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# Drought quantifications in semi-arid regions using precipitation effectiveness variables

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**Abstract:** This study proposes a new drought index (DI) based on several precipitation -based parameters to quantify drought hazard in semi arid region. In addition to the practice of using only rainfall volume for indexing drought, the proposed index verifies the potentials of nine (9) other precipitation effectiveness variables (PEVs); namely (onset of rain, cessation of rain, length of rainy and dry season, wet days and dry days within a wet season, dry days within the year, maximum dry spell length within a wet season and mean seasonal rainfall depth (MAR); in quantifying the drought conditions over a place.

The Conjunctive Precipitation Effectiveness Index (CPEI), as proposed in this study, utilizes a mathematical model, that algebraically combines "standardized seasonal PEV difference or deficit in each prevailing PEV" and terms of their sequent higher powers to define a single numerical value for this "at-site" drought index approach. Since the results expected from the use of various PEV combinations will defer; it is very necessary that the optimum PEVs combination be pre-determined and later employed for each "at-site" drought evaluation.

Some statistical comparison tests using historical drought data were employed to determine the most appropriate set of PEV that can be employed in the CPEI model to quantify the drought conditions at each study location. The daily rainfall data from seven stations in the semi-arid region of Nigeria were used to verify the effectiveness of this new method. The result shows that the set of PEVs for indexing drought varies with location.

Specifically, CPEI values obtained using various combinations of the 10 PEVs, were statistically and respectively compared with the values obtained for the Standard Precipitation Index (SPI), Rainfall Anomaly Index (RAI), and Bhalmey-Mooley Drought Index (BMDI). Results obtained showed that a maximum combination of six (6) PEVs gave an average correlation (R) value above 0.8. Those arrangements with $R > 0.8$ were further ranked and through a descriptive analysis, it was shown that the ultimate number of PEVs that can be effectively combined to get the optimum CPEI values for indexing the drought in the study area is three (3) PEVs for Gusau and Kano, five (5) PEVs for Sokoto and Maiduguri and four (4) for the rest stations under study. The trends observed in drought values obtained using the CPEI models employing these optimum PEVs also clearly earmarks the 1970-73 and 1983-1987 historical drought years within the study area. This approach seems to be significant for the specific area in the Sudano-Sahelian Region of Nigeria but would need to be verified in a wider regional context in similar future study.

***Keywords***: *Drought Quantification, Conjunctive Precipitation Effectiveness Index, Indexing, Precipitation Effectiveness Variables*

## 1. INTRODUCTION

Up to date, rainfall-deficiency concepts and techniques are a larger proportion of the existing drought evaluation or quantification techniques in literature. Conceptually, these techniques have mainly used only 'rainfall amount' in their formulation and analysis. They have neglected the use of some other derived characteristics of rainfall that equally measure the effectiveness of rainfall occurrence over an area; and that also infer the occurrence of drought over such an area. Such "neglected" rainfall variables (referred to as Precipitation Effectiveness Variables (PEVs)) include rainfall features such as its timing (i.e. onset and cessation of rainfall, length of rainy season), its availability (number of rainfall events and non rainfall events, (i.e. no of wet days, number of dry days)), its frequency and distribution over a place (Otun, 2005).

The premise for developing an operational drought index using these PEVs is firstly due to the presumption that the PEVs give the first indication of drought over a place. Secondly, the inclusion of more than one of these PEVs for evaluating a drought index for a place is also on the basis that the salient aspect of drought characterization that would have been lumped if not entirely omitted or hidden by one PEV, may be better revealed or earmarked by another (Smakhtin and Hughes, 2004, Keyansh and Dracup, (2002), Oladipo, 1985).

The inclusion of PEVs for the quantification of drought in semi-arid and arid regions (SAR) of the world is very significant in that in these regions, it is not so much the amount of rainfall that matters considering the arid nature of the area. What matters most is how effective it is. For instance, a delay in the onset of rains may result in poor seasonal distribution, even when the total amount of rainfall received within the same season is normal. Similarly, a pre-mature cessation may constitute a serious water deficit problem. A worse condition may be obtained when the onset is delayed and the rains ceases pre-maturely resulting in shortened rainy season.

This proposed approach conjunctively uses a combination of these PEVs to develop an operational drought index for quantifying the drought conditions over any semi-arid or arid region of the world. It is therefore hoped that this proposed drought quantification technique will serve as a reliable tool for better drought planning and management that can result in an effective management of the entire water resources systems of the SAR.

## 2. REVIEW OF INDEX-BASED DROUGHT QUANTIFICATION TECHNIQUES

Basically, the index-based drought quantification methods integrate various hydro-meteorological parameters (obtained from data series of rainfall, evapotranspiration, streamflow and other water deficiency indicators) into a single number to provide an overview of drought in a region. The index obtained, usually used for decision making, defines the magnitude, duration or severities of droughts. (Narasimhan, 2004, Hayes, 2002). The most commonly used of such meteorological drought indices include the Palmer Drought Severity Index (PDSI) (Palmer 1965), Bhalme and Mooley Drought Severity Index(BMDI) (Bhalme and Mooley, 1980), Rainfall Anomaly Index (RAI) (Rooy, 1965), Reclamation Drought Index (RDI), Surface Water Supply Index (SWSI) (Shafer and Dezman 1982), and Standardized Precipitation Index (SPI) (McKee et al 1993). The proposed CPEI is an index-based method aimed for quantifying meteorological drought over a place on a variety of time scale.

## 3. FORMULATION OF CPEI

The originality of the CPEI is related to the use of several precipitation-based parameters, not only precipitation amount for drought analysis and monitoring. The PEVs conjunctively used in CPEI include the following: onset of rainy season defined as the 1$^{st}$ day it rains in a season (ORS), cessation of rainy season defined as the last day it rains in a season (CRS), Length of the rainy season defined as the difference between CRS and ORS (LRS), Total wet days defined as the total number of days it rains within a season (TWD), Total number of dry spells within a season (TDS), Total number of dry days within a wet season (TDW), Total number of dry days within the whole season (TDY), Length of dry season (LDS), Maximum dry spell length within a wet season (MDL), and Mean seasonal rainfall depth (MAR).

By redefining these PEVs , their standardized values is mathematically given in equation 1 below.

$$ {}_{k}SV_{l,j} = \frac{{}_{k}V_{l,j} - {}_{k}\bar{V}_{l,j}}{\sigma_{{}_{k}V_{j}}} \tag{1} $$

where k stands for the PEV variable under consideration (i.e. for ORS, k=1, LRS, k=2, LRS, k=3 …., MDL, k=9 and MAR, k=10). l is the year under consideration, j is the season under consideration (for the monthly step data, j varies from 1 to 12 seasons, ${}_{k}\bar{V}_{l,j}$ and $\sigma_{{}_{k}V_{j}}$ are respectively the mean and standard deviation for the jth season and for variable k. By using Equation (1) the seasonality inherent in the PEVs can be removed and its values can be compared across various seasons.

Conceptually, the standardized difference value (${}_{k}SV_{l,j}$) and its higher powers for each PEVs is summed for the most suitable combination of PEVs to calculate CPEI for any year (l) or season (j) under consideration at any particular location. In formulating the model for CPEI in equation (2) below, the value of ${}_{k}SV_{l,j}$ was intentionally and respectively raised to the power of one, two and three so as to create a "magnifying effect of these standardized differences" in the evaluation of the CPEI index. The sign, ${}_{k}SGN$ was also included in the CPEI model, so as not to loose the effect of a negative difference (deficit) when it is squared or raised to higher power. Similarly, raising this standardized difference to a power of four or more has been proved to make little difference to the performance of the CPEI model (Otun, 2005).

$$ CPEI_{l,j} = \tfrac{1}{3}\left( \left[ \tfrac{1}{nv}\sum_{m=1}^{nv}\left({}_{k}SV_{l,j}\right) \right] + \left[ \tfrac{1}{nv}\sum_{m=1}^{nv}\left({}_{k}SV_{l,j}\right)^{2} * \left({}_{k}SGN\right) \right] + \left[ \tfrac{1}{nv}\sum_{m=1}^{nv}\left({}_{k}SV_{l,j}\right)^{3} \right] \right) \tag{2} $$

where nv is the no of PEVs in the arrangement, ${}_{k}SV_{l,j}$ is the standardized difference value and ${}_{k}SGN$ is the sign of the difference for the variable k.

By carrying out two comparative tests, the most appropriate PEVs combination for indexing the drought condition of any particular locality can be subjectively determined. The first test referred to as predictive-ability comparative test (PACT), uses some statistical procedures to compare the set of CPEI values obtained for various seasons and for each of the possible 1023 arrangements with the corresponding set of values obtained for each other three, four or five meteorological drought indices. This helps to determine the performance of each PEVs in the computation of CPEI and possibly serve as the clue in the preliminary elimination of some PEVs with poor performance.

After PACT, the sets of 'well-performed' PEVs will be used in the CPEI model and the values obtained will then be compared with their corresponding historical drought records to obtain the most appropriate PEVs and CPEI model for the locality under study. This second test constitutes what is referred to as the descriptive-ability comparison test (DACT).

### 3.1 Comparative Analysis ( CPEI Versus PDSI, BMDI, RAI and SPI)

As discussed above, the initial step in PACT involves a preliminary comparison of CPEI values with those of three other meteorological drought indices, namely the BMDI, SPI and RAI. The detail procedures for computing these three drought indices has been fully described by Otun (2005), Smakhtina and Hughes (2004), Kenyantash and Dracup(2002) and Hayes (2002). The statistical tool used for comparing the performances of these indices with each other is the Pearson correlation coefficient (R).

## 4. CPEI MODEL APPLICATION AND DISCUSSIONS

Using the available rainfall records between 1918 and 2002, for seven stations in the Sudano-Sahelian Region of Nigeria (SSRN), namely Gusau, Kano, Katsina, Maiduguri, Nguru, Potiskum and Sokoto, the CPEI values for each of the 1023 arrangements were computed and compared with the corresponding values obtained for BMDI, RAI and SPI.

The set of CPEI values for each of the possible 1023 arrangements was correlated with the set of corresponding values for BMDI, RAI and SPI indices. The arrangements with a correlation coefficient (R > 0.8) for each compared values of BMDI, RAI and SPI were selected. For each station under study, the total number of arrangements out of the possible 1023 arrangements with an average score of R>0.8 is shown in the first column of Table 1. (This procedure constitutes the 2nd stage of PACT).

It is clear from Table 1 that a combination of more than seven (7) PEVs was ineffective in indexing the drought in the SSRN. Using the maximum percentage of occurrence of the total variables as a criteria, the optimum no of PEVs for drought quantification in Gusau, Maiduguri and Potiskum is four (4), while the rest stations under study has five (5) variables as their optimum. The frequency of occurrence of total variables observed with the use of three (3) PEVs was also significant in most of the stations.

Table 1 above also gives a clue as to how many PEVs should be used in indexing drought in each of the stations under study. Although not conclusive, Table 1 signifies that the use or a combination of three (3), four (4) or five (5) PEVs have a fair potential for indexing the drought in most of the stations under study.

Table **1.** Percentage Distribution of Total PEVs Used to Obtain CPEI with an Average Score (R> 0.8) in each Station under Study

| | | Frequency of Occurrence of total variables Used to Score R > 0.8 (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | NOC[1] | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| Gusau | 37 | 0.0 | 0.0 | 13.3 | 40.0 | 33.3 | 6.7 | 6.7 |
| Kanoap | 43 | 0.0 | 16.3 | 30.2 | 25.6 | 18.6 | 7.0 | 2.3 |
| Katsina | 54 | 1.9 | 13.0 | 27.8 | 22.2 | 25.9 | 7.4 | 1.9 |
| Maiduguri | 28 | 0.0 | 3.6 | 14.3 | 35.7 | 32.1 | 10.7 | 3.6 |
| Nguru | 65 | 4.6 | 16.9 | 29.2 | 24.6 | 15.4 | 6.2 | 3.1 |
| Potiskum | 60 | 3.4 | 22.0 | 23.7 | 25.4 | 20.3 | 3.4 | 1.7 |
| Sokoto | 64 | 4.7 | 17.2 | 31.3 | 25.0 | 17.2 | 3.1 | 1.6 |

[1]NOC – Total number of occurrence (i.e No of arrangements out of 1023 with average score R> 0.8)

Table 2 below also gives the frequency of occurrence of each PEV in the lots of arrangements with average score R>0.8. At 50% level of occurrence, variables no 10 and 4 (i.e MAR and TWD) predominates in all the stations and at 40% level of occurrence, variables 10, 4, 8 and 1 (i.e. MAR, TWD, LDS and ORS) becomes the most predominant variables.

Table **2.** Performance Level of Each PEVs (%)

| | PEVs (with Corresponding Code and Variable No). | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | MAR | MDL | LDS | TDY | TDW | TDS | TWD | LRS | CRS | ORS |
| Station | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| Gusau | 100.0 | 13.3 | 46.7 | 20.0 | 20.0 | 0.0 | 73.3 | 40.0 | 0.0 | 33.3 |
| Kanoap | 100.0 | 14.0 | 48.8 | 20.9 | 27.9 | 37.2 | 79.1 | 44.2 | 4.7 | 46.5 |
| Katsina | 100.0 | 40.7 | 38.9 | 25.9 | 20.4 | 25.9 | 75.9 | 29.6 | 7.4 | 48.1 |
| Maiduguri | 100.0 | 21.4 | 28.6 | 28.6 | 3.6 | 46.4 | 71.4 | 14.3 | 0.0 | 42.9 |
| Nguru | 98.5 | 9.2 | 40.0 | 13.8 | 18.5 | 56.9 | 80.0 | 27.7 | 36.9 | 58.5 |
| Potiskum | 100.0 | 41.7 | 48.3 | 18.3 | 15.0 | 56.7 | 81.7 | 38.3 | 5.0 | 46.7 |
| Sokoto | 100.0 | 28.1 | 50.0 | 17.2 | 20.3 | 54.7 | 78.1 | 31.3 | 12.5 | 59.4 |

The average values of R obtained for the correlation of CPEI versus SPI, RAI and BMDI respectively for each station were ranked. The PEVs arrangement that was ranked first was assumed to give the optimum PEVs combination for computing the optimal CPEI. The ranking of some PEVs combinations used for indexing drought in the seven stations under study is shown on Tables 3.

Table 1 and 2 shows that the CPEI values obtained by using a combination of three (3), four (4), or five (5) PEVs respectively, has good rankings and highest frequency of occurrence in all the stations under study. The use of these variables has also resulted in high level of performance (average R > 0.9) in most stations under study.

Similarly, by combining the predictive ability test results obtained above with the use of the Pearson Correlation coefficient (R) and that of a descriptive ability test; in which CPEI values obtained for these 3, 4 and 5 PEVs were plotted and compared with respective historical drought records of each stations (see Figure 1), the following conclusion is put forward; as indicated on Table 3 below, it is suggestive that a combination of three (3) optimum PEVs (i.e. MAR, TDY and TWD) can be used for indexing the drought in

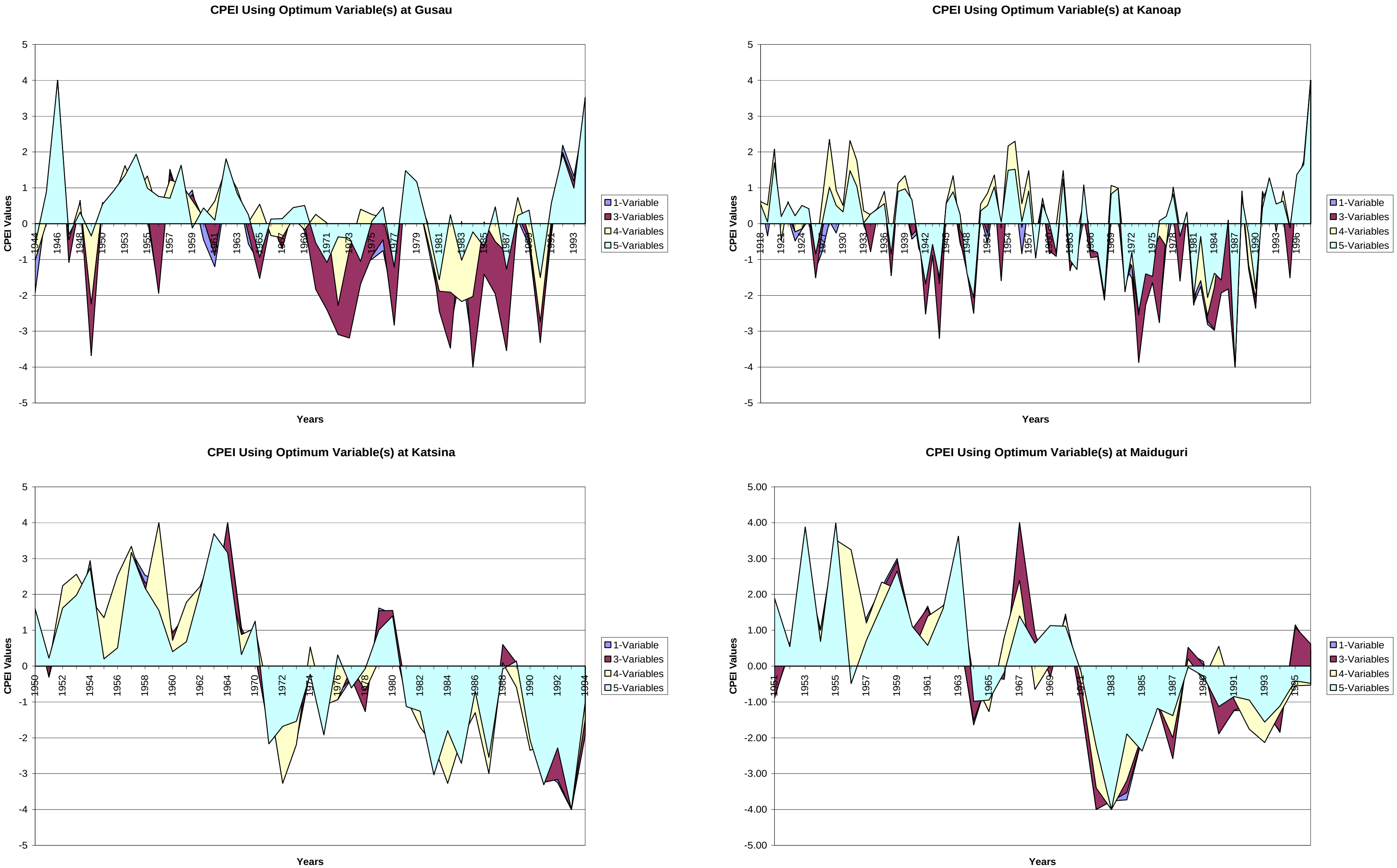


**Figure 1.** Comparison of optimum CPEI obtained using 1, 3, 4, and 5 PEVSs at four stations under study

Gusau and Kano, combination of five (5) optimum PEVs for Katsina and Sokoto and a combination of four (4) PEVs for the rest stations under study. The trends observed in each of these CPEI plots in Figure 1 also clearly earmarks the 1970-73 and 1983-1987 historical drought years within the study area.

The usual use of only rainfall depth i.e. one (1) PEV in indexing the drought in the study area might be elusive since some other distinctive drought features revealed with the use of three (3), four (4) and five (5) PEVs in Figure 1 might have remained hidden. Table 3 shows the results of the most suitable PEV combinations suggested for each station under study. It is obvious from these results that other PEVs apart from rainfall volume can be used to index the drought condition of a location.

Table **3.** Optimum PEV Combinations for Indexing Drought in each Station under Study

| **Station** | **Optimum No of PEV** | **Suggested PEV Combination (Codes)** | **[1]Combined PEVs** | **Pearson Correlation Coefficient (R)** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **SPI** | **RAI** | **BMDI** | **Average** |
| **Gusau** | 3 | 10,7,4 | MAR, TDY, TWD | 0.960 | 0.940 | 0.950 | 0.950 |
| **Kanoap** | 3 | 10,7,4 | MAR, TDY, TWD | 0.956 | 0.971 | 0.935 | 0.954 |
| **Katsina** | 5 | 10,7,4,3,1 | MAR, TDY, TWD, LRS, ORS | 0.935 | 0.943 | 0.944 | 0.941 |
| **Maiduguri** | 4 | 10,9,4,1 | MAR, MDL, TWD,ORS | 0.881 | 0.866 | 0.889 | 0.879 |
| **Nguru** | 4 | 10,4,3,1 | MAR, TWD,LRS,ORS | 0.936 | 0.929 | 0.934 | 0.933 |
| **Potiskum** | 4 | 10,6,4,1 | MAR, TDW, TWD,ORS | 0.915 | 0.924 | 0.923 | 0.921 |
| **Sokoto** | 5 | 10,7,4,3,1 | MAR, TDY, TWD, LRS, ORS | 0.944 | 0.965 | 0.971 | 0.960 |

[1] PEV Code (i.e. 10=MAR, 9=MDL, 8= LDS, etc.) are as defined in Table 2 above

The existing ubiquity and difficulty in the physical quantification of drought has led to the proliferation and increase in the number of techniques or indices used in quantifying, monitoring or predicting drought occurrences. This development has been well accepted in recent drought research studies because of the obvious reason that the salient aspect of drought characterization that would have been lumped if not entirely omitted or hidden by one drought index or technique may be better revealed or earmarked by another (Smakhtin and Hughes, 2004). The use of some 3, 4 or 5 PEVs for indexing drought has agreed with these assertions within SSRN. Similar works can however evolve in other similar arid and semi-arid regions of the world to also validate this claim.

It should therefore be clearly stated that the emphasis of this study was not in the formulation of a 'one-in-all' index but rather seeks to prove that more PEVs can be included in drought index formulation for a semi-arid / arid regions of the world. This study has used equation 2 above as a model sample. Therefore, this study should be regarded as a preliminary approach to drought quantification using PEVs. More research would be required for the development of a scientifically proved model for indexing drought using the suggested PEVs. Similarly, a further research would be required to determine the various weights to use for each of these PEVs in model formulation since some variables could be more important for drought than the others.

Drought indexing has been well documented to provide basic tool, particularly the role of information supply, identifying or generating sufficient data base; in a decision support system for effective drought monitoring. Particularly in less developed arid and semi-arid nations in Africa and Asia, CPEI will continue to always act as a dependable DSS tool for effective drought management.

## 5. CONCLUSIONS

A new drought indexing method, CPEI, using PEVs has been proposed for quantifying the drought conditions and occurrences in any semi-arid or arid region. It is a pioneering approach that has shown that drought indexing in these regions is related to the use of several characteristics of precipitation and not only precipitation amount. The application of CPEI can be applied to at-site specific drought evaluation studies.

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