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Study of the Spatio-Temporal Variability of Rainfall in the Nouhao Sub-Basin

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Abstract

Wide variations characterize rainfall trends in the Sahelian zone. Indeed, this zone is considered to be one of the most affected by climatic fluctuations. This study aims to analyze the spatio-temporal variability of rainfall in the Nouhao sub-basin. To this end, data on annual rainfall from 1981 to 2022 were collected from rainfall stations located in the basin, namely Dialgaye, Tenkodogo, Sangha, and Ouargaye in the Centre-Est region of Burkina Faso. Rainfall indices were calculated to identify years with wet, dry or normal periods. Additionally, the Pettitt test was used to detect break years in the rainfall data. The Mann-Kendall test was used to assess any trends in the rainfall series. The results show that rainfall has been highly variable, with a general upward trend. In addition, the Pettitt test identified rainfall breaks in 1990 at Ouargaye and Sangha, in 2003 at Dialgaye and in 2004 at Tenkodogo. The rainfall surplus obtained from the break years ranges from 12% to 21%, with an average value of 16%. The highest surpluses were recorded in Sangha (16%) and Tenkodogo (21%). The spatial distribution of mean annual rainfall over the period 1981-2020 reveals significant variations, marked by a shift in isohyets from north-west to southeast.

Keywords

Climate Variability, Spatio-Temporal, Rainfall, Break, Trend, Nouhao Sub-Basin

1. Introduction

Since the 1970s, West African countries, particularly those in the Sahel, have seen significant changes in their rainfall patterns, alternating between droughts and episodes of heavy rainfall [1]-[6]. Thus, between 1970 and 1980, the Sahelian region was severely affected by droughts, compromising production systems and exacerbating the vulnerability of the population [7]. This long series of droughts, which for a long time led to a reduction in rainfall, has been followed by a period of rainfall recovery since the 1990s [8]-[11]. Consequently, variations in climatic parameters, particularly rainfall, have had a major impact on West African countries. In Burkina Faso, key sectors such as agriculture, livestock breeding, and forestry are profoundly impacted by climatic variations and low rainfall [12]. These conditions, combined with an ecologically fragile region, leads to rapid environmental degradation. Climate fluctuations particularly affect these essential activities, which are crucial to employment, food security and the economy of over 80% of the population. Research into rainfall variability has evolved over the decades, with numerous studies examining its impacts on hydrological and ecological systems [13]-[18]. However, although many studies have been conducted at the regional level, few have specifically focused on rainfall variability in the Nouhao sub-basin. In fact, the Nouhao sub-basin is very poorly studied in terms of climate, except for those conducted by [19] on groundwater and [20] who worked on climate models. This gap in climate research calls for a better understanding of the climatic phenomena specific to this region. Our study aims to fill this gap by analyzing the spatio-temporal variability of rainfall in this region, a sector particularly vulnerable to climate fluctuations. The first step will be to analyze rainfall trends from 1981 to 2022 using the Nicholson and Hanning indices. Next, break years will be determined using the Pettitt test, and rainfall trends will be assessed with the Mann-Kendall method. Finally, the spatial evolution of rainfall will be analyzed to better understand the distribution of rainfall over time and space.

2. Data and Methods

2.1. Presentation of the Study Area

The Nouhao sub-basin, covering an area of 4050 km^2 [21], is a tributary of the main Nakanbé basin. It is located in the central-eastern region of Burkina Faso (see **Figure 1**), between latitudes 12˚35' and 10˚55' north and longitudes 1˚00' west and 0˚45' east. Climatically, the sub-basin lies in the Sudano Sahelian zone, characterized by a six-month dry season from November to May and a rainy season from May to October [22]. Rainfall ranges from 850 mm in the north to 950 mm in the south. The sub-basin's hydrographic network is dominated by the Nouhao river, as well as several secondary and tertiary tributaries. Flooding of these tributaries, the main ones being Masra, Kouroko, Koulounda, Koukougo, Kiniguerlo, Ouaré, and Sablogo [23], generally occurs between August and September. In addition, the Nouhao sub-basin has no permanent watercourses, the majority being temporary.

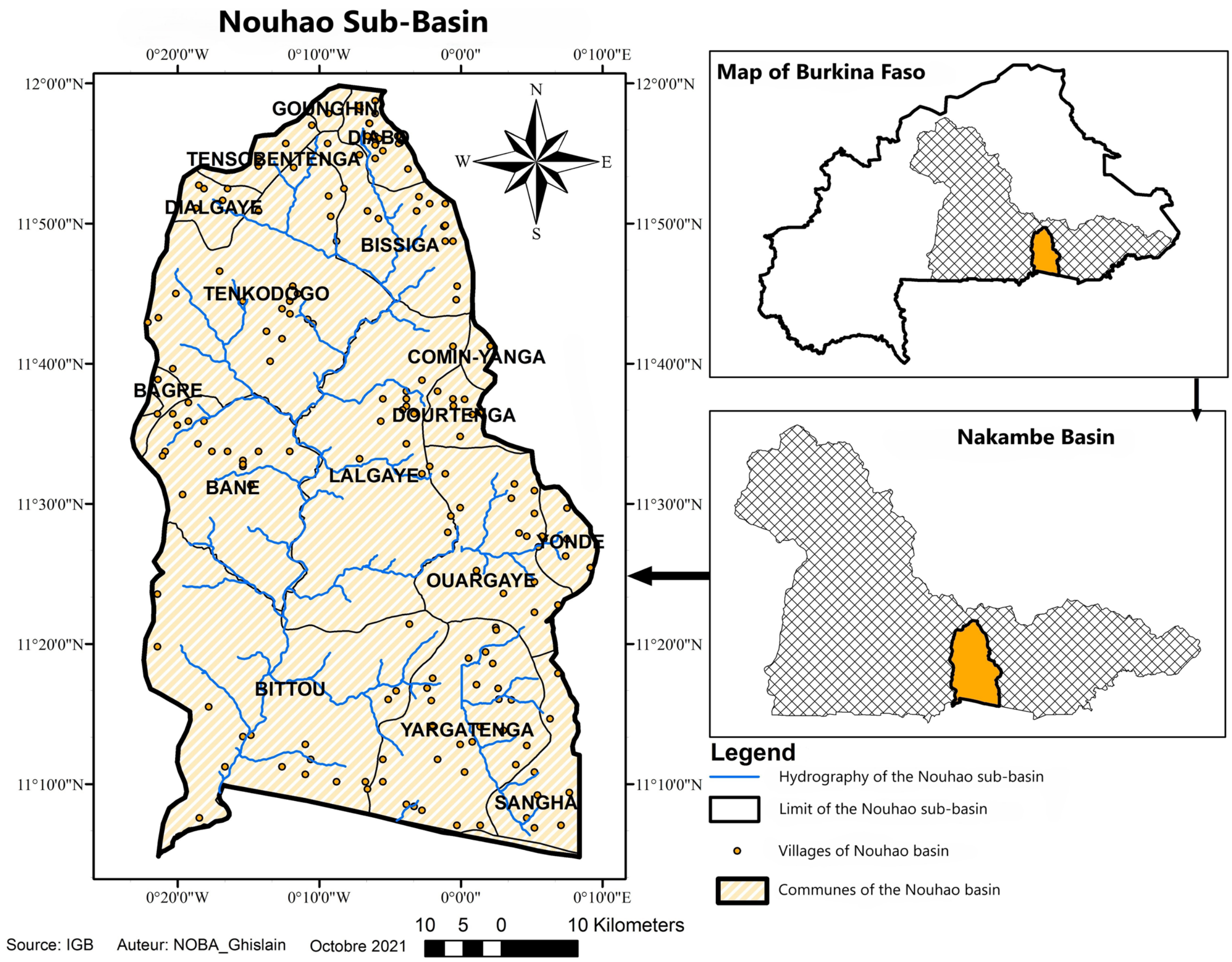

Figure 1. Location of the Nouhao sub-basin (Source: Author).

2.2. Data

The climatic data used in this study come from the archives of the National Meteorological Agency of Burkina Faso (ANAM). These include monthly rainfall time series from three rainfall stations (Dialgaye, Ouargaye, Sangha) and one climate station (Tenkodogo). All the chronicles cover the same period from 1981 to 2022. However, there is missing data in the chronicles, amounting to 5% or less. Given that the gaps are non-consecutive and the number of missing values is 5% or fewer, the missing values were replaced by the average of the surrounding values or the average of the entire series. The processing and analysis of these data were carried out using various tools and methods.

2.3. Methodology

2.3.1. Analysis of Interannual Variability

1) Nicholson Index

The Nicholson index measures the difference between observed precipitation and the long-term average, thus making it possible to characterize dry, surplus, or normal periods. This index is expressed as a centered and reduced variable and is calculated using the following formula (Equation (1)) [24] [25]:

$$I_i = \frac{X_i - X_m}{\sigma} \quad (1)$$

with

I_i: rainfall index,

X_i: rainfall for year i (in mm),

X_m: average interannual rainfall over the study period (in mm),

σ: standard deviation of interannual rainfall over the study period.

2) 2nd-Order Hanning Low-Pass Filter (Weighted Moving Averages)

To smooth the monthly and annual rainfall series from the various stations in the Nouhao sub-basin, we used a Hanning low-pass filter of order 2. This weighted moving average method eliminates seasonal variations, making the interannual fluctuation in more visible. Seasonal variations are eliminated by weighting the annual rainfall totals using the following equations [26]:

$$X'_{(t)} = 0.06X_{(t-2)} + 0.25X_{(t-1)} + 0.38X_{(t)} + 0.25X_{(t+1)} + 0.06X_{(t+2)} \quad (2)$$

pour $3 \le t \le (n-t)$

where:

$X'_{(t)}$ is the total rainfall for term t, $X_{(t-2)}$ and $X_{(t-1)}$ are the observed rainfall totals of the two terms immediately preceding term t and $X_{(t+1)}$ and $X_{(t+2)}$ are the observed rainfall totals of the two terms immediately following term t.

The weighted rainfall totals of the first two terms $X'_{(1)}$, $X'_{(2)}$ and the last two terms $X'_{(n-1)}$, $X'_{(n)}$ of the series are calculated using the following expressions with n the series size:

$$X'_{(1)} = 0.54X_{(1)} + 0.46X_{(2)} \quad (3)$$

$$X'_{(2)} = 0.25X_{(1)} + 0.50X_{(2)} + 0.25X_{(3)} \quad (4)$$

$$X'_{(n-1)} = 0.25X_{(n-2)} + 0.50X_{(n-1)} + 0.25X_{(n)} \quad (5)$$

$$X'_{(n)} = 0.54X_{(n)} + 0.46X_{(n-1)} \quad (6)$$

Centered and reduced indices of the weighted annual heights obtained are then calculated to better distinguish between periods of rainfall deficit and surplus.

2.3.2. Statistical Tests to Determine Breaks in Time Series

A break is defined as a change in the probability distribution of observed variables within a time series. The Pettitt test is an effective non-parametric test for identifying such breaks in climatic and hydrological series [4] [27]. It is based on the comparison of subseries before and after a possible breakpoint *t*, determined according to the difference in distributions between these two subseries [28]-[30]. The Pettitt statistic $U_{t,N}$ is defined by Equation (7):

$$U_{t,N} = \sum_{i=1}^{t} \sum_{t+1}^{N} D_{ij} \quad (7)$$

where $D_{ij} = \text{sgn}(x_i - x_j)$; with $\text{sgn}(Z) = 1$ if $Z > 0$; $\text{sgn}(Z) = 0$ if $Z = 0$ and $\text{sgn}(Z) = -1$ if $Z < 0$.

2.3.3. Calculating Average Variations

Once a break in the time series has been identified, it is useful to calculate the average variation in rainfall before and after the break. This enables us to assess the rainfall deficit or surplus between two sub-periods. The variation is calculated using the following formula (Equation (8)) [27]-[31]:

$$D = \frac{\bar{x}_j}{\bar{x}_i} - 1 \tag{8}$$

with $\bar{x}_j$ the average over the period after the break and $\bar{x}_i$ the average over the period before the break, D is the hydro-climatic deficit.

2.3.4. Mann-Kendall Trend Test

This is a non-parametric test used to assess the existence of a trend and to test the significance of trends and breaks in stationarity in the rainfall and hydrometric series in the study area [32]. The null hypothesis H0 states that there is no trend (data are independent and identically distributed).

The U_{MK} statistic is calculated as follows (Equation (9)):

$$U_{\text{MK}} = \frac{S}{\sqrt{Var(S)}} \tag{9}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\left(x_j - x_i\right) \tag{10}$$

$$\text{sgn}(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases} \tag{11}$$

The $Var(S)$ is given by Equation (12):

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \tag{12}$$

where S is the sum of the signs of the differences between the values in the series and $Var(S)$ is the variance of S. The p-value is used to test the significance of the trend. If U_{MK} is positive, the trend is upward; if U_{MK} is negative, the trend is downward.

The sen's slope method [33] was used to quantify the magnitude of the trend. The slope β is calculated using the following formula (Equation (13)):

$$\beta = \left[\frac{X_j - X_i}{j - i}\right]. \tag{13}$$

for $i < j$

where X_j and X_i are the values of the series at times j and i, respectively.

3. Results and Discussion

3.1. Results

3.1.1. Interannual Variation in Rainfall

Figure 2 illustrates the evolution of these indices, highlighted by the Nicholson index and the Hanning low-pass filter of order 2 (weighted moving average). Variations in these indices identify wet, normal, and dry periods.

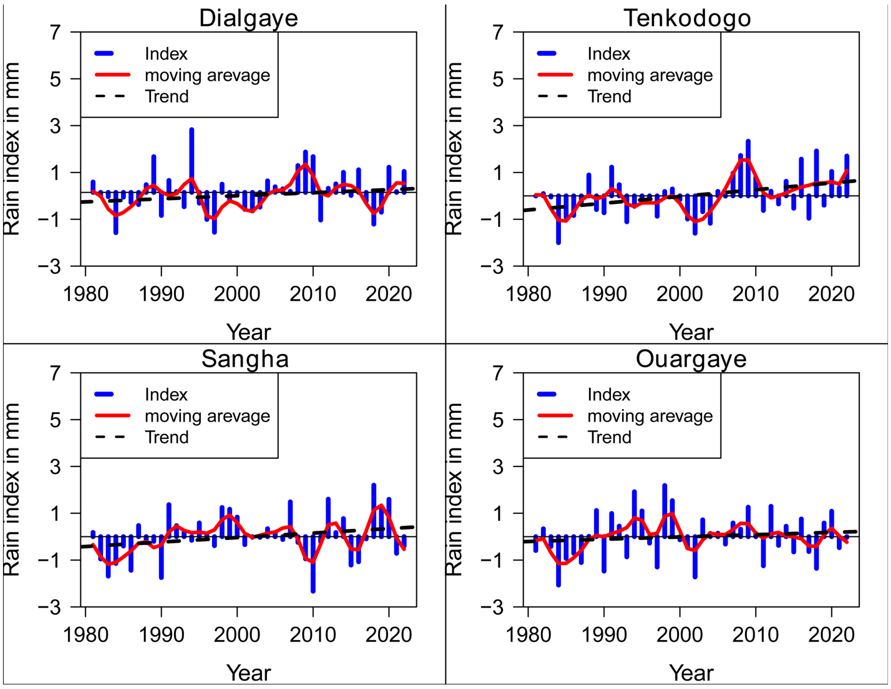

Figure 2. Interannual trend in rainfall indices in the Nouhao sub-basin from 1981 to 2022.

Between 1981 and 2003, Dialgaye recorded a rainfall deficit, with a particularly marked anomaly in 1984 (−1.83). However, 1989 and 1994 were characterized by abundant rainfall, with indices of 1.59 and 2.81 respectively. From 2004 onwards, the trend is reversed and a rainfall surplus is observed, although dry years such as 2011 and 2018 show anomalies of −1.26 and −1.46.

For Tenkodogo, the period from 1981 to 2004 is also characterized by a deficit. However, between 2005 and 2022, the alternation between drought and humidity is marked by particularly rainy years, notably 1991, 1998, 2007, 2008, 2009, 2016, 2018 and 2020. The most negative anomalies were recorded in 1984, 1993, 2002 and 2004.

In Ouargaye, from 1981 to 1990, a deficit was also observed, with an anomaly of -2 in 1984. From 1990 to 2022, there was a similar alternation between dry and wet years, with indices of 1.85 in 1994 and 2.10 in 1998.

Finally, in Sangha, the period from 1981 to 1990 shows indices close to normal. However, from 1991 to 2022, there is significant variation between wet and dry years, with a notable drought in 2010 (−2.32) and excess rainfall in 2018 (2.19).

3.1.2. Identification of Break Periods

The results obtained using Pettitt's method, presented in Table 1, enabled us to identify breaks in the stations' rainfall series. These breaks occurred on distinct dates: in 2003 for Dialgaye, in 2004 for Tenkodogo, and in 1990 for Sangha and Ouargaye. Of these stations, only Tenkodogo shows a statistically significant change (p-value < 0.05), while the others show no significant change (p-value > 0.05). This suggests that the variations observed at these stations are random.

Table 1. Results of the statistical breakpoint test.

Station	Pettitt test			Excess (%)
	P value	Statistic	Break date	
Dialgaye	0.23	165	2003	12
Tenkodogo	0.012*	254	2004	21
Ouargaye	0.40	142	1990	13
Sangha	0.15	108	1990	16

Test: Statistically significant change, *P < 0.05.

3.1.3. Trend Detection

The results of non-seasonal Mann-Kendall trend test, presented in **Table 2**, confirm the findings of the breakpoint test. At the Tenkodogo station, rainfall shows an upward trend, which is statistically significant at the 95% confidence level. In contrast, the Dialgaye, Ouargaye, and Sangha stations show no significant trend. Although these annual rainfall series show a general upward trend, this is not statistically significant at the 95% level, suggesting that the variations observed could be attributed to random fluctuations.

Table 2. Results of the statistical trend test.

Station	Mann Kendall Test		Sen Slope
	P value	Statistic	
Dialgaye	0.43	0.78	1.94
Tenkodogo	0.01*	2.44	5.25
Ouargaye	0.41	0.82	1.71
Sangha	0.21	1.23	2.78

Test: Statistically significant change, *P < 0.05.

3.1.4. Spatial Variability of Rainfall in the Nouaho Sub-Basin

In this section, we present the spatial variability of rainfall in the Nouhao sub-basin over the decades 1981-1990 (**Figure 3**), 1991-2000 (**Figure 4**), 2001-2010 (**Figure 5**), and 2011-2020 (**Figure 6**).

Between 1981 and 2020, isohyets show significant variations, reflecting climatic fluctuations.

During the decade 1981-1990 (**Figure 3**), high rainfall (>900 mm) was limited to the southeast, while the north and center received less than 750 mm. During the 1991-2000 decade (**Figure 4**), there was a general retreat of isohyets towards

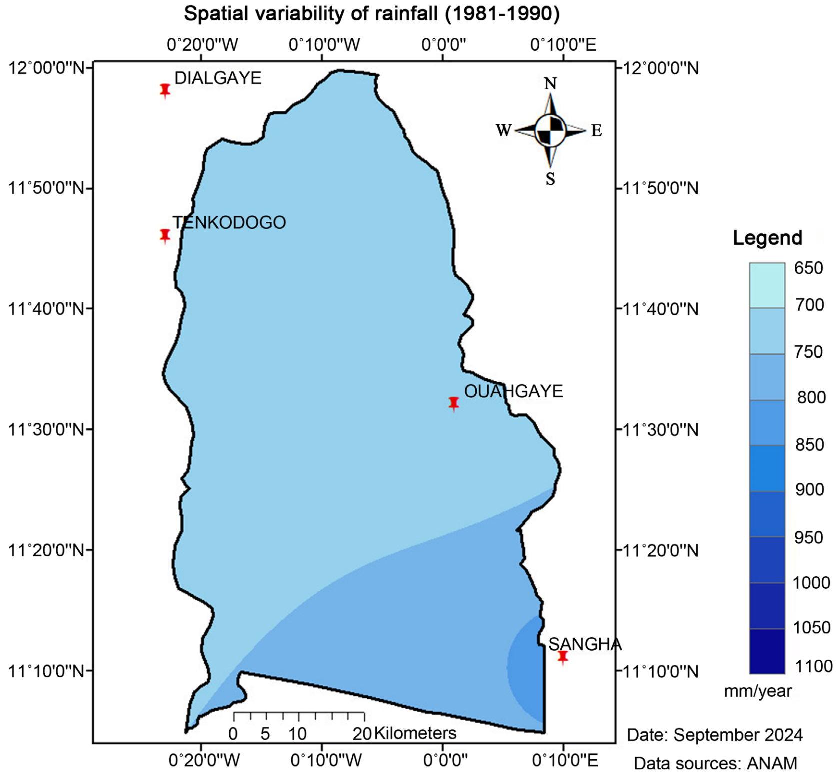

Figure 3. Spatio-temporal trends in rainfall in the Nouhao sub-basin over the decade 1981-1990.

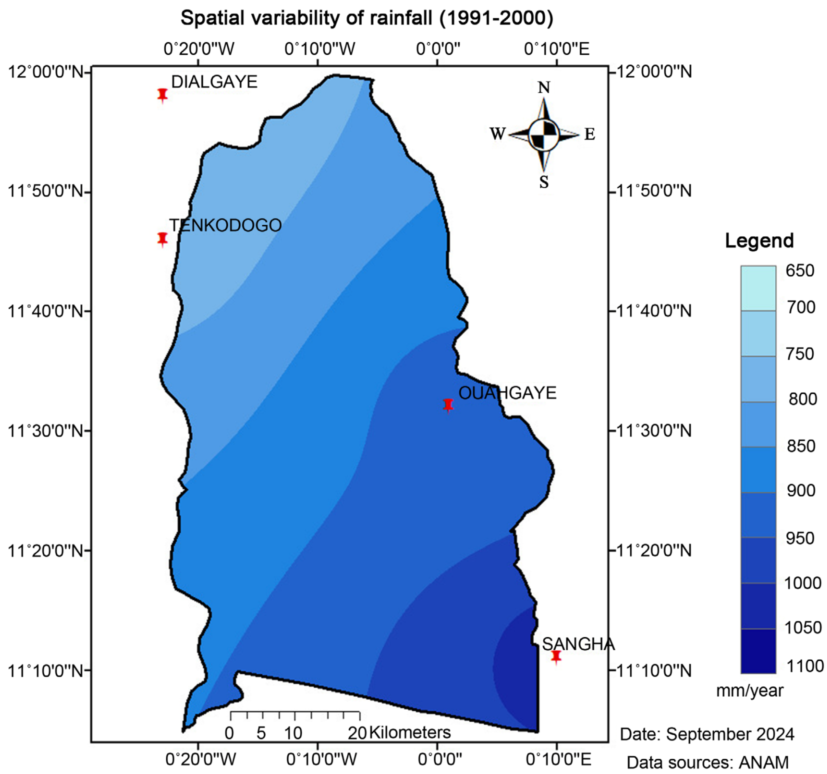

Figure 4. Spatio-temporal trends in rainfall in the Nouhao sub-basin over the decade 1991-2000.

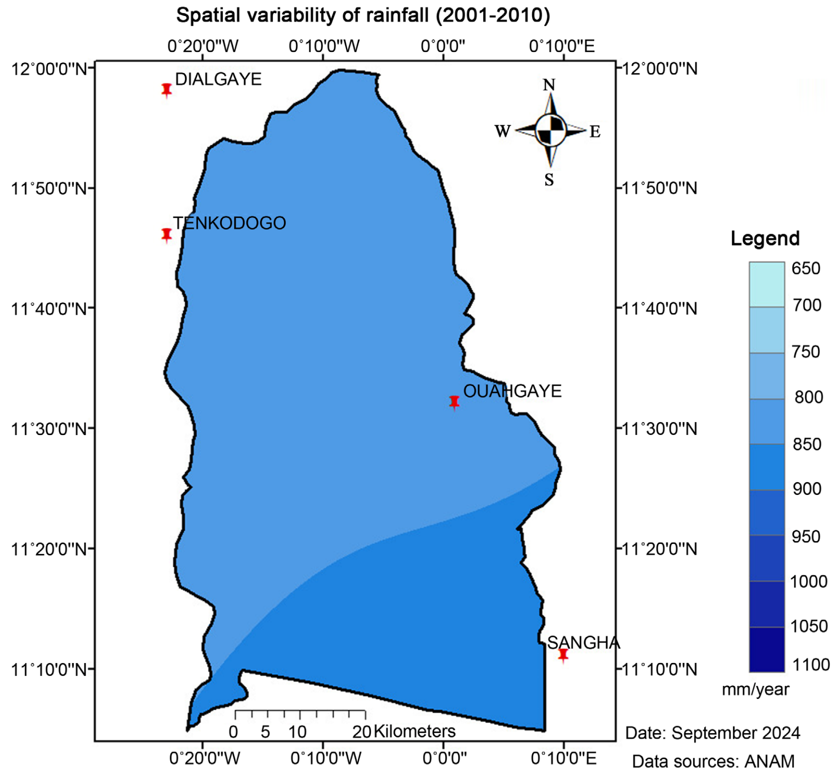

Figure 5. Spatio-temporal trends in rainfall in the Nouhao sub-basin over the decade 2001-2010.

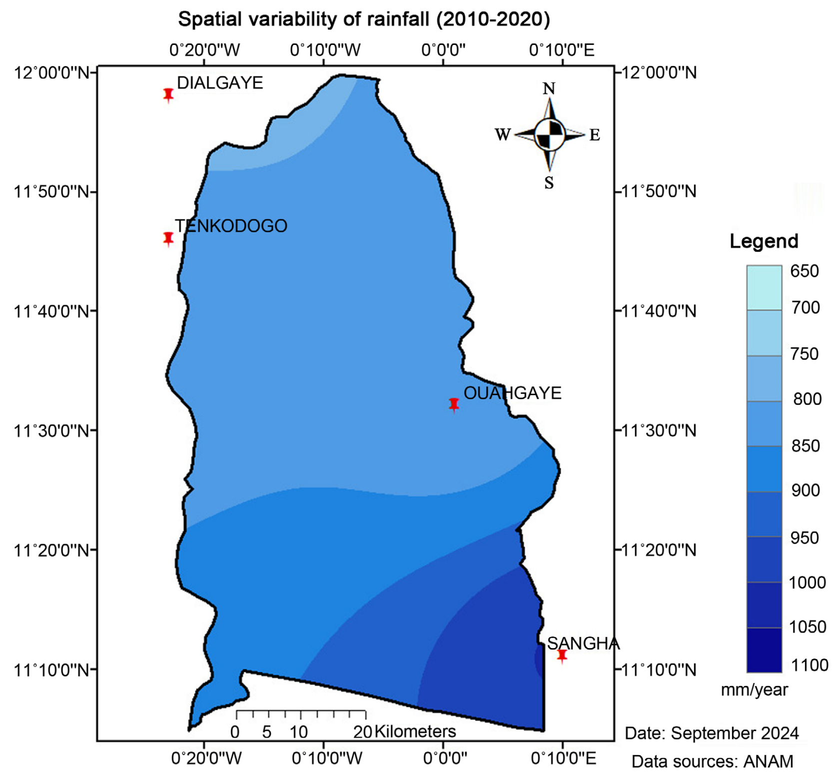

Figure 6. Spatio-temporal trends in rainfall in the Nouhao sub-basin over the decade 2011-2020.

the southeast, with a notable reduction in areas receiving 850 mm and 900 mm of rain, marking an increase in aridity, particularly in the northwest where 650 mm and 700 mm isohyets appeared. Between 2001 and 2010 (**Figure 5**), a slight upturn in precipitation is perceptible, with the 750 mm isohyets moving northwards and the 850 mm covering more of the central areas, while the 900 mm widens in the southeast, and a new 1000 mm isohyet emerges in the extreme southeast. Finally, during 2011-2020 (**Figure 6**), stability dominated in the north-west with 650 mm and 700 mm, while 750 mm and 850 mm remain in the central and south-eastern zones. The 900 mm are maintained in the extreme southeast, and new isohyets, 1100 mm, reflect an extension of very wet zones in this region, confirming a trend towards localized high rainfall.

3.2. Discussion

The index method has enabled us to accurately identify the years and periods of rainfall deficits and surpluses. The rainfall regime of the Nouhao sub-basin experienced alternating dry and wet periods between 1981 and 1990, with a general upward trend in annual precipitation. The analysis of the annual rainfall indices revealed a dry period from 1981 to 1990. This result corroborates previous studies in this sub-basin [34], which highlight the decline in rainfall starting in the 1980s. This decrease in rainfall was also reported in the central-northern region of the country [35]. Similar findings have been made in Côte d'Ivoire [16] and Senegal [14] [15]. During the dry period, one particularly dry year stands out in each of the studied stations. This was the year 1984, which is part of the major droughts that affected West Africa [17] [18]. The observed rainfall fluctuations indicate a return of precipitation to the basin starting in the 1990s, which aligns with other studies conducted in the central-northern region of Burkina Faso [10].

Analysis of the results of the Pettitt test applied to the time series shows that the null hypothesis, postulating the absence of a break, was rejected at the 90% confidence level at the Sangha, Ouargaye, and Dialgaye stations. However, only the Tenkodogo station showed a significant break (p-value < 0.05 in 2004). The Pettitt test allows for the identification of a significant break with an overshoot thresholdwhen the observation period is long enough [35]. Secondary breaks were observed in 1990 in Sangha and Ouargaye, and in 2003 in Dialgaye. These breaks signal the start of an increase in rainfall in the basin. These results are in line with those provided by the index method. This trend is also corroborated by the calculation of the average variation in rainfall based on the break years identified. This calculation indicates a surplus of 12% at Dialgaye, 16% at Sangha, 13% at Ouargaye and 21% at Tenkodogo, with an overall average of 16%. These results are similar to those of [35]. These authors also obtained recent break years (1990, 2000), resulting in an increase in rainfall with an average surplus of 13%.

Analysis of ten-year averages for precipitation in the Nouhao sub-basin reveals significant variations, including a shift in isohyets. Between 1991 and 2000, a significant increase in precipitation was observed, particularly in the southeast, where levels reached up to 1050 mm. This decade marks a return to wetter conditions compared with the previous period, with an extension of the wet zone, particularly in the southeast, and a slight increase in precipitation in the central and northwestern zones. However, between 2001 and 2010, although the south-east remains the wettest zone, precipitation there decreased slightly, while the central and north-west zones experienced a modest increase. Between 2011 and 2020, a notable drop in precipitation is observed in the central and north-western zones, while the south-east experienced a slight decrease. A study of the spatial dynamics of future precipitation in this sub-basin [20], shows a latitudinal shift in annual precipitation totals from northwest to southeast under the RCP 4.5 scenario, corroborating the trend observed in our analysis. This concordance suggests that the southeastward shift of isohyets could continue, or even increase, in the coming decades, underlining the need to integrate these dynamics into planning of adaptation strategies to climate impacts in the region.

4. Conclusion

This study aimed to analyze the spatio-temporal variability of rainfall in the Nouhao sub-basin over the period 1981-2022. Rainfall analysis using the index method shows fluctuating rainfall patterns with an upward trend. This fluctuation is marked by alternating dry, wet, and normally years. The 1981-1990 sub-period showed a deficit, followed by a recovery in rainfall from the 1990s onwards. Statistical tests identified breaks in the trend in 1990, 2003 and 2004. These breaks were accompanied by an increase in rainfall of between 12% and 21%. Analysis of ten-year averages of precipitation also revealed a shift in isohyets from the northeast. In short, this study underlines the need for continuous monitoring of precipitation patterns in the context of climatic vulnerability. The results obtained provide a sound basis for future research and the development of adaptation strategies aimed at mitigating the impacts of climate change in the region.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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