Analyzing meteorological drought in Liboré, Tillaberi, Niger, West Africa.

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ABSTRACT

Purpose: This study aimed to conduct a comprehensive examination of meteorological drought in Liboré, focusing on understanding the patterns and impacts of meteorological variables on drought conditions from 1990 to 2020. The goal was to identify and analyze trends in rainfall distribution, temperature variations, and drought indices to inform adaptive measures for mitigating the adverse effects of drought on agriculture.

Theoretical Framework: The study was grounded in the theoretical understanding of meteorological drought, utilizing established indicators and indices to measure and analyze drought severity and its impact on the environment. Key theoretical concepts include the Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), and Combined Drought Index (CDI), which are used to evaluate and interpret drought conditions and their variations over time.

Design/Methodology/Approach: The analysis employed a quantitative approach using meteorological data from 1990 to 2020. Indicators such as rainfall, evapotranspiration (ETP), Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), and Combined Drought Index (CDI) were utilized. The methodology involved regression analysis to explore the relationships between rainfall and temperature variables, as well as a detailed examination of SPI and CDI values to assess precipitation patterns and drought trends.

Findings: The study revealed distinct patterns in rainfall distribution, with peak precipitation occurring in July and August. Temperature variations showed Tmax peaking in June and Tmin decreasing from July to December. Significant associations were found between rainfall and meteorological variables, with Tmax negatively correlated and Tmin positively correlated with rainfall. SPI analysis highlighted precipitation deficits from January to May and surpluses from June to September, with challenges noted in September affecting late crops. CDI analysis indicated an upward trend in drought conditions, with moderate to severe drought observed in years like 1991, 1993, and 2011. PDSI analysis showed a progressive decrease in drought severity from May onwards.

Research, Practical and Social Implications: The findings underscore the urgency for adaptive measures to address worsening drought conditions in Liboré. From a research perspective, the study highlights the complex interplay between climatic variables and their impact on agricultural productivity. Practically, the results suggest the need for improved drought management strategies and timely interventions to mitigate the adverse effects of drought. Socially, the study emphasizes the importance of understanding and addressing the

challenges posed by drought to ensure sustainable agricultural practices and food security in the region.
Keywords: Meteorological drought, Rainfall patterns, SPI, CDI, PDSI, Climate change and Liboré.

INTRODUCTION

Drought exerts a profound influence on ecosystems, agriculture, and human communities, particularly in developing countries where its impacts are most severe. Between 1970 and 2019, drought claimed approximately 650,000 lives, with over 90% of these fatalities occurring in developing regions (FAO, 2021; Linong et *al*., 2021). Since 2000, the frequency and duration of droughts have increased by 29% compared to the previous two decades, posing a significant obstacle to sustainable development in less-developed countries (Zhongming et *al*., 2021). Sub-Saharan Africa is among the regions most severely affected by drought, and Niger faces considerable challenges. As a landlocked country in West Africa, Niger is highly vulnerable due to its dependence on rain-fed agriculture, high climate variability, and limited capacity to adapt to climate change (Challinor et *al*., 2007; Müller et al., 2010; Roudier et *al*., 2012). Agriculture, which accounts for nearly 40% of Niger's GDP and is predominantly based on small-scale subsistence farming, is especially at risk (Röhrig et *al*., 2022).

The Tillabéri region in southwestern Niger is particularly susceptible to drought. Recurrent droughts and climate change have triggered significant and potentially irreversible changes in the region. The agricultural systems, which are mainly extensive and cereal-based, are increasingly fragile under growing ecological and social pressures (FAO, 2012; INRAN, 2012). This fragility has intensified concerns about food security and chronic poverty in Tillabéri (ANADIA Niger, 2014). Given these challenges, this study aims to comprehensively examine meteorological drought in the Liboré area of the Tillabéri region. By analyzing key parameters such as precipitation, evapotranspiration, the Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and the Combined Drought Index (CDI) over a 30-year period, this research seeks to reveal evolving drought conditions and identify significant trends. A thorough review of existing literature on meteorological droughts in similar regions not only underscores the critical need for this study but also demonstrates its potential to fill existing knowledge gaps. This research is expected to contribute valuable insights that could inform adaptive strategies, improve resilience, and guide policy interventions in regions facing similar drought-related challenges.

NEED AND SIGNIFICANCE OF THE STUDY

The increasing frequency and intensity of droughts in the Tillabéri region underscore the urgent need for detailed, localized studies to guide effective adaptation strategies. This study is significant because it not only provides an in-depth analysis of drought trends over three decades but also uses multiple indices (PDSI, SPI, and CDI) to offer a comprehensive assessment of drought impacts. This approach is crucial for identifying specific drought patterns and trends, which are essential for developing targeted interventions to mitigate the adverse effects of drought on agriculture and food security in the region. The findings will also contribute to the broader understanding of climate resilience, particularly in semi-arid regions like Niger.

OBJECTIVES OF THE STUDY

This study aims to:

1. Determine meteorological drought trends in the Liboré area of Tillabéri over a 30-year period.
2. Assess the impact of key meteorological variables such as precipitation, evapotranspiration, and temperature on drought conditions.
3. Evaluate the effectiveness of different drought indices (PDSI, SPI, and CDI) in capturing the severity and frequency of drought in the study area.

4. Identify the implications of meteorological drought for agricultural productivity and food security in the region.

I. LITERATURE REVIEW

Climate change is causing significant and hazardous disruptions in natural ecosystems, affecting billions of lives worldwide. The most severe consequences are felt by vulnerable populations and ecosystems. Rising temperatures, droughts, and floods are already surpassing the tolerance limits of many plant and animal species, leading to widespread mortality. These extreme weather events have increased food and water insecurity for millions, particularly in Africa, Asia, Central and South America, small islands, and the Arctic (IPCC, 2022). Over the past decades, numerous studies have aimed to project the impacts of climate change, focusing on both average climate conditions such as temperature and precipitation, and the frequency and severity of extreme events like storms and droughts. These projections highlight the susceptibility of various regions to future climate scenarios, which could cause significant societal disruptions and profoundly impact the livelihoods of affected populations (Desquith & Renault, 2021).

Sub-Saharan Africa is recognized as one of the most vulnerable regions to climate change, regardless of the projected scenario. This vulnerability is primarily due to the region's geographical exposure and sensitivity to climatic hazards (Morris, 2023). West Africa, in particular, faces considerable challenges, being identified as one of the most vulnerable areas globally. Climate change poses severe risks to food security in this region. Multiple studies conducted across West Africa have documented the impacts of current and projected climate change on crop yields and food security (Abdoul Rachid et *al*., 2023).

Niger, a landlocked country situated in the Sahel, spans an area of 1 267 000 km², with three-quarters of its territory classified as desert. The country experiences a semi-arid tropical climate, with a population estimated at 22 million in 2021, most of whom are rural dwellers (CNEDD et *al*., 2022). Within Niger, the Tillaberi region, including the locality of Liboré, exemplifies the challenges posed by climate change. This area, heavily dependent on agriculture, is particularly vulnerable to meteorological droughts, which threaten food security and the livelihoods of local communities. The premature cessation of rains is the most critical climate risk for rain-fed agriculture, followed by strong winds at the beginning of the season and extended dry spells. The risks are more pronounced in northern regions, where delays in the onset of significant rains and irregular rainfall patterns are increasingly concerning. Conversely, southern regions face greater challenges with prolonged dry periods, strong winds at the end of the season, and flooding (Nassourou et *al*., 2018).

Despite extensive research on climate change, significant gaps persist, particularly concerning localized climate projections, socio-economic impacts, and the effectiveness of adaptation strategies. Specifically, in Liboré, more precise climate models are needed to account for microclimates, along with studies that integrate socio-economic data with climate projections. Additionally, there is a lack of empirical evidence on the long-term effectiveness of adaptation measures. Furthermore, research on optimizing agricultural practices under changing climatic conditions and developing interdisciplinary approaches that consider the interactions between climate, agriculture, socio-economic factors, and local governance remains critically underexplored. Addressing these gaps is crucial for developing effective, context-specific strategies to mitigate the impacts of climate change in Niger.

II. RESEARCH METHODOLOGY

2.1. Presentation of the study area

The rural commune of Liboré is situated between 13°24' and 13°31' north latitude and between 2°7' and 2°16' east longitude (Figure 1). This commune is located in the Kollo department (Tillabéri region), positioned between the urban community of Niamey and the town of Kollo (departmental capital), 15 km from Niamey. It spans an area of 110 km^2 and encompasses fifteen (15) administrative villages (Yabi, 2014).

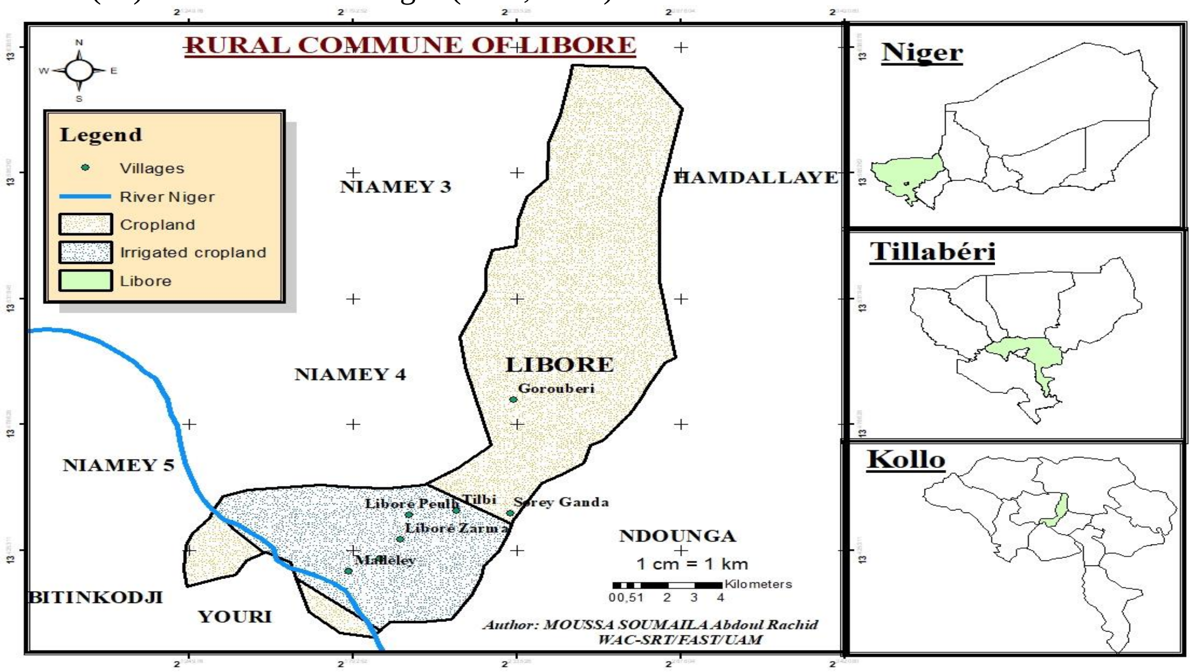


Figure 1: *Map depicting the study area's location.*

The climate of the study area is classified as Sudanian-Sahelian, characterized by two seasons of unequal length (Bachir, 2011). The rainy (humid) season lasts only four months (June to September), while the dry season extends over seven months (October to May). The average annual rainfall between 1979 and 2009 is comparable to that of Niamey, approximately 510 mm (Sanda, 2009). According to Bachir (2011), rainfall is predominantly marked by heavy rains or convective storms, during which substantial amounts of water can be discharged in a short period. Temperatures are generally high throughout the year, with seasonal variations. During the dry period, maximum temperatures can reach 45°C, whereas during the rainy season, they peak at around 36°C. Notably, during the Harmattan, minimum temperatures can drop to 10°C at night and in the morning before significantly rising during the day, resulting in a high thermal amplitude (over 20°C). Thus, the climatic conditions are harsh and naturally challenging for agropastoral activities.

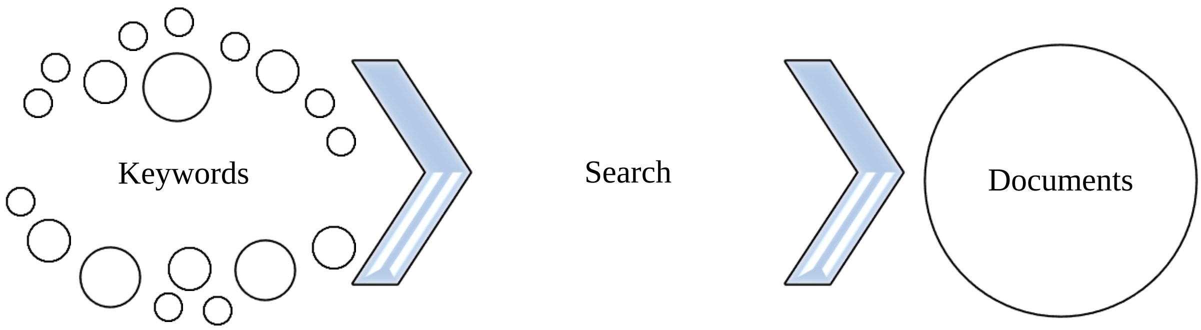
Regarding soil types, two main soil categories dominate the study area. The first are soils of the Niger River valley, including silt, hydromorphic, and sandy soils, which occupy most of the area. The second category comprises plateau soils found in exuded units. These soils are generally suitable for agricultural production (e.g., millet, rice) and support vegetation critical for pastoral activities. However, they dry out during water deficits and are prone to flooding during excessive rainfall events (PDC, 2017).

Hydro-geomorphologically, the study area is part of the Kollo department, dominated by the alluvial plain of the Niger River. The Niger River traverses the environment for approximately

8 km and includes permanent and semi-permanent ponds, as well as valleys and lowlands covering an estimated area of 1,800 ha. This relatively flat landscape is conducive to agropastoral activities, providing opportunities for irrigated and market gardening practices by local populations (Yabi, 2014).

2.2. Methodology for Documentary Research

During this phase, our primary objective was to gather a comprehensive range of information from pertinent prior research and documentation sources. We focused on assembling diverse data types, including reports, articles, books, field notes, and previously published materials. To enhance our search efficiency, we employed keywords such as drought, SPI, climate change, and Tillabéri across various search engines like Google, Google Scholar, ResearchGate, Mendeley, and Z-Library. Utilization of Boolean operators (such as "and" and "or"), proximity operators (like "adj" and "near"), truncations, and masks (including "*", and "$"), along with parentheses, quotation marks, and hyperlinks, enabled us to refine our search parameters. The research process comprised three main steps: initial data familiarization, followed by data reorganization and cleansing by eliminating irrelevant variables, and ultimately, data manipulation to extract pertinent insights. The methodology employed for the literature review is summarized in the figure below.



- Drought
- SPI
- PDSI
- Tillabéri
- Liboré
- Climate change
- Niger

- Google scholar
- Google
- Researchgate
- Mendeley
- Z-Library

- Report
- Items
- Books
- Articles
- field notes

Figure 2: *Documentary research methodology*

2.3. Data Collection Methodology

The meteorological data utilized in this research was sourced from the National Meteorological Department (DMN), an organization recognized for its reliability and authority in providing accurate climate information for the region. The DMN follows rigorous data collection and validation protocols, ensuring that the temperature, rainfall, and evapotranspiration records from 1990 to 2020 are both precise and consistent. These records, meticulously gathered and maintained by the DMN, form the cornerstone of this research, enabling a thorough analysis of climate trends in Liboré. The credibility of the DMN's data collection processes enhances the reliability of our findings, as it reflects the true climatic conditions of the area over the past three decades.

2.4. Method for calculating the standardized precipitation index

The method used to assess fluctuations in drought conditions in Liboré involves calculating the Standardized Precipitation Index (SPI) based on average monthly precipitation data from 1990 to 2020. The SPI calculation follows several sequential steps. First, the mean (μ) and standard deviation (σ) of the precipitation data were computed for each month over the study period. The SPI formula is expressed as:

$$SPI = \frac{X-\mu}{\sigma}$$

(Mckee, 1993).

(X): Represents the observed value of the month

(μ): Mean

(σ): Standard deviation

Interpreting the SPI is crucial for understanding weather conditions, as it provides a temporal profile that highlights months or seasons with abnormal precipitation patterns. This methodology offers a detailed perspective on drought variations in the Liboré commune, contributing to a deeper understanding of climate impacts in this region over the past three decades. The choice of the SPI for evaluating meteorological drought in Liboré is justified by its effectiveness in standardizing precipitation anomalies, allowing for direct comparisons across different timescales and locations. The SPI is widely recognized for its simplicity, versatility, and ability to detect both short-term and long-term droughts, making it an ideal index for capturing the variability and intensity of drought conditions specific to Liboré's unique climatic context.

Table 1: *Interpretation of SPI Levels.*

SPI level	**Interpretation**
SPI > 1	Very wet
0 > SPI > 1	wet
-1 > SPI > 0	dry
SPI < -1	Very dry

(Mckee, 1993).

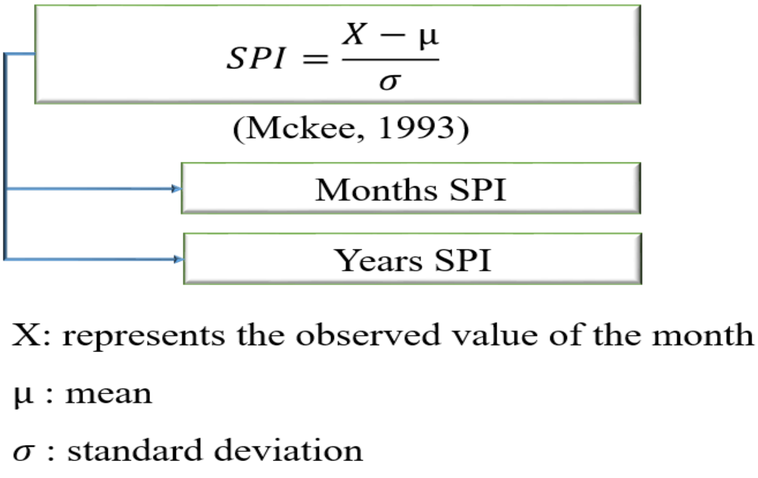


Figure 3: *SPI calculation method.*

2.5. Method for calculating the drought climate index

The method for calculating the Combined Drought Index (CDI) involves an approach that integrates average monthly data on maximum temperature, minimum temperature, and precipitation over the period from 1990 to 2020. This methodology aims to quantify drought conditions by incorporating both temperature and precipitation factors simultaneously. The calculation of the CDI follows several steps. First, z-scores were computed for the temperature and precipitation data using the standard z-score formula:

$$Z - score = \frac{X - \mu}{\sigma}$$

(Mckee, 1993).

(X): Represents the observed value of the month

(μ): Mean

(σ): Standard deviation

The CDI was then calculated using the formula: *CDI = rainfall z-score + temperature z-score*. This methodology provides an integrated view of drought conditions by considering both thermal and hydrological aspects, thereby enabling a more comprehensive assessment of climatic variations in Liboré over the last three decades. The choice of the CDI is based on its ability to incorporate multiple climatic variables, offering a holistic understanding of drought dynamics. By combining temperature and precipitation data, the CDI captures both moisture deficits and temperature anomalies, which are critical for assessing the multifaceted impacts of drought in the region. This approach, rooted in principles of statistics and climatology, can be adapted to specific regional or study needs, making it a versatile tool for evaluating drought conditions.

Table 2: *Interpretation of CDI levels.*

DCI level	Interpretation
CDI > 1	Very wet
0 > CDI> 1	wet
-1 > CDI > 0	dry
CDI < -1	Very dry

(Mckee, 1993).

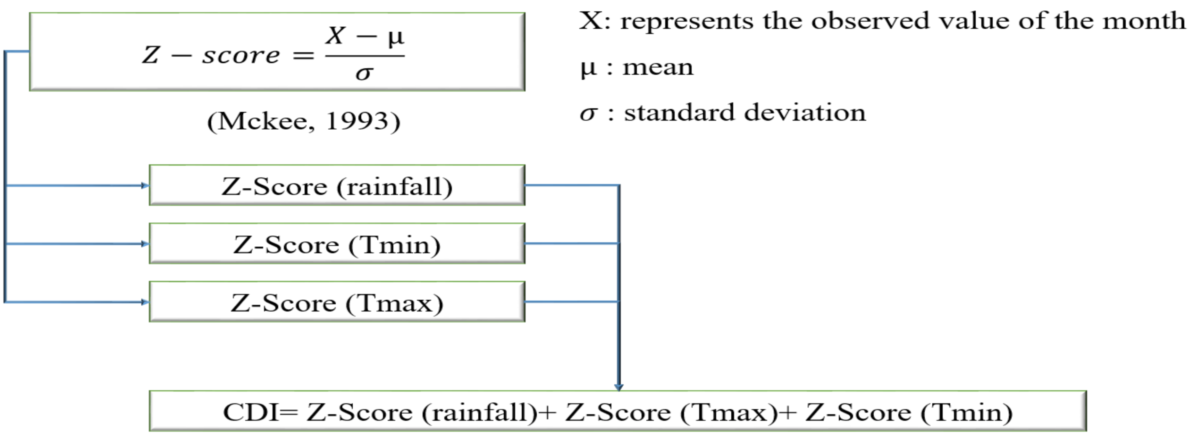


Figure 4: *CDI calculation method.*

2.6. Palmer Drought Index calculation method

The methodology used to evaluate the impact of drought on household cropping systems in Liboré involves analyzing average monthly climate data over a period of three decades, from 1990 to 2020. To assess the effects of drought, we utilized data on available water supply (precipitation) and water demand (evapotranspiration), allowing for the quantification of water that evaporates or transpires without water limitations. The water surplus or deficit was determined by subtracting water demand (ETP) from the available water supply (P) for each month, using the formula: Surplus (or deficit) = *P – ETP*

Subsequently, the Palmer Drought Severity Index (PDSI) was calculated by aggregating water surpluses or deficits over multiple months, taking into account the previous month's index for a long-term assessment. The general formula applied is:

PDSI = PDSI_anterior + (0.897 x water surplus or deficit)

Where 0.897 is the persistence factor, reflecting the tendency for drought conditions to persist over time. For the month of January, the previous PDSI is assumed to be 0 (Palmer, 1965).

This approach provides a comprehensive understanding of the cumulative impact of drought over time, capturing both short-term fluctuations and long-term trends in moisture conditions. The use of the PDSI is justified by its effectiveness in representing complex interactions between water supply and demand, making it a robust tool for assessing drought impacts on cropping systems in the region.

Table 3: *Interpretation of PDSI Levels.*

PDSI level	Interpretation
PDSI > +2	Very humid
+2 > PDSI > +1	Humid
+1 > PDSI > -1	Slightly damp
-1 > PDSI > -2	Slightly dry
-2 > PDSI > -3	Dry
PDSI < -3	Very dry

(Palmer, 1965).

III. RESULTS

3.1. Descriptive statistics

Table 4 provides descriptive statistics for key climatic variables, highlighting their variability and range. The maximum temperature (Tmax) averages 36.122°C with a low coefficient of variation (CV) of 0.0843, indicating relatively stable temperatures, ranging from 31.79°C to 41.07°C. In contrast, the minimum temperature (Tmin) shows more variability, with a mean of 23.336°C and a CV of 0.163, ranging from 16.84°C to 28.68°C. Evapotranspiration (ETP) displays moderate variability, with an average of 329.91 mm and a CV of 0.248, spanning from 195.25 mm to 454.12 mm. Rainfall (P) is the most variable, with a mean of 45.88 mm and a high CV of 1.403, ranging from 0 to 189.2 mm, reflecting the irregular and unpredictable nature of precipitation in the region.

Table 4: *Descriptive statistics.*

Variables	Mean	CV	Maximum	Minimum
Maximum temperature (Tmax) (°C)	36.122 ± 3.046	0.0843	41.07	31.79
Minimum temperature (Tmin) (°C)	23.336 ± 3.810	0.163	28.68	16.84
Evapotranspiration (ETP) (mm)	329.91 ± 81.89	0.248	454.12	195.25
Rainfall (P) (mm)	45.88 ± 64.39	1.403	189.2	0

3.2. Relationship between climatic variables

Table 5 examines the relationships between climatic variables, revealing significant correlations between several pairs. The positive correlation between maximum temperature (Tmax) and minimum temperature (Tmin) is strong (coefficient = 0.7485, p-value = 0.0051), indicating that as Tmax increases, Tmin tends to rise as well. Similarly, Tmax is positively correlated with evapotranspiration (ETP) (coefficient = 0.7339, p-value = 0.0066), suggesting that higher temperatures drive increased evapotranspiration. On the other hand, rainfall (P) shows a significant negative correlation with ETP (coefficient = -0.7212, p-value = 0.0081), implying that higher evapotranspiration is associated with lower rainfall levels. The correlations between Tmax and P, as well as Tmin with both P and ETP, are not statistically significant, indicating weaker or non-existent relationships between these variables in the dataset.

Table 5: *Relationship between climatic variables*

Variables		Coefficient	p-value
Tmax	Tmin	0.7485	0.0051*
Tmax	P	-0.3547	0.258
Tmax	ETP	0.7339	0.0066*
Tmin	P	0.315	0.3185
Tmin	ETP	0.1977	0.538
P	ETP	-0.7212	0.0081*
Signif. Codes : *0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*			

3.3. Analysis of ombrothermic diagram

The ombrothermic diagram (figure 5) illustrates the climatic conditions in Liboré based on key meteorological parameters. The rainfall distribution throughout the year shows a peak in July and August, with significant precipitation levels recorded during these months. This period marks the region's rainy season, characterized by intense rainfall that tapers off at the beginning and end of the year. Temperature variations are represented by Tmax (maximum temperature) and Tmin (minimum temperature) values. High temperatures are observed from April to June, with Tmax reaching its peak in April. Conversely, Tmin values remain relatively lower during this period. From July onwards, temperatures begin to decline gradually, reaching their lowest levels in December and January. Overall, the ombrothermic diagram provides valuable insights into the seasonal variations in rainfall and temperature, which are essential for understanding the climatic patterns and their impacts.

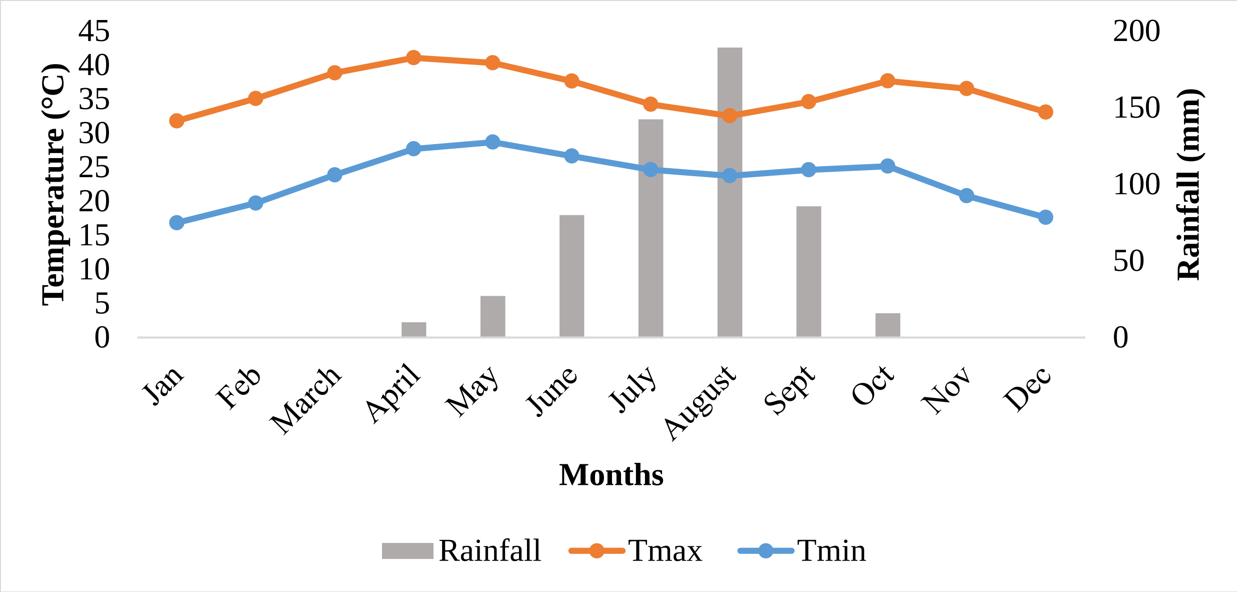


Figure 5: *Ombrothermic diagram.*

3.4. Rainfall Pattern Modeling

The regression analysis reveals intriguing dynamics between temperature variables and rainfall. Specifically, Tmax (maximum temperature) exhibits a negative relationship with rainfall, indicated by its coefficient of -28.380 and a highly significant p-value (0.0000195). This negative relationship suggests that as Tmax increases, rainfall tends to decrease. One possible explanation for this observation could be related to the mechanisms of evaporation and moisture retention. Higher maximum temperatures often lead to increased evaporation rates, potentially reducing the amount of moisture available in the atmosphere for precipitation. Additionally, elevated temperatures can sometimes enhance the stability of the atmospheric layers, making it less likely for convection to occur and, consequently, reducing rainfall. In contrast, Tmin (minimum temperature) shows a positive relationship with rainfall, as reflected by its coefficient of 22.307 and a highly significant p-value (0.0000223). This positive relationship suggests that as Tmin increases, rainfall tends to increase as well. One explanation could be that higher minimum temperatures correlate with increased atmospheric moisture, as warmer air can hold more moisture. Additionally, warmer minimum temperatures might be associated with more favorable conditions for cloud formation and precipitation, particularly during nighttime when temperatures are higher, thus supporting greater rainfall. Understanding these relationships requires consideration of local climatic conditions and the specific processes driving precipitation in the region. Tmax and Tmin influence rainfall in different ways, and their effects highlight the complex interplay between temperature variables and precipitation patterns. Further investigation into these mechanisms, including regional climatic factors and atmospheric dynamics, could provide deeper insights into the observed relationships.

Table 6: *Regression analysis.*

Variance Inflation Factor (VIF)				
variables		VIF		Acceptance
Tmax		2.27		Accepted
Tmin		2.27		Accepted
Regression Results				
	Estimate	Std.Error	t value	Pr(>|t|)
(Intercept)	550.461	88.868	6.194	0.00016 ***
Tmax	-28.380	3.492	-8.128	0.0000195 ***
Tmin	22.307	2.792	7.991	0.0000223 ***
Regression Equation : Rainfall= 22.307Tmin - 28.380Tmax + 550.461				

Tests on model Residual		
Type	Test	p-value
Normality Test	Shapiro-Wilk test	0.5736
Zero Mean Test	One Sample t-test	1
Homoscedasticity Test	Breusch-Pagan test	0.277
Autocorrelation Test	Durbin-Watson test	0.3121
Model Statistics		
Type	Test	p-value
Global significance test	ANOVA	0.00001949 ***
Non-linearity Test	RESET test	0.3816
Residual standard error: 23.4 on 9 degrees of freedom Multiple R-squared: 0.892, Adjusted R-squared: 0.868 F-statistic: 37.17 on 2 and 9 DF, p-value: 0.0000447		
Signif. Codes: *0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*		

3.5. Analysis of rainfall and evapotranspiration

The figure presented in this section highlights key months for rainfall and evapotranspiration, which have profound implications for agriculture in the rural commune of Liboré over the 30-year period from 1990 to 2020. Notably, the months of January, February, March, November, and December are marked by almost negligible precipitation, indicating severe drought conditions during these periods. This drought presents a significant challenge for local agriculture, as crops in the region are heavily dependent on rainfall for growth. Moreover, evapotranspiration consistently exceeds precipitation throughout the year, underscoring a high water demand by vegetation relative to the available water supply. This added pressure on water resources further complicates crop management in this semi-arid environment.

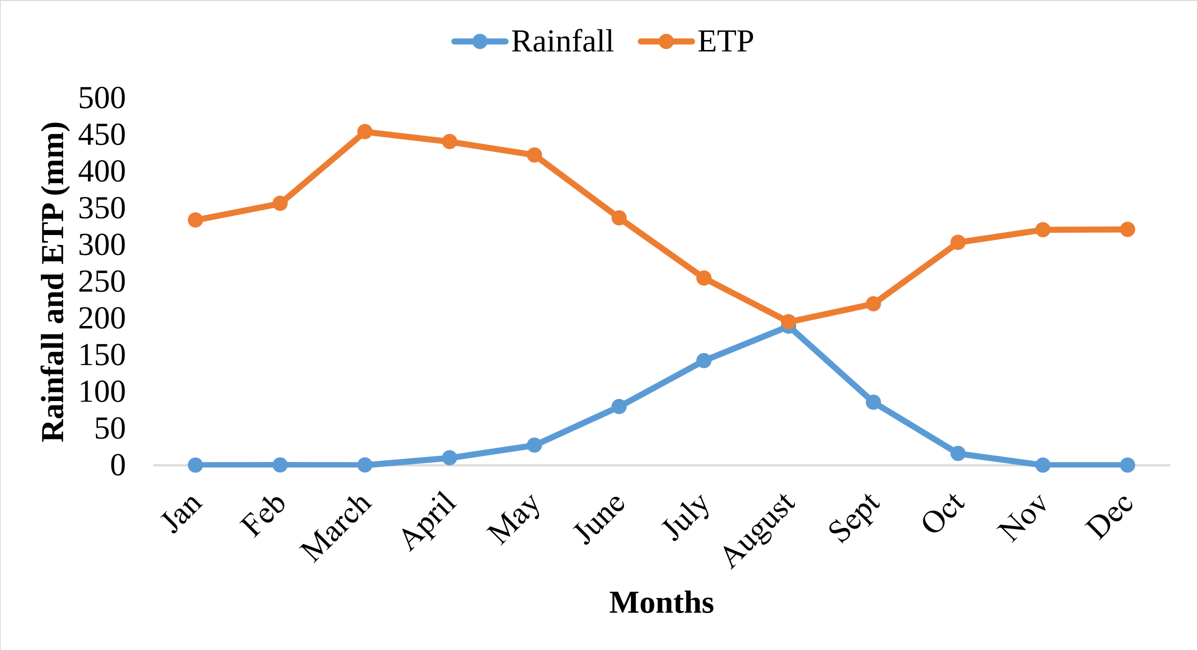


Figure 6: *Monthly variability of rainfall and evapotranspiration.*

3.6. Standardized Precipitation Index (SPI) Analysis

The analysis of climatic data over thirty years (1990 to 2020) for the Liboré commune has generated the Standardized Precipitation Index (SPI) for each month of the year. The SPI is a vital indicator for assessing precipitation variability and its impact on drought conditions, providing a comprehensive overview of the region's climatic patterns throughout the seasons.

Several key observations emerge from examining the SPI values. Firstly, the months from January to May show negative SPI values, indicating precipitation deficits during this period. This corresponds with the region's dry season and highlights the vulnerability of agriculture during these months. In contrast, the months from June to September are characterized by positive SPI values, suggesting precipitation surpluses during the rainy season. These months are crucial for local agriculture, as they provide significant water replenishment for soils and crops. However, it is noteworthy that despite these favorable months, challenges persist in Liboré, particularly in September, where SPI values remain positive but display a declining trend. This gradual reduction in precipitation could affect late-season crops. Furthermore, the SPI reveals critical months (October, November, and December) where negative values indicate the onset of a new drought period, underscoring persistent agricultural challenges in the commune. It is also important to note that the relatively low coefficient of determination (R^2) suggests a weak linear correlation between months and SPI values, indicating that other climatic and environmental factors may influence these variations.

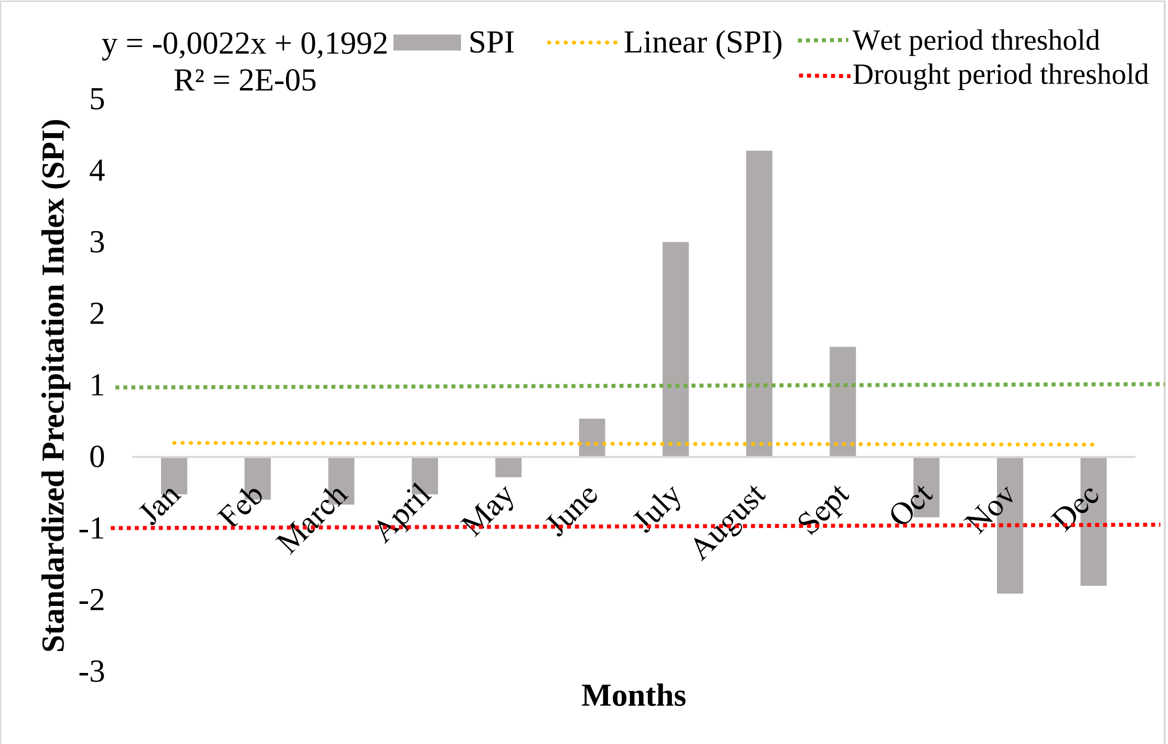


Figure 7: *Inter-monthly variation of standardized precipitation index.*

Observing the SPI values for each year reveals a significant diversity between periods of precipitation deficits and surpluses. Years such as 1998 and 2017 exhibit high positive SPI values, indicating favorable precipitation surpluses for agriculture. In contrast, years like 1991, 1993, and 2011 with negative SPI values, signaling drought periods and precipitation deficits that pose challenges for agriculture. This inter-annual variation highlights the complexity of climatic factors influencing water availability, with pronounced differences between years in terms of hydrological conditions.

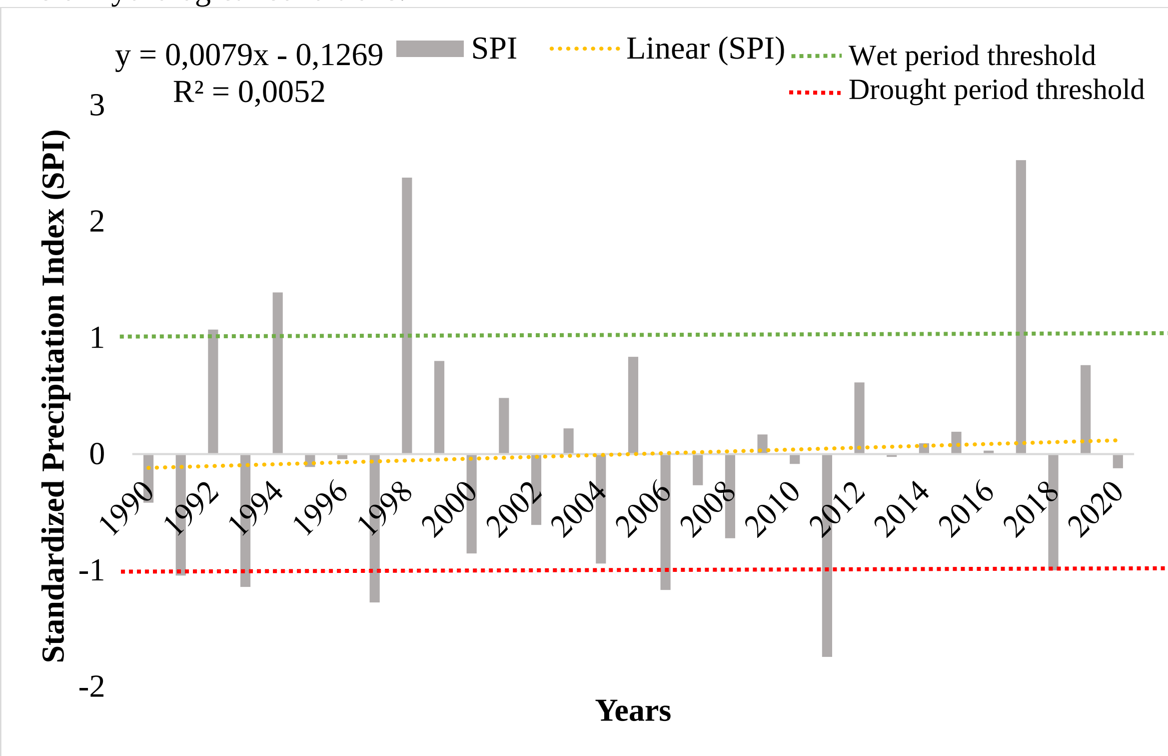


Figure 8: *Inter-annual variation of standardized precipitation index.*

3.7. Combined Drought Index (CDI) Analysis

The Combined Drought Index (CDI) is a key indicator for assessing drought conditions in the Liboré commune over a 30-year period (1990 to 2020). The results derived from CDI data provide an overview of the evolution of climatic conditions and their potential impacts on agriculture and the environment. The trend curve equation, with a coefficient of determination ($R^2 = 0.5411$), offers insights into the general trend of CDI over the years. The positive slope of the curve suggests a gradual increase in CDI, indicating a rising trend in drought conditions within the commune. However, the (R^2) value of 0.5411 indicates that, while the trend is notable, other non-linear factors may also be influencing the CDI. By examining CDI values for specific years, several important observations emerge. The years 1991, 1993, 1995, 1997, 2000, and 2002 stand out with negative CDI values, indicating episodes of moderate to severe drought during these periods. Conversely, the years 2010, 2013, 2017, and 2019 show positive CDI values, suggesting more favorable climatic conditions.

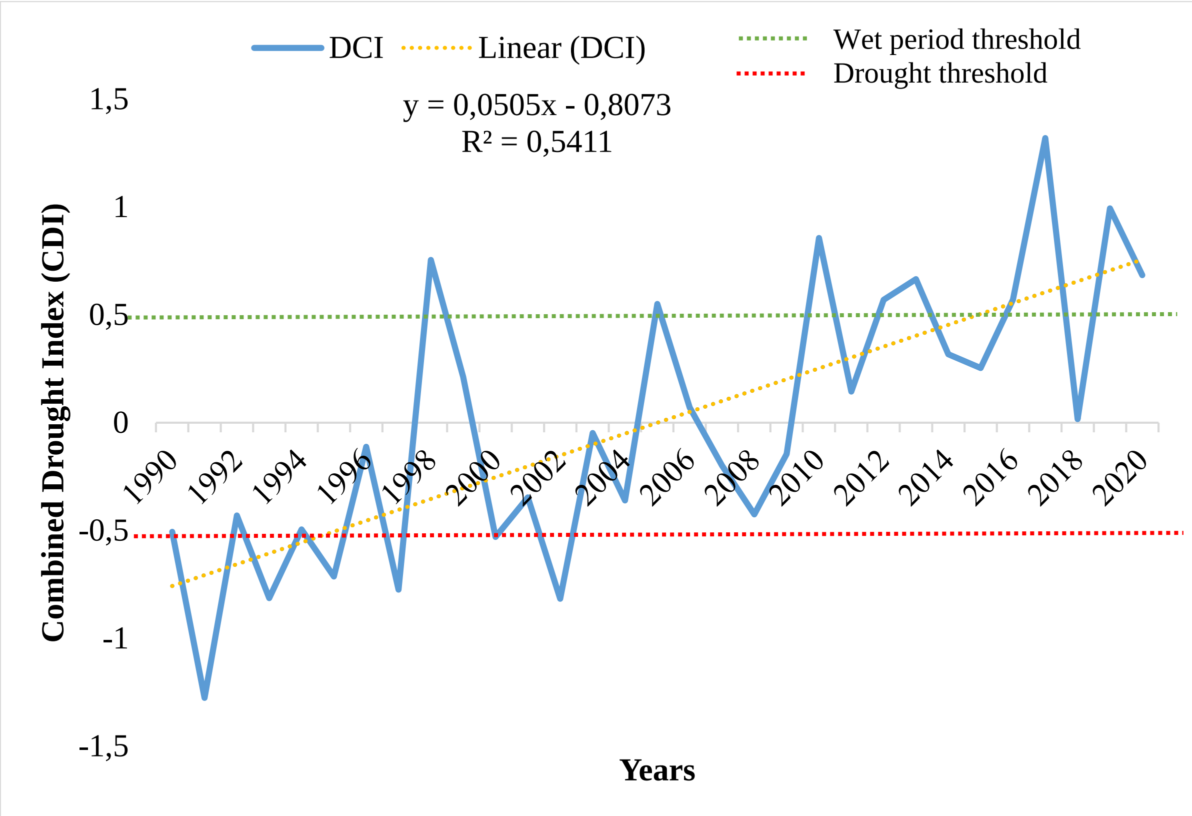


Figure 9: *Variation of the drought climate index.*

2.1.4. Palmer Drought Index Analysis

Figure 10 provides a detailed overview of the variations in the Palmer Drought Severity Index (PDSI) over a three-decade period (1990 to 2020) in the commune of Liboré, using specific PDSI interpretation levels. The monthly analysis based on these categories offers insights into the evolving climatic conditions. The calculated PDSI for this period is approximately-3740.35, confirming the prevalence of drought conditions in Liboré. A notable trend emerges, showing a progressive decrease in PDSI beginning in May, indicating an intensification of drought conditions over time. In particular, the months of January, February, and April display strongly negative PDSI values, classified as "very dry," reflecting significant drought concerns at the start of the year. From May to October, the PDSI values suggest "slightly dry" conditions, indicating a less severe drought trend during this period. Overall, the analysis confirms a trend of worsening drought conditions over the years, posing potential challenges for agricultural activities in Liboré, with most months categorized as "slightly dry" and some as "very dry." The trendline equation, (y = -152.22x - 268. 68), illustrates the general drought trend over the 30 years. The negative slope of the curve indicates that, on average, drought conditions tend to deteriorate, consistent with the seasonal fluctuations observed in the figure.

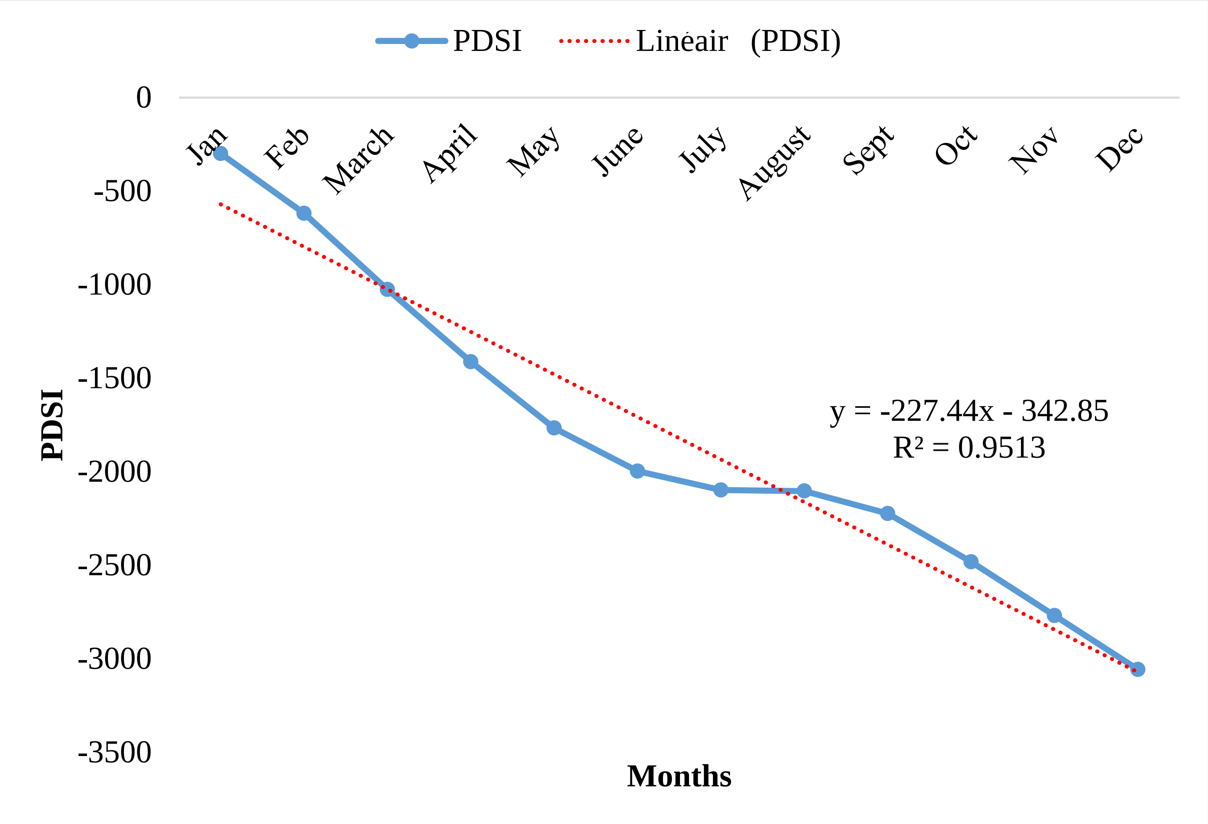


Figure 10: *Variation of the drought index of Palmer.*

IV. DISCUSSION

The findings from this comprehensive study on drought in Liboré over 30 years (1990 to 2020) provide critical insights into the evolving climatic conditions. Regression analysis reveals a complex interaction between temperature variables and rainfall. Maximum temperature (Tmax) demonstrates a significant negative relationship with rainfall, suggesting that higher temperatures are associated with reduced precipitation. This may be due to increased evaporation rates and enhanced atmospheric stability, which can reduce the likelihood of convection and subsequent rainfall. In contrast, minimum temperature (Tmin) exhibits a positive correlation with rainfall, likely due to increased atmospheric moisture capacity and more favorable conditions for cloud formation at higher nighttime temperatures.

These results align with broader regional studies, such as Giannini et *al*. (2008), who documented a sustained drought crisis in the Sahel since the 1970s, marked by increasing frequency and severity of drought events. The findings from Liboré substantiate this alarming trend, underscoring the severe climatic challenges faced across the Sahel. Similarly, Habib et *al*. (2014) project a potential intensification of drought conditions in the Sahel in the coming decades, a scenario that is consistent with the trends observed in Liboré. These studies emphasize the urgent need for adaptive measures to mitigate the impact of worsening climatic conditions, a need strongly supported by the findings from this study.

The use of the Standardized Precipitation Index (SPI) in this analysis provides a comprehensive understanding of seasonal climatic patterns in Liboré. The SPI values reveal significant precipitation deficits from January to May, aligning with the region's dry season and highlighting agricultural vulnerabilities. Conversely, the months from June to September show positive SPI values, indicating periods of surplus rainfall crucial for crop growth. However, the declining trend in SPI observed in September suggests potential challenges for late-season crops, despite generally favorable conditions during the rainy season. The Combined Drought Index (CDI) further illustrates a rising trend in drought conditions, with a positive slope in its trend line and a coefficient of determination ($R^2 = 0.5411$), indicating that other non-linear factors may also influence drought dynamics. The findings from Liboré align with those of Okpara and Tarhule (2015), who identified the SPI as the most robust index for detecting moderate and extreme drought events in the Niger River Basin.

The Palmer Drought Severity Index (PDSI) analysis offers additional insights into the drought conditions in Liboré. The PDSI values, calculated at approximately -37405.35 for the study period, confirm the prevalence of drought, with a significant decline beginning in May and intensifying over time. January, February, March, and April are characterized by "very dry" conditions, while the period from May to October shows "slightly dry" conditions. These results are consistent with the findings of Oguntunde et *al*. (2018), who projected an increase in drought intensity and frequency over the Niger River Basin, further emphasizing the urgent need for strategic responses to mitigate the effects of prolonged droughts.

Additionally, the findings from Wildemeersch et *al*. (2015) suggest that agricultural drought in the Sahel may not be driven solely by declining rainfall but also by factors such as rainfall distribution, frequency of dry spells, and poor soil water retention due to land degradation. Their research highlights the effectiveness of water and soil conservation techniques, such as zaï pits, in mitigating drought impacts by improving soil-water storage and crop yields. These insights are particularly relevant for Liboré, where adaptive land management practices could play a crucial role in enhancing resilience against future droughts.

Recent studies, such as Chai et *al*. (2021), also highlight the significant link between human activities and drought occurrences in the Sahel, pointing to the importance of considering anthropogenic influences in the analysis of climatic conditions. The findings from Liboré underscore the necessity of acknowledging these human factors, which contribute to the exacerbation of drought conditions, and call for coordinated efforts at both local and global levels to address this pressing issue effectively.

Overall, the results from Liboré corroborate observed trends in other regional and global studies, emphasizing the multifaceted nature of the drought crisis in the Sahel, shaped by both climatic and human factors. These findings highlight the urgent need for coordinated actions aimed at mitigating drought impacts and developing robust adaptive strategies to protect livelihoods and ecosystems in the Sahel and beyond.

By situating these results within the broader context of current knowledge, this study not only enhances our understanding of the complex interactions between climate variables, human activities, and land use but also provides a solid foundation for future research and policy-making to effectively address the challenges of drought in this vulnerable region.

4.1. Effectiveness of different drought indices (PDSI, SPI, and CDI)

PDSI, SPI, and CDI provide unique insights into the severity and frequency of drought. The Palmer Drought Severity Index (PDSI) has proven effective in capturing long-term drought trends and identifying periods of intense drought, particularly from May onwards, thereby reflecting both seasonal and progressive changes in drought severity. On the other hand, the

Standardized Precipitation Index (SPI) is valuable for its ability to analyze seasonal patterns and variations in precipitation, pinpointing critical drought periods throughout the year and offering a detailed view of precipitation deficits and surpluses. The Combined Drought Index (CDI) demonstrated its utility in tracking the overall trend of increasing drought conditions over a 30-year span, highlighting moderate to severe drought events and illustrating the cumulative effects of meteorological and soil-water drought factors. Overall, the study indicates that while each index has its strengths, PDSI for long-term trends, SPI for seasonal and annual variations, and CDI for combined drought dynamics. They complement each other in providing a comprehensive assessment of drought severity and frequency. This multi-faceted approach enhances our understanding of drought patterns and their impacts, offering a robust framework for drought analysis and management.

4.1. Implications of the study for agricultural productivity and food security

The findings of this study have significant implications for agricultural productivity and food security in Liboré. The observed patterns of drought, characterized by prolonged periods of low precipitation and high temperatures, directly affect the availability of water for crops, leading to reduced agricultural yields. The negative correlation between maximum temperature (Tmax) and rainfall suggests that rising temperatures may exacerbate water scarcity by increasing evaporation rates and reducing soil moisture, further stressing crops during critical growth periods.

The study's use of the Standardized Precipitation Index (SPI) and the Combined Drought Index (CDI) reveals that the periods of drought, particularly from January to May, pose significant challenges for agricultural productivity. These dry months coincide with the planting and early growth stages of many crops, making them especially vulnerable to water deficits. Conversely, while the rainy season months (June to September) provide essential water for crops, the declining trend in SPI values observed in September suggests potential risks for late-season crops, which may not receive adequate water for maturation.

Moreover, the Palmer Drought Severity Index (PDSI) indicates a worsening trend in drought conditions over time, which could further impact food security by reducing the stability and predictability of crop production. This trend is particularly concerning for smallholder farmers in Liboré, who rely heavily on rain-fed agriculture and have limited access to irrigation infrastructure.

Given these findings, this study underscores the urgent need for adaptive strategies to mitigate the adverse effects of drought on agricultural productivity and food security in Liboré. Implementing water management practices, such as rainwater harvesting, soil moisture conservation techniques, and the use of drought-resistant crop varieties, could help improve resilience against climatic variability. Additionally, the study highlights the importance of developing early warning systems and enhancing local capacity to respond to drought conditions, which are critical for safeguarding food security in the region. By providing a nuanced understanding of the local dynamics of drought, this study informs policy-making and resource management strategies aimed at improving agricultural sustainability and ensuring food security in Liboré.

4.2. Scope for further research

Future research should focus on integrating high-resolution climate data, such as localized soil moisture measurements and groundwater levels, to enhance the accuracy of drought assessments in Liboré. Additionally, examining the socio-economic impacts of drought on agricultural income, food security, and livelihoods could help tailor adaptive measures to local needs. Evaluating the effectiveness of adaptive land management practices, such as water conservation techniques and crop diversification, will be crucial for improving resilience against drought. Expanding studies to consider different climate change scenarios (e.g., RCP4.5, RCP8.5) can provide valuable insights into future drought patterns and their potential impacts. An interdisciplinary approach combining climatology, hydrology, agronomy, and socio-economic studies would support the development of integrated drought management strategies, ensuring sustainable agricultural productivity and food security in Liboré and similar semi-arid regions.

CONCLUSION

This study sheds light on the complex nature of drought conditions in the Liboré commune, revealing how both climatic variability and human factors contribute to evolving patterns of water scarcity. The distinct correlations between temperature variables and rainfall underline the sensitivity of local precipitation to changes in maximum and minimum temperatures, which directly impact agricultural productivity and water management. The use of multiple drought indices, such as the SPI, CDI, and PDSI, offers a multi-dimensional view of drought dynamics, capturing both short-term fluctuations and long-term trends that are critical for developing effective adaptation strategies.

These findings enhance our understanding of how seasonal and inter-annual climatic variations interact with local environmental and anthropogenic factors to influence drought conditions in a semi-arid region. The study's integrated approach represents a significant contribution to existing literature by providing a more detailed picture of drought in Liboré, aligning with observed regional trends in the Sahel, and highlighting the need for targeted climate resilience measures.

Acknowledging the limitations related to the reliance on historical data and the absence of more granular hydrological information, this research points to clear directions for future studies. By incorporating more precise, high-resolution data and exploring the socio-economic impacts of drought, future research can build upon these findings to create more tailored and effective responses. Given the projected intensification of drought under various climate change scenarios, continued investigation into adaptive practices will be vital for safeguarding livelihoods and enhancing food security in drought-prone regions like Liboré.

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