climate of the Blue Nile basin is mostly affected by tropical highland monsoon, with the majority of the rain falling in summer season, however, it varies seasonally and temporally over the basin [ABERA *et al.* 2016]. The climatic condition through basin varies specifically between the Ethiopian highlands and territorial countries spatially and temporally variation is affected by the movement of air masses [AWULACHEW *et al.* 2009]. The flow of the rivers reflects the seasonality of rainfall over the Ethiopian highlands, where there are two separate periods [AWULACHEW *et al.* 2009].

SPI, *RD*st, *SMI* AND *SRI* DROUGHT INDICES

Drought is one of the major problems in the Nile Basin due to climatic extremes.

SPI is efficient to monitoring meteorological and hydrological droughts [MCKEE *et al.* 1993]; although *SPI* varies with drought related issues [DURDU 2010] *RD*st applied for drought characterization and monitoring [TIGKAS 2008]. Drought threshold identified through the standardized form (*RD*st) to give meaningful expression of drought [TSAKIRIS, VANGELIS 2005].

*RD*st relied on results of cumulative precipitation and potential evapotranspiration, from which one is measured and one is calculated determinant [TSAKIRIS, VANGELIS 2005].

The soil moisture index (*SMI*) was developed by BERGMAN *et al.* [1988]. It relies upon the moisture mechanism of capturing precipitation and potential evapotranspiration. It operates within a two-layer soil model were applied to capture water regulation, to get saturated soil and soil moisture index is varied depending on Palmer drought index.

Runoff is an indicator of drought and flood which is a measure of existence of water in the soil.

We applied the methodology that used by [MCKEE *et al.* 1993] for the *SPI* to evaluate the surface runoff index (*SRI*). The percentile of surface runoff accumulated for a given duration 1, 3, 6, 12 month of time scales with a standard normal deviation associated. According to [MCKEE *et al.* 1993] the monthly precipitation data series fitted by using gamma distribution, and verified that this method is also applicable to other hydrological variables

important to drought. Therefore, we applied the gamma distribution for the surface runoff (*SRI*).

We derived *SPI*, *SMI*, and *SRI* indices from CHIRPS precipitation, soil moisture and runoff data, respectively.

DATA

This study relies on meteorological, agricultural and hydrological droughts in Upper Blue Nile from the period 1980 to 2016. The Upper Blue Nile region is accompanied by basins, high land and low land areas. Recharging of the basins and abundant water flows from highland regions which resist hydrological drought intensity. We used national meteorological monthly temperature and precipitation data from National Meteorology Agency (NMA) to determine drought for five selected regions. Runoff data from European Centre for Medium-Range Weather Forecasts (ECMWF), precipitation data from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), soil moisture from Earth System Research Laboratory's Physical Sciences Division (ESRL PSD) are derived to find the meteorological, agricultural and hydrological droughts and their relationships depending on the severity, duration and frequency. In order to achieve the lowest resolution similar to CHIRPS data, we interpolated the soil moisture and runoff data by using bilinear interpolation method. We applied different techniques to evaluate meteorological, agricultural and hydrological drought. By examining indices of precipitation, soil moisture, and runoff applying different time scales.

From National Meteorological Agency (NMA) we used precipitation and temperature data over Upper Blue Nile basin; to see the sensitivity *RD*st over *SPI* for five stations.

METHODS

The monthly rainfall and temperature recorded by local five meteorological stations over the Upper Blue Nile. These variables used to calculate the *SPI*, *RD*st and the drought categories. According to BAYISSA *et al.* [2015] by using many stations inside nearby regions of Upper Blue Nile monthly rainfall data was collected to evaluate *SPI* and drought category. The selection of five meteorological stations over Upper Blue Nile to evaluate *RD*st sensitivity compared to *SPI* during different time scale of drought.

The three and twelve time scales of *SPI* were implemented by BAYISSA *et al.* [2015] for assessment of drought condition over Upper Blue Nile.

The *SPI* and *RD*st values were computed for three (*SPI*3 and *RD*st3), six (*SPI*6 and *RD*st6) and twelve (*SPI*12 and *RD*st12) time scales for the selected five stations. The *SPI*-12 and *RD*st-12 are used to evaluate annual sensitivity drought. For six time scales of *SPI* and *RD*st are used to evaluate two consecutive rainy seasons and *SPI*3 and *RD*st are used to evaluate two rainy season Belg (March, April and May) and summer (June, July and August) drought condition and performance of each indices are examined.

The reconnaissance drought index (*RDIST*) is based both on cumulative precipitation (*P*) and potential evapotranspiration (*PET*), from which one is measured and one is calculated determinant [TSAKIRIS *et al.* 2007; TSAKIRIS VANGELIS 2005]. *RDIST* has three forms the initial value (α_k), the normalized form (*RDIn*) and the standardized form (*RDIST*). The initial value (α_k) of *RDIST* is calculated for the i^{th} year in a time basis of k (months)

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^k P_{ij}}{\sum_{j=1}^k PET_{ij}} \quad (1)$$

Where: $i = 1$ to N and $j = 1$ to k in which P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the j^{th} month of the i^{th} year, N is the total number of years of the available data.

The values of α_k follow satisfactorily both the lognormal and the gamma distributions for different time scales, in which they were tested [TIGKAS 2008].

For the calculation of *RDIST*:

$$RDIST_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\sigma_y} \quad (2)$$

Where: $y^{(i)}$ is the $\ln(\alpha_k^{(i)})$, \bar{y} is its arithmetic mean, σ_y is its standard deviation.

The gamma distribution is applied, the *RDIST* can be calculated by fitting the gamma probability density function (pdf) to the given frequency distribution of α_k [TIGKAS 2008; TSAKIRIS *et al.* 2007].

Using monthly rainfall data standard precipitation index (*SPI*) from monthly minimum and maximum temperature using Hargreaves method potential evaporation (*PET*) was calculated.

The reconnaissance drought index (*RDIST*) depends on cumulative precipitation (*P*) and potential evapotranspiration (*PET*).

The parameter gamma distribution function is used for both *SPI* and *RDIST* calculations for this analysis [VANGELIS *et al.* 2013]. This fitted distribution is used to calculate the cumulative probability density function for any given precipitation amount.

For the *RDIST* the initial value (α_k) for the i^{th} year, the normalized form (*RDIn*) and the standardized form (*RDIST*) were calculated.

Drought severity can be assessed through the computation of the standardized form (*RDIST*).

Correlation coefficients were computed between standard precipitation index (*SPI*), soil moisture index (*SMI*) and surface runoff index (*SRI*) for summer – June–September (*JJAS*) season. Pearson correlation analysis is used to determine the relationship among two drought indices.

Their correlation coefficients have the limit +1 and –1, however, zero correlation values indicate that no relationship among the two drought indices, while +1 and –1 imply strong linear association, which is the same association for positive and negative values respectively.

The equation of correlation is expressed as:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2} \sqrt{\sum(Y_i - \bar{Y})^2}} \quad (3)$$

Where r is the correlation coefficient between X and Y represents the variables of standardized precipitation, soil moisture and surface runoff indices.

Climate Prediction Center (CPC) applies soil moisture to predict monthly and seasonal temperature and precipitation. Increased evaporation from the soil results humidity to increase the likelihood of future precipitation [FAN, VAN DEN DOOL 2004]. Such qualitative assessment is possible because soil moisture changes little during the winter.

Soil moisture is important in temperature forecasts than precipitation. The correlation between soil moisture and temperature reaches maximum [HUANG *et al.* 1996].

The CPC soil moisture model can be represented by Equation (4).

$$\Delta S_{\text{moist}} = P - E - S_{\text{runoff}} - G_{\text{waterloss}} \quad (4)$$

Where: ΔS_{moist} is change in soil moisture over time, P is precipitation, E is evapotranspiration, S_{runoff} is surface runoff, $G_{\text{waterloss}}$ is groundwater loss.

Precipitation or temperature data from observations and evaporation estimates from Thornthwaite's expression for potential evaporation, uses temperature as an input and the soil pores hold water and the infiltration rate, affects the runoff and groundwater loss [EAGLESON, PETER 1978].

Soil moisture is important in temperature forecasts than precipitation.

Precipitation, estimated evapotranspiration, runoff, and groundwater loss are the parameters used in soil moisture calculations [HUANG *et al.* 1996].

RESULTS AND DISCUSSION

COMPARISON OF *SPI* AND *RDIST* INDICES

The drought and non-drought events evaluated based on criteria of the values either below (or) above the *RDIST* zero value. Drought threshold is considered when the values of *RDIST* fall below zero and to measure length of drought duration and magnitude of drought severity, a threshold value must be described.

The comparative studies of *SPI* and *RDIST* from 1980–2015, shows no more variations, although the *RDIST* varies with smaller amplitude from *SPI* in some time steps. In this study both annual *SPI* and *RDIST* indices are analyzed for assessment and coherence of drought over 5 selected stations above the parts of Upper Blue Nile region which are presented in Figure 1.

The *RDIST* is more sensitive index than *SPI* in different locations and time.

Extreme drought threshold occurred in 1980 in Fiche with both *SPI* and *RDIST* values of –3.03 and –3.02.

Extreme and severe drought is observed for Debermarkos and Deberberehan in 1984. Again in 2015 extreme drought occurred at Debermarkos which is –2.24 and –2.47 for both *SPI* and *RDIST* drought indices (Tab. 1).

Table 1. Annual standardized precipitation index (*SPI*) and reconnaissance drought index (*RDIST*)

Year	Value for location							
	Bedele		Deberberehan		Debermarkos		Fiche	
	<i>SPI</i>	<i>RDIST</i>	<i>SPI</i>	<i>RDIST</i>	<i>SPI</i>	<i>RDIST</i>	<i>SPI</i>	<i>RDIST</i>
1980	-0.03	-0.81	1.09	1.11	0.72	0.81	-3.03	-3.02
1981	0.87	0.88	0.18	0.27	-0.70	-0.56	0.28	0.45
1982	0.49	0.38	-0.84	-0.71	0.39	0.63	-0.91	-0.75
1983	0.73	0.44	0.77	0.72	-0.64	-0.38	-2.80	-2.80
1984	-2.18	0.56	-2.56	-2.49	-1.94	-1.71	-1.84	-1.78
1985	-0.94	-0.49	0.75	0.81	0.69	0.90	-1.36	-1.31
1986	-1.37	0.96	1.36	1.41	-2.05	-1.74	0.14	-0.06
1987	0.73	-1.17	-2.03	-2.19	-0.36	-0.27	-0.37	-0.33
1988	-0.24	-1.98	0.57	0.60	0.02	0.05	0.36	0.31
1989	1.19	0.52	-1.68	-1.54	1.00	1.57	0.33	0.45
1990	-0.32	0.54	-0.50	-0.36	-0.03	0.18	0.59	0.62
1991	-0.11	-0.61	0.09	0.07	-0.83	-0.68	-0.07	-0.06
1992	1.97	1.81	-0.05	0	-0.49	-0.29	0.28	0.36
1993	0.27	1.73	-1.14	-1.05	1.83	1.86	0.64	0.73
1994	-2.15	-0.95	-0.27	-0.18	-0.87	-0.9	-0.28	-0.26
1995	0.18	-1.36	-1.96	-2.01	-0.56	-0.71	0.39	0.38
1996	0.93	-1.39	0.67	0.76	2.07	2.05	2.08	2.18
1997	0.71	-0.03	-0.21	-0.19	1.55	1.39	0.13	0.13
1998	0.29	-1.13	-0.44	-0.47	-0.3	-0.43	0.33	0.30
1999	0.28	1.00	0.27	0.49	0.22	0.34	0.66	0.72
2000	-0.81	-0.72	0.68	0.87	0.56	0.59	0.38	0.44
2001	0.66	0.97	0.42	0.45	0.45	0.50	-0.23	-0.19
2002	-1.41	-1.01	-0.71	-0.87	-0.09	-0.29	-0.07	-0.14
2003	-1.12	-0.97	1.04	0.97	-0.88	-0.98	0.51	0.47
2004	-0.35	-0.20	1.00	0.96	-0.22	-0.27	0.15	0.13
2005	0.67	-0.03	0.22	0.12	-0.32	-0.45	-0.47	-0.50
2006	2.37	1.26	0.39	0.26	1.57	1.41	1.29	1.28
2007	0.66	1.48	1.49	1.40	0.66	0.52	0.32	0.34
2008	0.05	0.13	0.35	0.29	-0.02	-0.12	-0.14	-0.15
2009	0.46	0.19	-0.01	-0.17	-0.48	-0.80	0.72	0.64
2010	-0.20	0	0.31	0.13	0.90	0.58	1.00	0.90
2011	-0.82	0	1.30	1.23	1.29	1.04	0.79	0.75
2012	-0.78	0	1.22	1.24	-0.36	-0.61	0.76	0.70
2013	-1.38	0	-0.20	-0.22	-0.67	-0.83	0.27	0.18
2014	0.18	0	-0.24	-0.30	0.16	0.07	0.23	0.16
2015	0.52	0	-1.36	-1.41	-2.24	-2.47	-1.03	-1.20

Source: own study.

Annual drought events (Tab. 2) shows severity levels of drought across five meteorological stations. Mild drought events are occurred frequently than others moderate, severe and extreme drought events. The extreme drought at Deberberehan shows highest frequency while compared to other meteorological locations.

Table 2. Annual drought events

Location	Index	Drought				Total
		mild	moderate	severe	extreme	
Jimma	<i>SPI</i> ₁₂	5	6	0	1	12
	<i>RDIST</i> ₁₂	8	5	1	1	15
Bedele	<i>SPI</i> ₁₂	4	4	0	2	10
	<i>RDIST</i> ₁₂	6	5	0	0	11
Deberbirehan	<i>SPI</i> ₁₂	3	3	2	2	10
	<i>RDIST</i> ₁₂	2	2	1	3	8
Debermarkos	<i>SPI</i> ₁₂	7	0	1	2	10
	<i>RDIST</i> ₁₂	7	0	2	0	9
Fiche	<i>SPI</i> ₁₂	1	2	1	2	6
	<i>RDIST</i> ₁₂	2	2	1	2	7

Explanations: *SPI* = standardized precipitation index, *RDIST* = standardized reconnaissance drought index.

Source: own study.

Table 3 shows the 6-month *SPI* and *RDIST*, it shows drought at Jimma location with value of *SPI* and *RDIST* is found to be -2.64 and -2.83 in 1999.

Maximum drought threshold has been observed for different locations in different periods, for Fiche in the period of 1980 and 1983; for Debermarkos in 2015; for Deberberehan in 1987 and 1989 and for Bedele in 1986. For Fiche mild drought is observed starting from the 1990, whereas at Deberberehan mostly mild and moderate drought is observed in the same period.

Table 4 shows the 6-month *SPI* and *RDIST* values shows dryness at Debermarkos shows the highest drought events, *SPI* and *RDIST* is found to be 14 drought events. However, the extreme drought events are observed at Fiche

Table 3. Six-month (April–September) standardized precipitation index (*SPI*₆) and standardized reconnaissance drought index (*RDIST*₆)

Year	Value in location									
	Jimma		Bedele		Deberberehan		Deberemarkos		Fiche	
	<i>SPI</i> ₆	<i>RDIST</i> ₆								
1	2	3	4	5	6	7	8	9	10	11
1980	-1.19	-0.98	0.18	-0.73	0.77	0.67	1.00	1.12	-3.03	-3.09
1981	-0.91	-0.63	0.25	-0.53	-0.88	-0.91	0.23	0.20	0.15	0.24
1982	-0.70	-0.29	0.22	-0.63	-1.76	-1.83	-0.76	-0.50	-1.26	-1.03
1983	0.72	0.64	0.42	2.44	0.40	0.27	-0.98	-0.95	-2.92	-3.03
1984	-1.08	-0.92	-0.21	0.19	-1.48	-1.59	-1.00	-0.75	-1.04	-1.05
1985	-0.68	-0.17	1.26	1.06	1.11	1.28	1.39	1.79	-0.92	-0.83
1986	-0.78	-0.42	-2.57	-2.09	0.71	0.97	-1.29	-0.95	0.12	0.08
1987	-1.74	-1.69	-0.01	0.28	-2.30	-2.32	-0.90	-0.76	-1.19	-0.69
1988	0.36	0.47	-1.66	0.37	0.41	0.49	0.12	-0.07	0.40	0.37
1989	-0.34	0.04	-1.51	-0.83	-2.29	-2.20	0.30	0.84	0.07	0.17
1990	1.51	1.81	-0.20	0.25	-0.19	-0.23	0.59	0.70	0.44	0.39
1991	-0.19	0.07	-0.13	0.31	0.27	0.32	-1.10	-0.81	-0.18	-0.17
1992	1.26	1.64	0.80	-1.03	-0.09	0.10	-1.21	-0.98	-0.49	-0.46
1993	1.16	1.36	1.16	0.43	-0.89	-0.85	2.18	2.22	0.77	0.94
1994	0.55	0.90	0.11	0	-0.58	-0.49	-0.02	0.08	0.02	0.09
1995	-1.11	-1.23	1.20	0.47	-1.22	-1.27	-0.23	-0.14	0.44	0.45

continue Tab. 3

1	2	3	4	5	6	7	8	9	10	11
1996	-0.07	-0.04	-0.2	-1.12	0.70	0.81	2.01	2.03	1.88	2.09
1997	0.44	0.46	1.05	0.05	-0.67	-0.54	0.53	0.51	-0.15	-0.09
1998	0.71	0.24	-0.57	-0.85	0.08	-0.10	-0.74	-1.04	0.43	0.35
1999	-2.64	-2.83	1.68	1.56	0.40	0.40	-0.91	-0.84	0.69	0.65
2000	0.79	0.66	0.88	-0.03	0.87	0.83	-0.50	-0.29	0.81	0.87
2001	1.77	1.69	0.27	1.00	0.40	0.39	0.89	0.78	-0.17	-0.13
2002	-1.04	-1.23	-1.56	-1.73	-0.67	-0.77	-0.37	-0.55	-0.57	-0.68
2003	-1.41	-1.64	-1.81	-1.90	0.73	0.62	-0.70	-0.94	0.49	0.42
2004	-0.73	-0.87	0.05	-0.45	1.08	1.00	0.09	0.04	0.42	0.43
2005	0.49	0.25	0.22	0.97	0.55	0.45	-0.86	-1.09	-0.44	-0.51
2006	0.79	0.83	0.48	1.24	0.14	0.12	1.39	1.27	1.00	1.10
2007	-0.10	-0.35	1.29	0.89	1.77	1.68	1.07	0.95	0.51	0.45
2008	0.18	-0.01	1.49	1.35	0.68	0.60	0.51	0.47	0.18	0.08
2009	0.12	-0.01	-0.50	-1.11	-0.04	-0.04	-0.53	-0.96	0.80	0.67
2010	0.75	0.31	-0.74	0.72	0.10	0.09	1.44	1.15	0.90	0.78
2011	1.07	0.78	-0.88	-1.20	1.35	1.29	0.95	0.60	0.91	0.77
2012	0.43	0.43	-0.32	0.33	1.86	1.88	0.27	-0.01	1.12	0.95
2013	0.22	0.02	-1.30	-0.22	-0.26	-0.17	-0.96	-1.05	0.49	0.41
2014	-0.23	-0.44	0.54	0.34	-0.42	-0.37	0.20	0.12	0.35	0.24
2015	1.61	1.17	0.58	0.20	-0.63	-0.57	-2.09	-2.21	-0.97	-1.15

Source: own study.

Table 4. Six-months drought events

Location	Index	Drought				Total
		mild	Moderate	severe	extreme	
Jimma	<i>SPI6</i>	5	5	1	1	12
	<i>RD Ist6</i>	4	2	2	1	9
Bedele	<i>SPI6</i>	5	0	4	1	10
	<i>RD Ist6</i>	5	4	2	1	12
Debererebirehan	<i>SPI6</i>	6	2	1	2	11
	<i>RD Ist6</i>	5	1	2	2	10
Deberemarkos	<i>SPI6</i>	9	4	0	1	14
	<i>RD Ist6</i>	10	3	0	1	14
Fiche	<i>SPI6</i>	3	3	0	2	8
	<i>RD Ist6</i>	4	3	0	2	9

Explanations as in Tab. 2.

Source: own study.

and Debererebirehan. In comparison to other locations (Tab. 5) mild drought events frequently occurred at Deberemarkos for both *SPI6* and *RD Ist6*.

The 3-month time steps of *SPI* and *RD Ist* indices categorized into seasons as April–June and July–September. The sensitivity of *RD Ist* for five meteorological stations explored over Upper Blue Nile region.

From Table 5, it is observed that for Jimma and Debererebirehan locations more dryness is observed during the period of April–June, whereas for Deberemarkos and from different experiment tests of different time scales show different severity levels majority of occurrence of drought events over five locations fall under mild drought events (Tab. 6). For Jimma and Deberemarkos locations the highest events in comparison to other locations from April

Table 5. Three-months (Apr–Jun) standardized precipitation index (*SPI3*) and reconnaissance drought index (*RD Ist3*)

Year	Value in location									
	Jimma		Bedele		Debererebirehan		Deberemarkos		Fiche	
	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>
1	2	3	4	5	6	7	8	9	10	11
1980	-2.41	-2.25	0.34	-0.63	-0.24	-0.22	0.83	0.93	-1.64	-1.51
1981	-0.03	0.32	0.27	-0.71	-2.73	-2.71	-0.74	-0.62	-0.98	-0.92
1982	-1.27	-1.03	0.31	-0.67	-0.85	-0.78	-1.10	-0.95	-0.41	-0.14
1983	0.88	0.77	-0.20	1.34	1.10	1.12	-1.35	-1.28	0.17	0.30
1984	-0.62	-0.43	-0.22	-0.15	0.70	0.67	0.30	0.27	0.56	0.59
1985	-0.48	-0.04	1.38	1.70	0.30	0.38	-0.09	0.17	-0.37	-0.08
1986	-0.85	-0.64	-2.38	-1.98	1.17	1.26	-0.17	-0.07	1.22	1.40
1987	-1.17	-1.28	-0.20	-0.53	0.21	0.34	1.02	1.12	1.39	1.92
1988	1.50	1.68	-1.80	0.22	-0.42	-0.41	-0.94	-1.05	-1.00	-1.05
1989	0.39	0.47	-1.57	-1.50	-1.05	-0.89	-0.64	-0.21	-0.02	0.09
1990	1.78	1.94	-0.32	-0.17	-1.65	-1.61	-1.02	-0.89	-2.02	-1.92
1991	-0.27	-0.03	-0.22	-0.09	-0.03	-0.05	-0.31	-0.15	-1.20	-1.15
1992	1.26	1.60	0.98	-0.57	-0.46	-0.46	0.26	0.23	-0.83	-0.87
1993	0.12	0.27	1.20	0.67	0.72	0.82	1.52	1.58	1.54	1.59
1994	-0.19	0.03	0.17	0.07	-0.41	-0.45	0	0.04	-0.33	-0.39
1995	-0.75	-0.74	1.04	0.05	-0.37	-0.38	0.39	0.34	0.53	0.43
1996	-0.41	-0.43	0.15	-0.21	1.80	1.89	2.86	2.90	2.24	2.28
1997	-0.88	-1.15	1.33	1.37	0.96	1.03	0.44	0.52	0.46	0.47

continue Tab. 5

1	2	3	4	5	6	7	8	9	10	11
1998	1.36	1.22	-0.62	-1.23	-0.60	-0.74	-0.12	-0.39	-0.11	-0.31
1999	-2.85	-2.98	1.75	2.47	-1.63	-1.63	-0.76	-0.77	-1.91	-1.88
2000	0.68	0.61	1.19	1.25	-0.15	-0.17	-0.18	-0.04	-0.13	-0.17
2001	0.46	0.36	0.14	1.04	0.08	0.05	0.64	0.67	0.47	0.44
2002	-0.63	-0.87	-1.32	-1.42	-0.86	-0.89	-1.16	-1.22	-1.05	-1.06
2003	-0.34	-0.49	-1.55	-1.56	0.75	0.68	-1.25	-1.40	0.64	0.47
2004	0.26	0.25	0.19	-0.11	1.13	1.08	0.06	-0.02	1.49	1.38
2005	1.14	0.84	-0.36	-0.80	1.11	1.06	-0.86	-0.97	0.50	0.43
2006	1.20	1.23	0.25	0.87	-0.86	-0.86	0.39	0.41	0.15	0.19
2007	0.69	0.47	1.14	0.56	0.61	0.52	1.02	0.95	0.40	0.30
2008	-0.31	-0.33	1.47	1.77	0.48	0.45	1.55	1.45	-0.58	-0.60
2009	0.53	0.46	-0.10	0.09	-1.71	-1.74	-1.15	-1.35	-1.47	-1.50
2010	-0.40	-0.57	-1.09	-0.19	0.86	0.77	0.68	0.53	0.83	0.61
2011	0.41	0.25	-0.54	-0.45	1.19	1.11	1.30	1.09	1.18	0.95
2012	-0.03	-0.05	-0.50	-0.45	0.99	0.94	-2.17	-2.18	0.36	0.15
2013	-0.20	-0.23	-1.36	-0.64	-0.36	-0.41	-0.39	-0.55	0.38	0.17
2014	0.67	0.49	0.56	0.48	-0.56	-0.59	0.47	0.46	-0.43	-0.49
2015	0.79	0.30	0.49	0.08	0.88	0.92	0.62	0.44	-0.03	-0.12

Source: own study.

Table 6. April–June drought events

Location	Index	Drought				Total
		mild	moderate	severe	extreme	
Jimma	<i>SPI3</i>	7	5	1	0	13
	<i>RD Ist3</i>	5	6	1	0	12
Bedele	<i>SPI3</i>	3	3	3	1	10
	<i>RD Ist3</i>	7	2	3	0	12
Debere-birehan	<i>SPI3</i>	4	1	3	1	9
	<i>RD Ist3</i>	6	0	3	1	10
Deberemarkos	<i>SPI3</i>	6	6	0	1	13
	<i>RD Ist3</i>	6	5	0	1	12
Fiche	<i>SPI3</i>	3	4	2	1	10
	<i>RD Ist3</i>	3	3	4	0	10

Explanations as in Tab. 2.

Source: own study.

to June. Mild to extreme drought events observed in decreasing drought event orders in these months and this also functional for six- and twelve-month time scales in each selected location of the study area.

Bedele regions mild and moderate droughts were observed during this period.

But for July–September season (Tab. 7) mild and moderate droughts were observed for all locations except Bedele, which exposes mild wetness. In the same period a high drought episodes is also observed at Fiche in 1983. Our results clearly indicate that except Bedele all locations were affected frequently by droughts.

During the summer period the Upper Blue Nile region is accumulated abundant amount water because of high-land areas of Upper Blue Nile. From *SPI* and *RD Ist* analy-

Table 7. Three-months (Jul–Sept) standardized precipitation index (*SPI*) and reconnaissance drought index (*RD Ist*)

Year	Value in location									
	Jimma		Bedele		Debererebirehan		Deberemarkos		Fiche	
	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>	<i>SPI3</i>	<i>RD Ist3</i>
1	2	3	4	5	6	7	8	9	10	11
1980	-2.41	-2.25	-0.59	-0.50	1.00	0.70	0.53	0.49	-2.49	-2.42
1981	-0.03	0.32	-0.03	-0.28	0.11	0	0.83	0.61	0.46	0.60
1982	-1.27	-1.03	-0.31	-0.39	-1.36	-1.52	0.01	0.19	-1.09	-1.00
1983	0.88	0.77	2.68	2.19	-0.16	-0.41	-0.06	-0.10	-3.27	-3.33
1984	-0.62	-0.43	0.10	0.65	-2.03	-2.02	-1.30	-0.99	-1.25	-1.28
1985	-0.48	-0.04	-0.44	-0.04	1.10	1.09	1.64	1.88	-0.76	-0.91
1986	-0.85	-0.64	-1.36	-1.23	0.15	0.37	-1.24	-1.00	-0.27	-0.63
1987	-1.17	-1.28	0.84	0.84	-2.60	-2.71	-1.91	-2.11	-1.86	-1.63
1988	1.50	1.68	0.18	0.49	0.71	0.77	0.83	1.01	0.70	0.81
1989	0.39	0.47	-0.09	-0.05	-1.83	-1.92	0.84	0.88	0.13	0.10
1990	1.78	1.94	0.55	0.54	0.53	0.32	1.37	1.47	0.93	0.88
1991	-0.27	-0.03	0.45	0.53	0.38	0.49	-0.91	-0.87	0.20	0.24
1992	1.26	1.60	-0.65	-1.04	0.20	0.52	-1.52	-1.22	-0.20	0.02
1993	0.12	0.27	-0.07	0.03	-1.36	-1.41	1.29	1.24	0.30	0.30
1994	-0.19	0.03	-0.23	-0.02	-0.34	-0.04	0.04	0.14	0.17	0.38
1995	-0.75	-0.74	0.83	0.77	-1.04	-1.01	-0.51	-0.33	0.32	0.38
1996	-0.41	-0.43	-1.40	-1.58	-0.35	-0.35	-0.29	-0.45	1.20	1.14
1997	-0.88	-1.15	-1.16	-1.41	-1.29	-1.14	0.32	0.07	-0.26	-0.23
1998	1.36	1.22	0.17	0.02	0.44	0.51	-0.66	-0.64	0.51	0.66
1999	-2.85	-2.98	-0.22	-0.11	1.10	1.05	-0.37	-0.18	1.15	1.22
2000	0.68	0.61	-1.25	-1.39	1.07	0.98	-0.35	-0.33	0.89	0.98

continue Tab. 7

1	2	3	4	5	6	7	8	9	10	11
2001	0.46	0.36	0.65	0.59	0.46	0.46	0.55	0.26	-0.28	-0.24
2002	-0.63	-0.87	-1.20	-1.18	-0.23	-0.28	0.45	0.45	-0.21	-0.27
2003	-0.34	-0.49	-1.34	-1.31	0.45	0.36	0.16	0.29	0.34	0.34
2004	0.26	0.25	-0.53	-0.54	0.59	0.49	0.12	0.23	-0.05	-0.08
2005	1.14	0.84	2.45	2.20	0.01	-0.08	-0.24	-0.36	-0.58	-0.62
2006	1.20	1.23	1.09	1.13	0.61	0.53	1.31	1.13	0.99	1.00
2007	0.69	0.47	0.78	0.90	1.65	1.59	0.45	0.34	0.44	0.37
2008	-0.31	-0.33	0.19	0.33	0.54	0.43	-0.73	-0.76	0.39	0.27
2009	0.53	0.46	-1.65	-1.87	0.70	0.76	0.29	0.16	1.17	1.09
2010	-0.40	-0.57	1.32	1.34	-0.32	-0.15	1.14	1.02	0.69	0.64
2011	0.41	0.25	-1.42	-1.34	0.86	0.85	0.06	-0.21	0.58	0.48
2012	-0.03	-0.05	0.77	1.02	1.54	1.55	1.62	1.66	1.06	0.94
2013	-0.20	-0.23	-0.03	0.46	-0.02	0.27	-0.69	-0.52	0.43	0.52
2014	0.67	0.49	-0.04	0.07	-0.10	0.08	-0.08	-0.28	0.52	0.42
2015	0.79	0.30	0.52	0.17	-1.18	-1.08	-2.96	-3.16	-0.93	-1.04

Source: own study.

sis Table 8 indicates the occurrence of moderate, severe and extreme droughts in the years of 1984, 1986, 1987, 1991, 1992 and 2015 at Deberemarkos.

Table 8 shows much amounts of rain fall captured during summer seasons over the Upper Blue Nile region including Ethiopia. The events show drought occurrence probability frequency of moderate drought slightly higher than mild drought. But total events of drought compared to 6 and 12 months show relatively low values. The extreme drought for Jimma, Deberebirehan and Fiche locations observed same events for *SPI* and *RD1st*.

Table 8. July–September drought events

Location	Index	Drought				Total
		mild	Moderate	severe	extreme	
Jimma	<i>SPI</i> 3	4	2	0	2	8
	<i>RD1st</i> 3	5	2	0	2	9
Bedele	<i>SPI</i> 3	3	7	1	0	11
	<i>RD1st</i> 3	2	7	2	0	11
Deberebirehan	<i>SPI</i> 3	0	4	2	2	8
	<i>RD1st</i> 3	0	4	2	2	8
Deberemarkos	<i>SPI</i> 3	5	2	2	1	10
	<i>RD1st</i> 3	5	2	0	2	9
Fiche	<i>SPI</i> 3	3	2	1	2	8
	<i>RD1st</i> 3	3	3	1	2	9

Explanations as in Tab. 2.

Source: own study.

METEOROLOGICAL, AGRICULTURAL AND HYDROLOGICAL DROUGHT RELATIONSHIPS

The meteorological drought frequency is high and low duration compared to others drought variables which are considered in this study. However, as the time scale increases the longer duration of meteorological drought related to severity.

Climate variables such as precipitation, soil moisture and runoff alone cannot clearly evaluate drought characteristics, however the cross correlation between indices with different time scales have a capability to drive the characteristics and propagation meteorological drought proceeds to hydrological drought.

To evaluate the seasonal propagation of drought, seasonal precipitation (June, July, and August) precipitation and soil moisture indices are correlated with monthly runoff indices over Upper Blue Nile region.

By considering *SPI*, *SMI* and *SRI* of drought indices for different time steps we proposed the relation between we found meteorological, agricultural and hydrological droughts respectively.

The correlation coefficients among summer season drought indices (*SPI*, *SMI* and *SRI*) are evaluated and shown on Table 9. The highest maximum correlations among *SPI* and *SMI* is 0.82, *SPI* and *SRI* 0.63 and *SMI* and *SRI* 0.56 with time steps of 24 and 0.06, -0.13 and 0.17 lowest correlation is achieved at one months of time steps for each correlation of drought indices. These time steps are significant, as the time scales increase the correlation between the indices increase.

Table 9. Correlation between standard precipitation index (*SPI*), soil moisture index (*SMI*) and surface runoff index (*SRI*) for summer (*JJAS*) season

Index	Value in time step					P-value
	1	3	6	12	24	
<i>SPI</i> and <i>SMI</i>	0.064	0.099	0.56	0.78	0.82	0.00
<i>SPI</i> and <i>SRI</i>	-0.13	0.14	0.22	0.45	0.63	0.007
<i>SMI</i> and <i>SRI</i>	0.17	0.31	0.41	0.51	0.56	0.00

Source: own study.

By plotting the time series of comparison of three indices of different time scales shown in Figure 2 the one month of time shows high fluctuation frequency and short period of duration when compared to three, six and twelve month of time steps (Fig. 2a).

SRI indicates more extended duration of drought than fluctuation of frequency when compared with *SPI* across each time steps. In 1981, 1993 and 2015 severe hydrological droughts were identified with higher duration than other hydrological droughts periods in a time series over each time steps.

High runoff is observed in 1986, however, from 2007–2016 there is a gradual decreasing of runoff was observed over the Upper Blue Nile region.

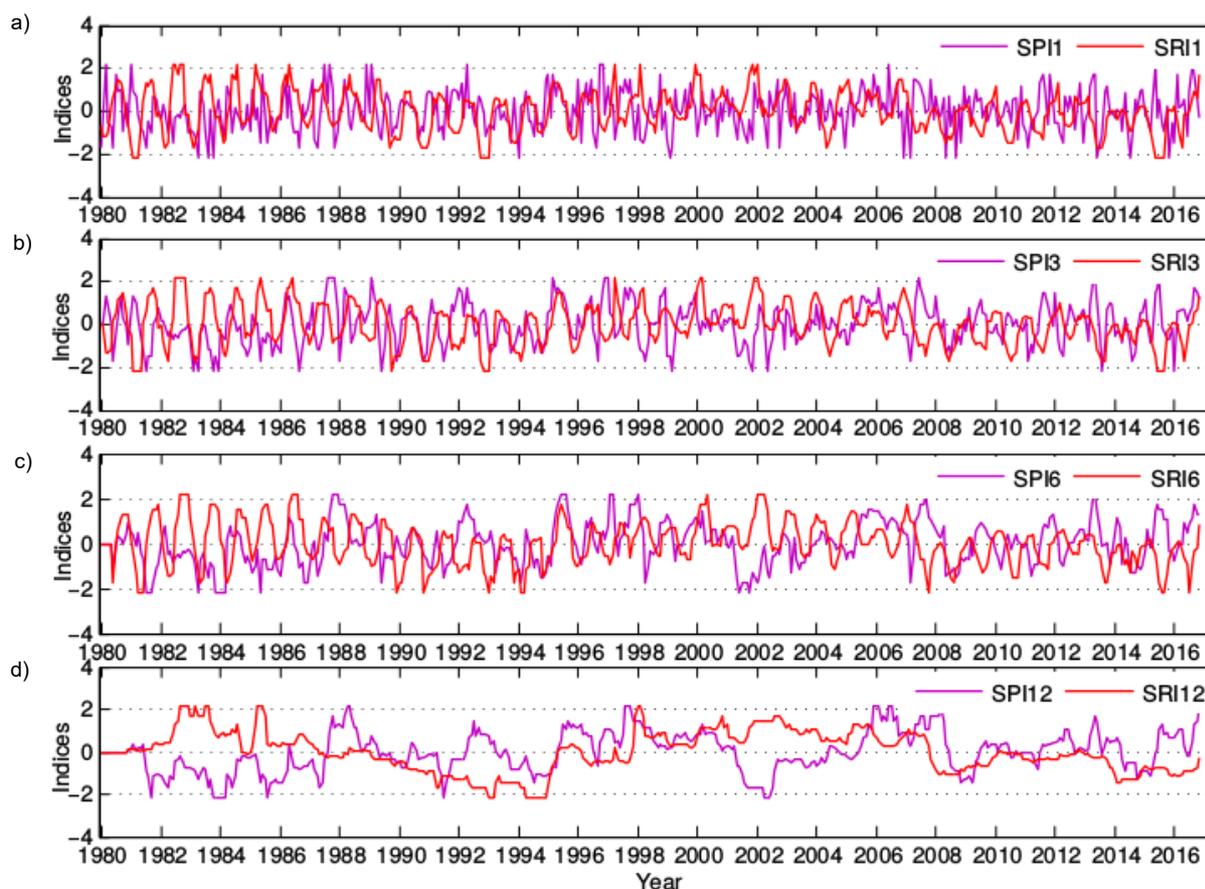


Fig. 2. Standard precipitation index (*SPI*) and surface runoff index (*SRI*) for different time steps: a) one month, b) three months, c) six months, d) twelve months; source: own study

The 3-month *SPI* and *SRI* (see Fig. 2b) analysis exhibits more fluctuations of positive and negative runoff anomalies. It also shows occurrence of meteorological drought before the start of hydrological droughts. The severity of runoff index (*SRI*) is higher than *SPI* for some years due to the time lag between hydrological and meteorological drought.

From 1990–1996 occurrence of hydrological drought with higher duration and severity than meteorological drought and 1982–1986 higher runoff due to surplus amount of soil moisture (Fig. 2c) in the Upper Blue Nile region.

The six-month of time steps (see Fig. 2c) less fluctuation and extended duration compared one with three month time steps of meteorological drought. From 1990–1995 hydrological droughts frequently observed with maximum severity comparison to meteorological drought.

Based on twelve-month time steps indices (Fig. 2d) we found that the drought which is not controlled by *SPI*₁₂ can be controlled by *SRI*₁₂ although these two types of drought indices plays a prominent role by evaluating drought strengths and duration. *SPI*₁₂ and *SRI*₁₂ have a capability to control drought at some lag time. The six- and twelve-month time steps clearly explain the drought years with their severity and duration.

For six month of time steps (Fig. 3) the meteorological drought leads the agricultural drought by the difference of some months of the year. From 1980–1999 the soil mois-

ture indicates almost all except some month observed maximum amount of soil moisture which is very important to regulate the runoff over Upper Blue Nile.

The extended duration with severity is evaluated since 1999–2016; however, the meteorological drought with its severity and longer duration (upset near normal and down set deficit of precipitation) which expose the moist soil into dryness is visualized across the 6- and 12-month time steps. Since 1982–1998 meteorological drought is severe than agricultural drought. In the years 2000–2006 we observed gradual decreasing trend of soil moisture for long period of months. Such situation is also occurred for other time steps from the usual previous periods. For 6-month time steps the meteorological drought leads the agricultural drought by the difference of some months of the year. The maximum soil moisture index occurred in the period of 1980–1999 except some months show the importance in regulating the runoff over Blue Nile. The extended duration with severity is evaluated since 1999–2016.

The 1-, 3-, 6- and 12-month time series of *SPI* and *SRI* indices visualizes the soil moisture leads to the dryness and can be converted of long duration and sever meteorological drought. Further the analysis shows that the meteorological drought is more severe than agricultural drought during the period of 1982–1988 and during the period of 2000–2006, there is a gradual decreasing trend of soil moisture for long period of months.

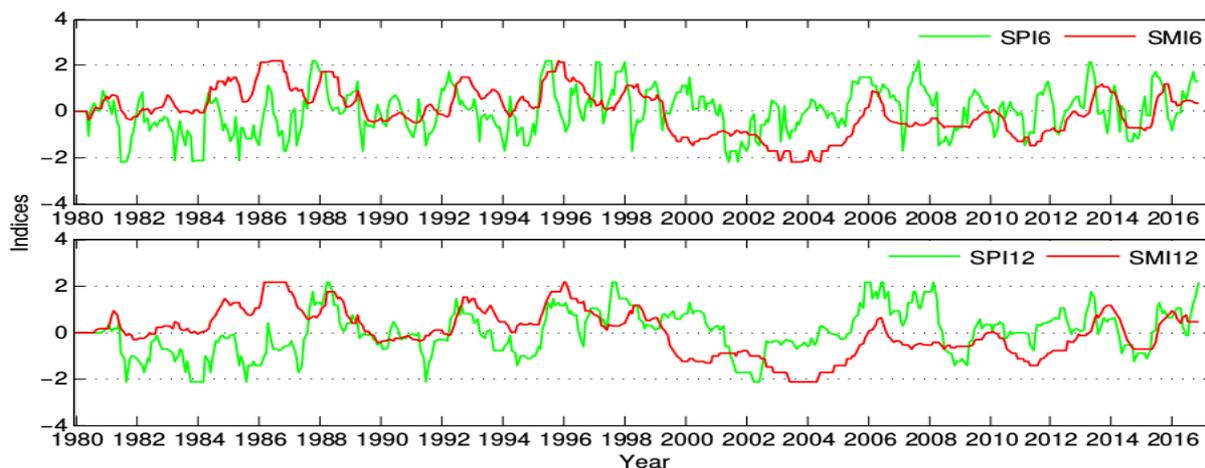


Fig. 3. Six- and twelve-month time steps soil moisture (*SMI6* and *SMI12*) and standardized precipitation index (*SPI6* and *SPI12*) respectively; source: own study

From 12-month time steps of *SMI* indices show the surplus amount of soil moisture since 1985–1988 period, which may integrate with hydrological drought. From our analysis we found that months of the year increase the hydrological drought link with meteorological and agricultural droughts. Sever meteorological drought with high fluctuations were frequently occurred than agricultural drought including 12-month time steps. Further we observed that the meteorological drought frequency decreases and drought duration increases as the time steps increases but the agricultural drought initially with higher duration and slowly extended its severity.

DROUGHT SEVERITY, DURATION AND INTENSITY

By using standardized reconnaissance drought index (*RDIst*) annual, April–September and July–September frequency of drought were determined and evaluated for different locations over part of Upper Blue Nile. Summer season reconnaissance drought index (*RDIst*) clearly indicates severity with correspondence to frequency for the selected locations on parts of Upper Blue Nile. Figure 4 depicts the severity, duration and intensity of *SPI* and *SRI* of meteorological and hydrological drought indices for 1-, 3-, 6-, 12-month time steps.

In this analysis drought severity is calculated over the length of climatic year from 1980–2016 at various time

steps. In addition to severity of drought, intensity of meteorological and hydrological droughts are also evaluated. The meteorological drought frequency values for *SPI1*, *SPI3*, *SPI6* and *SPI12* are 159.98, 169.9, 167.5 and 161.2 and also for hydrological drought values are 170, 169.5, 170.95, and 169.25 respectively.

We found that the maximum drought severity is observed at 6-month time steps of *SPI* (*SPI6*). The maximum drought duration is observed at 3-month time steps of *SPI* (*SPI3*) and intensity for 6-month time steps of *SPI* (*SPI6*).

From Figure 4a we observe that drought intensity is increases for *SPI* values as time steps are decreasing from higher order to lower order. However, in meteorological drought, severity of fluctuation observed.

From Figure 4b the severity of standard runoff index indicates almost closest values in the given duration. The intensity 1- and 12-month time steps indicate different values than 3- and 6-months of time steps of *SRI*.

CONCLUSIONS

The standard precipitation index (*SPI*) is evaluated by using precipitation, evapotranspiration variables.

We found that *RDIst* and *SPI* indices behaves similar manner at different time steps over five selected meteorological stations over Upper Blue Nile basin.

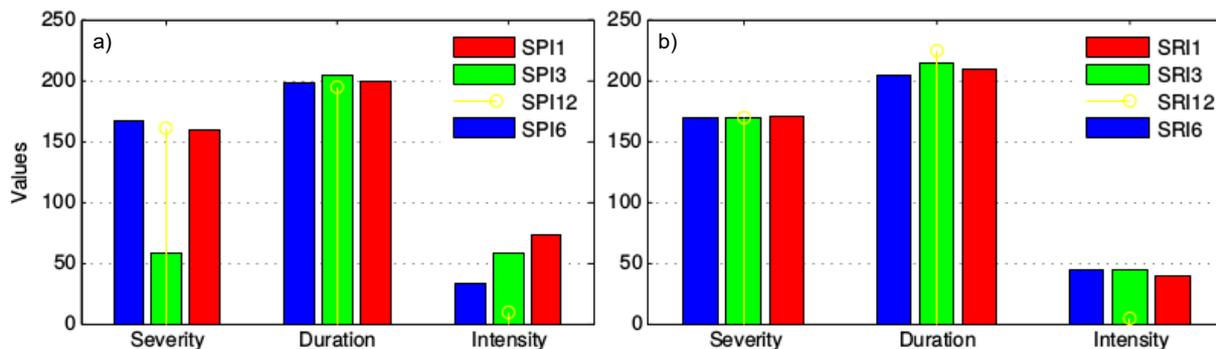


Fig. 4. Severity, duration and intensity of meteorological and hydrological drought over Upper Blue Nile: a) acc. to standardized precipitation index (*SPI*), b) acc. to standardized runoff index (*SRI*); source: own study

We examined meteorological, hydrological and agricultural droughts through short and long period time scales by using *SPI*, *SMI* and *SRI* indices. However, reconnaissance drought index (*RDIs*) incorporates both precipitation and potential evaporation. The 1-month time steps of drought indices shows high drought frequency and short period of duration with higher severity for meteorological drought. Runoff index indicates more extended severity of drought than frequency of drought it relies on extended duration with slow changes. The onset drought starts by meteorological drought with rapid change; however, the hydrological drought is slowly changed comparable to meteorological drought.

The six months drought time steps analysis indicates meteorological drought leads the agricultural drought over some months of the year.

But during the period of 1980–1999 the soil moisture shows maximum amount which indicates soil moisture is very important to regulate the runoff over Upper Blue Nile. The agricultural drought is extended with severity from 1999–2006; however, the meteorological drought exists during this moment with its severity and longer duration (upset near normal and down set due deficit of precipitation) which expose the moist soil into dryness and it is clearly visualized the 1-, 3-, 6- and 12-months of time steps. This phenomenon leads the soil moisture gradually decreasing trend, which exposed to the severity of agricultural drought over Upper Blue Nile basin.

The drought duration and intensity of meteorological and hydrological droughts are evaluated in addition to severity of drought. We found that meteorological drought frequency values for *SPI1*, *SPI3*, *SPI6* and *SPI12* are 159.98, 169.9, 167.5 and 161.2 and for hydrological drought values are *SRI1*, *SRI3*, *SRI6* and *SRI12* 170, 169.5, 170.95, and 169.25 respectively.

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Charakterystyka wrażliwości na suszę i zależności między jej wskaźnikami dla regionu górnego Nilu Błękitnego

STRESZCZENIE

Susza jest ekstremalnym zjawiskiem, które powoduje ogromne straty ekonomiczne i szkody środowiskowe. Celem badań było określenie wrażliwości na suszę, charakterystyk i propagacji suszy w regionie górnego Nilu Błękitnego. Dwa wskaźniki suszy – wskaźnik standaryzowanego opadu (*SPI*) i niedawno opracowany wskaźnik *RDIst* (ang. standardized reconnaissance drought index) zastosowano do danych z pięciu stacji meteorologicznych z lat 1980 do 2015, aby ocenić przydatność tego drugiego do oceny sytuacji w regionie. Z analiz przeprowadzonych przez autorów niniejszej publikacji wynika, że oba wskaźniki wykazywały podobny trend zmian w przedziałach czasowych 3-, 6- i 12-miesięcznych, ale w pewnych okresach wskaźnik *RDIst* cechowała mniejsza amplituda zmian niż wskaźnik *SPI*. W odniesieniu do pięciu stacji meteorologicznych i całego obszaru górnego biegu Nilu Błękitnego najbardziej surowe i długotrwałe susze stwierdzono w latach 1984, 2002, 2009 i 2015 w porównaniu z innymi latami badań. Wykonano także analizę korelacji między wskaźnikami suszy meteorologicznej *SPI*, suszy glebowej *SMI* i suszy hydrologicznej *SRI*. Najsilniejszą korelację między tymi wskaźnikami stwierdzono dla 24-miesięcznych przedziałów czasowych, a odpowiednie współczynniki korelacji wynosiły 0,82, 0,63 i 0,56.

Słowa kluczowe: *standardized reconnaissance drought index (RDIst)*, *standaryzowany wskaźnik odpływu (SRI)*, *susza*, *wskaźnik standaryzowanego opadu (SPI)*, *wskaźnik uwilgotnienia gleby (SMI)*, *zależność między wskaźnikami suszy*