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Spatiotemporal Coherence of Low Water Levels and Mechanism of Transfer from Meteorological to Hydrological and Agricultural Droughts

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Abstract Drought is a serious environmental disaster that affects many parts of the world. It is defined as a prolonged absence or marked deficiency of rainfall. It can be detected by various drought indices (meteorological, hydrological, and agricultural). This water deficit is accentuated by the drought that has persisted in the study area since the mid-1970s. Moreover, the absence of study on the characterization of drought in the Ouémé River Basin invites, through this research work, to study drought at the level of the Ouémé River Basin in Bonou and its impact on water resources. The data used covers a period of 30 years (1989-2020). Thus, for the characterization of drought, three indices (SPI, SDI, and Martonne aridity index) were determined. These indices were used to make a spatiotemporal analysis of the drought in the basin through some hydrometric stations. From the analysis of the results, the drought states vary from one year to another with a preponderance of the "Light" drought state even if in the most recent years, an evolution to a moderate or even extreme drought state has been observed. The drought conditions vary from one area to another due to the different rainfall, the nature of the soil and the human activities in each area. In addition, there is a higher probability of transition from meteorological to hydrological drought in the Ouémé River Basin.

Keywords: *Hydrological drought, Drought index, Ouémé River Basin*

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1. Introduction

Drought, as an ecological disaster, is associated with a deficit of water resources over a large geographical area, which continues for a significant period of time [1,2]. Climate change, particularly its impacts on river flow regimes, is likely to exacerbate droughts and intensify their effects on river flows [3]. It is a natural phenomenon occurring in all world regions, particularly in West Africa.

It is one of the extreme weather conditions that affects more people than any other form of natural disaster. In recent decades, the occurrence of major droughts over large areas on all continents underlines the importance of this phenomenon. Both developing and industrialized countries are affected. In underdeveloped countries, the effects can be disastrous. Drought is linked to a lack or decrease in rainfall in a given region. This results in serious water shortages at certain times of the year in various regions of Benin, particularly in the Ouémé River Basin at Bonou, which is an area of high agricultural activity. The study highlights the importance of understanding the spatiotemporal coherence of low water levels and the transfer mechanisms between different forms of droughts in the Ouémé River Basin [2].

Human-induced climate change and substantially associated heat waves are increasing the frequency of drought events, multiplying their duration and intensifying their severity [4,5,6]. This will increase the probability of occurrence of extreme drought events in the future and consequently increase the complexity of the hydrological cycle in many regions of the world and increase the risk of changing flow characteristics and extremes [7]. Compared to other natural phenomena (e.g., floods, landslides and earthquakes, etc.), drought has a broader impact on multiple sectors. It affects economic development and health systems [8]. It disrupts and threatens biodiversity through the disappearance of species or the proliferation of others, the aridification of wetlands, the displacement of populations, etc.

Drought is a natural phenomenon associated with a significant decrease in water availability over a significant period of time and over a large area. Hydrological drought, on the other hand, is associated with the effects of precipitation periods on surface or groundwater supplies, i.e., streamflow, reservoir and lake levels, and groundwater. Various hydrological variables are used to describe drought, but flow is by far the most significant variable in terms of water quantity. Thus, a hydrological drought event is related to a deficit in flow compared to normal conditions. Drought analysis generally consists of characterizing its severity, duration and intensity. Similar to most hydrological problems, variables such as drought characteristics are commonly not independent.

Therefore, drought prediction is a necessity to anticipate what the consequences of future climate change might be in this region and to try to adapt to it as best as possible. By delving into the spatiotemporal coherence of low water levels and the transfer mechanisms between different forms of droughts, a better understanding of the causes of these phenomena in the Ouémé River Basin will be achieved [3]. Currently, the detection and monitoring of drought conditions are mainly based on certain indices. The most commonly used indices for drought monitoring are the Palmer Drought Index (PDI) [9] and the Standardized Precipitation Index (SPI) [10] and the 'SDI' hydrometric index. The challenges of monitoring water resources, and in particular the anticipation of situations of scarcity, or even shortage, nowadays require fine-tuning. These findings will play a crucial role in improving water resource management, especially for agriculture, and implementing adaptive measures in response to climate change. The research will thus contribute to preserving fragile ecosystems and mitigating the impacts of droughts on biodiversity and the population in the Ouémé basin region. It is with this objective in mind that our study entitled: "Analysis of trends in hydrological drought in the Ouémé basin in Bonou: determination of the spatio-temporal coherence of low water levels and mechanisms of transfer of meteorological drought to hydrological drought, or even agricultural drought".

2. Materials and Methods

2.1. Study Area

Located in Benin, the Ouémé watershed is precisely located between 6°24' and 10°12' North and between 1°30' and 3°00' East [9]. It flows from north to south where it creates in its downstream part a valley very rich in organic minerals: the Ouémé valley. Its climate is determined by the action centers controlled by the West African atmospheric circulation [10]. It occupies an area of 203.03 km². The Ouémé River Basin is characterized by a "transitional tropical regime with a Dahomean variant" marked by strong interannual irregularity and flow values that vary greatly from one year to the next. The low water season is rigorous and the high-water season quite long. Figure 1 shows the Ouémé watershed with the different stations used in our study.

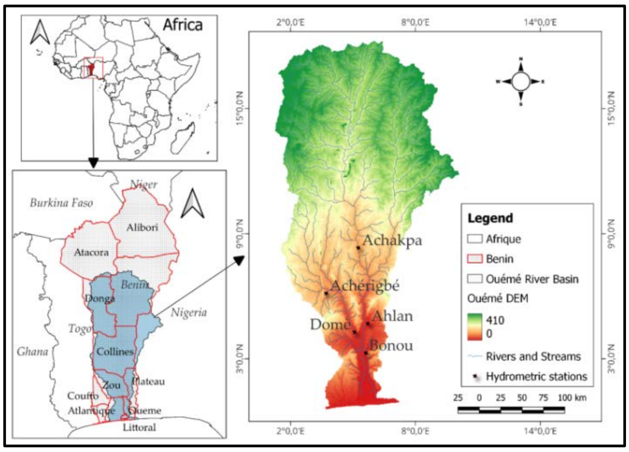

Figure 1. Ouémé watershed and the hydrometric stations

2.2. Data Used

For our study, we used mainly hydrometric and climatic data (rainfall, temperature, humidity and evapotranspiration).

Concerning the hydrometric data, we obtained flow data from five hydrometric stations in the Ouémé River Basin: Achakpa, Achérigbé, Ahlan, Bonou and Domè obtained from the Direction Générale de l'Eau (DGEau). Our study was carried out over the period from 1989 to 2020, considering the period from October to September as a hydrological year. Also, we had noticed missing data in our series of years that we imputed by the average of the same two days on adjacent years. Concerning the station of Domè, we had noticed that we had too many missing data on several years that we had not been able to fill them because of having biased results. Thus, we did not use the data from this station in the rest of our study.

Concerning the climatic data, the rainfall, temperature and humidity data were obtained from the NASA website [11] for a period from 1998 to 2020, and the evapotranspiration data were calculated using the AquaCrop model.

2.3. Methodology for determining the temporal consistency of hydrological drought in the Ouémé watershed in Bonou

First, we will study the evolution of drought through the determination of the SDI (Streamflow Drought Index) in the Ouémé watershed at Bonou at different time scales (1, 3, 6 and 12 months). In addition, the determination of the SPI (Standardized Precipitation Index) will allow us to characterize the rainfall deficit at these stations. After determining these indices, we will do a descriptive analysis to determine the driest years and/or seasons over the study period. Finally, we will use Markov chains to determine the transition between drought states and measure their severity.

The Streamflow Drought Index (SDI) which characterizes the severity of drought

Based on the cumulative flows, the flow drought index (SDI) is defined for each reference period k (k = 1 for January-March, k =2 April-June, k = 3 for July-September and k = 4 for October-December) of the i-th hydrological year. The SDI index is defined as follows:

$$SDI_{i,k} = \frac{y_{i,k} - \bar{y}_k}{s_{y,k}} i = 1,2,\ldots.k = 1,2,3,4 \tag{1}$$

Where $y_{i,k} = \ln(V_{i,k})$; $V_{i,k}$ is the flow rate at the i-th year and a reference period k

Based on the SDI, hydrological drought states are defined, which are identical to those used in the SPI and RDI meteorological drought indices.

Five states are considered which are designated by an integer ranging from 0 (non-drought) to 4 (extreme drought) and are defined through the criteria in the following Table 1.

Table 1. Description of drought conditions using the SDI

States	Description	Criteria
0	No drought	$SDI \geq 0$
1	Light drought	$-1{,}0 \leq SDI < 0$
2	Moderate drought	$-1{,}5 \leq SDI < -1{,}0$
3	Severe drought	$-2{,}0 \leq SDI < -1{,}5$
4	Extreme Drought	$SDI < -2{,}0$

Here we had used DrinC for the calculation of the index and also Rstudio for the temporal and spatial analysis for the determination of the hydrological drought.

The SPI Index

The Standardized Precipitation Index (SPI) [8,12] is a statistical indicator commonly used to characterize local or regional droughts. It provides a measure of the magnitude of drought (or moisture) for each period of the time series [13].

$$SPI = (P - Pm) / \sigma \tag{2}$$

With P: Total precipitation of a period (mm); Pm: Historical average precipitation of the period (mm); s: Historical standard deviation of precipitation of the period (mm).

Markov chain

In this section, we will first identify the different types of droughts using the monthly data and the classification used in the literature for each type of index. For example, according to the SDI, drought states are classified as "No Drought", "Moderate Drought", "Severe Drought", "Extreme Drought".

Next, we will model these states by a Markov chain of order 1. Let us denote by $(X_t)_{t=1,\ldots T}$ the stochastic process representing the different values of the drought states for each month over the whole period (T thus represent the total number of months over the whole period). Thus, for each month t, X_t can take the values "No drought", "Moderate drought", "Severe drought", "Extreme drought". This process is a Markov chain of order 1, which means mathematically that it has the Markov property, i.e.

$$\begin{aligned} &P(X_{n+1} = x_{n+1} | X_n = x_n, X_{n-1} = x_{n-1}, \ldots, X_1 = x_1) \\ &= P(X_{n+1} = x_{n+1} | X_n = x_n) \end{aligned} \tag{3}$$

where the index x_i represents a realization of the random variable X_i.

This means more precisely that the state of the next month depends only on the state of the previous month. This choice seems natural (logical) because it does not seem logical to use an order greater than one to model such a process. This chain is also characterized by a transition matrix which defines at each time, the probability of going from one state to the other. We will consider here a stationary Markov chain. This means that the transition matrix is the same for all times. The modeling of our Markov chain requires the estimation of the different probabilities composing this transition matrix. The maximum likelihood estimator is given by equation 4.

$$\hat{p}_{ij}^{MLE} = \frac{n_{ij}}{\sum_{u=1}^{k} n_{iu}} \tag{4}$$

Where n_{ij} represents the number of times in the data that one has moved from state i to state j.

2.4. Methodology for the Analysis of the Spatial Coherence of the Hydrological Drought in Bonou with Other Hydrometric Stations of the Ouémé Watershed.

In order to analyze the spatial coherence of hydrological drought, we will compare the drought conditions in Bonou with the other hydrometric stations in the Ouémé and Zou River Basins using the SDI data obtained previously. Thus, we will, based on the preceding work, select the driest years (where we have noticed fairly high drought rates) at Bonou to compare them with the drought states we have had at the other stations and compare them.

We are going to use Martonne's aridity index which allows to characterize the phenomenon of aridity by expressing the restrictive character for certain plant formations.

2.5. Methodology to Determine the Mechanism of Transfer of Meteorological Droughts to Hydrological or Agricultural Droughts

Here we will use the SPI index to characterize meteorological drought, the SDI index to characterize hydrological drought and the Martonne Aridity Index to characterize agricultural drought. Thus, after the calculation of the indices we will establish a new class of qualification that will allow us to model the types of droughts. Thus, we will consider the positive values of the calculated indices of SPI and SDI as the states of non-drought and the negative values as being respectively, the state of meteorological drought and the state of hydrological drought. Concerning the Martonne aridity index, the values between 20 and 55 will be considered as non-drought states and the values between 0 and 20, will be considered as agricultural drought states.

We are going to use Martonne's aridity index which allows to characterize the phenomenon of aridity by expressing the restrictive character for certain plant formations (equation 5).

$$I_a = P/\left(T+10\right) \qquad (5)$$

with P the rainfall and T the average temperature.

3. Results

3.1. Analysis of the Temporal Coherence of the Hydrological Drought in the Ouémé Watershed Through Some Hydrometric Stations More Precisely in Bonou.

In this part, we present the results of the temporal analysis after the calculation of the SDI in the station of Bonou accompanied by the variation of the SPI also calculated in Bonou. The results obtained after the temporal analysis of the hydrological drought through some hydrometric stations of the Ouémé watershed will follow. We present the results of the temporal analysis after calculation of the SDI.

Figure 10 shows the variation of SDI at different time scales of 1, 3, 6 and 12 months from 1989 to 2020 considering the water year of October to September. The results indicate that short time scales (Figure 2a. and Figure 2b.) have higher temporal variability in wet and dry periods, while long time scales have lower frequency. In general, there is an alternation between wet and dry years. During the small-time scales, there is a higher frequency of dry years, even though the severity (light, moderate, severe) of these dry years is mostly light.

This above-described situation is due to the influence of coastal upwelling (seasonal cold water upwelling) which mainly inhibits rainfall during July to August [14]. The same findings were reported by [15]. These researchers described that ocean surface temperatures decrease sharply in July and mainly in August due to coastal upwelling. These authors added that this period coincides with the presence of an atmosphere characterized by very low rainfall due mainly to a temperature inversion close to the surface. Such a situation prevents the development of convective clouds and, on the other hand, allows the formation of low stratus clouds that intercept solar radiation very strongly [16]. For high time scales (6 or 12 months), it can be seen that the intensity of the drought is mostly higher with extreme values, observed mainly during the hydrological year of 2014-2015. As confirmed in the following Figure 3, where the annual SPI values are presented, it is noticed that the year 2014-2015 is an extremely dry year. This result is consistent with the work of [17] who noted that the hydrological year of 2014-2015 records a strong hydrological drought.

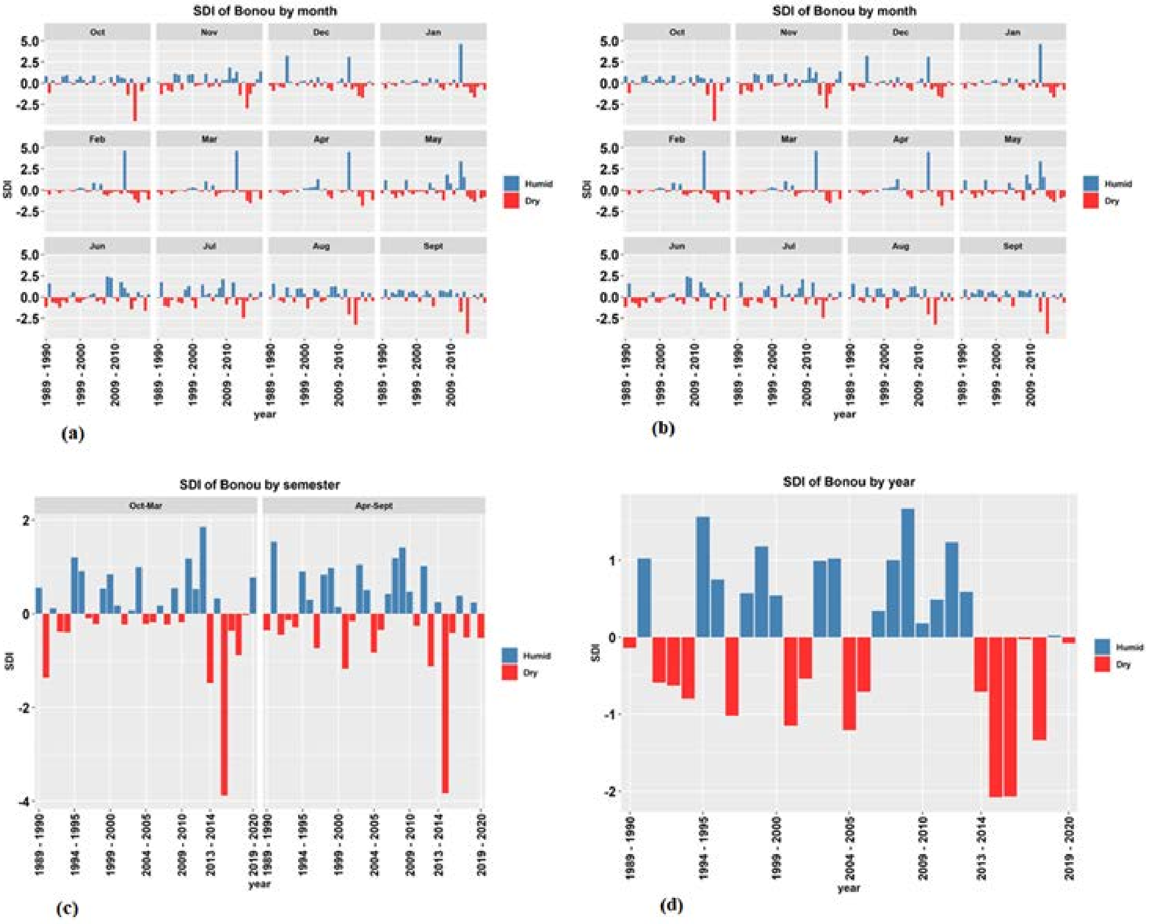

Figure 2. Variation in SDI at different time scales at Bonou. (a) 1 month; (b) 3 months; (c) 6 months; (d) 12 months)

In order to further analyze the drought in Bonou, we modeled the drought states classified by the SDI by a Markov chain. After estimation with R, we obtain the following transition matrix which shows the transition probabilities between the different drought states.

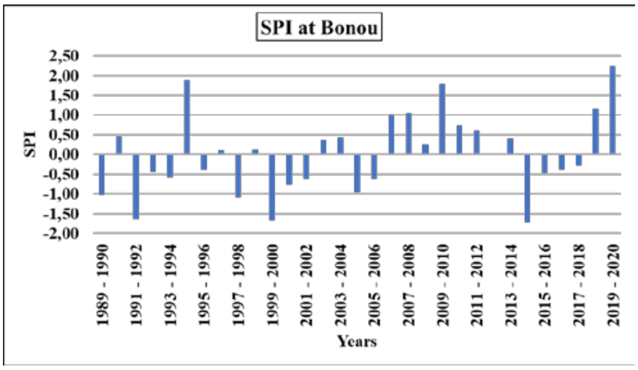

Figure 3. Variation in SPI obtained at Bonou

Table 2. Transition matrix of drought states at Bonou

	No Drought	Moderate drought	Severe drought	Extreme drought
No Drought	0.75	0.25	0.00	0.00
Moderate drought	0.19	0.79	0.01	0.01
Severe drought	0.00	0.50	0.50	0.00
Extreme drought	0.00	0.00	0.33	0.67

Through Table 2, we observe in the first line, for example, that if the previous month is "No drought", we remain in this state with a probability of 75% and where we leave for the state of "moderate drought" with a probability of 25%. The same interpretation can be made for the other rows of the table. The graph allows us to better understand the communication between the states in the chain. We observe that the passage from one state to another is conditional on the intermediate states following a hierarchy. In other words, one does not go directly from the state "No drought" to "Extreme drought" for example. One must necessarily go through the state of "moderate drought". We can also determine the annual average time of stay in a state and the average time of return to a state knowing that we left this state at time 0 (Table 3).

Table 3. Residence time and return time of drought conditions in Bonou

	No Drought	Moderate drought	Severe drought	Extreme drought
Average annual length of stay (in months)	4.94	6.61	0.258	0.194
Average time of return to the state knowing that we were in this state at the beginning	2.46	61.18	1.80	45.88

We observe that the average time spent in the "No Drought" state on average over the entire period is about 5 months each year. The states of "Severe Drought", "Extreme Drought" appear on average less than one month one year. These results are consistent with the average return time. For example, it takes about 46 months to return to the "Extreme Drought" state after leaving it. These results are consistent with the literature, because the position of the study area in relation to the coast, atmospheric parameters (atmospheric pressure, relative humidity, wind speed), ocean surface temperatures, including the coastal upwelling, latitude and altitude proves that the study area is more influenced in the north by rainfall related to the monsoon and orographic flow. In addition, the rainfall characteristic of southeast squall lines, responsible for thunderstorms and showers that can cause flooding. As justified by the work of Kodja (2018) [14].

In order to carry out a comparative analysis, we determined the drought conditions in other hydrometric stations located in the Ouémé River Basin and others in the Zou River Basin.

3.2. Analysis of the Spatial Coherence of the Hydrological Drought in Bonou with Other Hydrometric Stations of the Ouémé Watershed.

In this part, we made the analysis of the spatial coherence of the hydrological drought in Bonou and in other stations. Thus, we had selected the 10 driest years according to the results obtained previously with the determination of SPI, (1991 - 1992; 1993 - 1994; 1994 - 1995; 1996 - 1997; 1997 - 1998; 2002 - 2003; 2004 - 2005; 2005 - 2006; 2009 - 2010; 2015 - 2016). During these years, we noticed a variation of drought states in Bonou going from drought states "No drought" to "extreme" drought that we will compare with the other stations following the same years.

Analysis of Figure 4.a shows that during the January to March trimester, the drought conditions were the same at all stations. From April to June, there was a mild drought at all stations except Bonou, where there was no drought. The same observation was made during the July-September trimester. In the last quarter, Atchérigbé was the least dry.

Figure 4.b shows that in the first trimester, the degree of drought at Ahlan was higher than at the other stations. In the second trimester, drought was absent at Achérigbé, but present at the other stations (Atchakpa, Ahlan, Bonou). In the third trimester, drought was absent at Achérégbé and Ahlan, but present at Atchakpa and Bonou. In the last trimester, there was no drought at Atchakpa, Ahlan and Achérigbé, except at Bonou. In conclusion, drought was frequent at Bonou throughout 1994-1995, but not at the other stations.

We can see from Figure 4.c that in the first trimester, there was no drought at the Ahlan station, but it was present at the other three; in the second trimester, there was no drought at Bonou, but it was present at the other three stations; in contrast, in the third trimester, there was drought at Bonou and no drought at the other three stations. The fourth trimester was marked by the presence of drought at all four stations, although it was slightly weaker than in the first trimester.

From analysis of Figure 4.d, the trend at the Atchakpa, Achérigbé and Bonou stations is one of mild drought, in contrast to the Ahlan station over the last two trimesters.

Analysis of figure 4.e shows that, in the first trimester, Atchakpa and Bonou experienced a mild drought, while Achérigbé and Ahlan did not. In the second trimester, only the Bonou station was drought-free, and the situation was similar in the last trimester. From July to September, only the Ahlan station experienced a mild drought, while the other stations didn't.

From Figure 4.f, we can see that in the first trimester, all stations except Bonou were dry. In the second trimester, the Atchakpa station was drought-free. In the third trimester, all stations were slightly dry, except Bonou, which was extremely dry. In the final trimester, the Achérigbé and Ahlan stations experienced mild drought, while the other stations didn't.

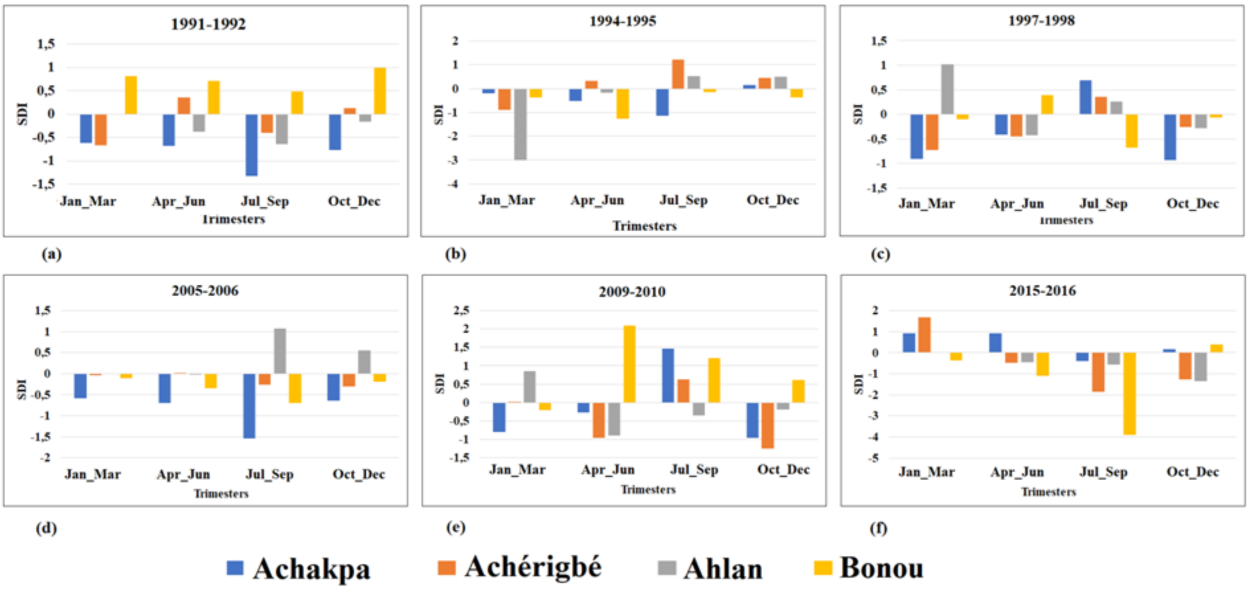

Figure 4. Spatial analysis of the SDI between stations. (a) year 1991-1992; (b) year 1994-1995; (c) year 1997-1998; (d) year 2005-2006; (e) year 2009-2010; (f) year 2015-2016.

3.3. The Transfer Mechanism from Meteorological Drought to Hydrological or Agricultural Drought

In this section, we have tried to determine how meteorological drought is transferred to hydrological, or even agricultural, drought. To do this, we used indices to identify each type of drought. We used the SPI for meteorological drought, the SDI for hydrological drought and the Martonne aridity index for agricultural drought. We also determined the correlation between the variables to see if there was a link between them.

The next step is to determine the correlation between the two indices. Here, we use Pearson's correlation with the following formula (equation 6).

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (6)$$

with, x and y the respective representation of each of the variables x_i and y_i

Our hypothesis is that:

- there is a strong link between meteorological drought and hydrological drought
- there is a strong link between meteorological drought and agricultural drought
- there is a strong link between agricultural drought and hydrological drought

Next, we carried out a statistical test to see whether the Pearson correlation is different from zero. The null hypothesis of this test is the absence of correlation. If the p-value is less than 5%, the null hypothesis can be rejected, and we conclude that the correlation is statistically significant at the 5% threshold. The results of these tests are shown in Tables 4, 5 and 6.

Table 4. Correlation Between Meteorological Drought and Hydrological Drought

Trimester	Correlation	Stat_test	p-value	Significance at 5% level
Jan-March	0.224	1.217	0.234	Not significant
April-June	0.211	1.142	0.263	Not significant
July-Sept	0.114	0.605	0.549	Not significant
Oct-Dec	0.501	3.061	0.005	Significant

Table 5. Correlation Between Meteorological Drought and Agricultural Drought

Trimester	Correlation	Stat_test	p-value	Significance at 5% level
Jan-March	0.362	2.054	0.0494	Significant
April-June	0.605	4.026	0.0003	Significant
July-Sept	0.683	4.953	<0.050	Significant
Oct-Dec	0.857	8.796	<0.05	Significant

Table 6. Correlation Between Hydrological Drought and Agricultural Drought

Trimester	Correlation	Stat_test	p-value	Significance at 5% level
Jan-March	0.290	1.608	0.119	Not significant
April-June	0.215	1.166	0.253	Not significant
July-Sept	0.505	3.095	0.005	Significant
Oct-Dec	0.316	1.763	0.088	Not significant

From the analysis of Table 4 for the October to December trimester, the correlation is 50%, and according to the significance test, there is a strong significant link between meteorological drought and hydrological drought. Based on the correlation results for each of the other trimesters, we cannot reject the null hypothesis of no correlation between meteorological drought and hydrological drought in our Ouémé à Bonou watershed.

According to the analysis in Table 5, for all trimesters, even if the correlation is weak for the Jan-March trimester (36%), the significance test shows that the relationship between meteorological and agricultural drought is not negligible. We therefore accept our hypothesis that there is a link between meteorological and agricultural drought in the Bonou Ouémé watershed. These results are justified. Indeed, after observation in the field, farmers, despite the presence of the Ouémé River, have difficulty draining the water available to their fields. So, if there's no rain in the commune, they won't be able to get a good yield this year. This will have repercussions for the whole population.

From analysis of Table 6, it is only in the July-September trimester that there is a link between hydrological and agricultural drought. Unlike the other trimesters, there is no significant correlation between hydrological drought and agricultural drought. This means that during this period, hydrological drought affects agricultural drought, since the absence of water in the watershed will affect agricultural crops. If, in addition, there is an absence of rain, yields will be greatly reduced.

Once we had determined the correlations between drought types, we created a transition matrix, as well as a Markov plot, to help us understand the transition from one type of drought to another.

3.4. Transition Matrix

3.4.1. Hydrological vs. Meteorological

The probability of transition from meteorological to hydrological drought is 0.40% and the probability of transition from hydrological to meteorological drought is 0.59.

Table 7. Probability of Transition from Meteorological Drought to Hydrological Drought

	No-D_No-D	No-D_Meteo_D	Hydro-D_No-D	Hydro-D_Météo-D
No-D_No-D	0.05	0.76	0.00	0.18
No-D_Meteo_D	0.58	0.02	0.40	0.00
Hydro-D_No-D	0.00	0.59	0.00	0.41
Hydro-D_Météo-D	0.63	0.06	0.31	0.00

With No-D: No drought; Hydro-D: Hydrological drought; Meteo-D: Meteorological drought; Arid: Agricultural drought

3.4.2. Hydrological vs. Agricultural

Table 8 shows the transition matrix from hydrological drought to agricultural drought and vice versa. For example, the probability of transition from agricultural drought to hydrological drought is 0.05 and that of transition from hydrological drought to agricultural drought is 0.67.

3.4.3. Meteorological vs. Agricultural

Table 9 shows the transition matrix from meteorological drought to agricultural drought and vice versa. The probability of transition from agricultural drought to meteorological drought is 0.24 and that of transition from meteorological drought to agricultural drought is 1. This means that when there is meteorological drought, there is always agricultural drought, but not vice versa. This can happen in areas of the commune where there are no rivers or streams nearby to bring water to the crops.

Table 8. Probability of Transition From Hydrological to Agricultural Drought

	No-D_ Arid	No-D_N-Arid	Hydro-D_Arid	Hydro-D_NArid
No-D_ Arid	0.46	0.26	0.23	0.05
No-D_N-Arid	0.42	0.25	0.29	0.04
Hydro-D_Arid	0.50	0.09	0.34	0.06
Hydro-D_N-Arid	0.67	0.17	0.17	0.00

Table 9. Probability of Transition From Meteorological to Agricultural Drought

	No-D_ Arid	No-D_N-Arid	Meteo-D_Arid	Meteo-D_N-Arid
No-D_ Arid	0.46	0.26	0.23	0.05
No-D_N-Arid	0.42	0.25	0.29	0.04
Meteo-D_Arid	0.50	0.09	0.34	0.06
Meteo-D_N-Arid	0.67	0.17	0.17	0.00

4. Discussion

In summary, drought conditions vary from year to year and from station to station. Overall, drought conditions at Bonou are different from those at other stations. The same applies to the other stations. These differences are due to the nature of the soil and the rainfall, which are different, given the SPI results obtained at each station.

Furthermore, spatial coherence refers to the closeness of relationships between different zones in terms of hydrology. For example, if two zones have poor hydrology, but good spatial coherence, they may be able to recover if they have regular hydration conditions and good soil conservation techniques.

From an analysis of the results obtained, we can deduce that the transfer mechanism from one drought condition to another depends on topography, soil type, climate and the proximity of a river or lake. Even if we had been able to determine the transfer probabilities from our analysis, it is rather complex to explain the transfer mechanism, which is linked to the explanatory variables for these types of droughts. If we take the transition from hydrological drought to agricultural drought, this will only have an effect if farmers are close to the Ouémé River, because they will be able to easily take this water to feed their crops. However, if there is a shortage of water, then crop yields will be affected, which will affect people's quality of life.

The transfer mechanism from hydrological to meteorological or agricultural drought can be complex and dependent on the conditions in our study area. However, there are several general mechanisms that can contribute to this transfer. Firstly, hydrological drought can lead to lower water levels in rivers, lakes and groundwater. This reduction in available water can affect soil recharge, which in turn can reduce soil and plant moisture. If this situation persists, it can lead to meteorological and agricultural drought, characterized by insufficient rainfall and reduced agricultural production. Hydrological drought can also affect the availability of water for irrigation, which is essential for crop growth. A reduction in the availability of water for irrigation leads to a reduction in agricultural production, which can have significant economic consequences for local and national communities. In addition, hydrological drought can affect local biodiversity, including natural ecosystems and the animal and plant species that depend on them. This loss of biodiversity can have significant consequences for agricultural production, particularly if local ecosystems provide ecosystem services such as pollination or protection against pests.

Overall, the mechanism of transfer from hydrological to meteorological and agricultural drought can be complex and multifactorial, as discussed by Mishra, A. K., & Singh, V. P. (2010) [18]. However, reduced water availability for soils, plants and human activities is a key factor that can contribute to this transfer. To prevent or mitigate the effects of hydrological drought on meteorological and agricultural drought, it is therefore important to implement measures for water conservation, sustainable management of water resources and protection of local biodiversity.

This study holds significant implications for the environmental management of the Ouémé watershed. By enhancing drought monitoring and prediction, it provides valuable insights for swift responses and mitigation measures [21]. Furthermore, the findings contribute to improved water resource management by identifying critical factors causing water shortages in the region. The study also supports environmental protection initiatives through targeted conservation measures to safeguard fragile habitats and aquatic biodiversity. Lastly, understanding the transfer mechanisms between different forms of drought enables the development of climate change adaptation strategies for sustainable water resource management [21].

5. Conclusions

Our study of the spatio-temporal analysis of hydrological drought in the Ouémé Basin at Bonou outlet has enabled us to gain a better understanding of the patterns and trends of this phenomenon. We also examined the transfer mechanisms from hydrological drought to meteorological and agricultural drought in our study area. These results are important, as they allow us to better understand the impact of drought on the study area and to formulate strategies for dealing with this phenomenon. In conclusion, this study provided a spatio-temporal analysis of a number of hydrometric stations in the Ouémé watershed, and more specifically in Bonou. The SPI index, the Martonne aridity index and, above all, the SDI index were used to assess the characteristics of drought conditions on different time scales. The results are based on long-term hydrological and meteorological datasets and widely used methods that are consistent with previous studies and observed statistics. Consequently, the results are credible to some extent and can be used to contribute to drought mitigation. The main conclusions are summarized as follows:

Drought conditions vary from one state to another over time, with a preference for light and sometimes moderate drought conditions.

Changing trends in drought conditions vary from station to station, although there is a fairly high correlation overall between the stations studied.

Using the Markov chain, we were able to determine the trends from one type of drought to another, with the greatest variation between the "No drought" and "Moderate drought" states, due to the increase in temperature caused by climate change.

Calculating the correlations between drought types shows that there is a significant link between meteorological drought and agricultural drought, which is justified because, despite the presence of the Ouémé River, most farmers do not have the necessary equipment to drain this water into their fields.

The results of this study provide an important database for assessing the risks associated with climate variability. In this context, improved observation systems and reliable data collection are needed to better characterize the climate and make good forecasts, which should contribute to better adaptation to the effect of climate variability in the Ouémé Basin at Bonou. This will enable more effective planning and management of water resources and water-related activities, especially agricultural ones, as well as the development of drought adaptation measures. We therefore suggest: developing adaptation plans for local communities, in particular by encouraging the adoption of sustainable agricultural practices and the diversification of income sources; raising awareness among local populations of the risks of drought and the measures to be taken to cope with it, for example by organizing awareness campaigns and providing information on agricultural practices adapted to drought; working with local governments, international organizations and NGOs to obtain additional funding and resources to combat drought and strengthen the resilience of local communities.

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