COMPARISON BETWEEN TWO METEOROLOGICAL DROUGHT INDICES IN THE CENTRAL REGION OF SOUTH AFRICA

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Abstract

The objective of this study was to characterize meteorological droughts in the Central Region of South Africa, Modder River Basin, C52A quaternary catchment using two popular drought indices: Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) and to compare the two indices. Drought events were characterized based on their frequency, duration, magnitude and intensity. The indices were computed for the time-scales that are important for planning and management of water resources, i.e. 3-, 6- and 12-month time-scales. The basic meteorological input data used in the computation of these indices were 57 years (1950-2007) of monthly precipitation and monthly temperature data which were recorded at The Cliff weather station in the quaternary catchment. It was found that both SPI and SPEI responded to drought events in similar fashion in all time-scales. During the analysis period, a total of 37, 26 and 17 drought events were identified in the area based on 3-, 6-, and 12-month times-scales, respectively. Considering event magnitude as severity parameter, results from both indices identified the periods 1984-1985, 1992-1993 and 2003-2005 as the severest drought periods in the area. However, when the effects of both drought duration and magnitude are considered (drought intensity), the most severest drought events were identified during the years 1982/83, 1966 and 1973 based on 3-, 6- and 12-month time-scales, respectively. It was concluded that although the SPEI generally exhibits veracity over SPI by including, apart from precipitation, additional meteorological parameter, mean temperature, SPI should be adopted as an appropriate drought monitoring tool in an area, like Africa, where meteorological data are scarce.

Keywords: Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI), meteorological drought, drought analysis, South Africa

1. INTRODUCTION

It is well established that precipitation characteristics have changed, and they will continue to change towards more intense and intermittent spells (Simonovic, 2009). This will translate into more frequent and more severe water-related extreme events (floods and droughts). For example, Rouault and Richard (2005) reported an increase in the spatial extent of drought in Southern Africa since the 1970's due to stronger relationship between ENSO and the Southern African rainfall albeit localized basin-level assessments are lacking.

Drought is a normal part of climate in almost every country, but it has serious economic, environmental and social impacts which affect more people than any other natural hazard, particularly the poor who are more vulnerable. This is a cause for concern as the world is entering a period of unprecedented climate change, which is predicted to result in higher average temperatures, changes in precipitation patterns and more frequent extreme weather events over extensive land areas (Richardson et al., 2007). Therefore, countries must address the underlying causes of drought vulnerability and improve monitoring and early warning systems. Moreover, understanding the severity of drought and predicting the trend of occurrences will help governments to take proactive actions regarding to the ability of the maximum resilience of the drought frequent regions. These include mitigation of the problem as well as introduction of adaptive practices that minimize the possible damage that can be brought by drought on the different sectors (Agriculture, Health, Industry, etc.).

In South Africa's arid and semi-arid rangelands, droughts are a frequent occurrence (Vogel, 1994; cited on Vetter, 2009). While these may be short-term and followed by recovery during subsequent years of higher rainfall (Ellis and Swift, 1988), in some cases droughts can trigger substantial and irreversible ecological and socio-economic changes. Model predictions indicate that reductions in mean annual rainfall, increased inter-annual variation and more frequent droughts in South Africa can lead to disproportionately large impacts on livestock production (Burns et al., 2006). Seymour and Desmet (2009) suggest that long-term drought research is essential in the country and underlined the importance of a suite of coordinated long-term field observations, experiments and models to inform agricultural policy and conservation planning.

Drought should not be viewed as merely a physical phenomenon or natural event. Its impacts on society result from the interplay between a natural event (less precipitation than expected resulting from natural climatic variability) and the demand people place on water supply. Human beings often exacerbate the impact of drought. Recent droughts in both developing and developed countries and the resulting economic and environmental impacts and personal hardships have underscored the vulnerability of all societies to this “natural” hazard. Droughts are classified based on precipitation amount (meteorological), streamflow level (hydrological), soil moisture status (agricultural) and their impacts on socio-economic activities.

Meteorological drought is defined usually on the basis of the degree of dryness (in comparison to some “normal” or average amount) and the duration of the dry period. Definition of meteorological drought must be considered as region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. Other definitions may relate actual precipitation departures to average amounts on monthly, seasonal, or annual time scales.

Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels, and so forth. A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity. Deficient topsoil moisture at planting may hinder germination, leading to low plant populations per hectare and a reduction of final yield. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield if subsoil moisture is replenished as the growing season progresses or if rainfall meets plant water needs.

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (i.e., streamflow, reservoir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency is evident through the hydrologic system.

The sequence of impacts associated with meteorological, agricultural, and hydrological drought further emphasizes their differences. When drought begins, the agricultural sector is usually the first to be affected because of its heavy dependence on soil water moisture. Soil water can be rapidly depleted during extended dry periods. If precipitation deficiencies continue, then people dependent on surface water (i.e., reservoirs and lakes) and subsurface water (i.e., ground water) will begin to feel the effects of the shortage and are usually the last to be affected. When precipitation returns to normal and meteorological drought conditions have abated, the sequence is repeated for the recovery of surface and subsurface water supplies. Soil water reserves are replenished first, followed by streamflow, reservoirs and lakes, and ground water. Drought impacts may diminish rapidly in the agricultural sector because of its reliance on soil water, but linger for months or even years in other sectors dependent on stored surface or subsurface supplies. Groundwater users are, often the last to be affected by drought during its onset, may be last to experience a return to normal water levels. The length of the recovery period is a function of the intensity of the drought, its duration, and the quantity of precipitation received as the episode terminates.

Although climate is a primary contributor to hydrological drought, other factors such as changes in land use (e.g., deforestation), land degradation, and the construction of dams all affect the hydrological characteristics of the basin. Because regions are interconnected by hydrologic systems, the impact of meteorological drought may extend well beyond the borders of the precipitation-deficient area.

Similarly, changes in land use upstream may alter hydrologic characteristics such as infiltration and runoff rates, resulting in more variable streamflow and a higher incidence of hydrologic drought downstream. Land use change is one of the ways human actions alter the frequency of water shortage even when no change in the frequency of meteorological drought has been observed.

All drought types (meteorological, agricultural, hydrological and socio-economic) originate with a deficiency in precipitation. The longer and the more spatially extensive this deficiency is, the more likely the occurrence of other types of drought. A matter of more concern to hydrologists is, therefore, how this deficiency is translated into various components of the hydrologic cycle. In general, agricultural drought is typically seen after the meteorological drought but before a hydrological drought. Knowledge of these time lags between the meteorological drought and other drought types (such as agricultural drought) can be used for drought planning and management purposes.

Although it is not possible to avoid drought, its impacts can be managed through drought preparedness planning. The success of drought preparedness and management depend, among others, on how well the droughts are defined and drought characteristics quantified. Various drought indices have been developed to characterize drought spatially and temporally based on its magnitude, duration, and intensity. Drought indices commonly applied around the world are summarized by Smakhtin and Hugghes (2004). Du Pisani et al. (1998) reported review of various drought assessment techniques that have been developed in South Africa prior to 1998.

For the purpose of this paper, two drought indices were used to characterize drought events in the Central Region of South Africa: the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). The SPI was developed for the purpose of defining and monitoring drought events based on a single meteorological determinant, the precipitation (McKee et al., 1993) whereas, SPEI was formulated based on two meteorological variables, precipitation and temperature. The SPEI can account for the possible effects of temperature variability and temperature extremes beyond the context of global warming.

2. MATERIALS AND METHODS

2.1 Location of the Study Area

The analysis was based on long-term (1950-2007) meteorological data of C52A quaternary catchment in the Modder River Basin, South Africa. The Modder River basin, located in the semi-arid regions of central South Africa, is experiencing intermittent droughts causing water shortages for agriculture, livestock and domestic purposes.

The basin has a total area of 17,380 km2 and is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. The C52A quaternary catchment is located in the Upper Modder between 26.48 and 26.87 East and 29.25 and 29.62 South (Figure 1). The catchment receives a mean annual rainfall of 537 mm/year and has an area of 927.6 km2 (Welderufael et al., 2013). The dominant soil types of the catchment are sandy clay loam and sandy clay. The irrigated agriculture in the basin uses water supplied mainly from rivers, pools and weirs. However, many of the rural farmers rely on rain-fed agriculture for crop production.

2.2 Drought characterization

Meteorological drought is commonly analyzed using standardized precipitation index (SPI) method. The SPI was originally developed in Colorado by McKee et al. (1993) and is based on the probability distribution of precipitation. It can be computed with different time scales (e.g. 1 month, 3 months,… 48 months) which allows evaluation of the effects of a precipitation deficit on different water resources components (groundwater, reservoir storage, soil moisture, streamflow). Moving total time series is constructed from the observed precipitation data and then used for the SPI computation. The first step in the calculation of the SPI is to determine a probability density function that describes the long-term series of precipitation data. Once this distribution is determined, the cumulative probability of an observed precipitation amount is computed. The inverse normal (Gaussian) function is then applied to the probability (Figure 2).

The values of SPI can be categorized according to the classes indicated in Table 1. SPI values are positive or negative for greater or less than mean precipitation, respectively. The departure from the mean is a probability indication of the severity of the wetness or drought that can be used for risk assessment. The time series of the SPI is used to characterize droughts based on duration, magnitude and intensity of events.

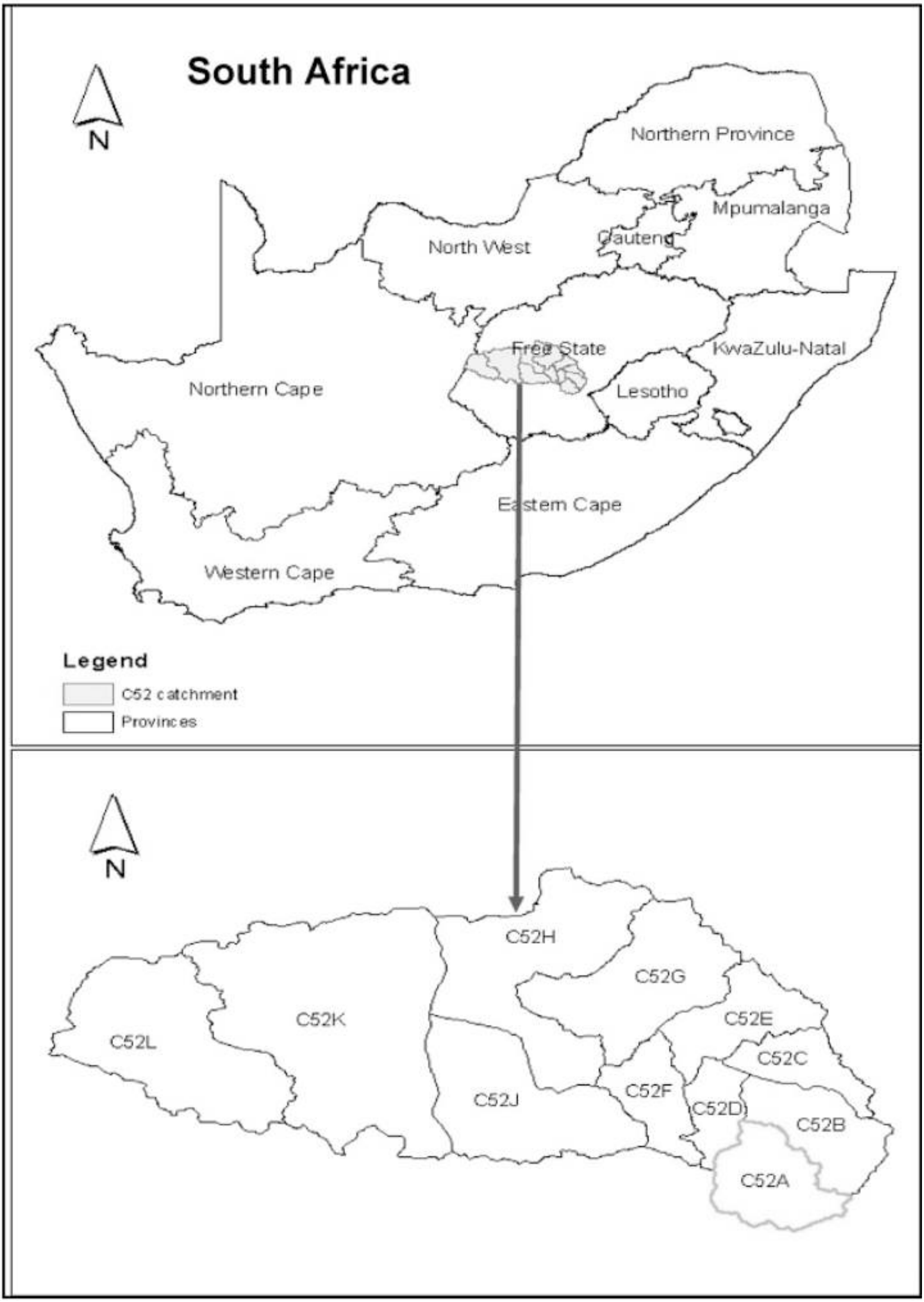

Figure 1. Location of C52A catchment (Source: Welderufael et al., 2013)

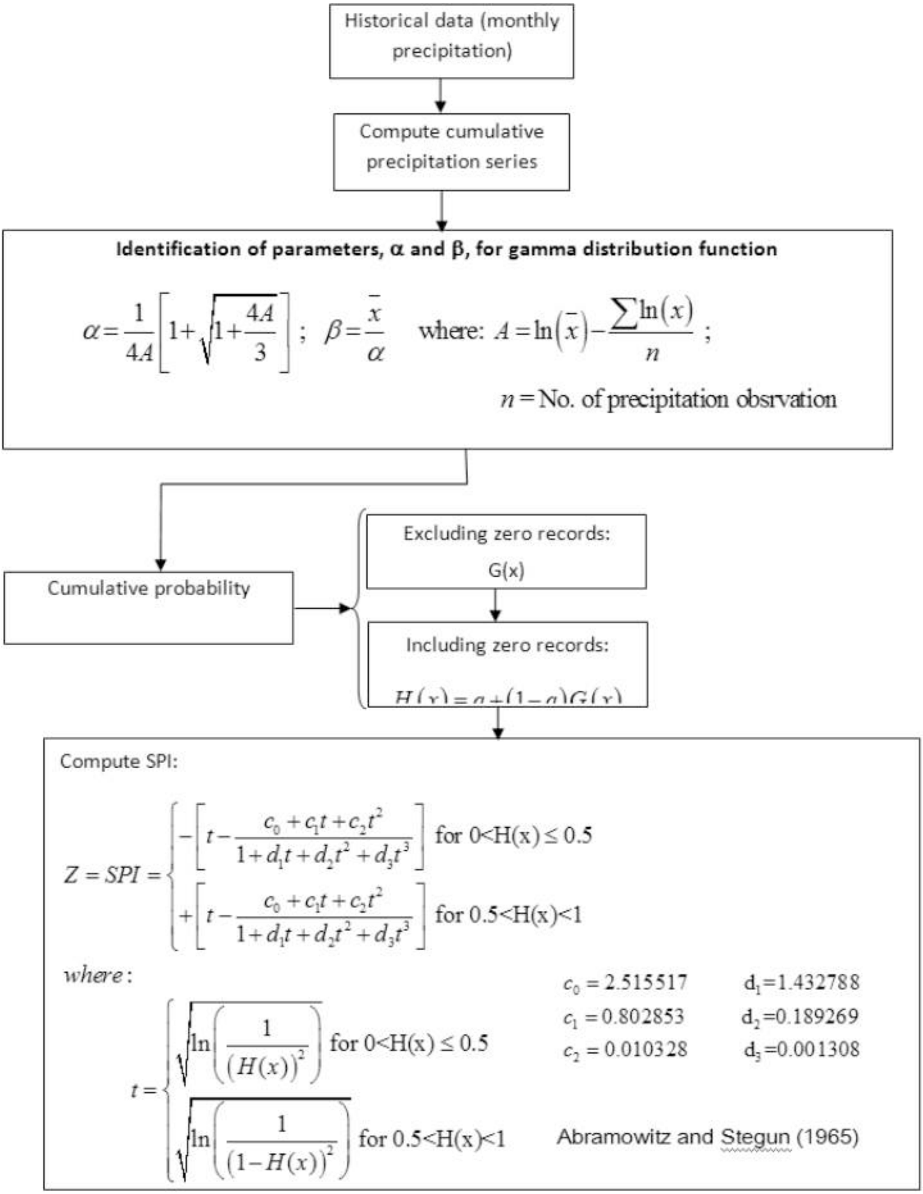

Figure 2. Flowchart of SPI computations (source: Edossa, 2005)

Table 1. Classification of SPI values

SPI class	Class description
	Extremely dry
-2 < SPI ≤-1.5	Severely dry
-1.5 < SPI ≤1	Moderately dry
-1 < SPI ≤ 0	Mild drought
0 < SPI ≤ 1	Near normal wet
1 < SPI ≤ 1.5	Moderately wet
1.5 < SPI ≤ 2	Very wet
SPI > 2	Extremely wet

Source: Vermes (1998)

The calculation of SPEI is also based on the original SPI calculation procedure. The SPI is calculated using monthly precipitation as the input data whereas the SPEI uses the monthly difference between precipitation and potential evapotranspiration (PET). This represents a simple climatic water balance which is calculated at different time scales to obtain the SPEI. The monthly PET is calculated based on Thornthwaite (1948).

3. RESULTS AND DISCUSSIONS

3.1 Relative frequency of drought events

Table 1 presents relative frequencies of various drought categories for the two drought indices with respect to the total number of drought events identified in the study area during the analysis period. In this analysis, an event is considered as 'drought' if the index value is consistently below zero for three and more months. Similarly, any short 'wet' spells (less than three months length) interspersed between dry spells are counted in the dry spell lengths.

The numbers are obtained by calculating the ratio of the number of drought events corresponding to each drought index, time scale and drought category to the total number of drought events record in the same drought index and time scale. The results show that for a given time scale mild droughts occur most frequently and extreme droughts occur least frequently in the area, as is expected. It was also found that both SPI and SPEI gave comparable values of drought frequencies across each drought category.

Table 2. Frequency of drought events

	Frequency of drought events (%)							
Drought category	**SPI-1**	**SPEI-1**	**SPI-3**	**SPEI-3**	**SPI-6**	**SPEI-6**	**SPI-12**	**SPEI-12**
Extreme drought	1.40	1.65	3.52	2.55	4.35	2.88	3.58	2.68
Severe drought	5.34	8.52	8.50	11.90	10.43	12.68	6.87	10.71
Moderate drought	16.57	21.70	20.82	20.40	15.65	19.31	22.99	24.70
Mild drought	76.69	68.13	67.16	65.16	69.57	65.13	66.57	61.90

3.2 Characteristics of drought events

Characteristics (duration, magnitude and intensity) of drought events in the study area during the period of analysis were determined for the time-scales of 3-, 6- and 12-months. However, characteristics of drought events based on 12-months time-scales are presented in Table 2 for illustrative purposes. Drought intensity is calculated by dividing the magnitude of drought event by its duration/length.

During the analysis period, a total of 37, 26 and 17 drought events were identified in the area based on 3-, 6-, and 12-month times-scales, respectively. In terms of length of drought period, both SPI and SPEI identified 2003-2005 as the longest drought period during the period of analysis based on 3- and 6-months time scales. However, based on 12-months time-scale (Table 2) the longest drought period occurred during 1983-1987 under both drought indices.

Considering event magnitude as severity parameter, results from both indices identified the periods 1984-1985, 1992-1993 and 2003-2005 as the severest drought periods in the area during the analysis period. However, when the effects of both drought duration and magnitude are considered (drought intensity), the most severest drought events were identified during the years 1982/83, 1966 and 1973 based on 3-, 6- and 12-month time-scales, respectively.

Table 2. Characteristics of drought events based on 12-months time scale

Event onset		Event end		Duration		Magnitude		Intensity /severity	
SPI	**SPEI**	**SPI**	**SPEI**	**SPI**	**SPEI**	**SPI**	**SPEI**	**SPI**	**SPEI**
Dec-1951	Dec-1951	Jun-1952	Jun-1952	7	7	-1.34	-1.85	-0.19	-0.26
Aug-1953	Aug-1953	Dec-1954	Dec-1954	17	17	-6.36	-4.95	-0.37	-0.29
Mar-1957	Mar-1957	Aug-1957	Aug-1957	6	6	-5.44	-4.65	-0.91	-0.78
May-1962	May-1962	Dec-1962	Dec-1962	8	8	-4.90	-5.51	-0.61	-0.69
Jan-1964	Jan-1964	Dec-1965	Dec-1966	24	25	-20.94	-21.41	-0.87	-0.86
Jul-1966	Jul-1966	Jan-1967	Feb-1967	7	8	-1.48	-1.51	-0.21	-0.19
May-1968	May-1968	Mar-1971	Apr-1971	35	36	-23.52	-26.91	-0.67	-0.75
Sep-1971	Aug-1971	Feb-1972	Feb-1972	6	7	-4.01	-4.32	-0.67	-0.62
Jan-1973	Jan-1973	Dec-1973	Dec-1973	12	12	-21.38	-19.66	-1.78	-1.64
Dec-1977	Dec-1977	Jan-1981	Jan-1981	38	38	-26.88	-26.09	-0.71	-0.69
Feb-1983	Jan-1983	Aug-1987	Aug-1987	55	56	-44.43	-58.08	-0.81	-1.04
Oct-1990	Oct-1990	Sep-1991	Sep-1991	12	12	-8.71	-9.84	-0.73	-0.82
Feb-1992	Feb-1992	Dec-1993	Jan-1994	23	24	-26.97	-31.68	-1.17	-1.32
Jan-1995	Jan-1995	Nov-1995	Nov-1995	11	11	-13.76	-15.13	-1.25	-1.38
Sep-1999	Jul-1999	Aug-2000	Mar-2001	12	21	-4.94	-9.29	-0.41	-0.44
Aug-2003	Aug-2003	Jan-2006	Jan-2006	30	30	-30.66	-30.67	-1.02	-1.02
Feb-2007	Feb-2007	Dec-2007	Dec-2007	11	11	-14.41	-14.15	-1.31	-1.29

3.3 Relationship between drought indices

Figures 1-3 show correlation between the outputs of SPI and SPEI based on the time scales of 3-, 6-, and 12-months. Results of these correlation analyses generally revealed that there is strong relationship between the two indices in all time scales. The higher the time scale of analysis, the stronger the relationship is. This is evidenced by the coefficient of determination (R2) between SPI and SPEI which increased from 0.958 for the 3-month time scale to 0.971 for the 12 month time scale (Figures 3, 4 and 5) showing the stronger correlation acquired at the higher time scale.

But Precipitation-based drought indices such as SPI rely on the assumption that the variability of precipitation is much higher than that of other variables, such as temperature and potential evapotranspiration (PET). In this scenario droughts are controlled by the temporal variability in precipitation. Therefore, in view of this assumption and based on its minimum input data requirement, the use of SPI in drought analysis is justified.

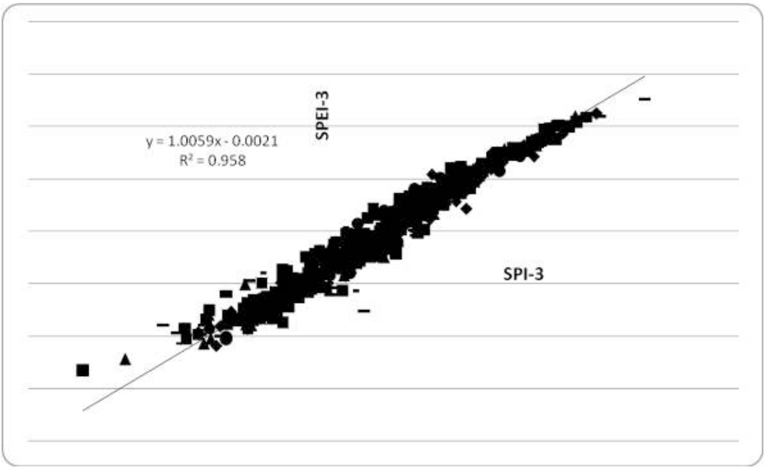

Figure 3. Correlation between SPI and SPEI based on 3-month time scale

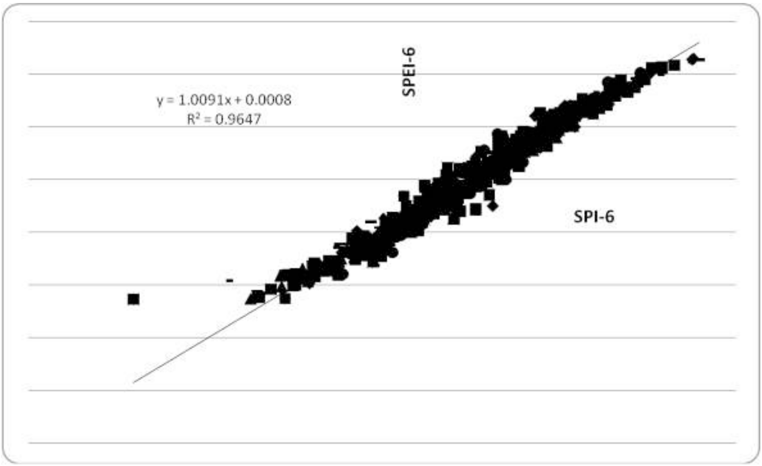

Figure 4. Correlation between SPI and SPEI based on 6-month time scale

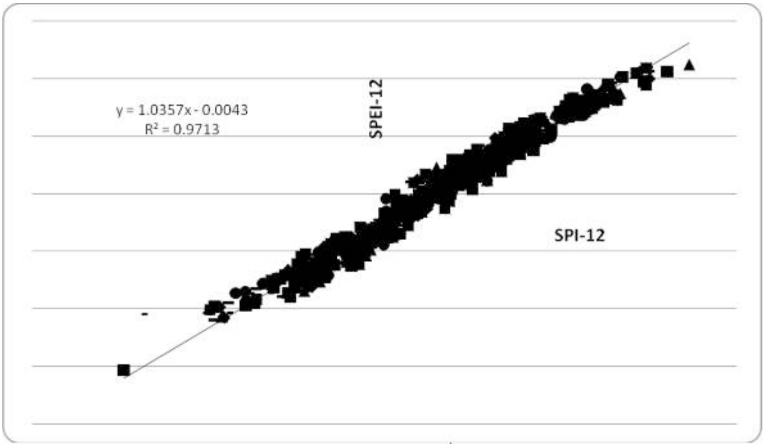

Figure 5. Correlation between SPI and SPEI based on 12-month time scale

4. CONCLUSION

During the 57 years analysis period, both drought indices (SPI and SPEI) identified the severest drought events in the years 1962, 1966, 1972/73, 1982/83 and 1999 based on both 3- and 6-months time scale. However, on the basis of 12-months time scale, the severest drought events were identified during the periods 1992/93, 1995 and 2003/06.

Any drought index is useful only to the extent that the input data used to compute it can be trusted.

This point is becoming increasingly relevant as demands increase for drought and other climate data with a long record length and high spatial resolution. However, historical observations are sparse or simply unavailable for temperature, precipitation, and other meteorological variables over many land areas, especially in Africa. It was concluded that although the SPEI generally exhibits veracity over SPI by including additional meteorological parameter, mean temperature, SPI should be adopted as an appropriate drought monitoring tool in an area, like Africa, where meteorological data are scarce.

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