Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/19062
DOI URL: http://dx.doi.org/10.21474/IJAR01/19062

ISSN NO. 2320-5407

RESEARCH ARTICLE

VULNERABILITY OF WATER RESOURCES TO DROUGHT RISK AND FLOOD PREVENTION IN MONO RIVER BASIN (GULF OF GUINEA REGION)

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Manuscript Info

Manuscript History
Received: 07 May 2024
Final Accepted: 14 June 2024
Published: July 2024

Key words:-
Water Resources, Drought Risk, Flood Prevention Mono River Basin

Abstract

The Mono River Basin in the Gulf of Guinea region faces significant challenges due to climatic variability, resulting in heightened vulnerability of its water resources to both drought and flood risks. This article explores the susceptibility of the basin's water resources to drought, as measured by the Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI), and Standardized Groundwater Index (SGI), and investigates flood prevention strategies using Intensity-Duration-Frequency (IDF) curves. The study also, aims to establish a correlation between these indices (SPI, SPEI) and SGI index to develop a comprehensive understanding of the region's hydroclimatic dynamics. The results show that, for each return period, more IDF duration increases, more intensity decreases. Additionally, the results indicate that the Mono Basin experiencedsignificant drought events in2000-2006, 2014-2016 and 2018-2020. Regarding the correlation analysis between the SPI, SPEI, and SGI, the results indicate that the SPEI exhibits a good correlation with the SGI for accumulation periods of 12–48 months.

Introduction:-

The region West African is extremely exposed to climate change and fluctuation. The fragile environment is being destabilized by growing fluctuation in rainfall volume and seasonality, which poses a threat to food and economic security[1]. The nature, intensity and frequency of extreme weather events, like droughts and floods which have negative impacts on crop production, livestock rearing and human health are critical among the sub-region's vulnerability to climate change and variability [2]. In recent years, excessive rainfall damages the crops over a particularly the countries such as, Togo, Benin, Ghana, Burkina Faso, Ivory coast in this region and finally ends up in the destruction of agriculture and infrastructure water.

Thus, flood protection has become a major issue in west Africa for decision makers and managers ofwater-related risks.The applications of IDF curves range from assessing rainfall events, classifying climaticregimes, to deriving design storms and assisting in designing urban drainage systems, etc. [3]. Based on the above, the use of IDF curves is then highly recommended for rigorous, efficient and safe design of hydraulic structures and flood protection works[4]. They can be easily integrated and used to plan, design, and build infrastructure assets to be more resilient

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to climate change [5]. Thus, the elaboration of theIntensity-Duration-Frequency (IDF) curves represents a tool of primary importance in the planning, management and prevention of the rainfall risk.

Meteorological drought is also most often expressed in terms of rainfall compared to agiven average amount and the duration of a dry period, and can be defined as a periodwith a lack of precipitation or with rainfall lower than average, lasting sufficiently to causehydrological and agricultural hazards [6]. Toidentify and characterize drought events, a variety of indices have been developed, encompassingmeteorological, hydrological, agricultural, and socio-economic aspects [7–10].These drought indices serve the purpose of assessing the qualitative state, extent, severity, and duration of drought events [11]. One widely used index worldwide is the StandardizedPrecipitation Index (SPI) [12], which calculates cumulative precipitation over consecutivemonths across different timescales. Another important index is the Standardized PrecipitationEvapotranspiration Index (SPEI) [13], which considers the difference between precipitationand potential evapotranspiration (PET) to reflect changes in the surface water balance. Numerous studies have consistently affirmed the utility of both the (SPI) and the(SPEI) as indispensable tools for characterizing historical drought trends and evaluatingthe potential risk of future droughts [14–17]. Additionally, the Standardized GroundwaterIndex (SGI) plays a crucial role in quantitatively assessing groundwater fluctuationsduring drought periods. The combined use of meteorological indices such as the SPI, SPEI, and SGI enables theanalysis of climate change impacts on groundwater resources [18,19]

This study had two main objectives. Firstly, this work is to analyze the intensity-duration-frequency curves (IDF) of rainfall over mono basin so that to increase knowledge. Secondly, it aimed to assess the evolution of meteorologicaland groundwater droughts in the Mono watershed in in the Gulf of Guinea region from 2000 to 2020using standardized indices (SPI, SPEI, and SGI) and to examine the correlations betweenthe SGI–SPI and SGI–SPEI.

The rest of the paper is organized as follows: the study area, data, materials, and methods used are described in sections 2. Section 3 and section 4 presents the results and discussion while section 5 concludes the paper.

Study area, Data, Materials and Methods: -

In this section, Study area, Data, Materials and Methods are described.

Study area

This study area has already been described by Lamboni. et al. [20].Mono basin, the study area, is located in the Gulf of Guinea region, between 6°16 N and 9°20 N and °42 E and 20°25 E (Fig. 1). It is a transboundary river basin shared by Togo and Benin Republic the Mono basin, one of the major basins of Togo, drains 25400 km^2. It houses a dam of hydroelectric power plant called Nangbeto. The climate of this basin is the one of West Africa which is controlled by the interaction of two air masses; the influence of which varies throughout the year with the north-south movement of the Intertropical Convergence Zone (ITCZ). Hot and dry continental air masses originating from the high-pressure system above the Sahara Desert give rise to dusty Harmattan winds over most of West Africa from November to February. In summer, moist equatorial air masses coming from the Atlantic Ocean bring annual monsoon rains. Within this West African context, rainfall in the study area is characterized by two types of rainfall regimes. In the southern basin, (from 6°16 N to 7°30 N) there are two rainy seasons which extend from mid-March to mid-July and from mid-August to October. In the northern basin (from 7°30 N to 9°20 N), there is one rainy season which goes from April to October. According to the report of West African Economic and Monetary Union (WAEMU) in 2006, the population of the basin exceeds two million, with an annual increase of 2.9%.

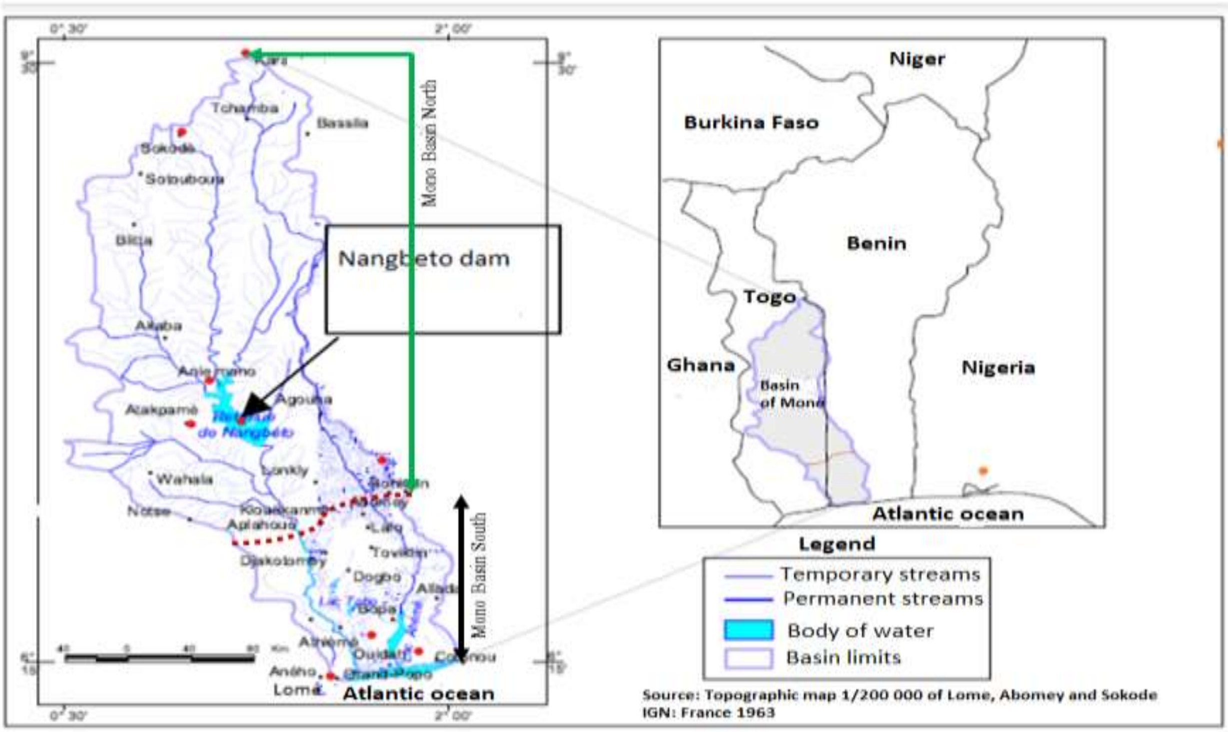

Fig. 1:- Study area (source: Lamoni et al.[20]).

Data Collection

Daily rainfall, temperature (for calculating evapotranspiration rates) andGroundwaterleveldata for climate stations within the MRB for the period 2000–2020 were acquired from National Meteorological Service of Togo and Benin Meteorological Department.Rainfall data was recorded at varying intervals (e.g., daily, monthly), with a focus on high- Steps to Calculate the Parameters of the Gumbel Fitting Line.

Material:-

Computational analytics using programming syntax has been present since the earliest days of computing, but has recently gained new popularity from the advent of big data analytics, artificial intelligence, and the larger data science movement. By programming in a syntactic language, such as R or Python [21], analysts can apply complex methods that are not easy to parameterize with spreadsheet or graphical, menu-driven software. Computation offers analysts the ability to run simulations that test particular scenarios and create novel solutions and custom visualizations, which were not considered by others, or are rather specific to one’s own use case. In our study, software R (version 4.4) was used to compute all the statistical parameters and graphics. Libraries such as forecast, will facilitate data manipulation and model fitting[20]. The dataset will be divided into training and testing subsets. The models will be trained on historical data, and their performance will be evaluated on the testing set. The latest version of the R software for your operating system is available from the CRAN archive at the http://www.r-project.org..

Methods:-

Duration of rainfall, the estimation of the return

For a given duration of rainfall, the estimation of the return period of each precipitation event involves the following steps:

Step 1: Preparation of the precipitated slide data set:

Step 2: Compute the empirical frequency for each rank. In practical terms, the objective is to estimate the probability of non-exceedance $F(x)$ that should be attributed to each value x. Various formulas exist for estimating the distribution function using the empirical frequency. These methods require sorting the data series by increasing values, which allows assigning to each value its rank r. For Gumbel's law, the empirical frequency of Hazen is recommended: $F(x[r]=\frac{r-0.5}{n}$(1)

Step 3: Calculation of the reduced variable “u” of Gumbel (equation 2). The distribution function of the Gumbel law, $F(x)$, is given by: $F(x) = \exp(-\exp(-u))$ with, $u = -ln(-ln(F(x)))$(2)
Step 4: Graphical representation of the pairs (ui, xi) of the series to be adjusted.
Step 5: Fitting a linear relation of type:$xq = \alpha + \beta uq$ to the pairs (ui, xi) (3).

At this point, it is statistically verified that the observed values are satisfactorily estimated by the model.
Estimation of Rainfall for Different Return Periods. The statistical model is employed to estimate precipitation for different return periods T. This involves:
-Calculating the non-exceedance frequency according to relation: $T=\frac{1}{1-F(x)}$. (4)
-Computing the corresponding Gumbel reduced variable according to relation: $F(x[r]=\frac{r-0.5}{n}$ (5)
-Calculating the corresponding quantile using the linear relation (withαand β determined in step 5).

The Intensity-Duration-Frequency (IDF) curves depict the rainfall intensity i as a function of the duration of the rainfall event and its return period T. This involves calculating the maximum average rainfall intensity (duration-return time) for each considered return period and rainfall duration. resolution data for accurate IDF curve development.

Assessing drought

The formulas and descriptions for calculating the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Groundwater Index (SGI)Below are:
The SPI is calculated as:$SPI_k=\frac{x-\mu_k}{\sigma_k}$ (6)
The SPEI is calculated as: $SPEI_k=\frac{d-\mu_d}{\sigma_d}$ (7)
The SGI is calculated as: $SGI_k=\frac{g-\mu_g}{\sigma_g}$ (8)
where x,d, gare the precipitation, difference between precipitation and PET and groundwater level for the desired periodrespectively, μ is the mean, and σ is the standard deviation.The indices for a specific time scale (e.g., 1 month, 3 months, 12 months) is calculated by converting the data amount to a z-score in the standard normal distribution.

Results and Discussion:-

Developed IDF curves for multiple stations in the Mono Basin.

In Figure 2, the IDF curves for the different series at each station are displayedfor return periods of 2, 5, 10, 20, and 50 years, arranged in ascending order from bottom to top. The are observed differences in rainfall intensities and Intensity-Duration-Frequency (IDF) curves among Visualization of 60-minutes, 120-minutes, 180-minutes, 240-minutes, 300-minutes, 360-minutes rainfall intensities for different return periods (e.g., 2, 5, 10, 20, 50 years). The intensities at Sokodé station notably differ from those at Nangbeto and Anié. Sokodé station' results is somewhat intermediate, aligning closely with Atakpaméstation. The higher altitude of the Sokodé station significantly influences its precipitation patterns through orographic lifting and cooler temperatures, leading to increased rainfall compared to lower-altitude stations like Nangbéto and Anié. Atakpamé, with a similar altitude to Sokodé, also experiences enhanced precipitation, although its geographical context within the Togo Mountains plays a crucial role. So, this variance underscores the influence of altitude on rainfall patterns, with the orographic effect of the Atacora chain playing a significant role in modifying rainfall characteristics in Sokodé and Atakpamé stations. The orographic effect, a classic meteorological phenomenon, results from the ascent of moisture-laden air masses over mountainous terrains, leading to cooling, condensation, and precipitation. As the monsoon winds, laden with moisture, ascend the Atacora chain, increased precipitation occurs. However, as these air masses continue inland and lose moisture, the duration of rainfall events increases, while the intensity decreases. This dynamic is a plausible explanation for the variability of rainfall intensities observed in the Sokodé and Atakpamé stations, highlighting the interaction between the positions.

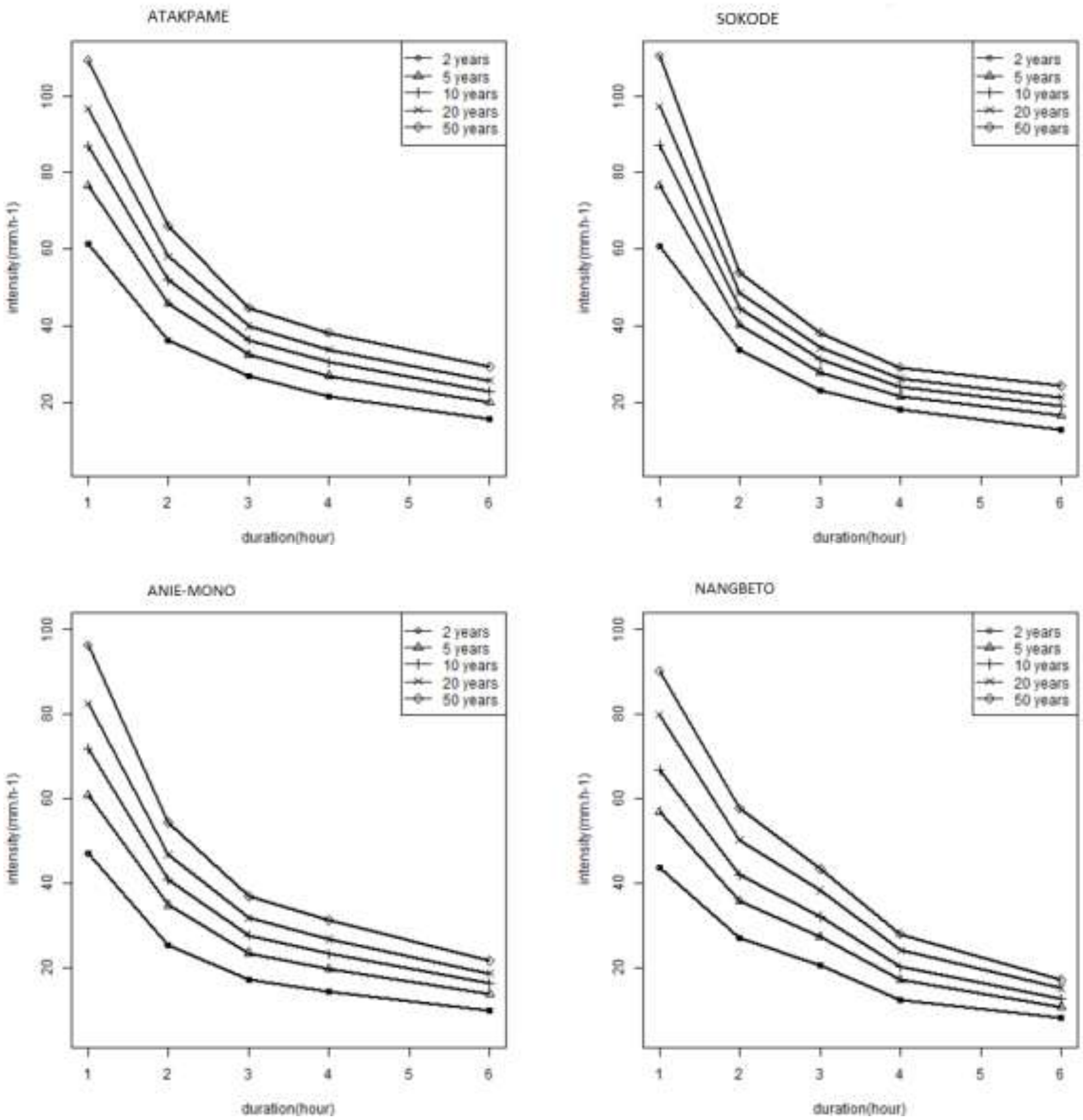

Figure 2:- IDF curves for nangbeto, Atakpamé, Anié-Mono and Sokodé stations for return periods of 2, 5, 10, 20 and 50 years (points represent estimated quantile values and curves are arranged in ascending order of return periods from bottom to top).

SPI and SPEI Indices

This section conducts a comprehensive analysis of the Standardized Precipitation Index (SPI), the Standardized Precipitation-Evapotranspiration Index (SPEI) across various weather stations in the Mono River Basin.We examine in each station, these indices at different temporal scales (12, 24, and 48 months) to assess their behavior during dry and wet periods (2000-2020).

Results revealed significant spatial variability, reflecting the diverse climatic and hydrological conditions within the Mono River Basin, shown in Figure 3, Figure 4, Figure 5, and Figure 6.

According to the SPI results shown in Figure 3 and Figure 4, there is general agreement among stations during major events within the 12- to 48-month accumulation periods, although some differences are observed in certain years.At the 48-month scale, Stations exhibited prolonged dry periods (Atakpamé and Nangbeto: 2006-2009,2014-

2016 and 2018-2020:Sokodé: 2006-20012 and 2016-2020, and Anié: 2016-2020) with SPI values consistently below -1, indicating severe drought conditions.

Analyzing the results based on the 48-month time window for the SPEI, as shown in Figure 5 and Figure 6, it is evident that all stations experienced a drought period starting in 2000, although the end of this period varied across stations. Three stations (Nangbeto, Atakpamé, and Sokodé) saw the end of the drought in 2006, while Anié station (stating in 2008) experienced the end in 2012. The second drought period occurred from 2000 to 2006 at all stations. It is noteworthy to mention the occurrence of drought during the latter years of the study period, specifically between 2018 and 2020.

Furthermore, the study period witnessed the occurrence of drought years, with a notable concentration in 2018, towards the end of the periodas shown in Figure 3 and Figure 4. During the periods of 2000–2006 and 2014–2016, moderately wet to very wet years were experienced. The highest SPI values were recorded in 2014–2020 at Nangbéto, AtakpaméandSokodé, ranging from 1.8 to 2.2.

Analyzing the results based on the 48-month time window for the SPEI, as shown in Figure 5 and Figure 6, it is evident that all stations experienced a drought period starting in 2000, although the end of this period varied across stations. Three stations (Nangbeto, Atakpamé, and Sokodé) saw the end of the drought in 2006, while Anié station (stating in 2008) experienced the end in 2012. The second drought period occurred from 2000 to 2006 at all stations. It is noteworthy to mention the occurrence of drought during the latter years of the study period, specifically between 2016 and 2020. The lowest SPEI values were obtained from 2000 to 2004 at Anié.

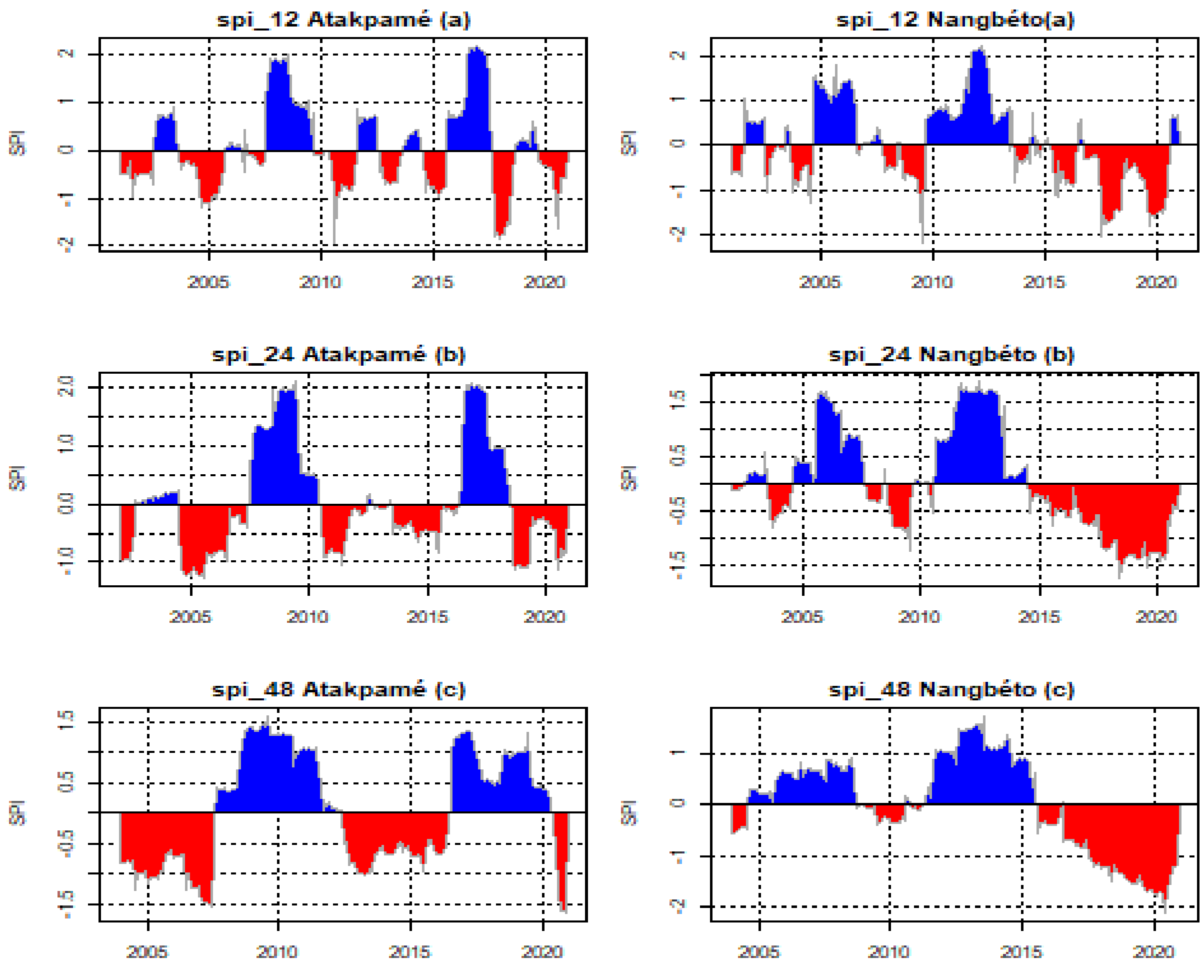

Figure 3:- Evolution of SPI at station Atakpamé and Nangbéto, during the sutdy period (2000–2020). Thered and blue colors indicate dry and moist conditions.

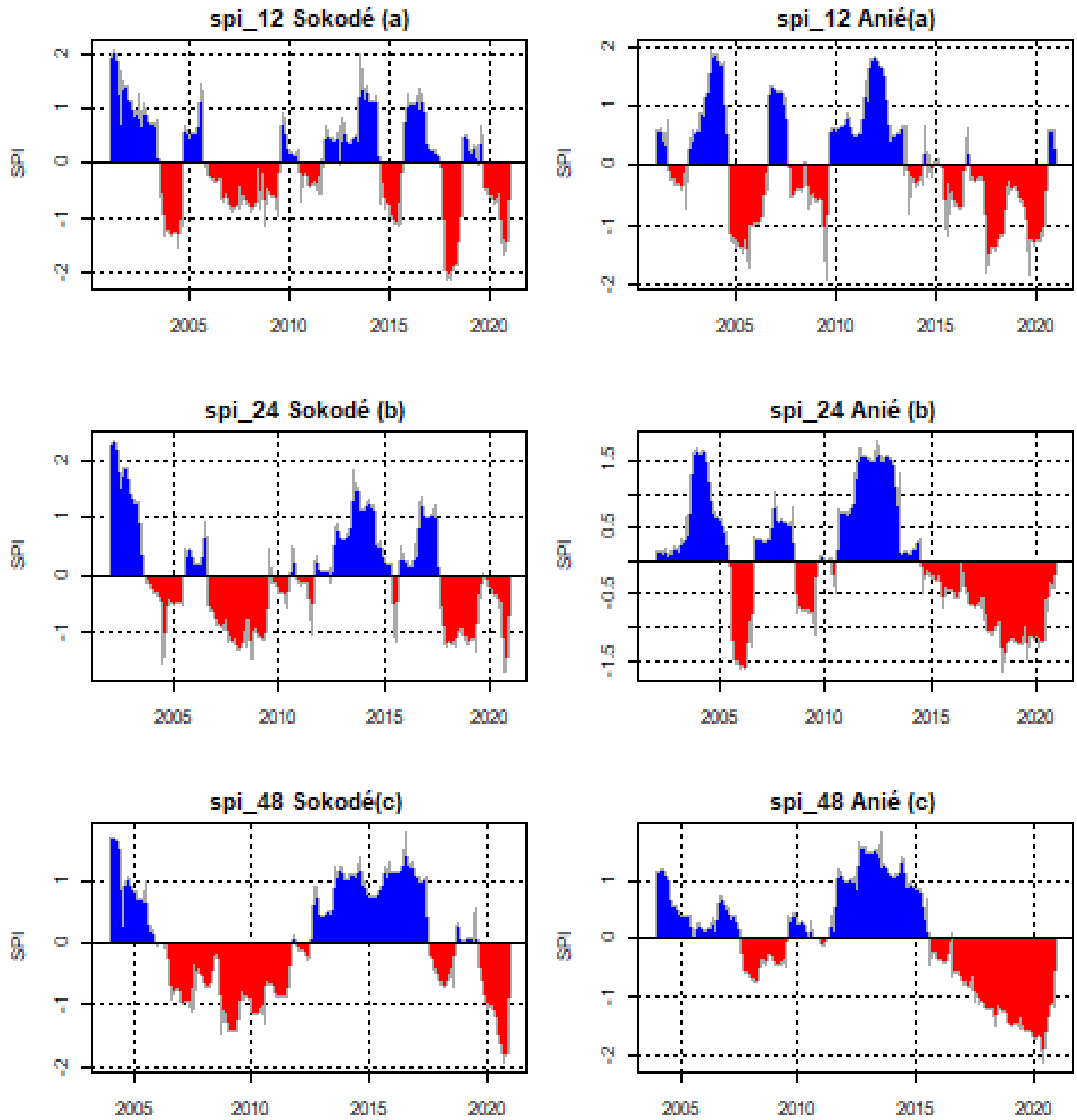

Figure 4:- Evolution of SPI at station Anié and Sokodé, during the study period (2000–2020). The red and blue colors indicate dry and moist conditions.

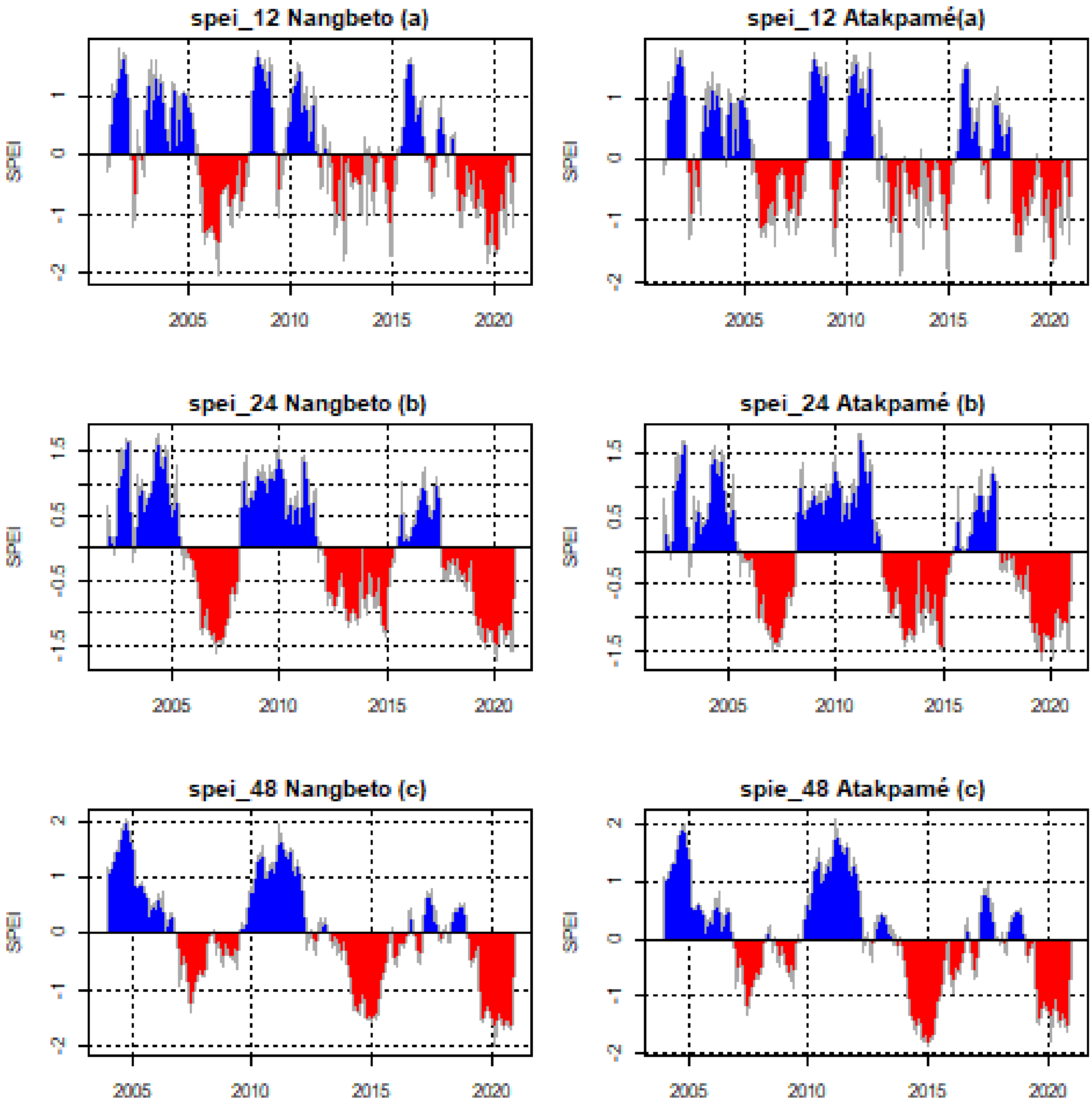

Figure 5:- Evolution of SPI at station Anié and Sokodé, during the study period (2000–2020). The red and blue colors indicate dry and moist conditions.

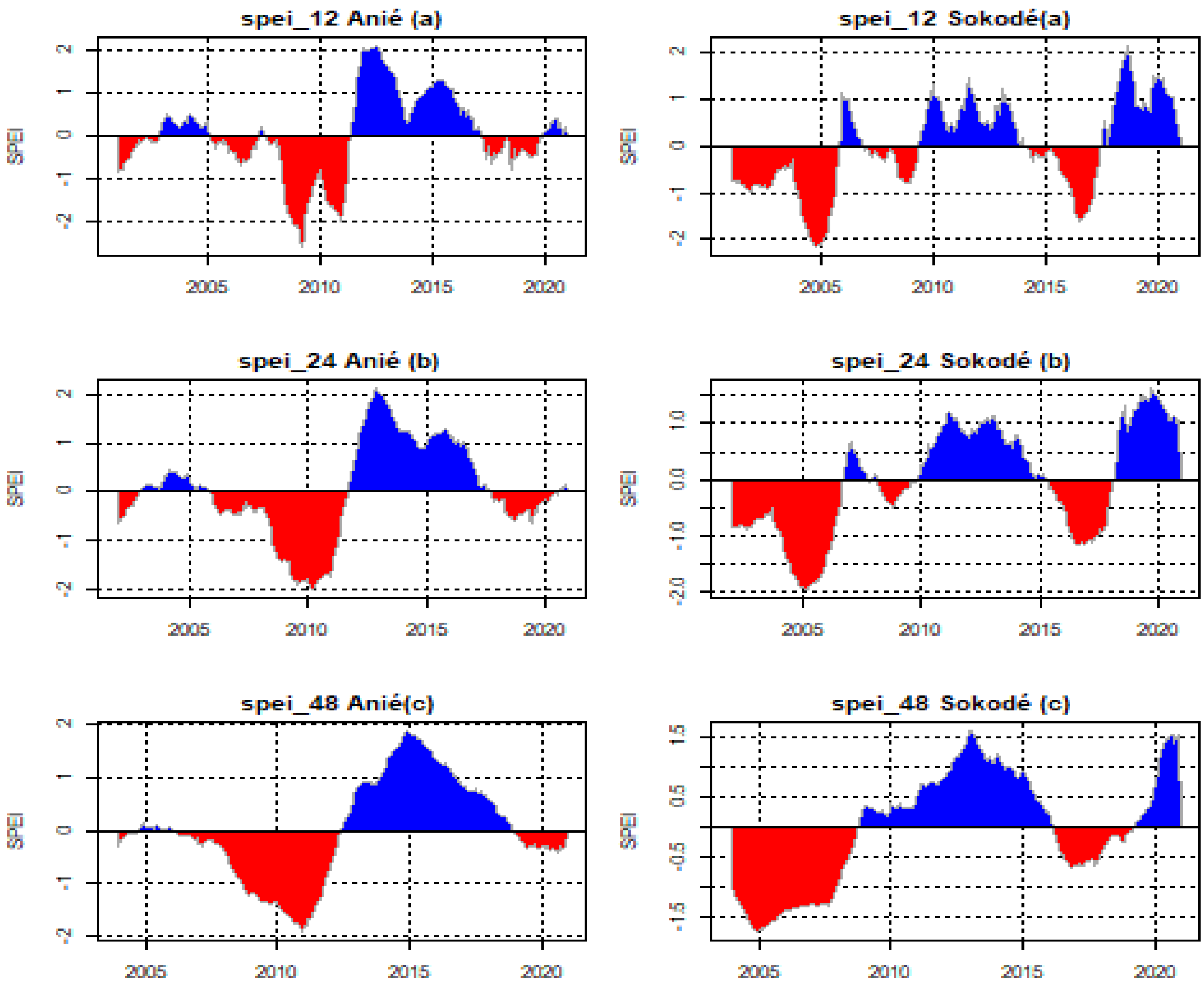

Figure 6:- Evolution of SPI at station Anié and Sokodé, during the study period (2000–2020). The red and blue colors indicate dry and moist conditions.

Groundwater Drought Index

The groundwater drought analysis was conducted using the Standardized Groundwater Index (SGI) based on data collected from 2000 to 2020. The SGI results, as depicted in Figure 7, reveal distinct drought periods that align with the findings of the SPI and SPEI analyses. SGI values also indicated a decline in groundwater levels during these dry periods, highlighting the cumulative impact of reduced precipitation and increased evapotranspiration.Notably, the drought period from 20017 to 2020affected the well in Nagbéto (SGI ≤--2)for accumulation periods48 months,and from 20017 to 2019 (SGI ≤--2)for accumulation periods24 months. Similarly, the drought periods from 2017 to 2019 was evident in the well of Nangbéto (SGI ≤--3)for accumulation periods12 months.

SGI values reflected rising groundwater levels during these wet periods, demonstrating the positive recharge effects of prolonged precipitation. SPEI analysis at the same scale confirmed these findings, with negative SPEI values aligning with identified dry periods, suggesting increased evapotranspiration exacerbating drought conditions as shown in Figure 7. SGI values also indicated a decline in groundwater levels during these dry periods, highlighting the cumulative impact of reduced precipitation and increased evapotranspiration.These findings highlight the occurrence of drought events in the groundwater system, with specific emphasis on the notable drought periods from 2000 to 2006,2014 to 2016 and 2018 to 2020. Additionally, a dry period was observed towards the end of the study period, as indicated by the SGI values.

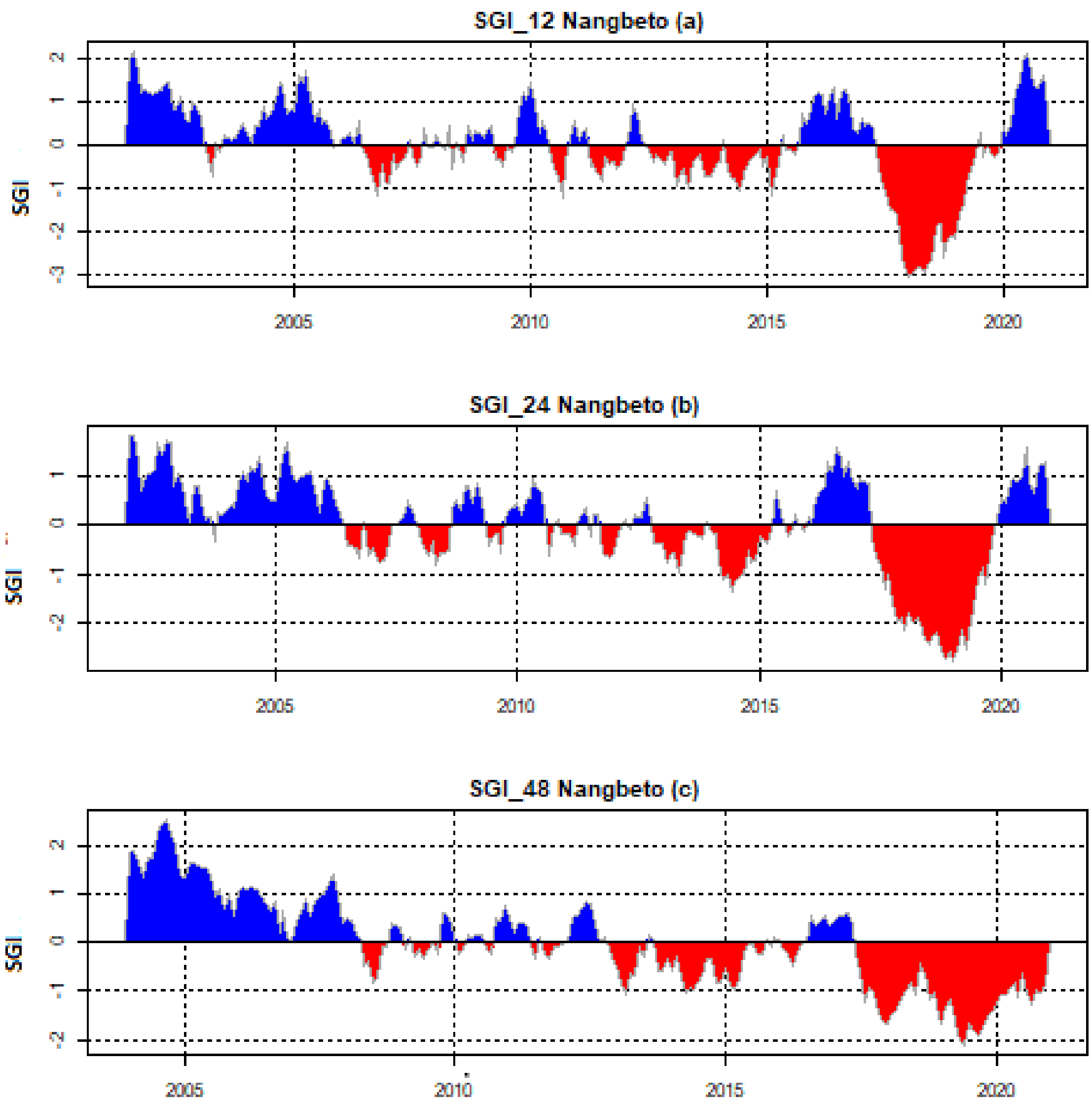

Figure 7:- Evolution of SPI at station Nangbéto, during the study period (2000–2020). The red and blue colors indicate dry and moist conditions.

Relationships between Meteorological and Groundwater Drought Indices

Understanding the relationships between meteorological and groundwater drought indices through correlation coefficients can provide valuable insights into hydrological processes and drought management.To examine the relationship between meteorological and groundwater droughts, the Pearson correlation coefficient was employed, which is a widely used method in various studies worldwide. The analysis considered three different time scales (12, 24, and 48 months) to assess the correlations. Figure8 presents the Pearson correlation results between the Standardized Groundwater Index (SGI) and other drought indices.In this Figure, correlations less than 0.5indicates a weak positive or negative correlation, equal to or greater than 0.5 are considered moderate, while correlationsequal to or greater than 0.7 are classified as strong.

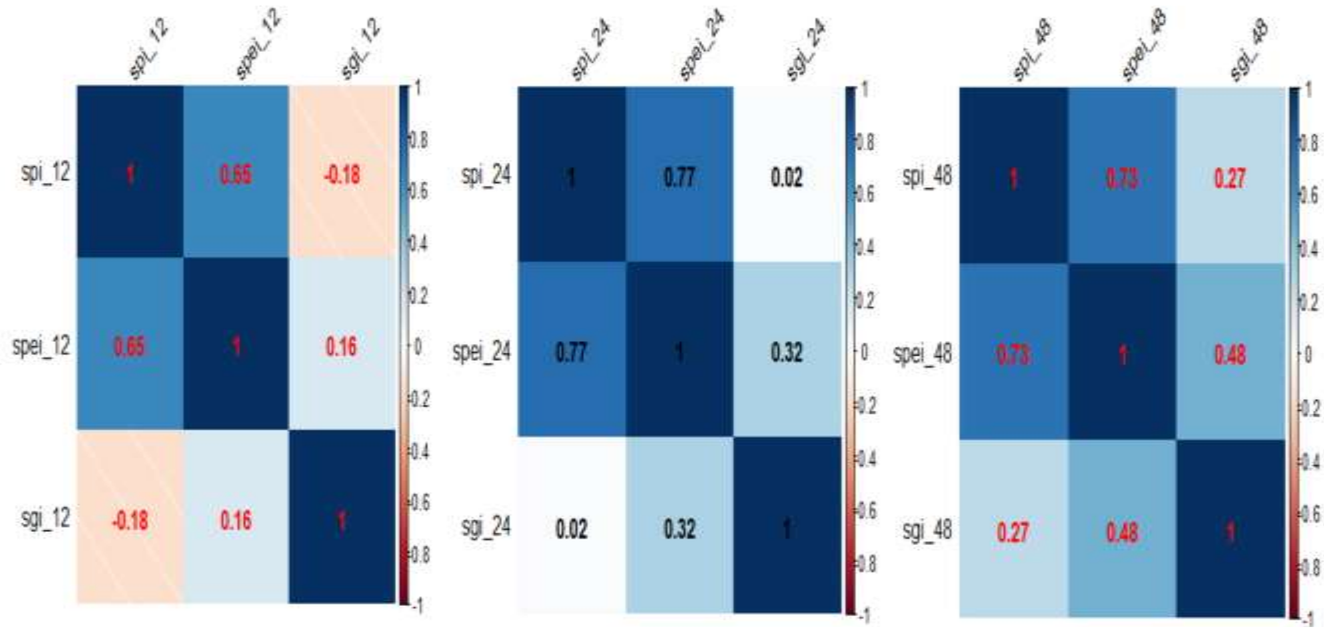

Figure 8:- Pearson correlation coefficients between SPI-SPEI, SPI–SGI and SPEI–SGI for accumulation periods ranging from 12 to 48 months.

In Generally, the Standardized Precipitation Index (SPI) exhibits weak positive or negative correlations with the SGI for accumulation periods ranging from 12 to 48 months.A weak correlation suggests that changes in precipitation (as captured by SPI) do not directly or strongly translate to changes in groundwater levels (as captured by SGI).This can be due to several factors: Groundwater levels often respond to precipitation with a delay, influenced by soil infiltration rates, aquifer properties, and recharge times.Groundwater levels can also, be affected by other factors such as groundwater extraction, land use changes, and soil characteristics, which may not be directly related to immediate precipitation patterns.

Similarly, the Standardized Precipitation Evapotranspiration Index (SPEI) demonstrates moderate correlations to strong with the SPI for accumulation periods of 12 to 48 months, particularly at scale 12 month.A lower correlation suggests that while both indices measure meteorological drought, there are differences in what they capture. SPI only considers precipitation, while SPEI includes both precipitation and evapotranspiration.The weak correlation can indicate that evapotranspiration plays a significant role in the drought conditions that SPEI measures, making it a more comprehensive drought index under certain climatic conditions.

However,the Standardized Precipitation Evapotranspiration Index (SPEI) demonstrates moderate correlations to strong with the SGI for accumulation periods of 12 to 48 months. A strong correlation between SPEI and SGI suggests that the combined effects of precipitation and evapotranspiration (as in SPEI) have a significant and direct impact on groundwater levels (as in SGI).

This strong relationship implies that SPEI can be a good predictor of groundwater conditions, as it accounts for both water input (precipitation) and output (evapotranspiration), making it more representative of the water balance affecting groundwater.For drought management, this strong correlation means that SPEI can be effectively used to anticipate groundwater droughts, aiding in better groundwater resource planning and management in the study area.

Discussion:-

The IDF curves developed in this study provide essential data for designing and implementing flood prevention infrastructure in the Mono Basin. High-intensity rainfall events are critical for sizing drainage systems, retention basins, and other flood mitigation structures. The variability in rainfall intensities across different return periods underscores the need for robust infrastructure capable of handling extreme weather events. The results demonstrate an increase in the maximum annual intensity of short-duration rainfall, in consistent to the increase observed in the

Sahel by Chagnaud et al. (2023)[22]. These findings are also in agreement with those of Attogouinon et al. (2024)[23] in Benin, and they corroborate the results obtained in Côte-d'Ivoire by Kouassi et al. (2018)[24].

The results of this study have significant implications for water management in the west africa region, particularly during periods of drought. The utilization of drought indices such as the SPI, SPEI, and SGI can assist water managers in identifying drought-prone areas and developing appropriate strategies for mitigation. Based on the SPI and SPEI results, the study area has experienced varying severities and durations of drought periods at each station. The driest years across all stations were 2000-2006, 2014-2016 and 2018-2020, while the wettest years were 2010-2012. The SGI results, as depicted in Figure 8, reveal distinct drought periods that align with the findings of the SPI and SPEI analyses at Nangbéto station. SGI values also indicated a decline in groundwater levels during these dry periods, highlighting the cumulative impact of reduced precipitation and increased evapotranspiration.According to M. Medewou et.al. (2021)[3], the inflow to the Nangbeto Dam in recent years showed low levels during 1989-2020. The irregularity of the rains, the decrease in the input volume of Mono river, the decrease in the flows of the Mono River, the increase in temperatures which, consequently, causes an increase in evaporations in Nangbéto [20].

Conclusion:-

In conclusion, the vulnerability of water resources in the Mono River Basin (Gulf of Guinea region)to drought and flood risks presents significant challenges exacerbated by climatic variability. The integration of Intensity-Duration-Frequency (IDF) curves with climatic indices such as the Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI), and Standardized Groundwater Index (SGI) has provided a comprehensive understanding of hydroclimatic dynamics in the region.

The results show that, for each return period, more IDF duration increases, more intensity decreases. Additionally, the results indicate that the Mono Basinin the Gulf of Guinea region experienced significant drought events in 2000-2006, 2014-2016 and 2018-2020. Our study also, underscores the strong correlation observed between SPEI, and SGI indices, highlighting their utility in forecasting and mitigating drought and flood events.

By addressing both drought vulnerability and flood prevention through a coordinated approach, this research contributes to sustainable water management practices in the Mono River Basin, ultimately supporting socio-economic development and environmental sustainability in the Gulf of Guinea region.

Acknowledgements:-

This research has been supported by IsDB-TWAS. We acknowledge the financial support from IsDB-TWAS.We are also grateful to the anonymous reviewers whose thoughtful and constructive comments have improved the quality of the article.

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