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Research Article

West Africa's Drought Dynamics: An Investigation of SPI and SPEI indices (1979-2021)

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Abstract

West Africa's population is projected to reach 500 million by 2050, exacerbating the need for reliable drought detection and management strategies to ensure food and water security. This study investigated drought detection in West Africa using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The objective is to evaluate the performance of SPI and SPEI in detecting droughts and compare their strengths and limitations. The results revealed that both indices detected droughts effectively, but SPEI was more sensitive to evapotranspiration and temperature change. The findings offer valuable insights into climate change impacts, drought monitoring, and sustainable water resource management in the regions under investigation in West Africa.

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Introduction

Droughts are a reoccurring feature of West Africa's climate landscape, with significant implications for agriculture, water resources, food security, and human well-being [1,2]. The Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are two widely utilized indices for drought detection and characterization [3,4]. However, their performance and comparability in West Africa have not been thoroughly investigated [5].

To comprehend the characteristics of drought, different studies have been made using several indices [6]. According to Svoboda, et al. [7], drought indices are understood as numerical representations of drought severity, computed from climatic or hydrometeorological input data. Therefore, among the indices implemented to assess drought SPI, SPEI, Vegetation Condition Index (VCI) and Normalized Difference Vegetation Index (NDVI) are the most common ones. Due to its characteristics of simplicity, flexibility, and strong adaptation to different climates [8], SPI has been identified as one of the most commonly used indices in more than 70 countries worldwide [9]. Various studies [10,11] have considered the temperature variations is considered successfully implemented SPI to assess and forecast drought occurrences, but, studies [9,12] show that the dependence of SPI only on precipitation as an input to assess drought and its inability a major weakness. A performance comparison study by Vicente-Serrano, et al. [13] argued that even though precipitation is the primary controlling factor of drought occurrences, the influence of temperature through the facilitation of evapotranspiration in the context of global warming cannot be ignored. However, SPEI, a variant of SPI and a multi-component drought index developed by [12], uses the variabilities of precipitation and temperature to assess drought in an area, hence, making it sensitive to global warming [12,14].

As a result, SPEI has been used in different drought-related research worldwide [15,16]. Moreover, performance comparison studies by Vicente-Serrano, et al. [13], & Gurrapu, Chipanshi, Sauchyn, and Howard A. [17] between SPI and SPEI indicated that SPEI performs better than SPI on most occasions. Regardless of these facts, however, SPI continues to be widely used in different parts of the world. In Ethiopia, SPI is also a more commonly used index than SPEI. Only a few studies Delbiso, et al. [18] and Ghebrezgabher, Yang, Yang [19] used SPEI to assess drought in Ethiopia. Due to the climate variability, which could be accounted for by the undulating topography of the study area Gebrehiwot & van der Veen [20], variation in drought ratings from SPI and SPEI is expected. Precious study primarily focused on drought detection, without thoroughly assessing the effectiveness of management strategies. Hence, this study aims to evaluate the performance of SPI and SPEI in detecting drought in West Africa. This provides information on the acceptability level of using SPI in place of SPEI as a drought assessment tool, in the study area, especially in the absence of temperature data.

Study area and data

Study area: West Africa as defined by the United Nations is the 16 countries of Benin, Burkina Faso, Cameroon, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. It is located at coordinate 13.5317°N, 2.4604°W and covers an area of 6.14 million km^2. It is bordered by the Atlantic Ocean on the west, the Gulf of Guinea on the south, and the Sahara and the Sahel, a semiarid belt-shaped transition region between the Sahara desert and the Sudanian Savanna, on the north. Owing to the latitudinal oscillation of the Inter-tropical Discontinuity (ITD), West Africa exhibits a bi-modal rainfall pattern. The dry season begins in October and lasts until March of the following year, whereas the wet season begins in April and lasts until September [21]. The dry Sahara to the north and east, which produces dry winds during the harmattan, and the humid climate of the Atlantic to the south and west, which produces seasonal monsoons, have a significant impact on the climate and ecosystem.

West Africa can be split into five broad east-west bands that define the climate and vegetation from north to south or from the Sahara to the humid southern coast. The bioclimatic regions are referred to as the Saharan, Sahelian, Sudanese, Guinean, and Guinea-Congolian Regions. The Sahel and Sudan zones are the "harsh lands" of West Africa.' These arid and semi-arid lands include parts of present-day Senegal, Mali, Northern Ghana, Mauritania, Niger, Northern Benin, Upper Volta, Chad, and Northern Nigeria. The term "harsh lands" describes an area of extreme environmental uncertainty, but it also describes a place where man has learned to survive by taking advantage of its natural resources and its productive microenvironments, by cooperating with people who lead different but complementary lifestyles, and by creating biologically rich habitats where specific plants can grow (Scott, 1979). In West Africa, farmers and nomads frequently use these survival strategies; while they may not be particularly effective by Western standards, they are very trustworthy [22]. The study area covers the Sahara, Sahel, and Sudan zones.

The Sahara Desert to the north and the Sudanese Savana to the south are divided by the West African Sahel region, which extends from the Atlantic Ocean eastward to Chad. The area is one of the poorest and most environmentally damaged in the world, and because temperature rises are expected to be 1.5 times higher than elsewhere in the world, it is also one of the locations that are most sensitive to climate change. Sahel is well known for the severe droughts that ravaged the region in the 1970s and 1980s [23]. The Sahel region features a hot, semi-arid environment with high temperatures (average of 21.9°–36.4°C) all year long, a long, harsh dry season from October to May, and a short, erratic rainy season related to the West African monsoon.

The Sahara, also known as the Saharan Region, is the whole northern portion of West Africa and is made up of the Sahara Desert. It has several different desert environments, from sand sheets and dune fields to gravel plains, low plateaus, and rough mountains. Sahara records between 0 and 150 mm of rainfall on average each year. The Saharan region is the hottest big region on earth due to the high position of the Sun, the extremely low relative humidity, the lack of vegetation, and rainfall.

Sudan sits in the transitional zone between the humid, lush equatorial rainforest and the Sahelian arid desert environment. The range of the yearly average temperature is between 23 to 29 °. The coldest months have highs of 20 degrees Celsius, while the hottest months have highs of 30 °C. Hay, forest cliffs, and gallery forests along the rivers are characteristics of Sudan. Desertification is a problem in the area due to the drought and livestock grazing Figure 1.

Data collection

Many researchers in climatology and related areas rely on long-term observations from precipitation stations. This data is necessary for analyzing climate variability and change [24]. Monthly precipitation data are primarily used in drought analysis to specify the absence of precipitation at various time scales. These time ranges represent the consequences of drought on the ability to utilize various water supplies [25]. The meteorological data (precipitation and temperature) used in this research were collected from the Copernicus Service managed by The European Commission. Based on long-term recording data and a combined record period duration of 42 years (1979–2021), the monthly precipitation data of 12 stations across three climate zones in West Africa have been chosen. Four different time scales (3, 6, 12, and 24) were considered.

Methodology

Standard Precipitation Index (SPI)

Standardized Precipitation Index (SPI) is a popular metric for describing meteorological drought on various timescales. The SPI is a multi-scalar probability indicator that determines the amount of precipitation lacking during periods of both wet and dry weather and permits drought monitoring at various timescales [26]. It is the most widely used indicator for identifying and describing meteorological droughts worldwide. Due to its simplicity, monthly data requirement, and general acceptance on a larger scale, this index was recommended by the World Meteorological Organization as a starting point for meteorological drought monitoring and has been utilized in numerous prior research [27].

SPI was developed by McKee, Doesken, and Kleist in 1993 [26], and described in detail by Edwards and McKee in 1997 [28]. The goal of SPI is to categorize precipitation into a single numerical number that may be compared across places with distinctly differing climates. Any location's SPI computation typically needs a long-term precipitation record

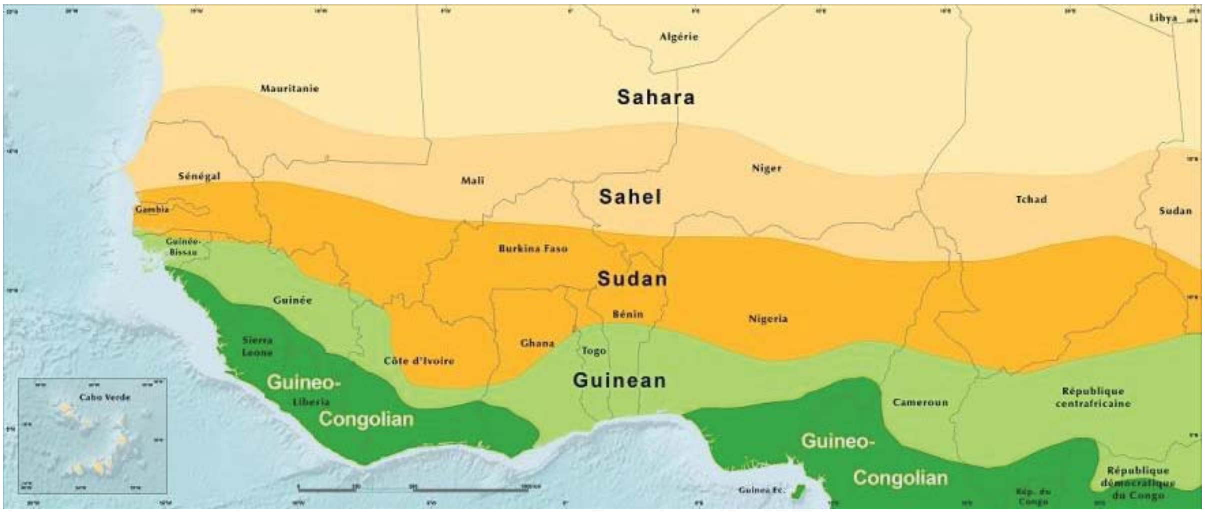

Figure 1: West Africa bioclimatic regions.

for the relevant period. After fitting the long-term data to a probability distribution, which is then transformed into a normal distribution, the mean SPI for the place and desired period is set to zero [28]. Using monthly input data, the SPI can be constructed for various periods ranging from 1 to 36 months. The Index was designed to show that it is possible to simultaneously experience wet conditions on one or more time scales, and dry conditions at other time scales. Consequently, a separate SPI value is calculated for a selection of time scales. Strictly speaking, the SPI does not have a specific threshold, but a drought is regarded as drought when the SPI is −1.0 or lower [29]. Table 1 reveals the drought category as classified by [26] and [29]

SPI has been acknowledged as the standard index that should be used for quantifying and reporting meteorological drought on a global scale. However, given that it ignores changes in evapotranspiration, questions have been raised about the SPI's usefulness as a gauge of drought changes brought on by climate change. SPEI and other indexes that address evapotranspiration have been suggested.

Standard Precipitation Evapotranspiration Index (SPEI)

An expansion of the often-used Standardized Precipitation Index (SPI) is the Standardized Precipitation Evapotranspiration Index (SPEI). When determining drought, the SPEI is intended to consider both precipitation and Potential Evapotranspiration (PET). Thus, in contrast to the SPI, the SPEI effectively measures the primary effect of rising temperatures on water demand.

Since its creation in 2010, a rising number of meteorological and hydrological researchers have used the standardized precipitation evapotranspiration index (SPEI) [30]. Like the SPI, the SPEI can be calculated on a range of timescales from 1-48 months, it can determine the beginning and end of drought events as well as the severity of the drought based on its intensity and duration. Moreover [31] suggested that drought indices must be simply produced, statistically reliable, and have a transparent and understandable calculating process. Table 2 presents its classification according to the moisture state as stated by Quenum, et al. [32].

Table 1: Drought intensity with SPI.

SPI values	Drought category
0 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.50 to −2.00	Severe drought
< −2.00	Extreme drought

It was observed that at a 3-month times scale for all the regions, the highest drought index value (magnitude 12) (Figure 2) was in 1982 in the Sudano region. This implied that crops whose period of maturity was three months were affected by drought.

At 6-month time scale, the results of the study further revealed that the highest drought index value (magnitude 5.9) (Figure 3) was in 1990 in the Sahelian region. This implied that crops whose period of maturity was six months would be significantly affected by drought in the Sahelian zone.

At 12months times scale, the results of the study revealed that the highest drought index values were recorded in 1981 in the Sudano zone (magnitude 10) (Figure 4). This implied that crops whose period of maturity was twelve months would be adversely affected by drought.

At a 24-month time scale, the results of the study further revealed that the highest drought index values were recorded in 1982 in Dry-sub-humid (magnitude 5.0) (Figures 5, 6).

Table 2: Classification of moisture level with SPEI.

SPEI values	Drought category
+2.0 and greater	Extremely wet
+1.5 to 1.99	Very wet
+1 to 1.49	Moderately wet
−0.99 to 0.99	Near Normal
−1.49 to −1.0	Moderately dry
−1.99 to −1.5	Severely dry
Less to −2.0	Extremely dry

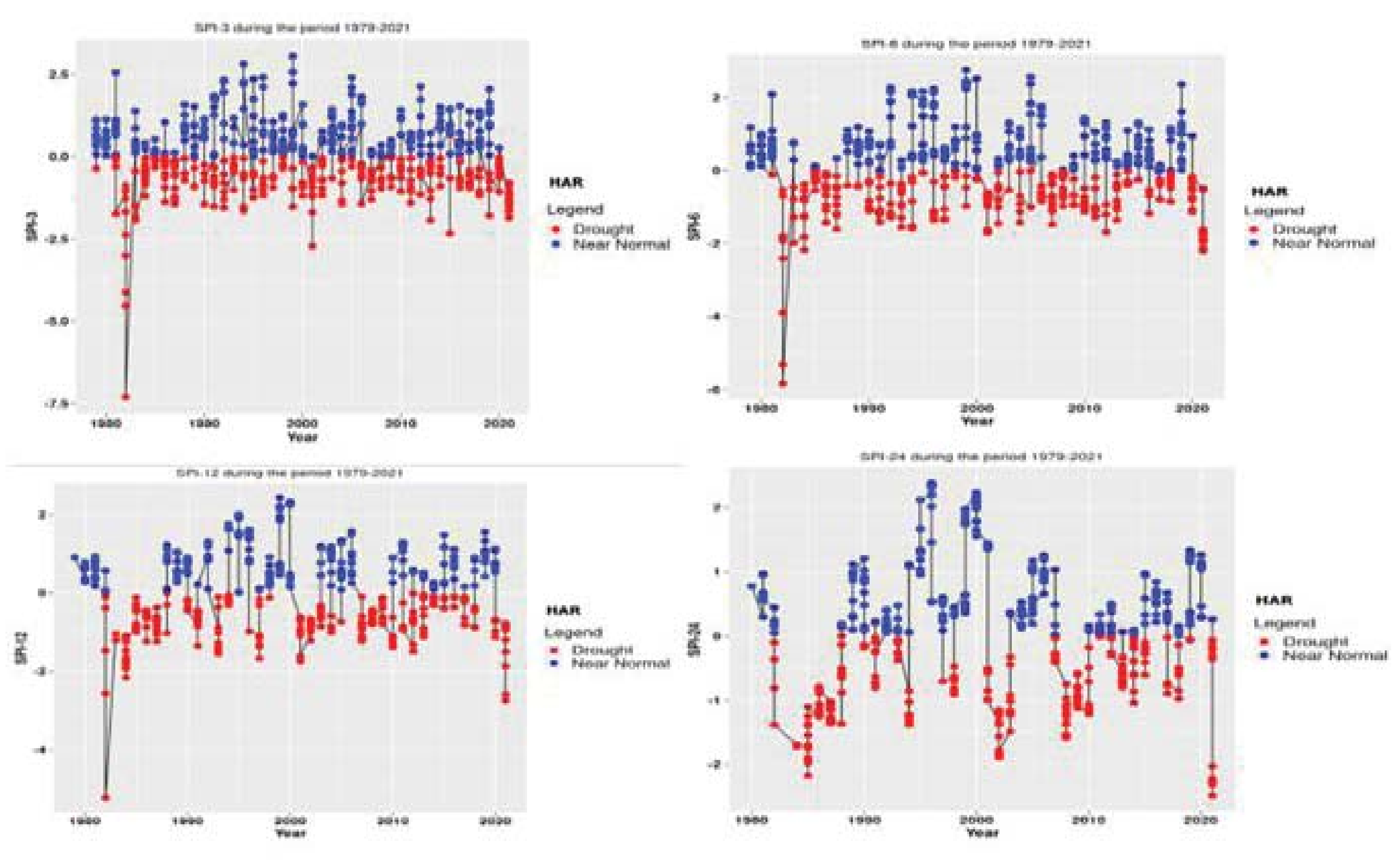

Figure 2: Distributions of Standardized Precipitation Index (SPI) Series for Drought Detection over Hyper-Arid Region in West Africa.

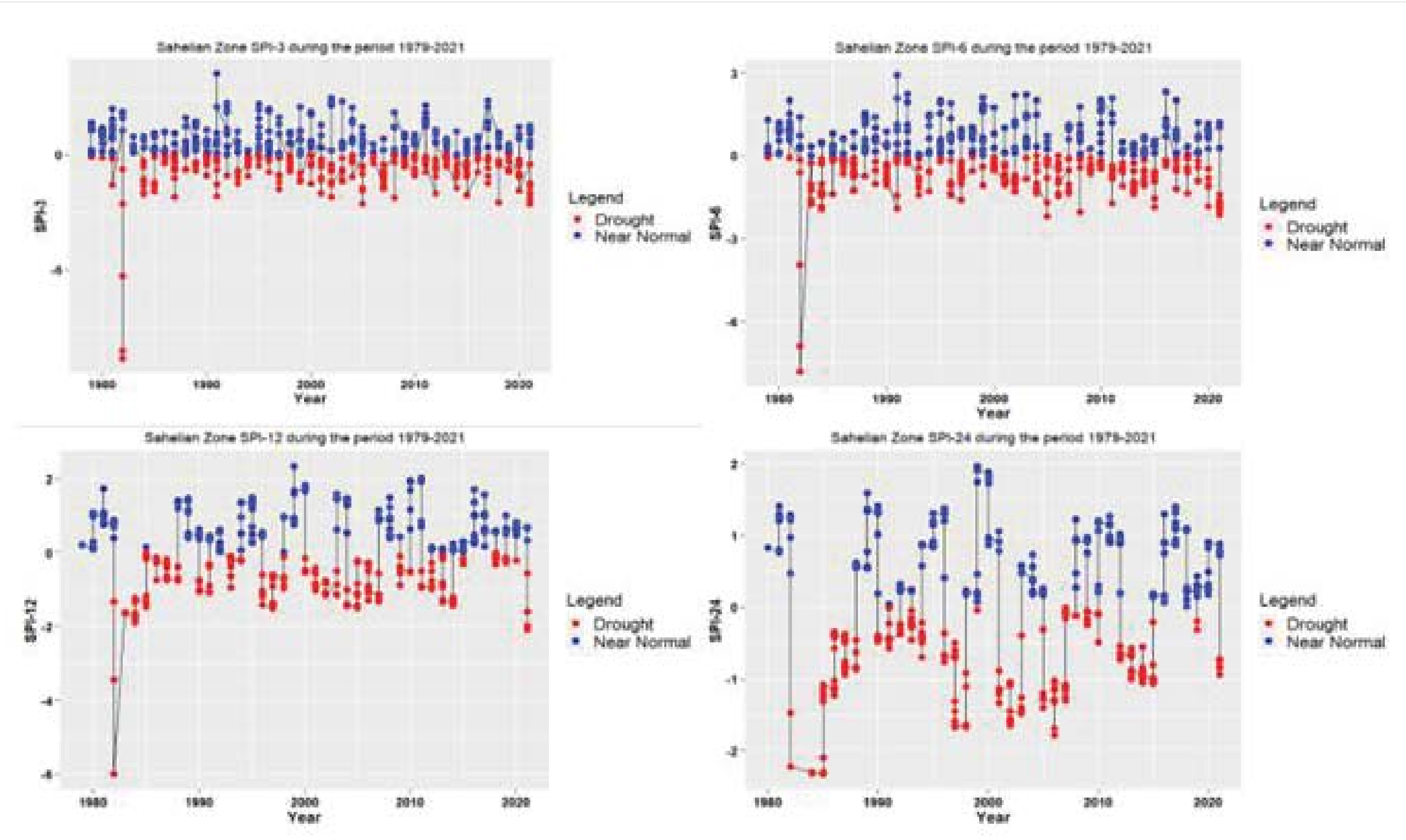

Figure 3: Distributions of Standardized Precipitation Index (SPI) Series for Drought Detection over Sahelian Region in West Africa.

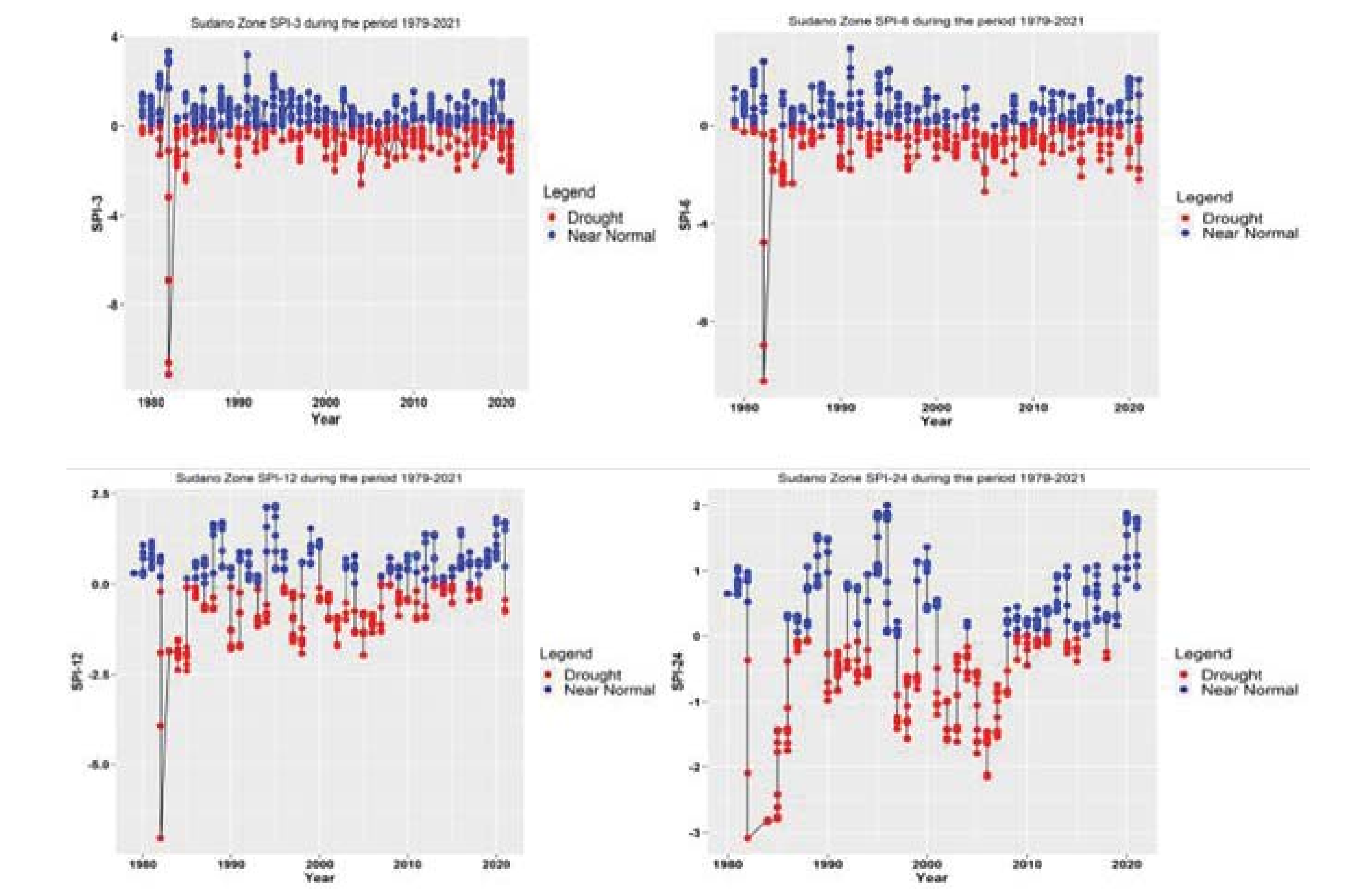

Figure 4: Distributions of Standardized Precipitation Index (SPI) Series for Drought Detection over Sudano Region in West Africa.

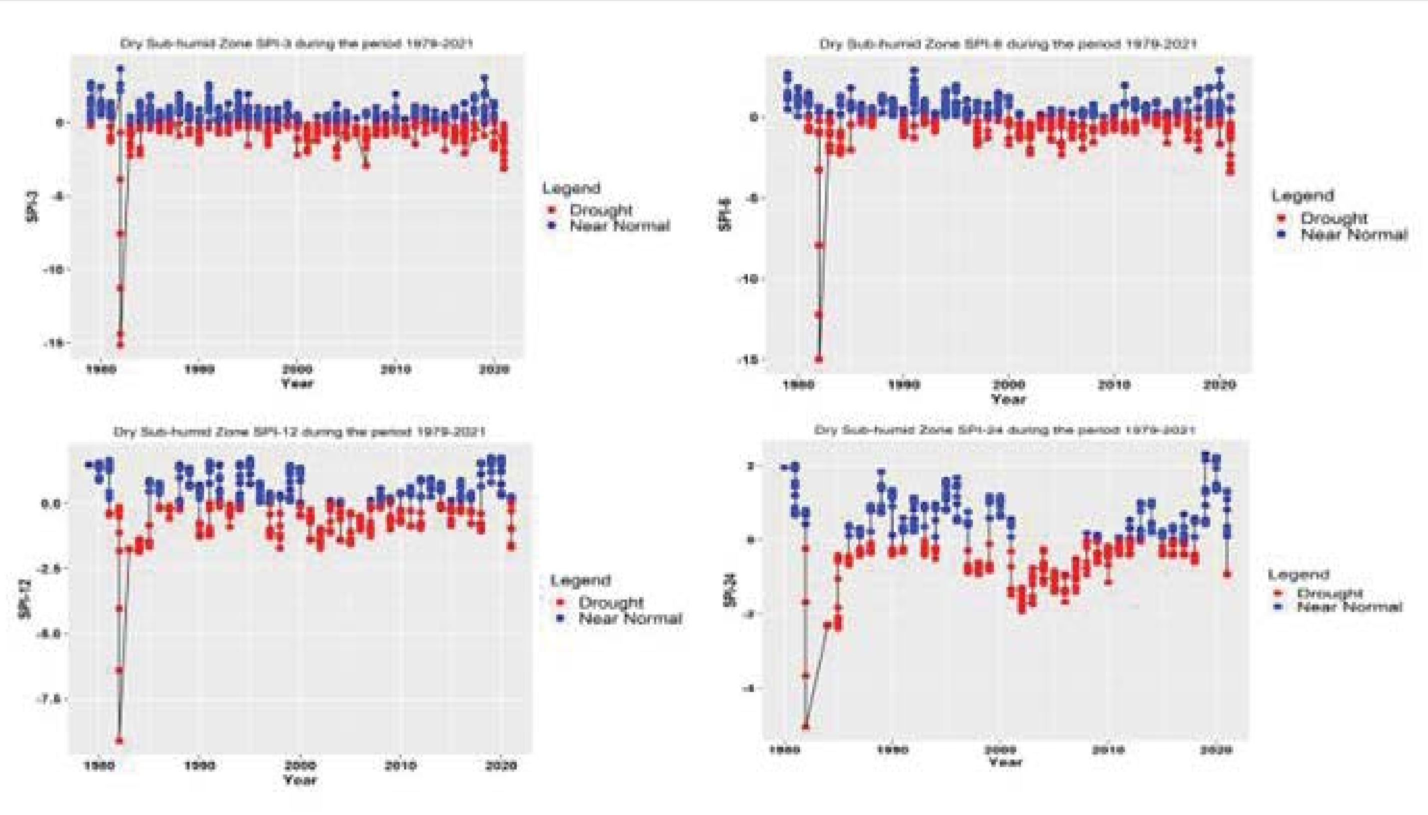

Figure 5: Distributions of Standardized Precipitation Index (SPI) Series for Drought Detection over Dry Sub-humid Region in West Africa.

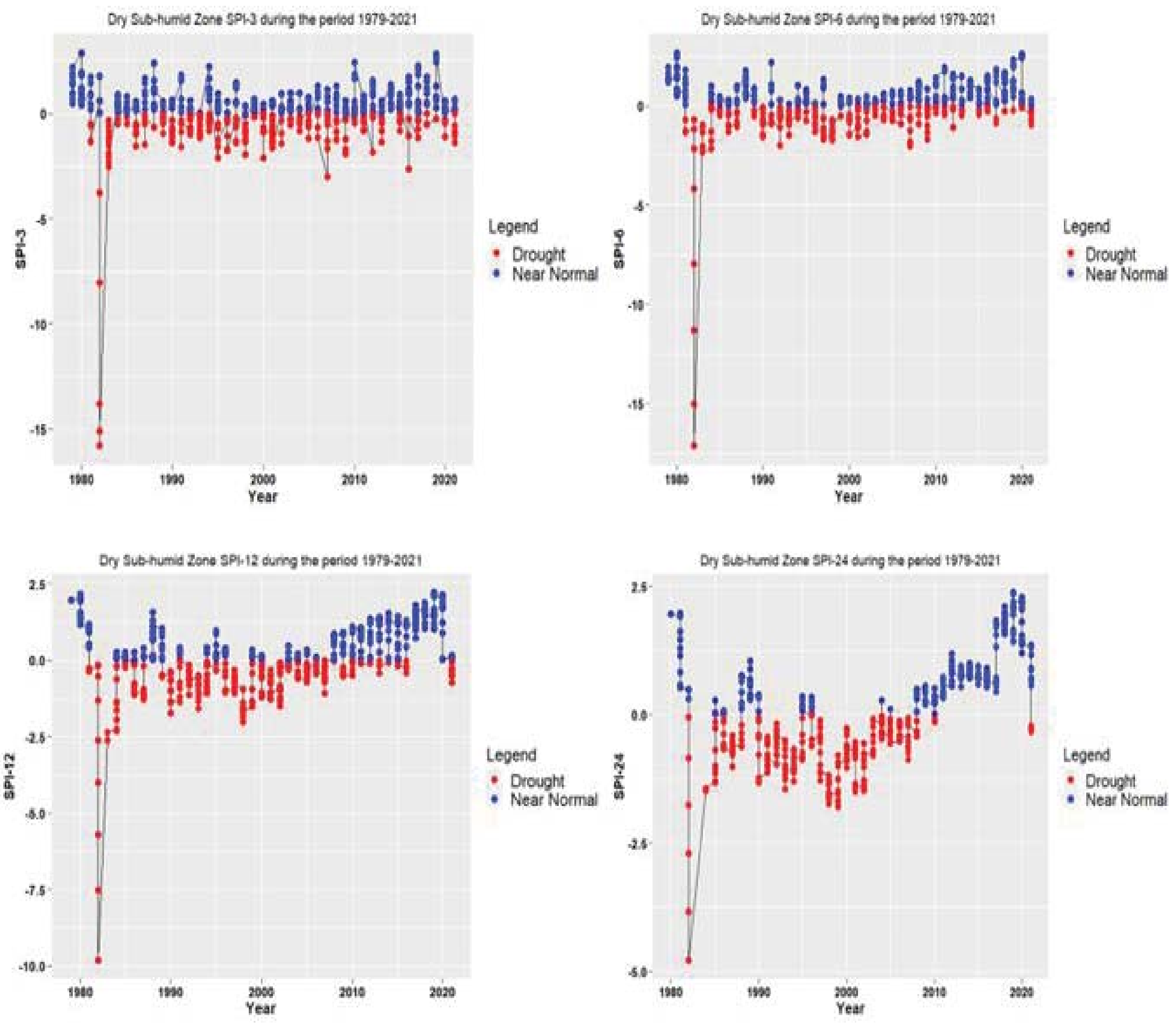

Figure 6: Distributions of Standardized Precipitation Index (SPI) Series for Drought Detection over Moist Sub-humid Region in West Africa.

This implied that the rivers in that zone would be adversely affected by the drought. Consequently, there would be famine.

At a 3-month time scale, the results of the study revealed that the highest drought index values were recorded in 1982 in the Moist-sub-humid zone (magnitude 3.6) (Figure 7). This implied that crops whose period of maturity was three months would be adversely affected by drought.

At 6-month time scale, the results of the study revealed that the highest drought index values were recorded in 1982 in the Moist-sub-humid zone (magnitude 3.5) (Figure 8). This implied that crops whose period of maturity was six months would be significantly affected by drought.

At a 12-month times scale, the results of the study revealed that the highest drought index values were recorded in 1983 in the Moist-sub-humid zone (magnitude 3.0) (Figure 9). This implied that crops whose period of maturity was twelve months would be adversely affected by drought.

At a 24-month time scale, the results of the study revealed that the highest drought index values were recorded in 1982 in the Moist-sub-humid zone (magnitude 2.9) (Figures 10,11). This implied that the rivers in that zone would be adversely affected by the drought. Consequently, there would be famine.

The potential of SPI and SPEI indices in West Africa

The "West Africa's Drought Dynamics" study demonstrates the potential of SPI and SPEI indices in understanding drought dynamics, with far-reaching applications:

Applications of SPI and SPEI indices

1. **Drought monitoring and early warning systems:** Implement SPI and SPEI indices to detect droughts, enabling early warnings and proactive measures.
2. **Agricultural planning and management:** Use SPI and SPEI to optimize crop selection, planting dates, and irrigation management.

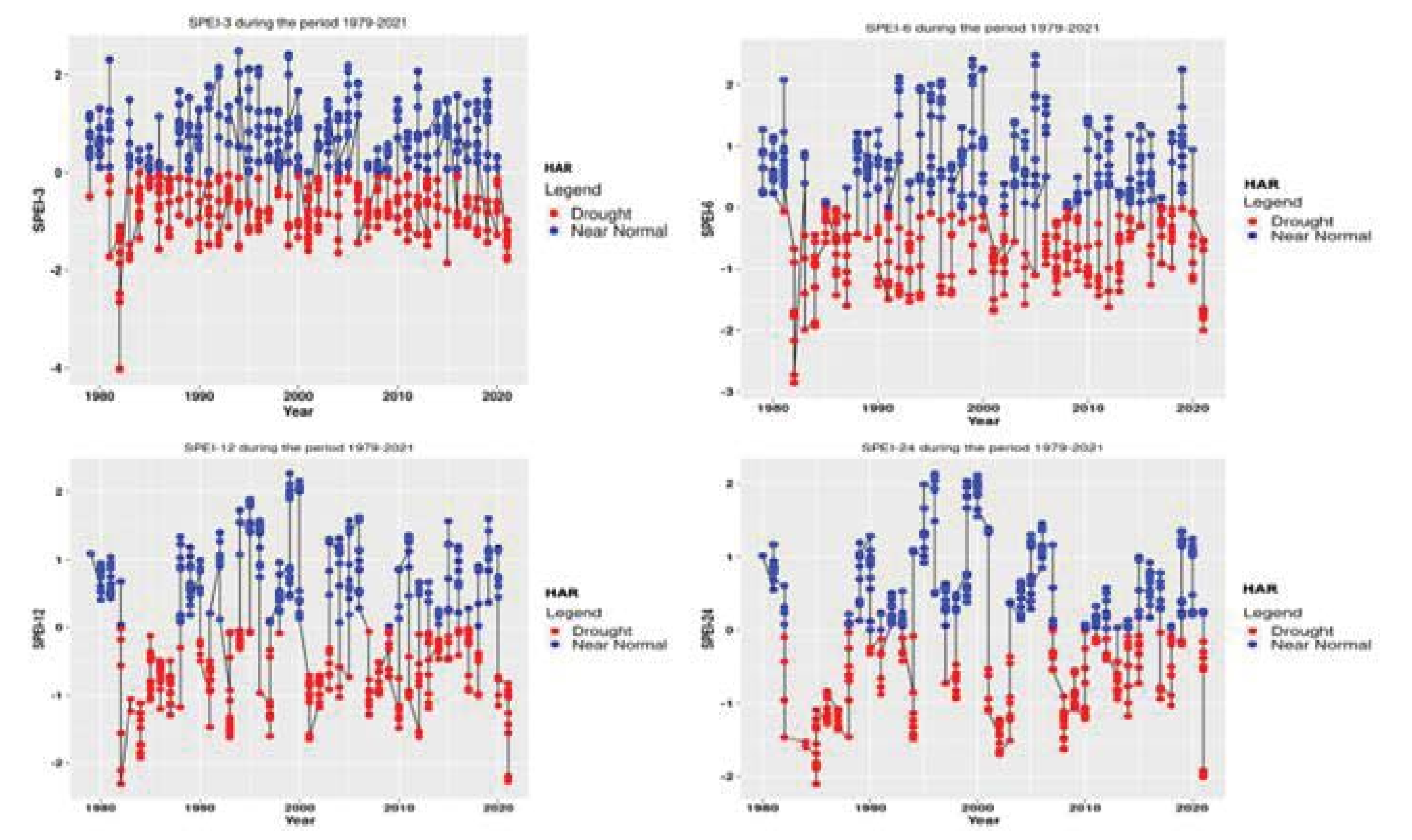

Figure 7: Distributions of Standardized Precipitation-Evapotranspiration Index (SPEI) Series for Drought Detection over Hyper-Arid Region in West Africa.

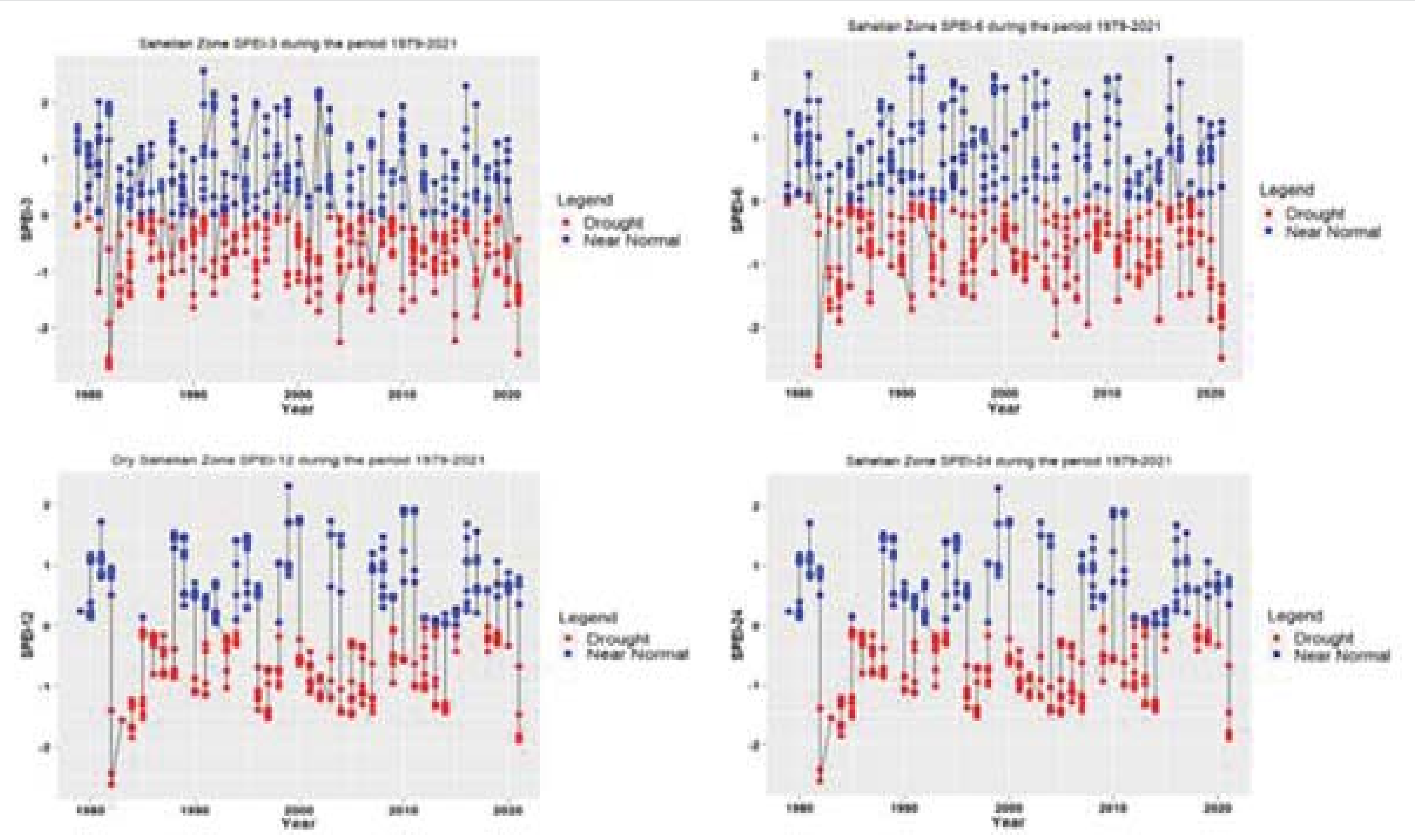

Figure 8: Distributions of Standardized Precipitation-Evapotranspiration Index (SPEI) Series for Drought Detection over Sahelian Region in West Africa.

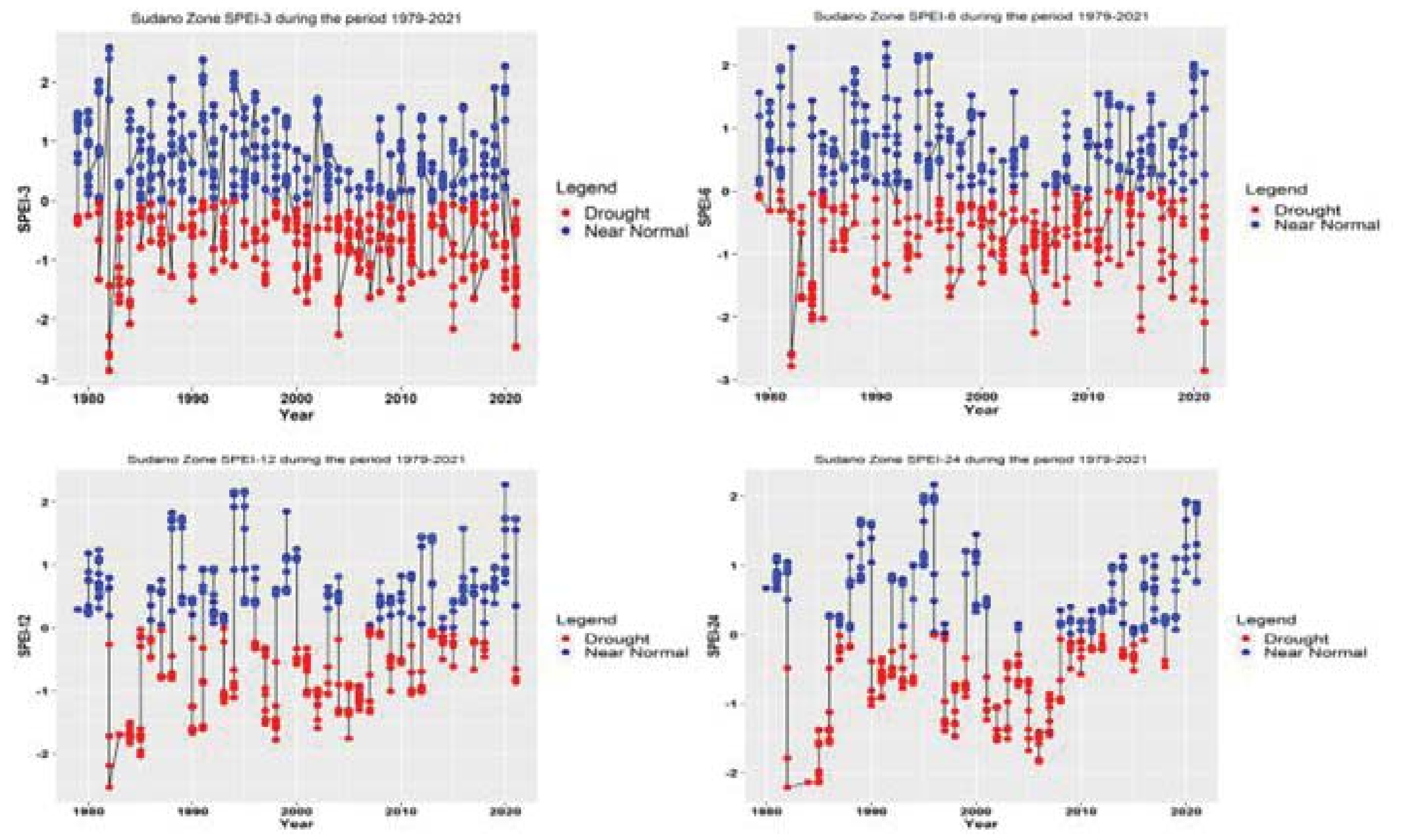

Figure 9: Distributions of Standardized Precipitation-Evapotranspiration Index (SPEI) Series for Drought Detection over Sudano Region in West Africa.

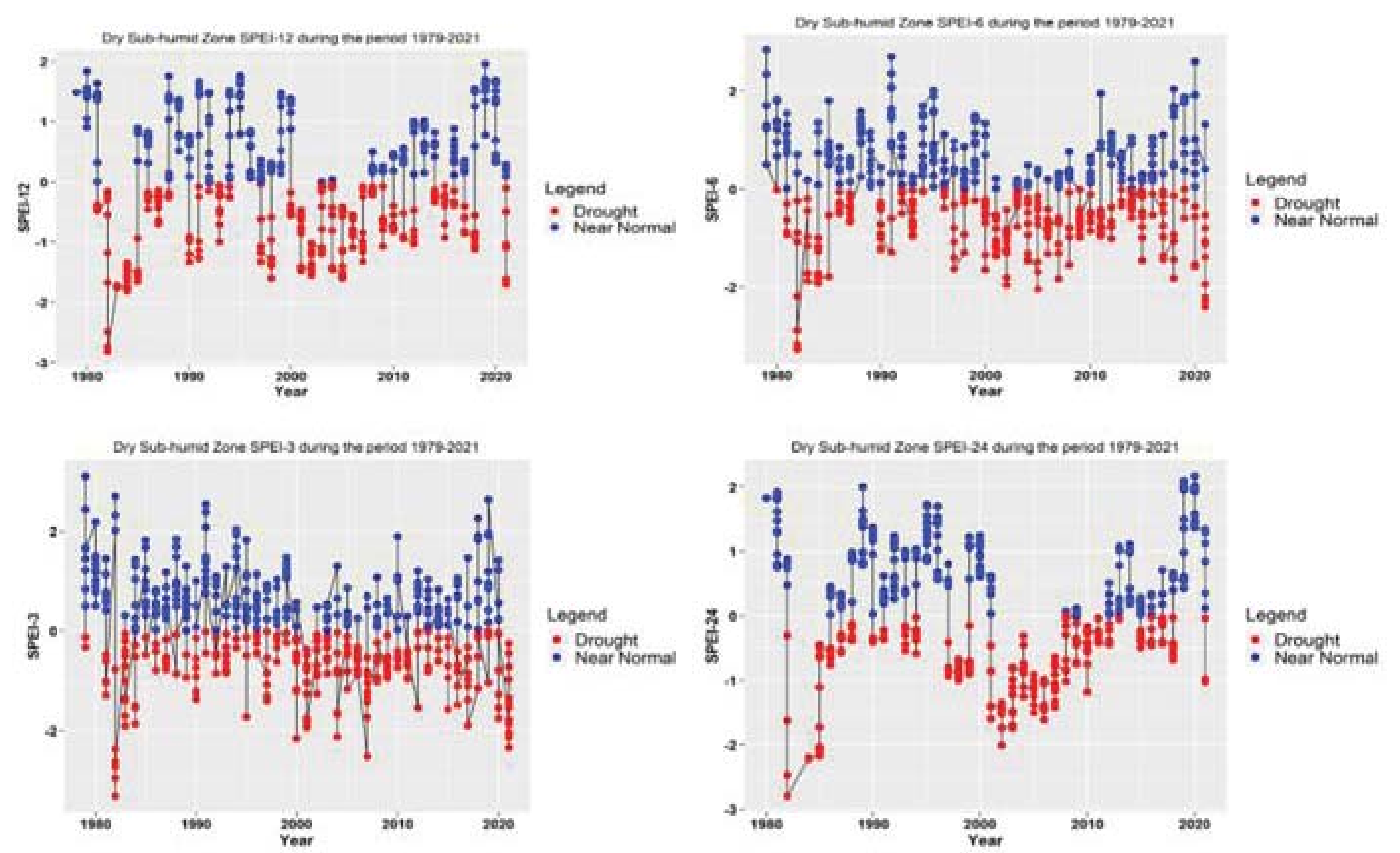

Figure 10: Distributions of Standardized Precipitation-Evapotranspiration Index (SPEI) Series for Drought Detection over Dry Sub-humid Region in West Africa.

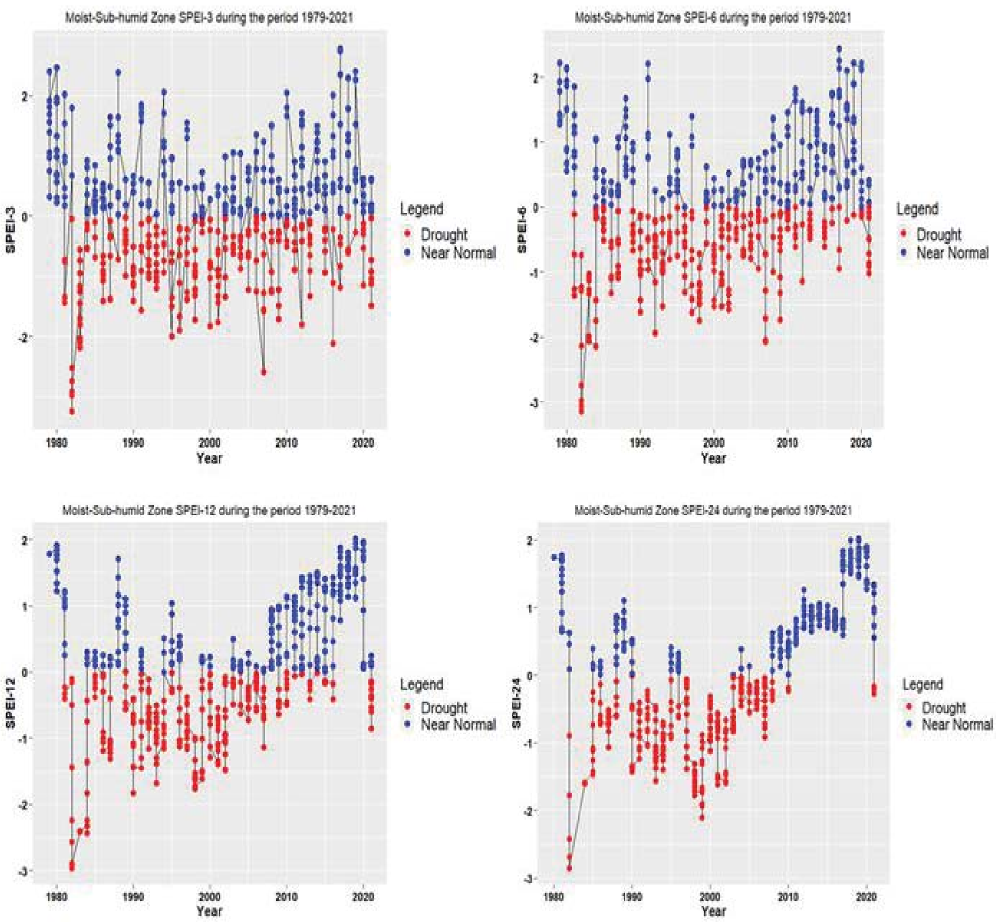

Figure 11: Distributions of Standardized Precipitation-Evapotranspiration Index (SPEI) Series for Drought Detection over Moist Sub-humid Region in West Africa.

3. **Water resources management:** Apply SPI and SPEI to manage water resources, predict water scarcity, and optimize water allocation.

4. **Climate change impact assessments:** Utilize SPI and SPEI to evaluate climate change impacts on drought dynamics and develop adaptation strategies.

Limitations of the study

While the study provides valuable insights into West Africa's drought dynamics, it has some limitations:

1. **Data quality and availability:** The study relies on available data, which may have gaps, errors, or inconsistencies, affecting accuracy.

2. **Spatial resolution:** The study's spatial resolution may not capture local-scale drought variability, masking regional differences.

3. **Temporal resolution:** The study's focus on annual and seasonal scales may overlook shorter-term drought events or intra-seasonal variability.

4. **Index selection:** The study only uses SPI and SPEI, neglecting other drought indices that might provide complementary insights.

5. **Calibration and validation:** The study may not have calibrated or validated the indices against local conditions, potentially affecting their accuracy.

6. **Climate change projections:** The study does not incorporate future climate change projections, limiting its ability to inform long-term adaptation strategies.

Addressing these limitations can enhance the study's accuracy, relevance, and impact, ultimately supporting more effective drought management strategies in West Africa.

Recommendations for future work

1. **High-resolution analysis:** Conduct high-resolution analysis (monthly, weekly) to capture short-term drought events and intra-seasonal variability.

2. **Multi-index approach:** Use multiple drought indices (e.g., PDSI, EDI) to provide a comprehensive understanding of drought dynamics.

3. **Regionalization:** Investigate regional differences in drought dynamics, tailoring findings to specific areas.

4. **Socio-economic integration:** Incorporate socio-economic data to assess drought impacts on vulnerable populations and inform targeted interventions.

5. **Climate change projections:** Integrate future climate change projections to develop long-term adaptation strategies.

By addressing these recommendations, future research can build upon the foundation laid by "West Africa's Drought Dynamics" and provide more comprehensive insights into drought dynamics, ultimately supporting effective drought management and sustainable development in West Africa.

Results and discussion

The distributions of the standardized precipitation index (SPI) series for drought detection over Hyper-Arid, Sahelian, Sudano, Dry Sub-Humid, and Moist Sub-Humid regions in West Africa are shown in Figure 1(a)-1(e).

Both SPI and SPEI have been widely utilized for modeling drought across the globe [33-38]. According to Stagge, et al*.* [39], SPI and SPEI gave room for comparisons across climates using a univariate probability distribution to normalize the index, but when it comes to the implementation of SPI and SPEI, the deviation between results obtained using these techniques was unavoidable. It was observed in this study 3-month time scale (SPI) for Sudano region indicated that the highest drought index value was recorded in 1982 (Magnitude of 12), while the 3-month time scale (SPEI) for Sudano region indicated that the highest drought index value was recorded in 1982 (Magnitude of 15).

By comparison, SPEI identified a higher number of drought years in the Sudano, Dry Sub-Humid, and Moist Sub-Humid regions. The finding was in agreement with an SPI and SPEI conducted by Ayoaye, et al*.* 2019 [40].

Conclusion

This study examined the performance of SPI and SPEI for the detection of drought in West Africa. The results showed that there were slight differences between SPI and SPEI values. The SPI values were higher at all time scales 3, 6, 12, and 24 months than SPEI values in Hyper-Arid and Sahelian regions. However, the SPEI values were higher than the SPI values in the remaining four regions of the study area.

Hence, based on the findings of this research, it could be inferred that SPEI performed better than SPEI in the Sudano, Dry Sub-Humid, and Moist Sub-Humid regions.

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