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EVALUATION OF SUITABLE STANDARDIZED PRECIPITATION INDEX TIME SCALES FOR METEOROLOGICAL, AGRICULTURAL AND HYDROLOGICAL DROUGHT ANALYSES

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ABSTRACT

The research was aimed at identifying suitable Standardized Precipitation Index (SPI) time scales for drought analysis to prevent researchers from illogical SPI time scale application. The selection of the relevant time scales for drought analysis is important in the context of climate change, which poses serious environmental degradation challenges to mankind. SPI at different time scales of 1, 3, 6, 12 and 24 months were computed from 30 years of rainfall data collected from seven meteorological stations in Sudano-Sahelian Region of Nigeria, and analyzed to draw conclusion on the relevant SPI time scale suitable for the analysis of each drought categories: meteorological, agricultural and hydrological droughts. The relevance of the different SPI time scales to various drought categories, both at short-term and long-term, was established to determine the choice of SPI time scale for the respective drought analysis. The findings showed that SPI at time scale of 1 month could be suitable for short term investigation such as drought monitoring, real-time forecasting and few weeks' meteorological drought analysis while 3 months time scale could be suitable for few months' meteorological drought and agricultural drought analysis. SPI at 6 and 12 months time scales could be used for hydrological drought assessment in relation to surface water and groundwater resources management respectively, while longer time scales showed unreliable results. Conclusion drawn was that illogical application of SPI by drought analysts might yield confusing and poor results. It is recommended that SPI time scales should be appropriately applied to the study of various drought categories and water resources management as outlined in this study so that drought research efforts will yield outcomes of significance.

Keywords: Drought, Standard Precipitation Index, Meteorological Drought, Agricultural Drought, Hydrological Drought

INTRODUCTION

Drought is a period of dry environmental condition as a result of insufficient or lack of rainfall and high evaporation occurring for a short or prolong period (Wilhite, 2011). It constitutes a costly natural hazard that impacts different sectors of society and different countries according to their vulnerability (EM-DAT, 2013). Regional- to large scale droughts are driven by a prolonged precipitation deficit which mainly impact agriculture and hydrology and depending on the demand on water resources, this can then lead to water scarcity (Dutra *et al.*, 2014). Drought is a natural creeping phenomenon with insidious beginning and occasionally, its severity progressively becomes intense giving rise to different categories: meteorological, agricultural, hydrological and socio-economic droughts (Wilhite and Glantz, 1985; NDMC, 2014). In other words, the deficiency of rainfall starts as a drought; the longer and more spatially extent this deficiency, the more likely the occurrence of the other types of drought. The types signify basic approaches to measuring drought at different level of severity. The first three deal with ways to measure drought as a physical phenomenon while the last deals with drought in terms of supply and demand, tracking the effects of water shortfall as it ripples through socioeconomic systems, such as an increase in prices of agricultural commodities.

Meteorological drought refers to a deficiency of precipitation, as compared to average conditions, over an extended period of time; it basically originates from the deficiency of precipitation and focuses on the physical characteristics of drought (Mokhtari, 2005) rather than impacts associated with shortage of precipitation. Meteorological drought leads to a depletion of soil moisture (Legesse, 2010). Agricultural drought is defined by a reduction in soil moisture available below the optimal level required by a crop during the different growth stages, resulting in impaired growth and reduced yields. It typically occurred after meteorological drought but before hydrological drought (Okorie, 2003). Hydrological drought results when precipitation deficiencies begin to reduce the availability of natural and artificial surface and subsurface water resources. It occurs when there is substantial deficit in surface runoff below normal conditions or when there is a depletion of ground water recharge. Drought can be analyzed by different methods such as Palmer Drought Severity Index (PDSI), used for evaluating meteorological drought. Normalized Difference Vegetation Index (NDVI) and Surface Water Supply Index (SWSI) are used for analysing agricultural and hydrological droughts, respectively. Standardized Precipitation Index (SPI) was developed by McKee *et al*. (1993) and has the potential to be a superior, yet one of the simple indices of drought severity evaluation tools (Guttman, 1998; Panu and Sharma, 2002). It is the most widely used index for understanding the magnitude and duration of drought events. It is designed to quantify the impacts of precipitation deficit on groundwater, streamflow, reservoir storage and soil moisture for multiple time scales. Hence, it is flexible compared to other methods because of its suitability for evaluating meteorological, agricultural and hydrological droughts using different time scales. The choice of SPI time scale for the analysis depends on the category of drought under consideration. The SPI could be computed for rainfall totals of different time scales such as one month, denoted as SPI_1, three months (SPI_3), six months (SPI_6), twelve months (SPI_12), twenty four months (SPI_24) and so on. However, the selection of suitable and relevant time scale for studying various drought categories is confusing to some researchers and they erroneously apply them in their investigations thereby leading to findings of less significant impacts. As a result, this study attempts to identify suitable SPI for analyzing different drought categories so that further investigations will be more focused, specific and yield significant findings in the context of climate change.

MATERIALS AND METHODS

Study area

The study area is the Sudano-Sahelian Zone (SSZ) of Nigeria. It lies roughly between Latitudes 11^0 and 13^0N and Longitudes 4^0 and 15^0E (Maduakor, 1991) and, constitutes most of Borno, Kano, Sokoto, Adamawa, Bauchi, Gombe, Jigawa, Katsina, Kebbi, Yobe and Zamfara States in Nigeria as shown in Figure 1. It has been estimated that 50% to 75% of the eleven frontline states in the Northern Nigeria are being affected by drought (Medugu, 2007). These states with a population of about 50 million people account for about 38% (35,125km^2) of the country's total land area (Medugu, 2007). The meteorological stations located in the Nigerian Sudano-Sahelian Region (NSSR) are Sokoto, Katsina, Nguru, Potiskum, Maiduguri, Kano and Guzau Station.

Data Collection

Data were collected from the Nigerian Meteorology Organization, Lagos. The data consists of records of rainfall for a period of 30 years (i.e 1979 to 2008) covering the seven synoptic stations in the Nigerian Sudano-Sahelian Region namely, Sokoto, Katsina, Nguru, Potiskum, Maiduguri, Kano and Guzau Stations.

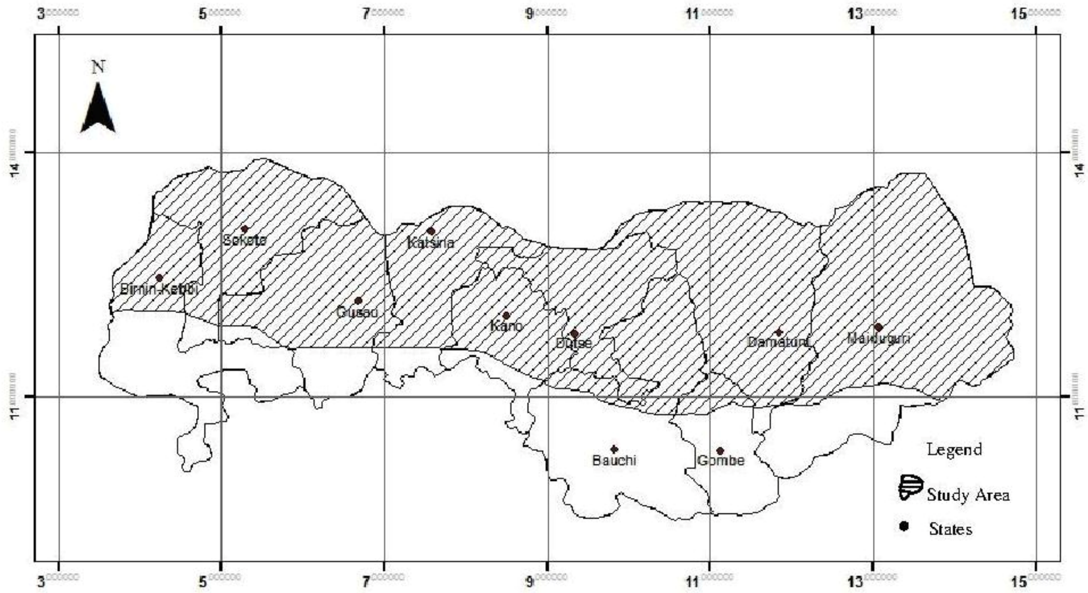


Figure 1: **Study Area: Sudano-Sahelian Region of Nigeria**

Derivation of SPI

SPI values requires monthly rainfall data to be fitted to gamma distribution whose probability density function is defined as (Usman *et al*., 2014)

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad (1)$$

where, $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter and $x > 0$ is the amount of rainfall and $\Gamma(\alpha)$ defines the gamma function. In this case, rainfall is the variate (x) in the gamma distribution function. The solution is to transform cumulative probability gamma function into a standard normal random variable Z with mean of zero and standard deviation of one. A new variate is formed, and the transformation is done in such a way that each rainfall amount in the old (gamma) function has got a corresponding value in the new (transformed) Z function. The probability that the rainfall is less than or equal to any rainfall amount will be the same as the probability that the new variate is less than or equal to the corresponding value of that rainfall amount. However, in order to simplify the computation of SPI, a useful SPI computation program which can run in Windows environment was used to calculate SPI from monthly precipitation data at required time scales. The program has been used to assess droughts by researchers in different parts of the world, for instance; San Pedro River basin, Arizona, USA (Polyakov *et al*., 2010), Ethiopia (Belayneh and Adamowski, 2012), Italy (Kumar *et al.*, 2013), Katsina, Nigeria (Usman *et al*., 2014). The WHO (2012) and the United States NDMC (2014) produced useful guides for the application of the software. The latest SPI program (SPI_SL_6.exe) for Windows/PC was used to compute the SPI at different time scales (SPI_1, SPI_3, SPI_6, SPI_12, and SPI_24) using the precipitation data from the synoptic stations for analyses of drought in the study area. The SPI program input file was prepared with all the data for each station in the following column format: Header yyyy mm pppp in which, Header = a string which described the name of the station, yyyy = year, mm = month (in digit format 1,2,3 etc), pppp = precipitation multiplied by 100. The yyyy mm and pppp were separated by space. This file was named stdin (with no extension) and saved in the same directory as the SPI program. The directory was accessed at the DOS prompt by typing SPI and then uploading the file (stdin). The SPI time scales were specified before running the program. The output was automatically written to a file, stdout (in the same directory). The output of the program was in the following format: Header yyyy mm spi1 spi3 spi6 spi12 spi24 in which, yyyy and mm are as before, spi1 = SPI for a 1-month rainfall total, spi3 = SPI for a 3-month rainfall total, spi6 =

SPI for a 6-month rainfall total, spi12 = SPI for a 12-month rainfall total, spi24 = SPI for a 24-month rainfall total. The time series of the output SPI at different time scales were then plotted for comparison and further analysis of drought in the study area. The SPI represents the amount of rainfall over a given time scale, with the advantage that it provides not only information on the amount of rainfall, but in addition, it gives an indication of what this amount is in relation to the normal, thus leading to the definition of whether a station is experiencing drought or not. The program gives outputs in units of standard deviation from the average based on as-long-a-rainfall-distribution-as-there-is-data-for. Hence, drought is happening when SPI is negative and its intensity is classified using Table 1, while drought stops when SPI is positive (McKee *et al*., 1993)

Table 1: Standardized Precipitation Index

SPI Values	Class
2.0 and more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

Source: McKee *et al.*, (1993)

In other words, the interpretation of the SPI in Table 1 is such that high SPI value (closer to 3) indicates heavy precipitation event, medium SPI value (approximately = 0) implies normal precipitation event while low SPI value (closer to -3) reflects low precipitation event over the time period specified (which reflects drought).

Drought Analysis using different SPI Time Scales

The SPI time series at different time scales were plotted over the study period and the numbers of drought occurrences were estimated using SPI_1, SPI_3, SPI_6, SPI_12 and SPI_24, respectively. A drought occurrence was identified with the important parameters and attributes quantifying a drought condition such as drought duration or length and severity (Panu and Sharma, 2002; Kayode and Francis, 2012). For each of the SPI time scale, the portions of the time series graph below the x-axis were regarded as droughts and drought severities were identified using the inverted peaks of these portions. The corresponding negative values of the peaks, traced to the y-axis, were compared with the SPI values in Table 1 to identify the classes of droughts while drought durations were identified as the corresponding widths on the x-axis, opposite the inverted peaks used to determine drought severities. Using the aforementioned approach, the total numbers of drought episodes observed for each of the SPI time scales were identified during the study period. The observed droughts of different SPI time scales were compared in terms of frequency and duration to establish their reliability. Each SPI time scales' representing total precipitation deficiencies for 1- month (SPI_1), 3 – month (SPI_3) and so on, depicting droughts for the respective time scales was compared to short-term and long-term drought categories to establish the relevance of the former to the latter.

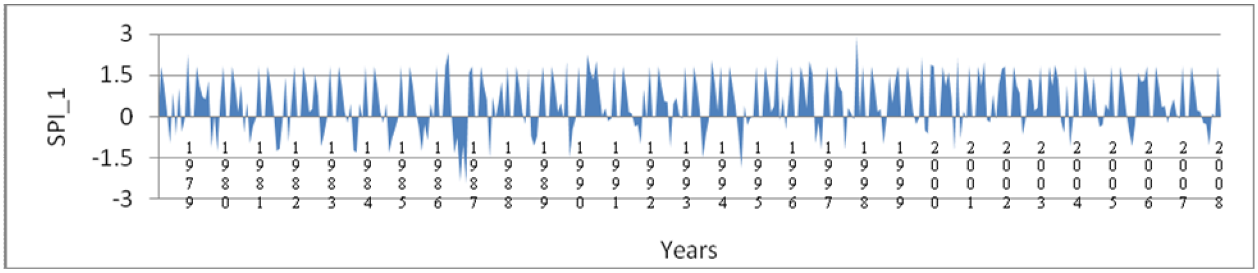
RESULTS

Time Series of different SPI Time Scales

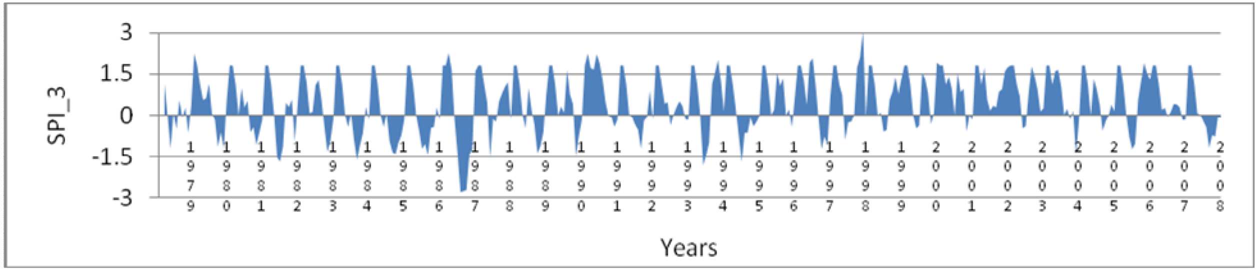
SPI values have been computed for 7 stations in Northern Nigeria, but only the SPI time series of 1- month, 3-month, 6-month, 12-month and 24-month time scales for Sokoto Station, extreme North West, and SPI time series of 1-month and 24-month time scales for Maiduguri Station, extreme North East, of the study area were presented in Figures 1(a-e) and Figure 2 (a and b), respectively. Drought occurrences were identified, using durations and severities as stated before, for each SPI time scale. The drought occurrences identified for other stations at different SPI time scales were presented in Table 2.

Drought Analysis using different SPI Time Scales

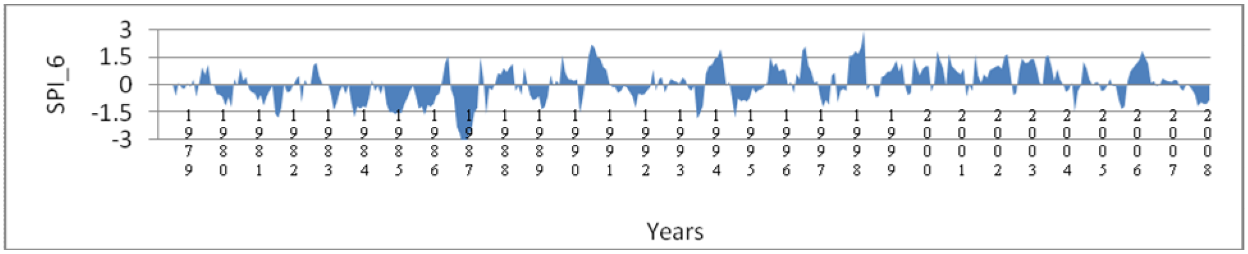
1 – Month SPI: The result of 1 – month SPI time series for Sokoto Station was presented in Figure 1a and it showed that even though drought was a recurring phenomenon in the study area, its frequency and intensity varied temporarily during the study period. For instance, from 1979 to 1993 (50% of the study period), there were 25 drought occurrences out of which 7 were mild, 14 moderate, 2 severe (1988 and



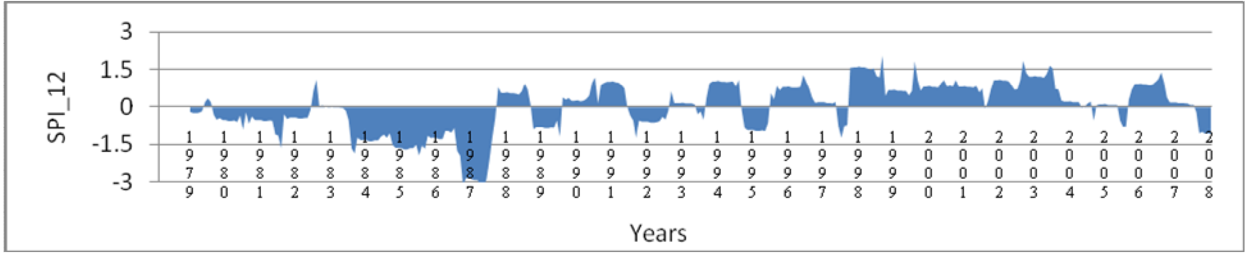
(a) 1- month SPI Time Series



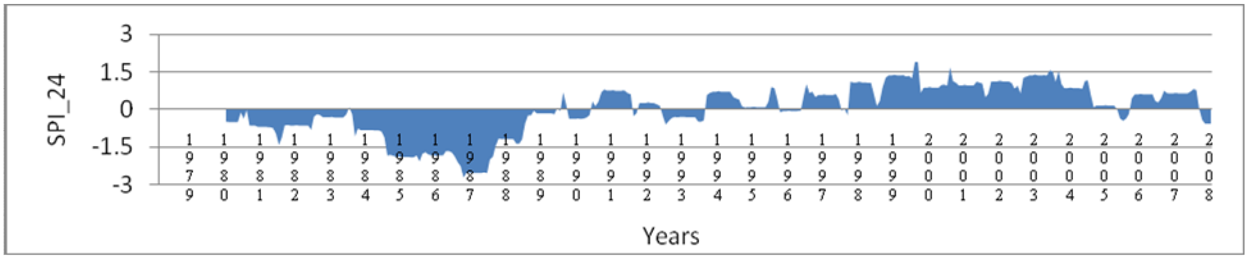
(b) 3 - month SPI Time Series



(c) 6 - month SPI Time Series

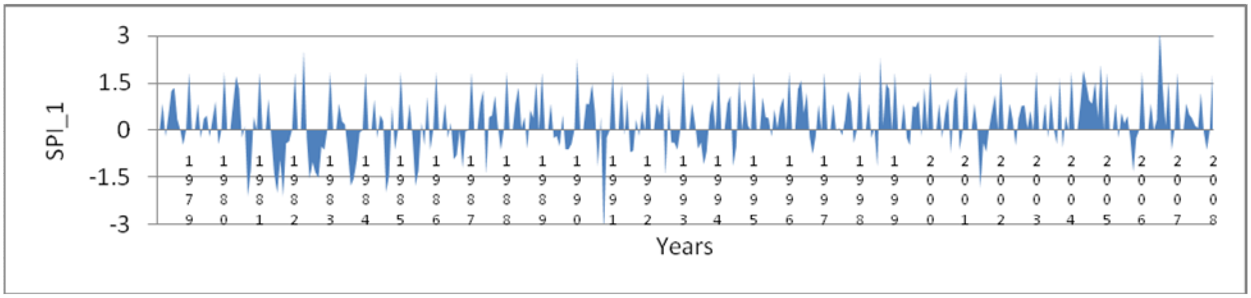


(d) 12 - month SPI Time Series

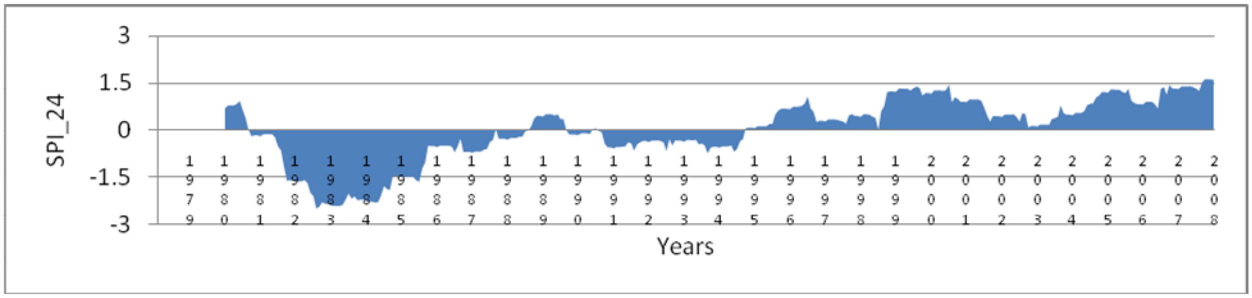


(e) 24 - month SPI Time Series

Figure 1: SPI time series for Sokoto Station using time scales of 1, 3, 6, 12 and 24 months



(a) 1 month SPI



(b) 24 month SPI

Figure 2: SPI time series for Maiduguri Station using time scales of 1 and 24 months

Table 2: Drought Frequency in Northern Nigerian (from 1979-2008) Using SPI_1 to SPI_24

SPI	Sokoto	Katsina	Nguru	Potiskum	Maiduguri	Kano	Gusau
SPI_1	46	43	45	54	51	38	52
SPI_3	36	37	38	42	38	33	39
SPI_6	35	34	32	33	31	31	30
SPI_12	11	10	12	18	8	6	11
SPI_24	9	4	10	15	5	2	8

1990) and 2 extreme (in 1987). From 1994 to 2008, there were 21 drought events in which 11 were mild, 8 moderate, 2 severe, in 1994 and 1995, and no extreme drought. Hence, there were 46 drought episodes, mostly mild and moderate droughts, observed during the study period using SPI_1 time scale. The analysis of drought occurrence using SPI_1 showed quick response to monthly precipitation deficiency and reflected on set of droughts or mild droughts which build up gradually. Hence, it could be suitable for drought monitoring, real-time forecasting and few weeks' meteorological drought analysis.

3 - Month SPI: The plot of SPI_3 time series computed for Sokoto State was presented in Figure 1b. The first half of the study period reflected 20 drought events out of which 6 were mild, 10 moderate, 3 severe (in 1982, 1984 and 1988) and 1 extreme drought, in 1987, as shown in Figure 1b. The remaining part of the study period showed 16 drought episodes consisting of 10 mild, 4 moderate, 2 severe and no extreme droughts. In total, there were 36 drought events observed during the study period using SPI_3 time scale. The result of 3-month SPI time scale reflected drought response to 3 month precipitation deficiency, which could have adverse impact on crop growth. Hence, SPI_3 time scale could be of importance in agricultural drought analysis.

6 – Month SPI: The result of SPI_6 time series was plotted as shown in Figure 1c and the figure showed that the first half of the study period was exposed to19 drought events in which 6 were mild, 7 moderate, 5 severe and 1 extreme, in

1987. The second half of the study period showed 16 drought episodes consisting of 9 mild, 5 moderate, 2 severe, in 1984 and 1985, and no extreme one. Hence, the analysis of drought using SPI_6 reflected 35 drought events during the study period. The 6-month time scale showed drought response to 6-month precipitation deficiency. It is possible that cumulative precipitation deficiency or less rainfall than normal, for a period of 6 months might cause reduced stream flow.

12 – Month SPI: The plot of 12-month SPI time series computed was presented in Figure 1d. From 1979 to 1993, that is, 50% of the study period, there were 5 drought events out of which 1 was mild, 2 moderate, 1 severe, in 1982, and 1 extreme, in 1987, as shown in Figure 1d. The period 1994 to 2008 reflected 6 drought events in which 3 were mild, 3 moderate and no severe and extreme ones. The total drought occurrences during the entire study period using SPI_12 were 11 droughts. The 12-month time scale reflected drought occurrences of longer duration compared to shorter time scales of 1-month, 3-month and 6-month time scales. This implied that total precipitation deficiency, or less rainfall than normal, for 12 months cumulatively reflected as longer duration drought. For instance, a noticeable drought of long duration, spanning several years from 1984 to 1988, was observed in Figure 1d. Most likely, this type of long duration drought could reduce groundwater. Consequently, hydrological drought or studying of this nature could be investigated using SPI_12. Besides, SPI_12 time scale reflected the years 1999 to 2004 as period of no drought occurrence unlike the other shorter SPI time scales that reflected drought during the stated years. The implication of this observation was that although, drought occurred in the stated years (1999 to 2004) as showed in SPI_1 to SPI_6 analysis but, precipitation deficiency, or less rainfall than normal, over an average of 12 months, was such that it might not adversely reduce groundwater or impact other aspects of water resources that respond longer to precipitation deficiency during this period.

24 – Month SPI: The plot of 24 – month SPI time series computed for Sokoto Station was reflected in Figure 1e. From 1979 to 1993, there were 5 drought occurrences out of which 3 were mild, 1 moderate, 1 extreme, spanning 1984 to 1989, and no severe one as shown in Figure 1e. The remaining part of the study period showed 4 drought events that were mild. There were 9 drought occurrences during the study period using SPI_24 time scale for drought analysis in Sokoto. The drought trends observed using SPI_24 time scale were similar to those of SPI_12 analysis although, the period of drought occurrence or otherwise were longer, for instance, drought of 1984-1988 observed using SPI_12 ended in 1989 with SPI_24 time scale analysis as observed in Figure 1e. As a result of longer drought duration, the number of drought occurrences or frequency reduced from 46 occurrences in SPI_1 to 9 occurrences in SPI_24 analysis.

The most striking characteristic of the drought was the change in drought frequency as the time scale changed. On shorter time scales, say SPI_1, droughts became frequent but with shorter durations while on longer time scales, such as SPI_24, droughts became less frequent but last longer as presented in Figures 1. Moreover, the longer duration of drought observed using longer SPI time scale was reflected as an increase in the duration of drought of 1987, from short-term observed using SPI_1 to long-term, spanning many years, from 1984 to 1988/1989, in SPI_12 and SPI_24.

In same manner, the results of SPI time scales computed for other stations showed the same trend as discussed for Sokoto Station and to buttress the common trend, the time series of SPI_1 and SPI_24 computed for Maiduguri Station reflected that as the SPI time scale increased, in this case, from 1-month to 24-month, there was notable changes in drought frequency and duration as presented in Figures 2(a and b).

SPI_1 reflected the highest number of drought occurrences in all the stations while SPI_24 showed the least occurrences as presented in Table 2. Moreover, SPI_24 analysis showed that there were 2 drought occurrences in Kano during the 30 years study period, from 1979 to 2008, as presented in Table 2. Similarly, there were 4 drought episodes observed in Katsina as shown in the Table during the same period. SPI of longer time scale than 12-month could be unreliable as presented in Table 2 as the frequencies of drought events were grossly underestimated by SPI_24. Moreover, the trends of drought frequencies for the SPI time scales are the same for all the stations as presented in Table 2.

DISCUSSION

Both cases (more drought but shorter duration, fewer droughts but longer duration) could be interpreted differently for different drought categories and water resources studies. As stated before, SPI_1 time scale could be suitable for drought monitoring because it showed drought occurrences frequently than the remaining time scales. This implies that if SPI_1 is used for drought monitoring, it can aid in early preparedness at the onset of droughts unlike the long-term SPI time scales that mask some drought events and consequently had low drought frequency. As stated before, meteorological drought refers to a deficiency of precipitation, rather than impacts associated with the shortage of precipitation. Consequently, few weeks' meteorological drought could be assessed using SPI_1. This statement is in agreement with Narendra (2008) observation that SPI_1 time scale, unlike long term time scales, has a high and significant correlation with monthly rainfall deficiency.

According to Ali (2001), soil moisture can be more sensitive to a 3- month drought and since SPI_3 time scale reflects 3-month precipitation deficiency, that is, negative SPI_3, in form of droughts, this implies that agricultural drought, implying reduction in soil moisture thereby affecting crop growth, can be analysed using SPI_3. The results observed for the study area, Northern Nigeria, is in agreement with a study by Usman *et al.,* (2014) on an assessment of temporal variability of drought in Katsina, Nigeria, using SPI_3 and SPI_6 only. The researchers concluded that 3-month SPI could be more relevant to crop production in the area, as this is the most critical period for growth and grain filling of most of the crops grown in the area. Hence, agricultural drought can be investigated using a number of indices such as Normalized Difference Vegetation Index (NDVI) and SPI_3 and this enables researchers to make comparison of their results for non-linear and robust analyses since, according to Smakhtin and Hughes (2004), no single drought index is ideal for all regions and tasks.

Long-term hydrological drought, such as those that impact stream flow, reservoirs and aquifers, could be studied using SPI_6 and SPI_12 since, these relatively long-term time scales reflected 6-month and 12-month precipitation deficiencies, respectively. Surface water resources, such as stream flow and reservoirs could be more sensitive to a 6-month drought, that is, 6-month precipitation deficiency and this is in agreement with Usman *et al.,* (2014) finding, while groundwater resources could be more sensitive to a 12-month drought since the latter resources respond to precipitation deficiency longer than the former. Hence, SPI_6 and SPI_12 could be used for surface water and groundwater resources planning, respectively. In other words, knowledge of the frequency of historic drought observed using SPI_6 could be used in proper scheduling and allocation of water available in reservoirs in a region at risk of drought especially, in the context of climate change.

CONCLUSIONS AND RECOMMENDATIONS

In this study, drought was analysed, in the northern Nigeria, using SPI at different time scales. The analysis showed that the study area had been exposed to drought events of varying intensities, durations and severities using different SPI time scales. Drought episodes of high severities were observed from 1979 to 1993 and the notable ones were 1982, 1984, 1985, 1987 and 1988 drought events while the latter part of the study period showed less frequent drought occurrences. SPI_1 show the highest frequency of drought occurrence while SPI_24 reflects lowest frequency of drought episodes across the study area and the relevance of the different SPI time scales to various drought categories, both at short-term and long-term, was established.

As a result of these findings, areas of contribution to knowledge are identified. SPI_1 could be suitable for drought monitoring, real-time forecasting and few weeks' meteorological drought analysis, while SPI_3 could be used for few months' meteorological drought and agricultural drought assessment in the area. The study of long-term hydrological drought impacts on both surface and groundwater resources could be investigated using SPI_6 and SPI_12 respectively, while longer SPI time scales, such as SPI_24 might be unreliable for drought investigation in Northern Nigeria.

Due to climate change, the frequency, duration, severity and impact of drought might be alarming in the near future. It is recommended that SPI time scales should be appropriately applied to the study of various drought categories and water resources management as outlined in this study so that research efforts will be channelled towards sound application of SPI thereby, obtaining outcomes that are more useful.

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