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Drought Monitoring in Northern Nigeria Using Four (4) Indices

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ABSTRACT

Drought can generally be defined as the extreme persistence of precipitation deficit over a region for a specific period. Eight study locations were picked from the Sudano-Sahelian agro-ecological zones of Nigeria (Bauchi, Bida. Kaduna, Kano, Maiduguri. Sokoto, Nguru, and Katsina) from 1981 to 2015. The Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index- Thornthwaite (SPEI.T), Standardized Precipitation Evaporation Index-Hargreaves (SPEI-H) and Standardized Precipitation Evaporation Index-penman (SPEI-P) were used as the primary indicators of meteorological and agricultural droughts. The correlation coefficient shows an increasing correlation among the indices with increasing time scale, with SPI and SPEI-H having the highest correlation. The regression analysis shows a monotonic increasing relationship between indices while SPI vs SPEI-H has the highest correlation coefficient. The number of drought occurrences captured by the indices also increases with increasing time scale with SPEI-P detecting the highest number of drought events. All the drought indices reflect the historical drought periods between 1982-1989, 1992-2002, and 2008-2011. SPI, SPEI-P, and SPEI-H detected similar duration and intensity for the historical drought between 1982 and 1989 while SPEI-P showed the highest intensity and duration for the historical droughts between 1992 and 2002 and between 2008 and 2011.Analytic Hierarchy Process (AHP) evaluated that SPEI-P was more robust and sophisticated, SPI and SPEI-P had the same score for tractability while SPEI-H being the least tractable, and SPI had the highest for transparency and extendibility.

Keywords- Analysis, Drought, Trend, Northern Nigeria.

I. INTRODUCTION

Drought is one of the world's most costly natural disasters, causing annual global damage of US $ 6-8 billion on average and impacting more people than any other form of natural disaster [20]. According to [48], a broad variety of opinions on the concept of droughts is one of the key challenges to the investigation of droughts. Similarly,[46] argued that it is necessary to differentiate between philosophical and operational meanings when describing a drought.

In the most general context, drought is caused by a moisture deficit for a prolonged period of time. Drought is a temporary aberration; it varies from aridity, which is limited to low rainfall regions and is a permanent characteristic of the climate[23].

Deforestation (people chopping down forests), global warming, and diverting rivers or emptying reservoirs can also cause drought.

For the detection, classification, and control of drought conditions, drought indices are used. They allow quantitative evaluation of the severity, length and spatial scale of anomalous climatic conditions and thus help decision-making processes (e.g., triggering mitigation actions).Several drought indices have been developed to measure droughts, including the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), the Palmer Drought Severity Index (PDSI), the Standardized Runoff Index (SRI), and the Reconnaissance Drought Index (RDI). Of these indexes, the most commonly used are SPI and PDSI [42].

Common drought indices, such as the Standardized Precipitation Index, SPI, or based on water demand (evapotranspiration) and losses (runoff), such as the Palmer Drought Intensity Index, PDSI, and the standardized precipitation evapotranspiration index, are either precipitation-based only (SPEI) [12].There are benefits and disadvantages of all indexes. Northern Nigeria was picked in this analysis because it is the hottest region of Nigeria and therefore very vulnerable to drought. Wide areas of Northern Nigeria within the agro-ecological zones of the Sahel and Sudan between latitudes 9-14oN are vulnerable to persistent droughts in one form or another[13];[5];[3];[24]. The region is estimated to be around 38 percent of the total land area of Nigeria and it is the grain belt of the country inhabited by small-scale subsistence farmers and nomadic livestock herders.

Information insufficiency can be an obstacle to the creation of successful mechanisms for detecting, tracking and mitigating droughts, which are a requirement for the sustainable use and planning of water resources. Therefore, the need arises to research the characteristics of drought and track the occurrence of drought in this area using different drought indices and also to use the most suitable one to monitor drought minimizing the possibility of drought in Nigeria.

The research aims to implement indices in monitoring the event of drought in the northern part of

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Nigeria. The research enabled us to (1) have an overview of the individual performance relative to other indices of the same category. (2) ascertain the indices suitability for detecting, monitoring, and early warning of the different historical drought episodes. (3) determine the best index for monitoring drought in northern Nigeria amongst fourindices.

II. MATERIALS AND METHOD

2.1 Study Area

The study area is located in northern Nigeria between latitude 10^{0}N and 14^{0}N and longitude 4^{0}E and14^{0}E. This zone occupies almost one-third of the total land area of the country. It extends from the Sokoto Plains to the Chad Basins across the northern portion of the high plains of Hausa Land [25]. The tropical wet and dry type, defined by Koppen as A_w, is the climate of the district. The average annual precipitation in the extreme northeastern part of the zone is around 500 mm to 1000 mm in the southern sub-region [1]. The rainfall takes place between April and October, with a high in August. The pattern of rainfall in the region is highly variable in spatial and temporal dimensions with interannual variability of between 15 percent and 20 percent. This region is vulnerable to regular dry spells due to the high inter-annual variability in rainfall, which can lead to extreme and extensive droughts [28]. The temperature in the region is high throughout the year with a mean minimum value of about 23°C and a mean maximum of about 34°C. The temperature is fairly constant in the rainy season because cloudiness and moisture inhibit back radiation, so the diurnal temperature range is relatively limited, and it is around 2 °C [28]. A lot of back radiation is experienced at night in the dry season, which leads to reduce night temperature levels. A high daily temperature range, thus, can often be as high as 12 °C is observable.

2.2 Data Set

Observed daily precipitation and temperature data from eight (8) meteorological stations (Figure 1) were obtained from the National Meteorological Agency (NIMET), Lagos, Nigeria. The obtained data covered a period of 35 years from 1981 to 2015 which is approximately a climatic age. The data set was then checked for error before further analyses were carried out on it. Detailed information on the climatic data is presented in Table 1.

Table 1: Location of Meteorological Stations

Station Name	Latitude (° N)	Longitude (° E)
Bauchi	7.28	5.30
Bida	9.07	6.01
Kaduna	10.6	7.45
Kano	12.05	8.20
Maiduguri	11.85	13.08
Sokoto	13.01	5.24
Nguru	12.88	10.47
Katsina	13.02	7.68

2.3 Error Check

In dealing with big datasets, errors are the usual, not the exception. 88 % of spreadsheets contain bugs, according to estimates. Since we can not confidently presume that all of the knowledge we deal on is error-free, errors must be identified and handled in the most effective manner possible. There are numerous methods to search for errors in data sets, but the few ones used in this analysis are here.

2.3.1 Look for Missing Values

The best way to locate missing values is if you have this feature available, to do a count. If not, there are other ways to locate values that are missing. To see if there are any missed values in your tables, consider sorting your columns (both 'ascending' and 'descending') or searching your dataset so that you're only looking at documents with a missing value. Although often missed values are undoubtedly due to chance, it's worth double-checking to see whether there may be an underlying cause for missing values and fix them as best you can.

2.4 Drought Indicators

Collectively, the drought indexes used in this analysis characterize meteorological drought. Standardized Precipitation Evaporation Index (SPI), Standardized Precipitation Evaporation Index (SPEI-Thornthwaite), Standardized Precipitation Evaporation Index (SPEI-Penman), Standardized Precipitation Evaporation Index (SPEI-Hargreaves) (using multiple time scales such as 1, 3, 6, 12 and 24-months). In the following section, these indexes are briefly listed.

2.4.1 Standardized Precipitation Index (SPI)

The SPI ideally uses a monthly time series of rainfall data (30 years or more) to measure its value. The uniform departure calculated by SPI is that the observed precipitation on a given time scale deviates from the normal long-term precipitation. The equation matches a function of probability density to the frequency distribution of precipitation rounded up over the span of interest and then transitions to a regular distribution. Meteorological droughts are categorized into various degrees of intensity based on SPI values, as seen in Table 2 below.

Table 2: SPI values that show different categories of drought severity

Value	Drought Category
≥ 2.0	**extremely wet**
1.5 –1.99	**very wet**
1.0 – 1.49	**moderately wet**
-0.99 - 0.99	**near normal**
-1.0 - -1.49	**moderately dry**
-1.5 - -1.99	**severely dry**
≤ -2.0	**extremely dry**

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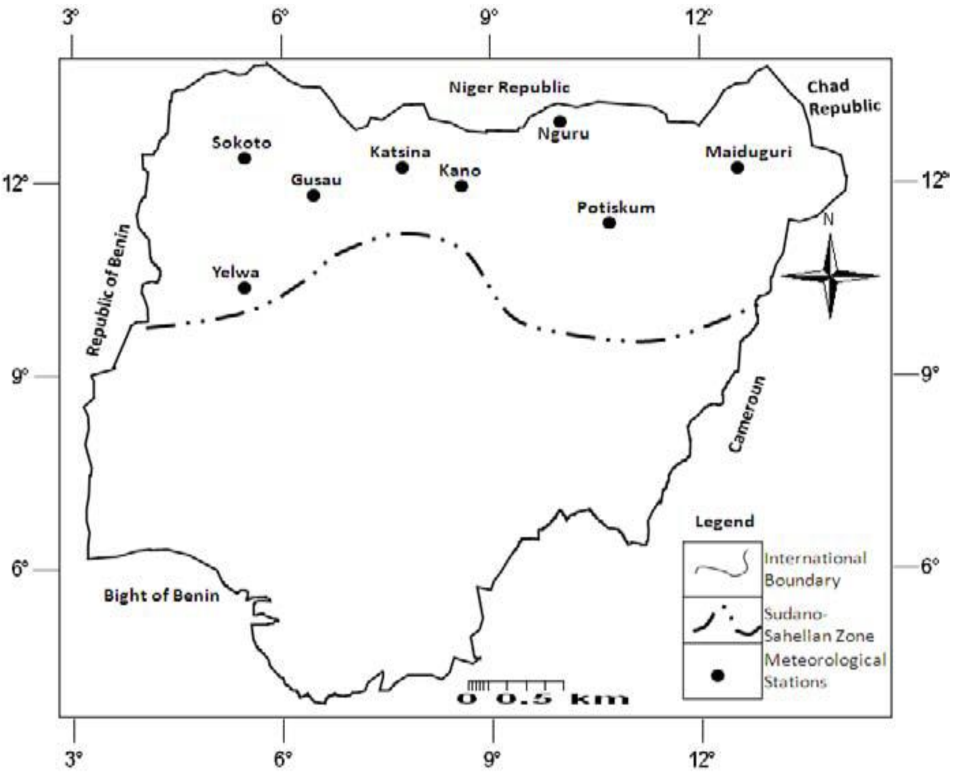

Figure1: The Sudano-Sahelian Agro-ecological Zone of Nigeria (Extracted from Iloeje, 1982)

Standardized Precipitation Index (SPI) is a tool of drought monitoring and has been used to measure the rainfall deficit for drought monitoring. To measure the SPI values, first, the long-term rainfall record is fitted with a probability distribution. In [37] and [40], the gamma distribution was used as it matches the rainfall time series well. Gamma distribution was also used in the current study to match the long-term rainfall record; gamma distribution is defined by its probability density function of Equation (1).

$$f(x;\alpha;\beta) = \frac{1}{\beta^{\alpha}\Gamma\,(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}\, for\; x, \alpha, > 0 \quad (1)$$

Where α and β are the shape and scale parameters respectively; x is the rainfall Where the shape and scale parameters are α and β respectively; x is the rainfall the number, and Γ(α) is the gamma function. The maximum likelihood method was used to estimate the optimal α and β parameter values the amount, and Γ(α) is the gamma function. The maximum likelihood method was used toestimate the optimal values of α and β parameters using Equations (2)

The resulting parameters are then used to determine the cumulative probability for non-zero rainfall using Equation (2).

$$F(x,\alpha,\beta) = \int_0^x f(x;\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \quad (2)$$

2.4.2 Standardized Precipitation Evaporation Index (SPEI)

The Standardized Index of Precipitation-Evapotranspiration (SPEI) was established by [43]. This amendment preserves the flexibility of the calculation, the multi-temporal nature and the statistical interpretability of the SPI, while at the same time offering a broader measure of the availability of water, including a broader measure of climate conditions[18].

The first step was to quantify PET using a possible evapotranspiration (PET) model already developed, such as Penman-Monteith (PM), Thorthwaite, Hargreaves, etc. The selection of the PET model to be used would be dependent on the availability of variables available.

After the same method, the measured D*i* values are aggregated at various time scales.

As it did with the SPI. Depending on the selected time scale, *k*, the difference in a given month *j* and year *i*. For example, with a 12-month time scale, the accumulated difference for one month in a given year is measured according to:

$$X_{i,j}^{k} = \sum_{i=13-k-j}^{12} D_{i-1,l} + \sum_{i=1}^{j} D_{i,l}, \qquad if\; j < k \quad (3)$$

$$X_{i,j}^{k} = \sum_{i=j-k+1}^{j} D_{i,l}\;, if\; j \geq k, \qquad (4)$$

D*i* is then fitted to a three-parameter log-logistic distribution [43]. The probability density function of a log-logistic distributed variable with three parameters is expressed as:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left(1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)^{-2} \qquad (5)$$

Where α, β, and γ are scale, shape, and origin parameters, respectively, for D values in the range (γ > D > ∞).

Log-logistic distribution parameters can be derived following various procedures. The L-moment technique is the most robust and simplest method among them.

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \qquad (6)$$

Having obtained *F(x)* the SPEI can easily be obtained as the standardized values of *F(x)*.

In this research, the Hargreaves method, the Thornthwaite method, and the Penman method were used to obtain PET [39]. R scripts were used to analyze both the SPEI and SPI on a 1, 3, 6, 12, and 24-month time scale for all the eight stations in Northern Nigeria.

i. Thornthwaite method (SPEI-T)

A frequently used method for estimating possible evapotranspiration was obtained by [39] correlating mean monthly evapotranspiration temperature with mean monthly evapotranspiration temperature as calculated from the valley water balance where enough moisture was sufficient to support active transpiration. The computational steps of the Thornthwaite equation are discussed in order to explain the current system. [38]

1. The estimation of the annual value of the heat index *i* is based on the number of monthly indices for 12 months.

The monthly indices are obtained from the equations

$$i = \left(\frac{T_a}{5}\right)^{1.5} \qquad (7)$$

In which *i* is the annual heat index, *i* is the monthly heat index for the month *j* (which is zero when the mean monthly temperature is 0 °C or less), *j* is the number of months (1–12 and) T_a is the mean monthly air temperature (°C).

2. The Thornthwaite general equation, Equation (8) calculates unadjusted monthly values of potential evapotranspiration, ET_0 (in mm), based on a standard month of 30 days, 12 h of sunlight/day.

$$ET = C(10T_a/\,I)^a \qquad (8)$$

In which C= 16 (a constant) and a=*67.5 *10*$^{-8}I^3$*-77.1* 10*$^{-6}I^2$ *+0.0179I + 0.492.*

In the preceding equation, the value of the exponent *a*ranges from zero to 25 [38], the annual heat index ranges from zero to 160, and ET_0 is zero for temperature below 0 °C.

3. The unadjusted monthly evapotranspiration, ET_0values are adjusted depending on the number of N days per month and the average monthly or daylight d (in hours) duration, depending on the season and latitude.

ii. Hargreaves method.(SPEI-H)

For the Hargreaves (1975) equation for estimating grass-related reference ET, Hargreaves proposed several improvements. Because data on solar radiation is often not available, it is recommended to estimate R_s from extraterrestrial radiation, R_A, and the difference between the mean monthly maximum and minimum temperatures, TD (in °C). The resulting form of the equation is;

$$ET = 0.0023\, R_A\, TD^{\frac{1}{2}}(T_a + 17.8) \qquad (9)$$

R_A, the extraterrestrial radiation, is expressed in evaporation equivalent units for a specified latitude and day. R_A is derived from tables or can be measured using a series of equations. Air temperature is the only variable for a given position and time. The Hargreaves method, thus, has become a method dependent on temperature.

iii. Penman Method (SPEI-P)

A semi-empirical equation that incorporates mass transfer (E*a*) and energy budget (H) methods is the penman formula. The formula was developed in 1948 by Penman and is now commonly used to implement synoptic meteorological data to measure the potential evaporation. According to Penman, the E*o* (in mm/day) potential evaporation can be calculated as :

$$\lambda ET = \frac{\Delta\,(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1+\frac{r_s}{r_a}\right)} \qquad (10)$$

Where R*n* is the net radiation, G is the soil heat flux, (e_s-e_a) indicates the air vapor pressure deficit, ρ_a. The mean air density at constant pressure is the mean air density, c_p is the special heat of the air, Δ is the slope of the relationship between saturation vapor pressure and temperature, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances. In the FAO-56 manual, the complete description of each parameter can be found.

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III. RESULT AND DISCUSSION

3.1 Result of Descriptive Statistics

The descriptive statistics of the four indexes on time scale 6 are shown in Table 3 below. The descriptive statistics are Mean, Standard Error, Median, Mode, Standard Deviation, Sample Variance, Kurtosis, Skewness, Range, Minimum and Maximum values, Sum and Count are the properties of each index and have been calculated as shown below.

3.2 Correlation Between Drought Indices

By comparing the computed values of drought indices, a comparison was made between different drought indices. The Pearson correlation coefficients have been calculated and computed for this reason between paired time series. For example, SPI 1-estimated severity values are paired with SPEI-T 1-estimated severity values, and the correlation coefficient (0.493) is calculated to form one matrix cell for this pair. Similarly, the severity values calculated using SPI-1 are combined with the severity values estimated using all time steps using other drought indexes, and so on. A cross-correlation matrix of 24 rows and 24 columns, that is, a matrix of 24 by 24, was developed. For the all-time series, from January 1981 to December 2017, the Correlation matrix was completed.

Table 3: The Descriptive Statistics of the Four Indices.

	SPI 6	SPEI-T-6	SPEI-H- 6	SPEI-P-6
Mean	0.095	-0.001	0.007	0.003
Standard Error	0.046	0.048	0.047	0.048
Median	0.115	0.055	0.009	0.018
Mode	0.629	0.000	-0.545	0.000
Standard Deviation	0.935	0.976	0.973	0.979
Sample Variance	0.874	0.952	0.947	0.957
Kurtosis	-0.292	-0.534	-0.653	-0.465
Skewness	-0.096	0.003	0.235	0.006
Range	4.639	4.673	4.863	5.003
Minimum	-2.434	-2.401	-2.258	-2.685
Maximum	2.205	2.272	2.605	2.319
Sum	39.842	-0.597	2.993	1.261
Count	420	420	420	420

	SPI 1	SPI 2	SPI 3	SPI 6	SPI 12	SPI 24	SPEI-T 1	SPEI-T 2	SPEI-T 3	SPEI-T 6	SPEI-T 12	SPEI- T 24	SPEI-H 1	SPEI-H 2	SPEI-H 3	SPEI-H 6	SPEI-H 12	SPEI-H 24	SPEI-P 1	SPEI-P 2	SPEI-P 3	SPEI-P 6	SPEI-P 12	SPEI-P 24
SPI 1	1																							
SPI 2	0.7629	1																						
SPI 3	0.66846	0.83031	1																					
SPI 6	0.575184	0.682382	0.757413	1																				
SPI 12	0.246873	0.332867	0.405648	0.603324	1																			
SPI 24	0.22294	0.287313	0.3459	0.487766	0.780599	1																		
SPEI-T 1	0.492528	0.405546	0.347748	0.276109	0.076482	0.017994	1																	
SPEI-T 2	0.35964	0.522801	0.442286	0.329341	0.121897	0.037386	0.736961	1																
SPEI-T 3	0.298806	0.439519	0.53139	0.374424	0.164585	0.065885	0.613111	0.842551	1															
SPEI-T 6	0.209016	0.310284	0.392602	0.552279	0.333364	0.183406	0.42948	0.605175	0.731569	1														
SPEI-T 12	0.082548	0.141034	0.182198	0.301122	0.52923	0.324393	0.25543	0.376528	0.458301	0.680875	1													
SPEI- T 24	0.085919	0.130243	0.166448	0.237306	0.339334	0.504903	0.116971	0.19389	0.262365	0.427806	0.652747	1												
SPEI-H 1	0.874139	0.679623	0.592536	0.510216	0.249194	0.211577	0.492052	0.361877	0.305723	0.208422	0.070071	0.061879	1											
SPEI-H 2	0.646991	0.911978	0.764613	0.624572	0.32425	0.265441	0.418219	0.519711	0.448627	0.318828	0.131306	0.105405	0.731855	1										
SPEI-H 3	0.562894	0.748565	0.923577	0.701986	0.391497	0.318461	0.353356	0.444264	0.529117	0.403629	0.168572	0.141585	0.645355	0.819384	1									
SPEI-H 6	0.491017	0.618887	0.694695	0.944602	0.585512	0.457966	0.286064	0.33374	0.3786	0.549335	0.289024	0.215257	0.555043	0.675086	0.746662	1								
SPEI-H 12	0.249423	0.333762	0.407268	0.602861	0.998292	0.779867	0.078124	0.124585	0.168511	0.335564	0.531971	0.3437	0.250998	0.325091	0.392783	0.585426	1							
SPEI-H 24	0.223457	0.286812	0.345763	0.487689	0.780973	0.998508	0.020133	0.039242	0.068184	0.184335	0.323432	0.497814	0.211975	0.265335	0.318459	0.457994	0.780228	1						
SPEI-P 1	0.541058	0.453452	0.418014	0.365495	0.227595	0.184594	0.633129	0.461757	0.379272	0.224164	0.085934	0.024829	0.564957	0.443771	0.412169	0.365448	0.224004	0.186325	1					
SPEI-P 2	0.41808	0.574814	0.524626	0.44305	0.311008	0.249365	0.47786	0.602521	0.509125	0.331096	0.149419	0.067281	0.444313	0.571362	0.510636	0.436298	0.308183	0.249547	0.757914	1				
SPEI-P 3	0.348385	0.496264	0.600307	0.488731	0.375911	0.304097	0.376088	0.505857	0.581119	0.396138	0.188752	0.102589	0.380244	0.503889	0.59439	0.483332	0.373437	0.30265	0.630554	0.861381	1			
SPEI-P 6	0.262922	0.381332	0.477722	0.654533	0.555995	0.429673	0.219508	0.323967	0.407782	0.574681	0.328212	0.190631	0.285652	0.39278	0.486667	0.652112	0.551636	0.428176	0.455025	0.631369	0.75475	1		
SPEI-P 12	0.136381	0.206596	0.270637	0.442772	0.786035	0.602903	0.086119	0.136341	0.181528	0.33599	0.520108	0.280487	0.145185	0.208254	0.265946	0.431938	0.780611	0.599871	0.285015	0.403731	0.491641	0.711236	1	
SPEI-P 24	0.153237	0.202545	0.252398	0.384624	0.64246	0.829622	0.005047	0.025345	0.052759	0.174518	0.320176	0.51648	0.141149	0.180992	0.225841	0.353966	0.633713	0.824686	0.244206	0.333439	0.396337	0.548759	0.734899095	1

Figure 2: Pearson correlation matrix of product-moment correlation coefficients computed between paired values of drought index times series showing the most correlated index

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Results from Figure 2 indicate that the four indexes are correlated significantly. If the time scales increase, the correlation between SPI, SPEI-P and SPEI-H increases, with the highest correlation recorded being (0.9985) between SPI 24 and SPEI-H 24. The correlation between SPEI-P and SPEI-H also increases with increasing time scales, with the highest value recorded being (0.825 between SPEI-P 24 and SPEI-H 24). In comparison, the result shows that the correlation between SPEI-T and other indices (SPI, SPEI-H, and SPEI-P) increases with a maximal value of up to time scale 6 (0.575 between SPEI-T 6 and SPEI-P 6), but decreases for time scales 12 and 24. It was observed that each index correlates with the SPI, with 0.999 (between SPI 24 and SPEI-H 24) being the highest correlation observed and 0.493-H 24 being the lowest (between SPI 1 and SPEI-T 1).

SPI and SPEI-H were both the most correlated, with the lowest value being between SPI-1 and SPEI-H 1 (0.874) and the maximum being between SPI-24 and SPEI-H 24 (0.998). The correlation between the various indices and the different time scales was also observed to be much smaller than that of the same indices and the same time scale. This was also apparent from the observations of the other stations in the study area.

3.3 Linear regressions between SPI and SPEI-T, SPEI –H and SPEI-P

The statistical relationship indices were checked by fitting a trend of linear regression to their time-series. A monotonous increasing relationship between all the different indices is shown in the regression analysis.

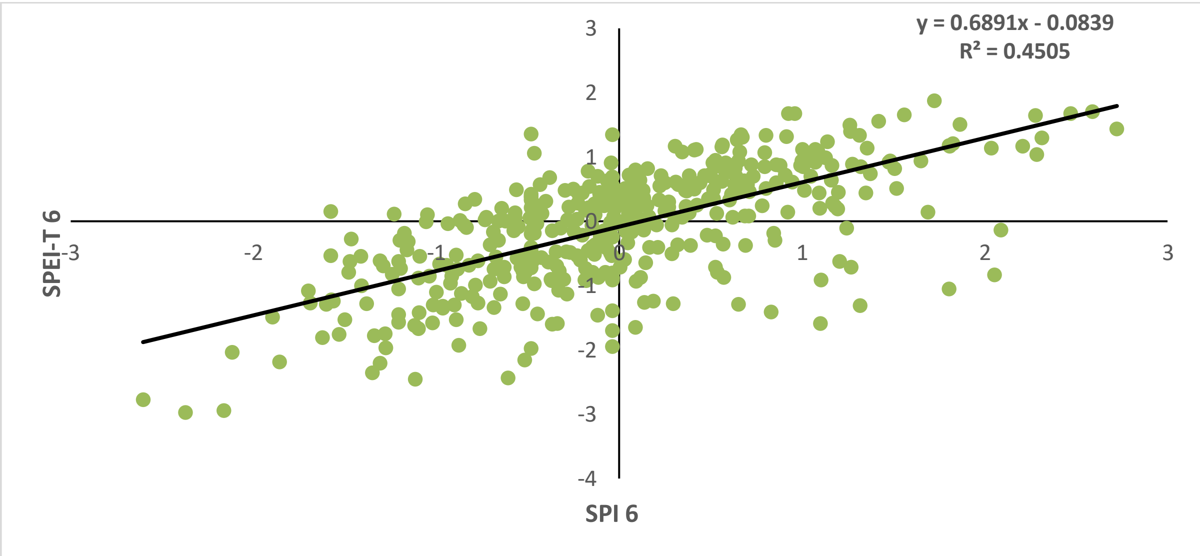

Figure 3a: The scatter diagram of SPI6 vs SPEI-T 6 showing the linear equation and R^2 value.

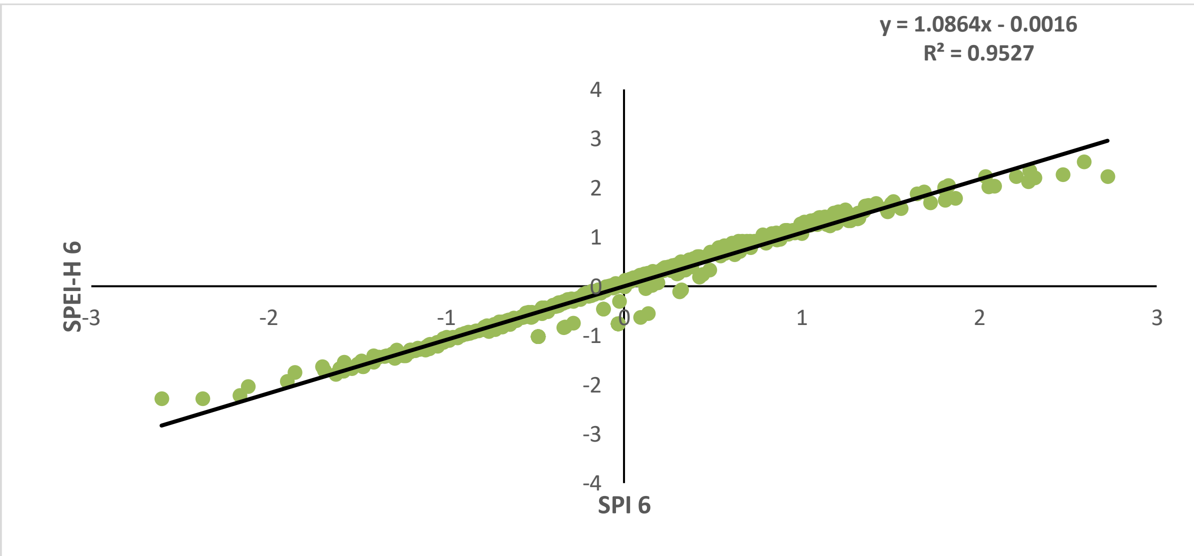

Figure 3b: The scatter diagram of SPI6 vs SPEI-H 6 showing the linear equation and R^2 value.

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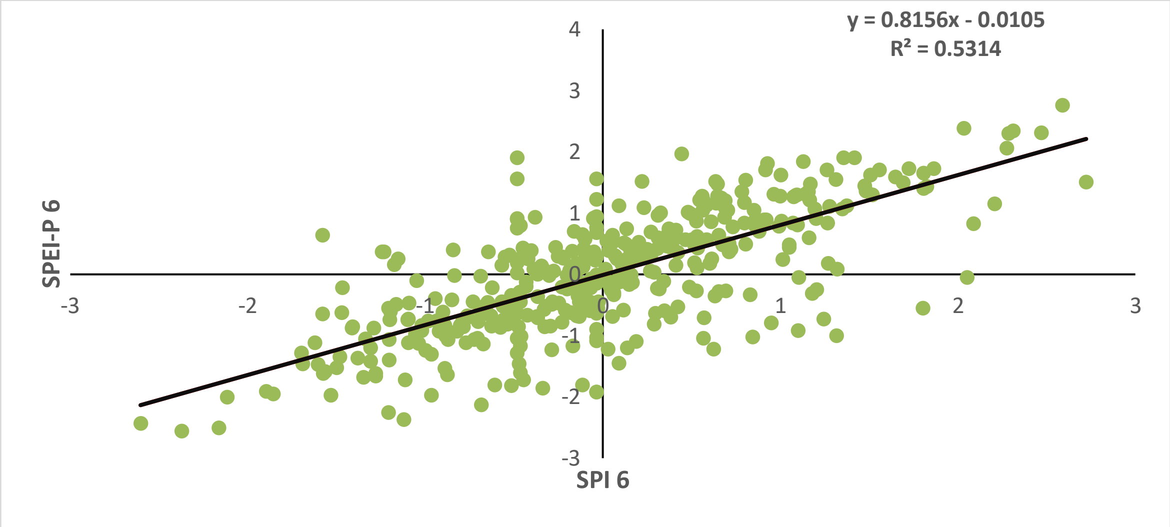

Figure 3c: The scatter diagram of SPI6 vs SPEI-P 6 showing the linear equation and R^2 value.

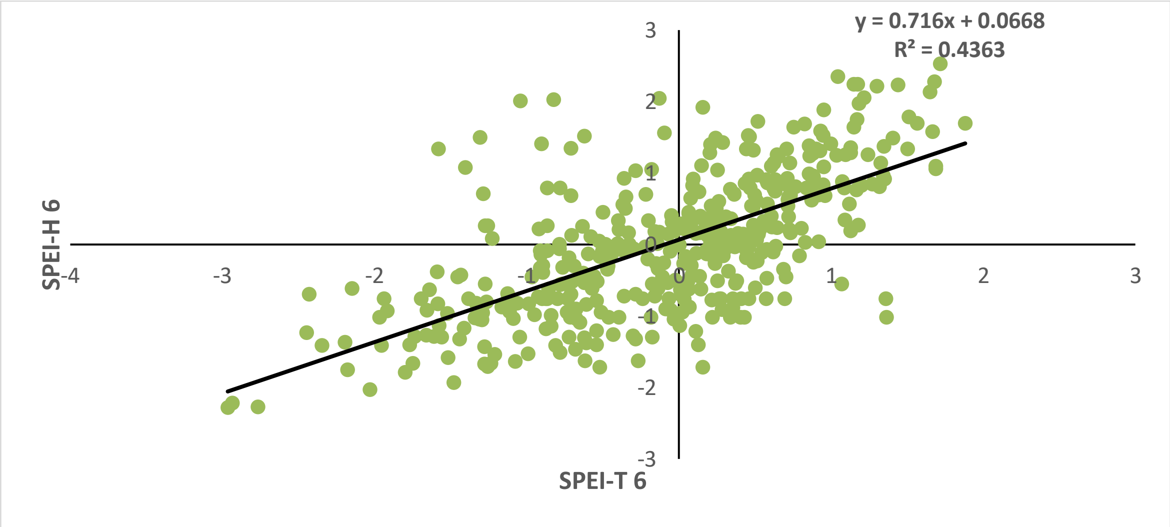

Figure 3d: The scatter diagram of SPI-T 6 vs SPEI-H 6 showing the linear equation and R^2 value.

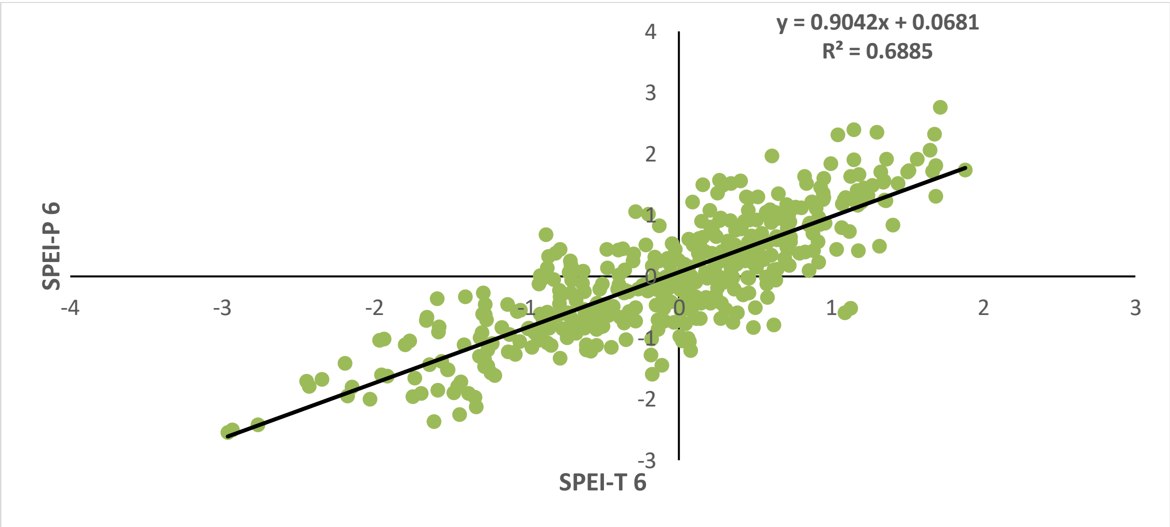

Figure 3e: The scatter diagram of SPEI6 vs SPEI-T 6 showing the linear equation and R^2 value.

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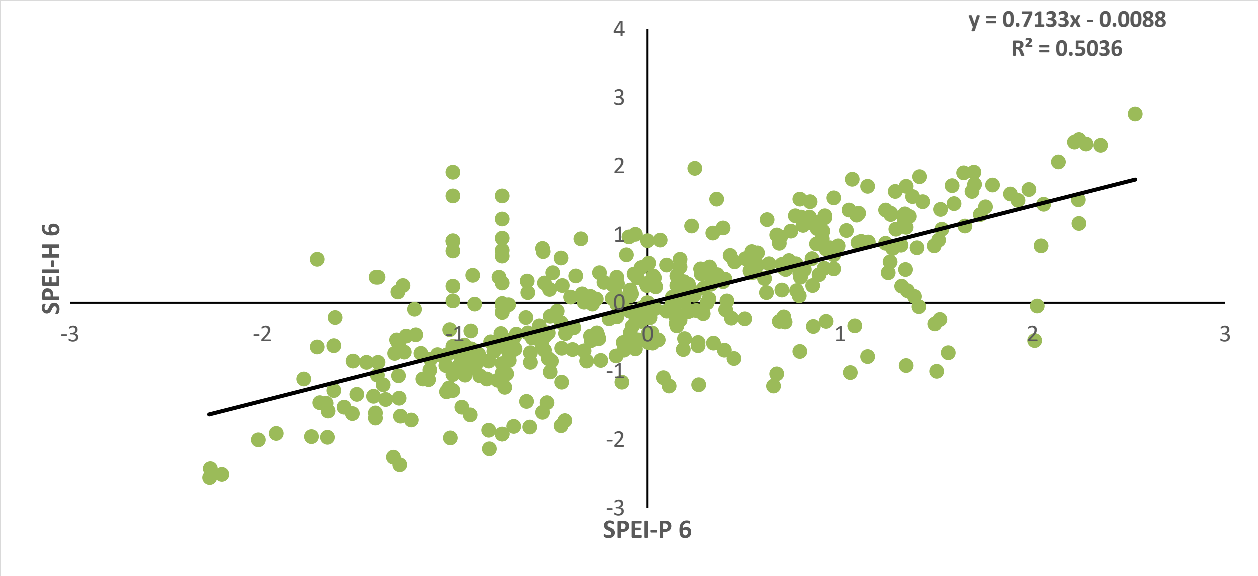

Figure 3f: The scatter diagram of SPEI-H 6 vs SPEI-P 6 showing the linear equation and R^2value.

SPI 6 VS SPEI-H 6 has the highest R^2 value (0.9527), which is a very good fit, as shown in figures 3a, b, c, d, e and f above, i.e. the values fit the regression analysis model, while SPEI-T 6 and SPEI-H 6 have the lowest R2 value (0.4363), which is a very bad fit, i.e. the values do not fit the regression analysis model. As seen in figure 4, the highest R^2 value recorded is between SPI 12 and SPEI-H 12 (0.9918), which is a very good fit.

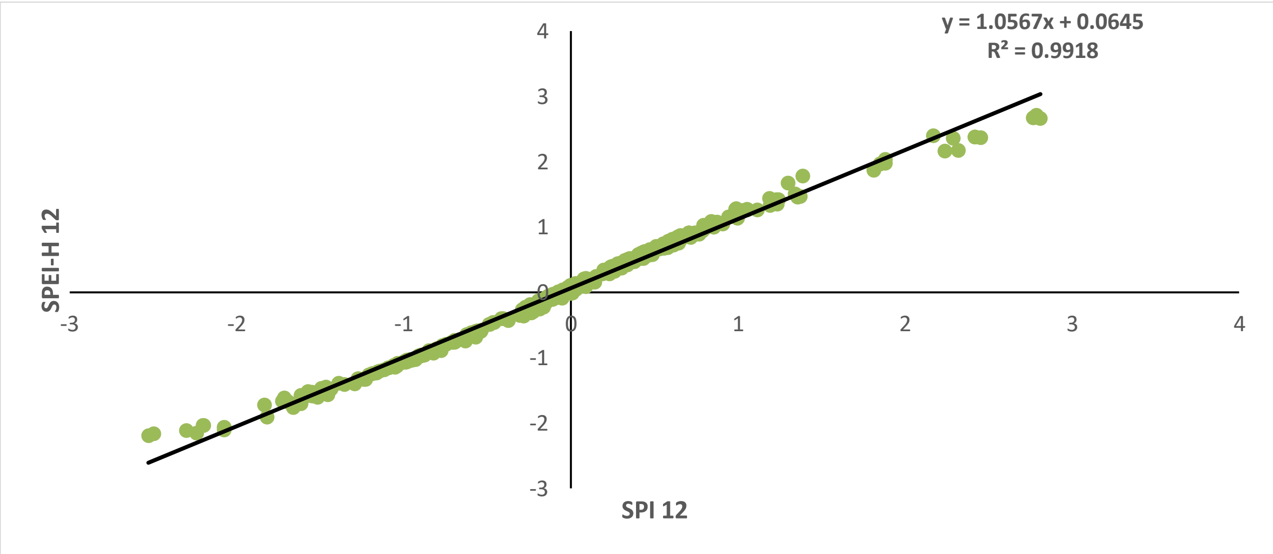

Figure 4: Linear regression between SPI 12 and SPEI-H 12 showing R^2 value.

From the results of the regression analysis obtained (Figure 4), it was observed that the determinant coefficient (R^2) increases to time scale 12 as the time scale increases, but decreases to time scale 24 as seen above.

3.4 Comparison of Drought Indices Based on Drought Characteristics

3.4.1Comparison of Number of Drought Occurrences Recorded

A comparison of the drought indices based on the features of the drought, such as the percentage of drought months, overall drought intensity and length of the drought, was evaluated and used for each index as additional parameters for comparison. In this section, the results obtained at three (3) stations representing the majority of the study region were discussed. The percentage of drought months reflects, as seen in Table 9 below, the proportion of the overall number of drought months.

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3.4.2 Comparison of the Type of Drought Severity Detected

Within the sample cycles (1981-2015) of each station, the percentage of drought months represents the proportion of the total number of drought events (moderate, medium, and serious droughts). Figure 5 below displays the number of drought events reported by all indices for two (2) stations.

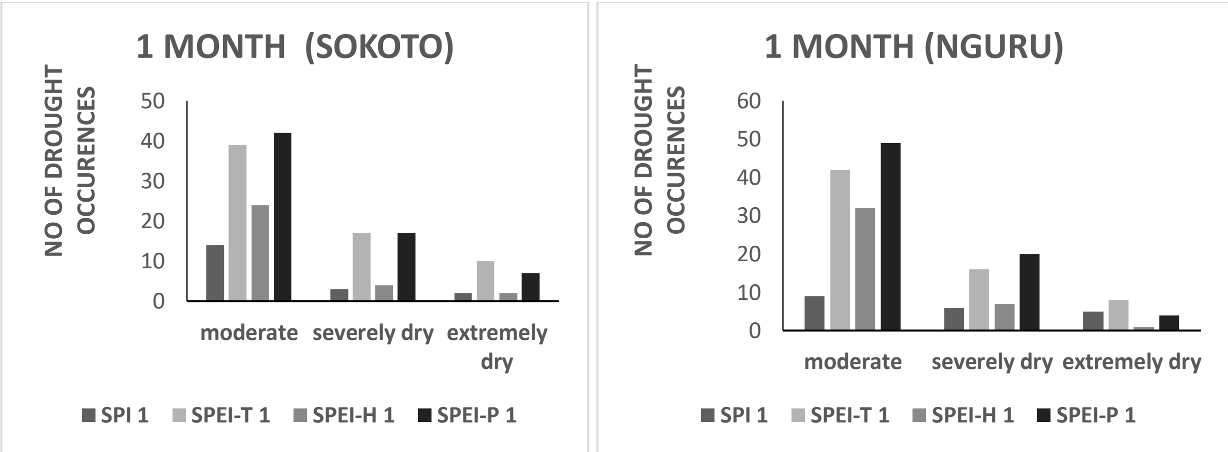

Figure 5a: Histograms showing the frequency of drought intensities category captured by the various indices for 1-month time scale.

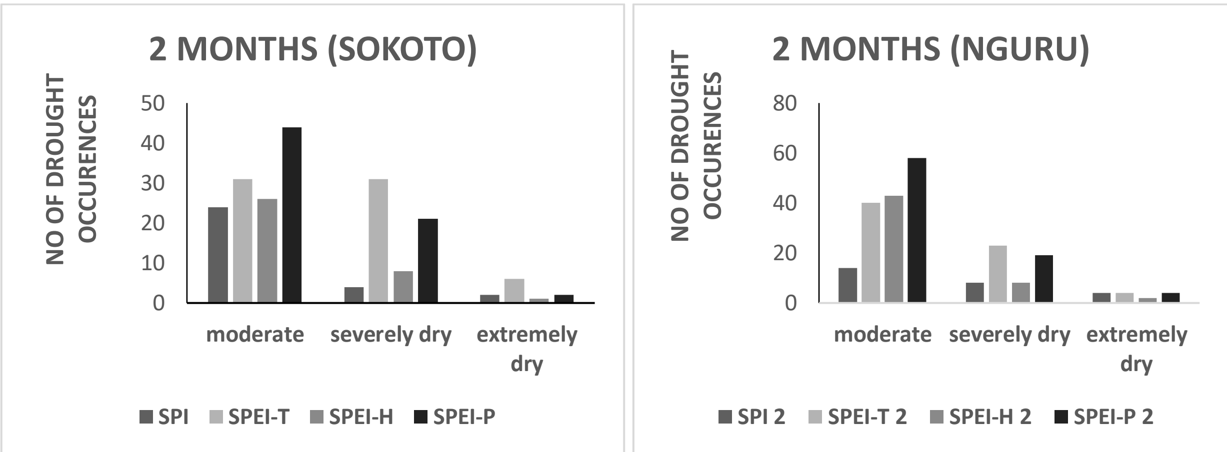

Figure 5b: Histograms showing the frequency of drought intensities category captured by the various indices for 2-month time scale.

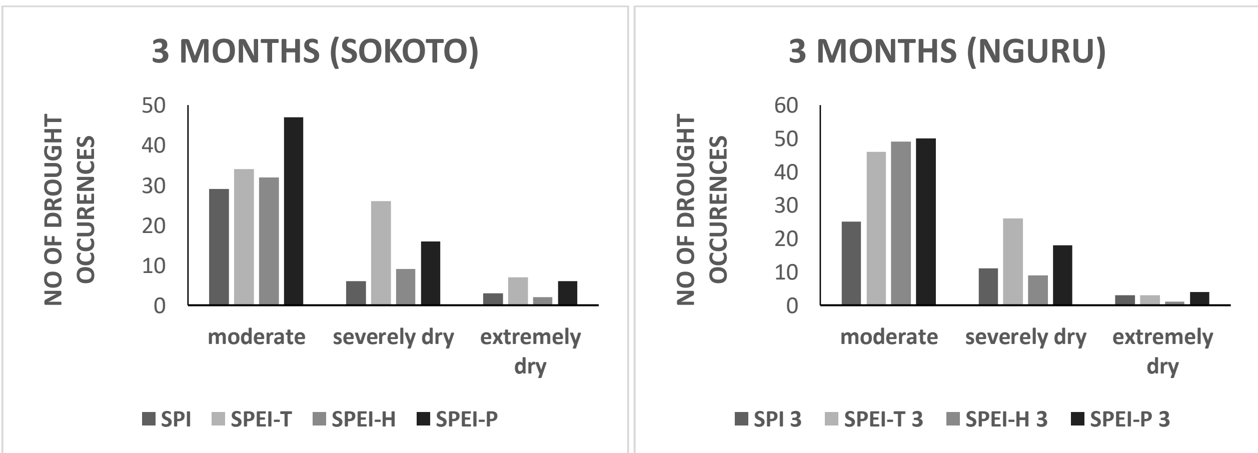

Figure 5c: Histograms showing the frequency of drought intensities category captured by the various indices for 3-month time scale.

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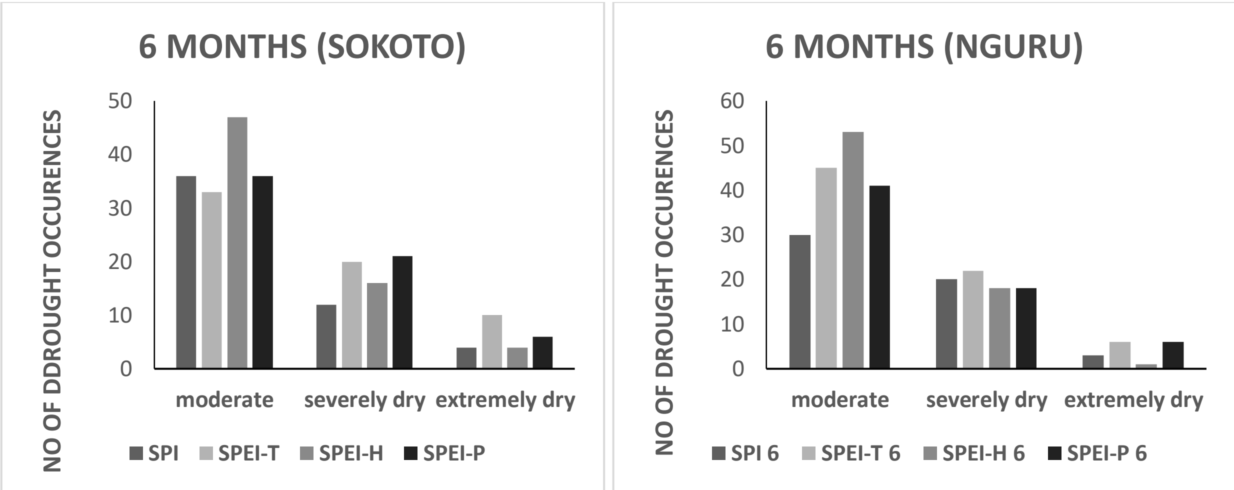

Figure 5d: Histograms showing the frequency of drought intensities category captured by the various indices for 6-month time scale.

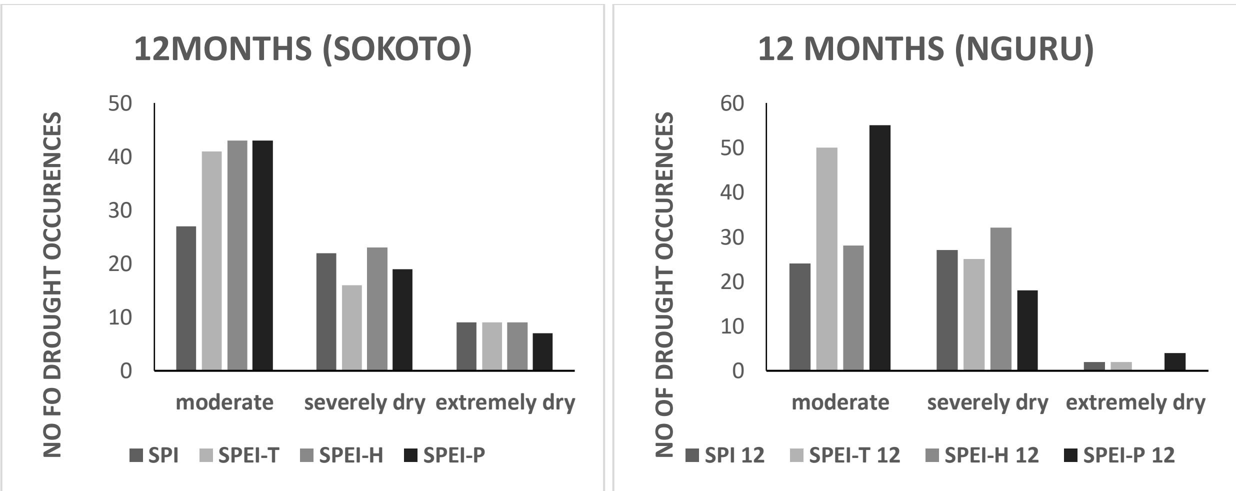

Figure 5e: Histograms showing the frequency of drought intensities category captured by the various indices for 12-month time scale.

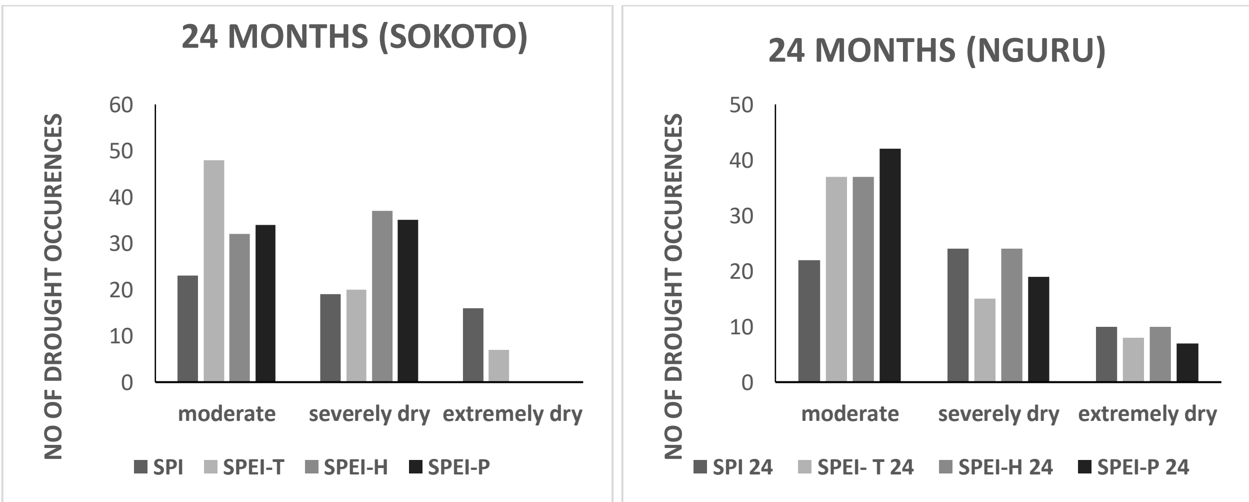

Figure 5f: Histograms showing the frequency of drought intensities category captured by the various indices for 24-month time scale.

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The results of the histograms in Figures 5a, b, c, d, e, and f above show that SPEI-P recorded the highest number of moderate drought occurrences for time scales 1,2,3 and 12 in both stations, while SPEI-T recorded the highest for time scale 24 and the second highest moderate drought for all-time series in both stations. For both stations, SPEI-T recorded the highest number of severely dry droughts for time scales 1,2,3 and 6, as well as the highest number of SOKOTO extremely dry droughts for time scales 1,2,3,6 and 12. It was also noted that for both stations, for all-time series, SPI reported mostly the lowest amount of moderate, severe, and extreme drought. For the six (6) month time series, SPEI-H identified the largest number of moderate droughts. It was found that for both stations, the 6-month time series was better associated. This was also apparent from the observations of the other stations in the study area. This was also apparent from the observations of the other stations in the study area.

3.4.3 Comparison of Maximum Drought intensity, Severity, and Duration

In addition to the number of cumulative drought months, the maximum duration of a single drought occurrence (continuous drought months) is often calculated using separate indexes over all time intervals. Another reference criterion for drought indexes for all periods was often known to be the overall length of the drought. Tables 4 and 5 below display the duration, onset and offset times, severity, magnitude, and intensity of two (2) stations.

Table 4: The maximum duration, magnitude, intensity, and severity of Sokoto for four (4) indices and three-time scales

	DURATION, D (MONTHS)	ONSET DATE	END DATE	MAGNITUDE (M)	INTENSITY	SEVERITY (MxD)
SPI 6	41	Sep-83	Jan-87	-0.89	-2.60	-36.49
SPI 12	81	Dec-81	Aug-88	-1.128	-2.53	-91.37
SPI 24	103	Dec-82	Jun-91	-1.129	-2.23	-116.29
SPEI-T 6	31	Jun-07	Dec-09	-0.441	-2.96	-13.67
SPEI-T 12	26	May-82	Aug-88	-0.917	-2.48	-23.84
SPEI-T 24	79	Dec-82	Jun-89	-1.0837	-2.41	-85.61
SPEI-H 6	41	Sep-83	Jan-87	1.027	-2.27	42.11
SPEI-H 12	81	Dec-81	Aug-88	-1.126	-2.18	-91.21
SPEI-H 24	103	Dec-82	Jun-91	-1.091	-1.86	-112.37
SPEI-P 6	17	June-08	Oct-09	-1.282	-2.55	-21.79
SPEI-P 12	50	Jun-84	Jul-88	-1.18	-2.58	-59.00
SPEI-P 24	58	Jun-84	May-89	-1.2	-1.92	-69.6

Table 5: showing the maximum duration, magnitude, intensity, and severity of Katsina for four (4) indices, and three-time scales

	DURATION, D (MONTHS)	ONSET DATE	END DATE	MAGNITUDE (M)	INTENSITY	SEVERITY (Mx D)
SPI 6	42	Jul-91	Dec-94	-0.962	-3.43	-40.40
SPI 12	116	Aug-91	Mar-01	-0.99	-1.89	-114.84
SPI 24	128	Jul-91	Jun-00	-0.99	-1.91	-126.72
SPEI-T 6	76	Apr-82	Jul-88	-0.6964	-2.75	-52.926
SPEI-T 12	77	Apr-82	Aug-88	-0.92	-1.88	-70.84
SPEI-T 24	79	Nov-82	Jun-89	-1.01	-1.9	-79.79
SPEI-H 6	35	Aug-97	Jun-00	-0.639	-2.21	-22.36
SPEI-H 12	108	Jul-91	Jun-00	-1.09	-2.31	-117.72
SPEI-H 24	118	Aug-91	May-01	-0.59	-1.9	-69.62
SPEI-P 6	27	Apr-98	Jun-00	-0.7896	-2.14	-21.32
SPEI-P 12	84	Oct-90	Sep-97	-0.99	-2.34	-83.16
SPEI-P 24	119	Aug-91	Jun-01	-0.59	-2.05	-70.21

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The result for both stations indicates that the maximum drought period observed by each index increases with an increase in the time scale (Tables 10 and 11). Both SPI and SPEI-H respectively detected the same maximum drought duration for SOKOTO, i.e. 41, 81 and 103 months for time scales 6, 12 and 24. The maximum duration for both locations was also detected by SPI 12 and SPI 24, while SPEI-H detected the second maximum duration for both locations. With the exception of the 1-month time series, SPEI-P detected the third highest period for time series 12 and 24 and SPEI-T detected the least duration, which was marginally higher than SPEI-P as seen in figure 6 below.

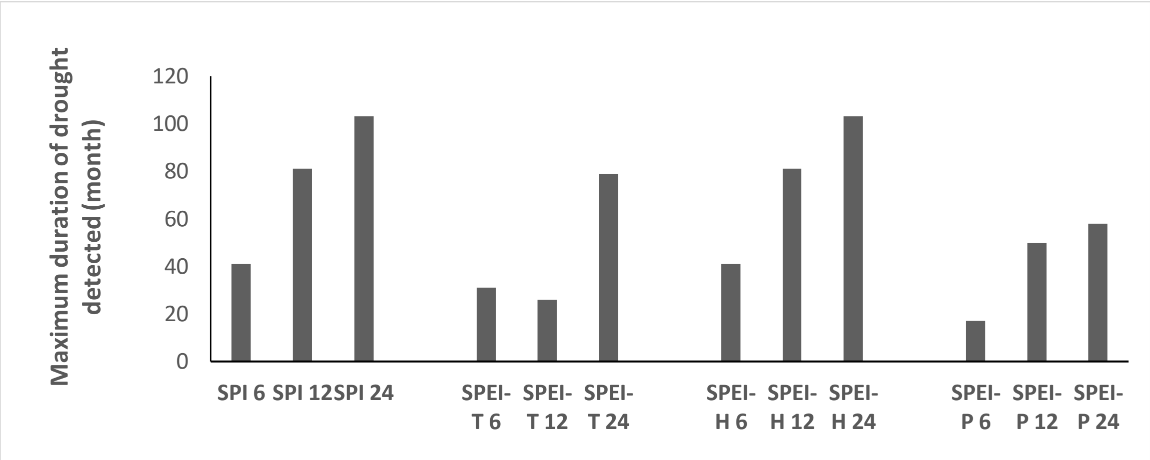

Figure 6a: Histograms showing maximum drought duration detected by drought indices inSokoto

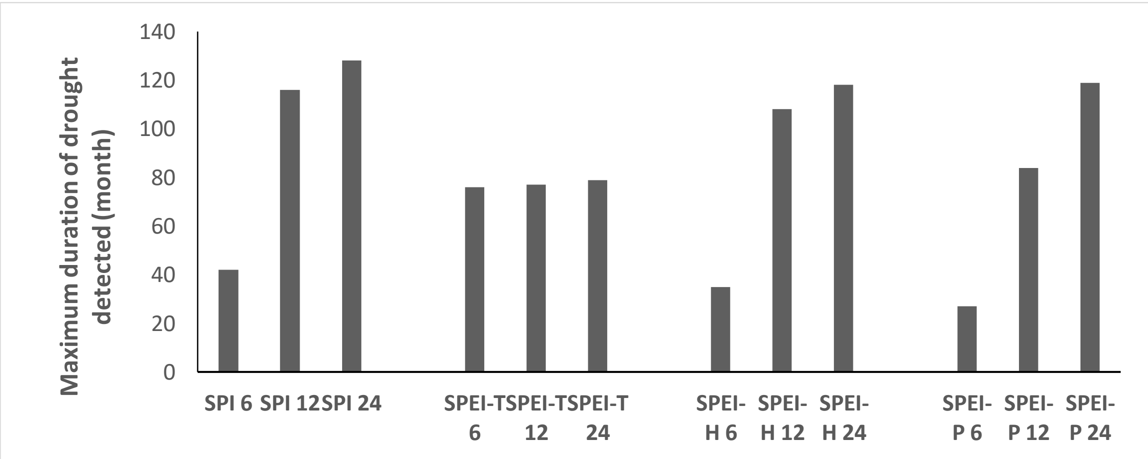

Figure 6b: Histograms showing maximum drought duration detected by drought indices in Katsina

It was found for the onset date that time series 12 and 24 appear to correspond for all positions with the onset date. This is valid since all indexes for the 12-month time series on the Pearson correlation matrix had a higher correlation. Both locations had the same onset and end date for SPI 24 and SPEI-H 24. This should be true since both indices have the highest correlation coefficient and R^2 value. The magnitude of the drought was observed to increase with increasing time scales. For Sokoto, SPEI-P had the highest magnitude for the three timescales (-1.282, -1.18, -1.2 for time scales 6, 12, and 24 respectively) which is followed closely by SPI (-0.89, -1.128, -1.129) while SPI had the highest magnitude for the three-time scales in Katsina (-0.962, -0.99, -0.99) followed closely by SPEI-P (-0.7896, -0.99, -0.59).

The result further reveals that the intensity of the droughts for both stations seems to decrease with increasing time scale. The highest intensity for both stations was recorded by SPI 6 (-2.604 and -3.43 for Sokoto and Katsina respectively). The drought severity which is a product of magnitude and duration (M*x*D) increased with increasing time scale. The maximum severity for both time scales was detected by SPI-24 (-116.287 and -126.72 for Sokoto and Katsina respectively).

4.5 Comparison of Drought Indices through Characterizing the Historic Drought Events

Characteristics of historical droughts as detected by SPI 6, SPEI-T 6. SPEI-H 6 and SPEI-P 6 are presented in figures 7aand 7b.

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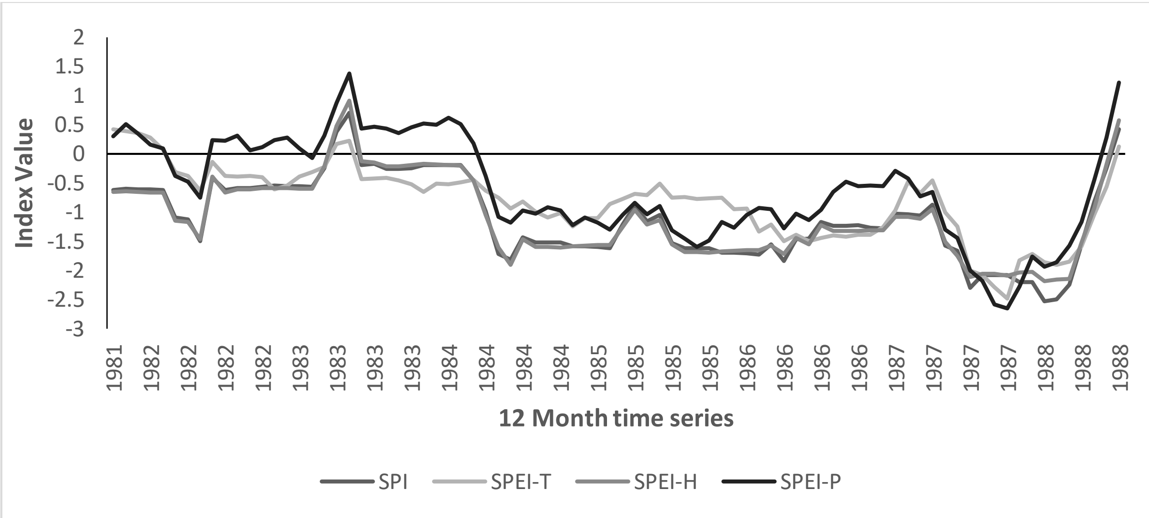

Figure 7a: Graphs showing historical drought (1982-1989) in Sokoto for 12-months' time series.

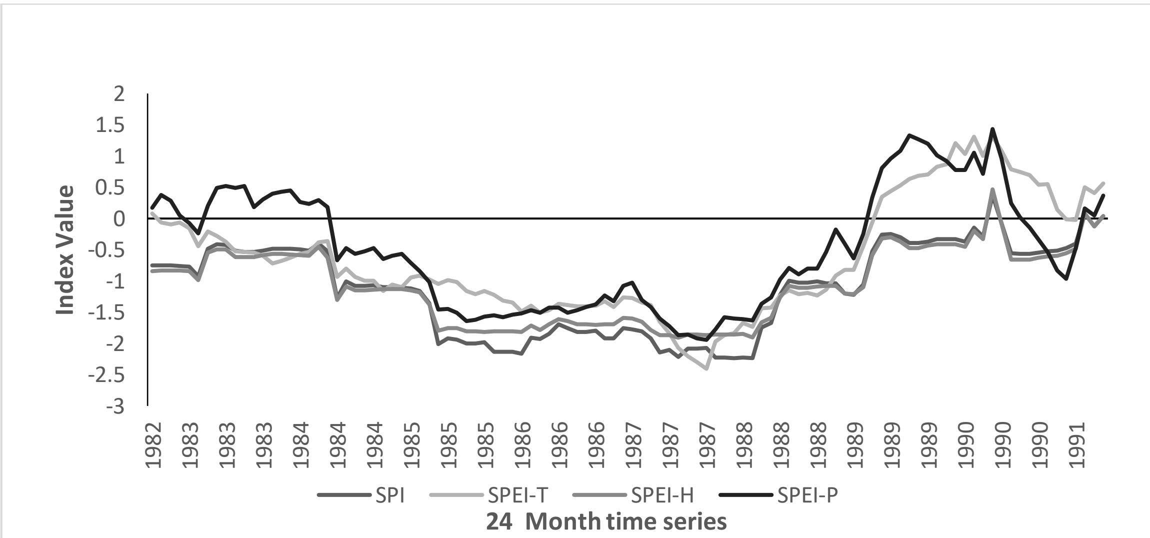

Figure 7b: Graphs showing historical drought (1982-1989) in Sokoto for 24-months' time series.

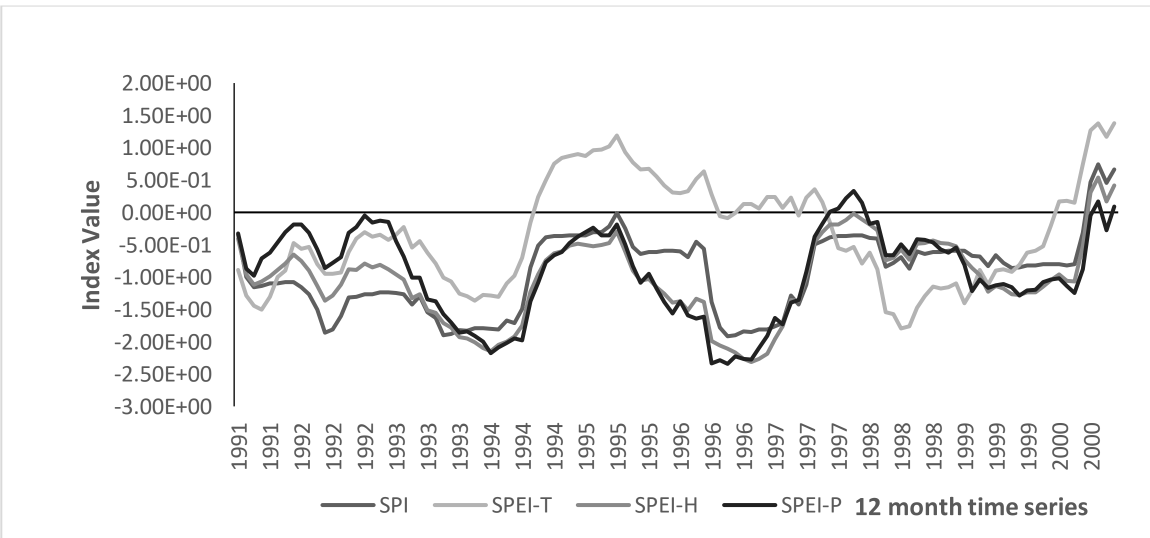

Figure 8a: Graphs showing historical drought (1992-2000) in Katsina for 12-months' time series

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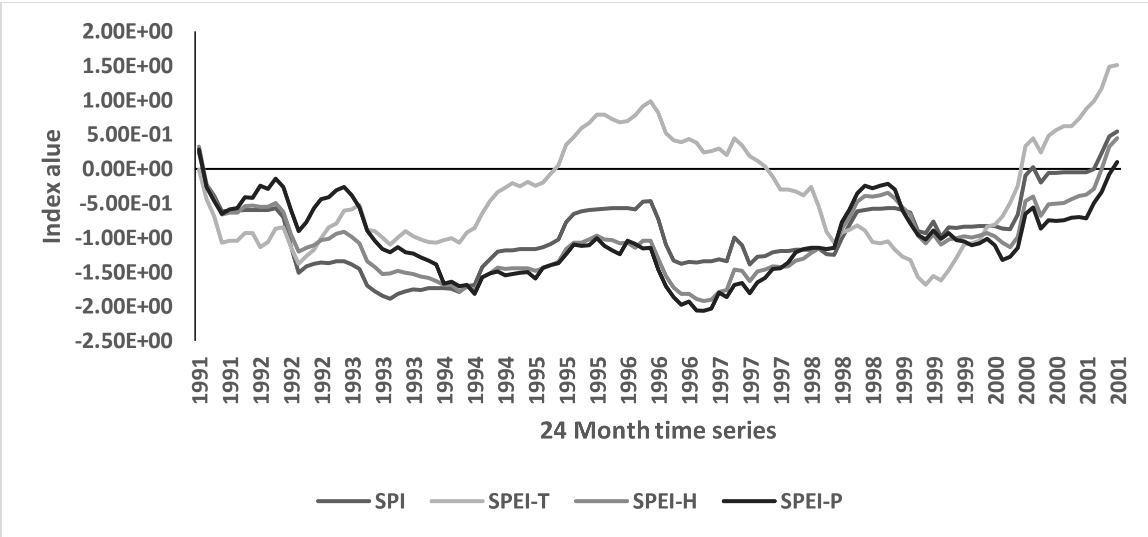

Figure8b: Graphs showing historical drought (1992-2000) in Katsina for 24-months' time series.

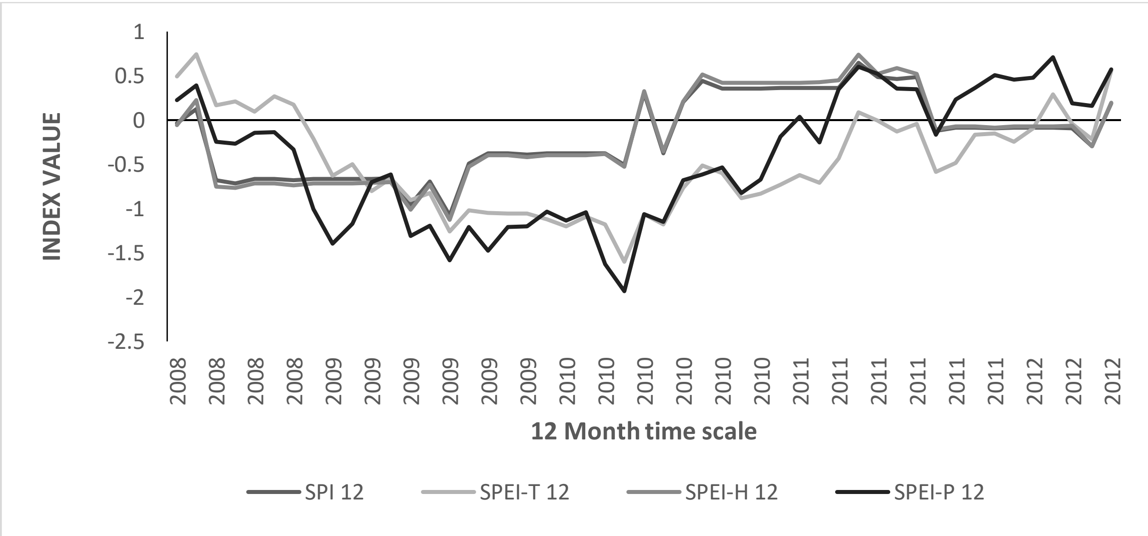

Figure 9a: Graphs showing historical drought (2008-2011) in Sokoto for 12-months' time series.

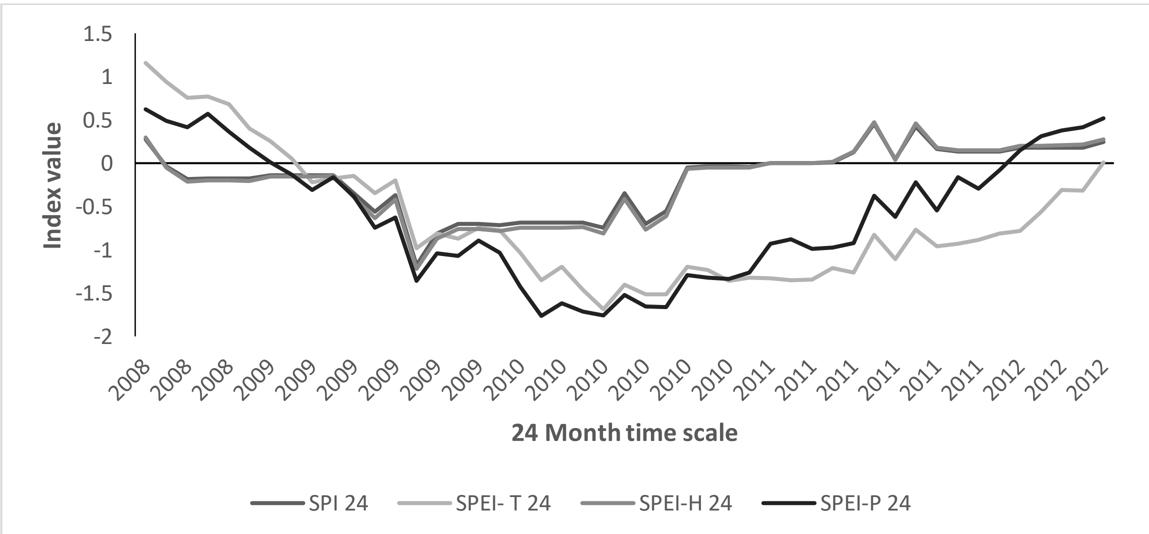

Figure 9b: Graphs showing historical drought (2008-2011) in Sokoto for 24-months' time series.

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The results from figures 7a and 7b reveal that in the historical drought between 1982-1989 in Sokoto, SPI and SPEI-H recorded the earliest onset for both time series followed by SPEI-T. SPEI-P recorded the latest onset and the earliest ending date for both time scales. The highest historic drought intensity (1987) was recorded by SPI and SPEI-H for time scale 12 and SPEI- and SPEI-P recorded the same intensity while SPEI-T recorded the highest for time scale 24 followed by SPI and SPEI-P recorded the lowest. Also, as the time scales increase, the onset and end date of the drought increased. All four indices show the same characteristics for historic drought in this locationbut SPI and SPEI-H are arguably the most appropriate because they both indicated the longest duration.

The result from figures 8a and 8b reveals that in the historical drought between 1992-2000 in Katsina, the four indices recorded the same onset date for both time series and SPEI-T was the first to end. Also, the result further reveals that SPEI-H and SPEI-P have the highest intensity for both time scales and SPEI-P has the longest duration. SPEI-T is revealed to be the poorest for measuring drought in this area and SPEI-P is revealed to be the most appropriate followed by SPEI-H and SPI.

The results from the figure 9a and 9b reveal that in the historical drought between 2008-2011 in Nguru, both SPI and SPEI-H show the earliest onset of drought but ended relatively quickly when compared to the other indices. The highest drought intensity was recorded by SPEI-P followed by SPEI-T for both locations. SPEI-P is revealed to be the most appropriate in this area because it showed the longest duration and maximum intensity for both time series.

3.6 Performance Evaluation of the three Drought Indices

The results of the weightings of the six evaluation criteria carried out using Saaty's pairwise comparison of the Analytic Hierarchy Process (AHP) approach showed that the robustness criterion has the highest weight of 32% due to its relative importance. This is closely followed by tractability and transparency with relative weightings of 27% and 21% respectively. Then sophistication weights

8% and extendability and dimensionality criteria had equal weights of 7% each. The results of the acceptable consistency level in the pairwise comparison of the criteria adjudged by the computed values of Consistency Index (CI) and Consistency Ratio values (CR) were 0.0502 and 0.0401respectively; which are less than 0.1. Saaty proposed that forCR< 0.1, the level of consistency in assigning the pairwise comparison rank istolerable (Saaty, 1980, 1986,).

This weighting is slightly different from therelative weights used by [31]. For instance, [31] obtained the same relative weight of 30% for robustness, but had 25%, 15%, and 10% each for tractability, transparency, and sophistication, extendibility, and dimensionality respectively; as against 27%, 21 and 7% obtained in this paper.

With the weightings of the evaluation criteria achieved, the performance of each of the indices four SPI, SPEI-T, SPEI-H, and SPEI-P subsequently evaluated following the same procedures for the criteria evaluation. Table 10 below is the pairwise comparison matrix of the ranks assigned to each index, for each of the six criteria. The normalized pairwise comparison matrix is obtained by dividing each element in the matrix by its column sum. The results of the eigenvector that defines the index weight for the criteria in consideration obtained by averaging across the rows of the normalized pair wise matrix is shown in Table 6.

The product of the obtained values of the eigenvector and the relative importance weight of the respective six evaluation criteria produced the final weightings and rankings of the indices and result (table 6) shows that SPI is the most highly ranked meteorological drought index (40%) followed by SPEI-P (26%), SPEI-T (19%) which slightly ranked ahead of SPEI-H (15%). Overall, the SPI had a rating of 0.39645441. The emergence of SPI as the most ranked meteorological drought index is supported by works of [31] and [20].

Table 6: Pair wise Comparison Matrix for Drought Criteria

	Robustness	Tractability	Transparency	Sophistication	Extendibility	Dimensionality
Robustness	1	2	2	3	4	4
Tractability	0.5	1	3	3	4	4
Transparency	0.5	0.33	1	3	4	5
Sophistication	0.33	0.33	0.3	1	1	1
Extendibility	0.25	0.25	0.25	1	1	1
Dimensionality	0.25	0.25	0.2	1	1	1
Summation	**2.83**	**4.16**	**6.75**	**12**	**15**	16

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Table 7a: The Pairwise Comparison Matrix Generated for Robustness

Robustness	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	3	2	0.2
SPEI-T	0.33	1	0.33	0.14
SPEI-H	0.5	3	1	0.33
SPEI-P	5	7	3	1
Sum	**6.83**	**14**	**6.33**	**1.68**

Table7b: The Pairwise Comparison Matrix Generated for Tractability

Tractability	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	3	4	7
SPEI-T	0.33	1	2	5
SPEI-H	0.25	0.5	1	4
SPEI-P	0.14	0.2	0.25	1
sum	**1.72**	**4.7**	**7.25**	**17**

Table 7c: The Pairwise Comparison Matrix Generated for Transparency

Transparency	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	5	7	9
SPEI-T	0.2	1	4	6
SPEI-H	0.14	0.25	1	3
SPEI-P	0.11	0.17	0.33	1
sum	**1.45**	**6.42**	**12.33**	**19**

Table7d: The Pairwise Comparison Matrix Generated for Sophistication

Sophistication	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	0.25	0.5	0.33
SPEI-T	4	1	2	0.5
SPEI-H	2	0.5	1	0.25
SPEI-P	3	2	4	1
sum	**10**	**3.75**	**7.5**	**2.083**

Table7e: The Pairwise Comparison Matrix Generated for Extendibility

Extendability	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	2	3	5
SPEI-T	0.5	1	3	4
SPEI-H	0.33	0.33	1	3
SPEI-P	0.2	0.25	0.33	1
sum	**2.03**	**3.58**	**7.33**	**13**

Table7f: The Pairwise Comparison Matrix Generated for Dimensionalityn

Dimensionality	SPI	SPEI-T	SPEI-H	SPEI-P
SPI	1	2	1	1
SPEI-T	0.5	1	0.5	0.5
SPEI-H	1	2	1	1
SPEI-P	1	2	1	1
Sum	**3.5**	**7**	**3.5**	**3.5**

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From Table 7a and 7c, the result shows that the SPEI-P was more robust and sophisticated than the other indices with a value of 0.5757 for robustness and 0.4617 for sophistication. SPEI-H was a little more robust than SPI and SPI wasa little more robust than SPEI-T. In terms of the tractability criterion, SPI and SPEI-P had the same score (0.54) and more tractable than the other two indices, SPEI-H being the least tractable (0.0547). The result also shows that SPI had the highest score for transparency (0.627) followed by SPEI-P, SPEI-T, and SPEI-H (0.2334, 0.0941, and 0.0456 respectively). Finally, SPI and SPEI-T were found to be more extendable with values (0.385, 0.308 respectively) than SPEI-H and SPEI-P (0.231,0.077).

Table 8: The Final Matrix after Computation

	SPI	SPEI-T	SPEI-H	SPEI-P
Robustness	0.199	0.064	0.161	0.576
Tractability	0.546	0.244	0.156	0.055
Transparency	0.627	0.233	0.094	0.046
Sophistication	0.098	0.293	0.147	0.462
Extendability	0.461	0.311	0.155	0.073
Dimensionality	0.286	0.143	0.286	0.286

Table 9: The Ranking of Index

Indices	AHP value	Ranking (%)
SPI	0.40	40
SPEI-T	0.19	19
SPEI-H	0.15	15
SPEI-P	0.26	26

Table 9 shows the ranking index result. From the result, SPI is ranked the highest with a value of 40% followed by SPEI-P 26%, SPEI-T 19%, and the least ranked SPEI-H with a value of 15%.

IV. CONCLUSION

Drought assessment has been a challenging task among drought researchers and professionals. In this study, an examination of the performance of four DIs namely; Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index-Thornthwaite (SPEI-T), Standardized Precipitation Evaporation Index-Hargreaves (SPEI-H), and Standardized Precipitation Evaporation Index-Penman (SPEI-P) was evaluated. The findings can be summarized as follows:

The correlation coefficient between indices increases with increasing time scale. SPI and SPEI-H were the most correlated among all the indices. The coefficient of determination R^2 from the regression analysis was highest between SPI and SPEI-H which shows their values fit together.

SPEI-H and SPEI-P detected the highest number of drought months for all stations and the number of months detected increased with increasing time scale. SPEI-H and SPEI-P detected higher numbers of moderate and severe drought. SPI and SPEI-H detected the longest drought duration and intensity for most of the stations followed by SPEI-P.

SPI, SPEI-P, and SPEI-H detected similar duration and intensity for the historical drought between 1982 and 1989. SPEI-P showed the highest intensity and duration for the historical droughts between 1992 and 2002 and between 2008 and 2011.

The results of the Analytic Hierarchy Process (AHP) showed that the SPEI-P was more robust and sophisticated than the other indices. SPEI-H was a little more robust than SPI and SPI wasa little more robust than SPEI-T. In terms of the tractability criterion, SPI and SPEI-P had the same score and more tractable than the other two indices, SPEI-H being the least tractable. SPI had the highest score for transparency followed by SPEI-P, SPEI-T, and SPEI-H. Finally, SPI and SPEI-T were found to be more extendable than SPEI-H and SPEI-P.

Using an appropriate weighting system that accounts for the relative importance of each criterion (AHP), the results show that SPI is the most ranked drought index with a priority weight of 0.40 followed by SPEI-P with a priority weight of 0.26, SPEI-H with a priority weight of 0.15 and SPEI-T with the least weight of 0.19.

From these findings, it can therefore be concluded that SPI is the most appropriate index for monitoring drought in Northern Nigeria.

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