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CONTRIBUTION OF A GIS TO MAPPING AND SPATIAL-TEMPORAL CHARACTERIZATION OF RAINFALL VARIABILITY: CASE OF THE NORTHERN PART OF IVORY COAST

CONTRIBUTION D'UN SIG A LA CARTOGRAPHIE ET A LA CARACTERISATION SPATIO-TEMPORELLE DE LA VARIABILITE PLUVIOMETRIQUE : CAS DE LA PARTIE NORD DE LA CÔTE D'IVOIRE

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ABSTRACT

The knowledge of rainfall variability is necessary for development projects planning related to water which is increasingly rare in semi-arid areas. This study aims to map and perform a qualitative and quantitative analysis of the spatial and temporal dynamics of rainfall in the northern part of Ivory Coast on a decadal scale over 1961-2000 period in order to ensure the proper functioning of development projects. A GIS was therefore used. The results showed the disappearance of isohyets with high rainfall towards West in favor of those with low rainfall which appear in East. However, rainfall resumption is reported in the last decade (1991-2000). This rainfall dynamic is consistent with covered surfaces analysis by persistent isohyets and with the preponderance of the low rainfall isohyets class which reached 72% of covered surface in the driest decade (1981-1990). During this drier decade, a significant rainfall deficit of -224.62mm was recorded against -168.79mm in the last decade 1990-2000 when a relative rainfall recovery is perceived. The implementation of development projects must therefore be adapted to spatial and temporal evolution of rainfall.

Keywords: SIG, mapping, rainfall variability, isohyets, Northern part of Ivory Coast.

RESUME

La connaissance de la variabilité pluviométrique est importante pour la planification des projets de développement liés à l'eau qui est de plus en plus rare dans les zones semi-arides. Cette étude vise à cartographier et à analyser qualitativement et quantitativement la dynamique spatio-temporelle de la pluviométrie de la partie Nord de la Côte d'Ivoire, à l'échelle décennale sur la période 1961-2000 en vue d'assurer une bonne planification des projets de développement. Un SIG a donc été utilisé. Les résultats ont montré le glissement et la disparition des isohyètes de fortes pluviométries vers l'Ouest au profit de celles de faibles pluviométries qui apparaissent à l'Est. Cependant, une faible reprise pluviométrique est signalée à la dernière décennie (1991-2000). Cette dynamique pluviométrique est conforme à l'analyse des surfaces couvertes par les isohyètes persistantes et à la prépondérance de la classe d'isohyètes à faibles pluviométries qui a atteint 72% de surface couverte à la décennie la plus sèche (1981-1990). Durant cette décennie plus sèche, un déficit pluviométrique important de -224,62 mm a été enregistré contre -168,79mm à la dernière décennie 1991-2000 où, une reprise pluviométrique relative est perçue. La réalisation des projets de développement doit donc être adaptée à l'évolution spatio-temporelle de la pluviométrie.

Mots clés : SIG, cartographie, variabilité pluviométrique, isohyètes, partie Nord de la Côte d'Ivoire.

INTRODUCTION

Global rainfall evolution is much more contrasted, since it is subject to strong spatio-temporal variability (Nouceur and Laignel, 2015). In West Africa, the downward trend in rainfall has favored other climatic events, particularly temperatures increase observed at the global level and drought. Indeed, drought is mainly reflected by a drastic decrease in the flow of rivers, or even by a cessation of flow in certain rivers (Nicholson et al., 2000; Dai et al., 2004). This hydrological drought is also marked by a decrease in floods, severity of low flows, and early drying up (Faye et al., 2015). However, given the increase in temperature, a probable increase in rainfall is expected (Nouceur and Laignel, 2015), which could mitigate observed adverse effects.

In Côte d'Ivoire, specifically in the northern part of the country, a decrease in surface water and groundwater inflows has already been observed, resulting in water shortage problems at certain dry periods of the year in various regions. The water retention dams built for this purpose, also to promote the development of agro-pastoral activities, are sometimes subject to rapid drying up. Consequently, these agro-pastoral activities related to water are increasingly disrupted with a significant decrease in agricultural production. Thus, characterization of rainfall annual variability by using of a GIS, is always important in development projects planning, as in several studies carried out (Servat et al., 1999; Dacosta et al., 2002; Saley et al., 2009; Bodian et al., 2011; Sebbar 2013; Sambou et al., 2018). The objective of this study is to map and perform a qualitative and quantitative analysis of the spatio-temporal dynamics of rainfall on a decadal scale to ensure the proper functioning of water-related activities. The study is conducted over 1961-2000 period following four decades during which an average annual rainfall spatialization is performed, followed by the qualitative analysis of the rainfall isohyets spatial dynamics. The quantitative analysis of rainfall variability will concern covered areas by persistent rainfall isohyets, rainfall isohyet classes that will be defined and average water level per decade.

PRESENTATION OF THE STUDY AREA

The study area is the northern part of Ivorian territory, located between 8th and 11th parallels, between -3°00' and -8°00' West longitudes and 8°00' and 11°00' North latitudes (Fig. 1). It extends from East to West from the regions of Gontougo (Bondoukou) and Boukani (Bouna) to the regions of Bafing (Touba), Kabadougou (Odienné) and Folon (Minignan), covering an area of about 137,400 km^2. This upper part of Ivorian territory is marked by a vast plain followed by a region of low plateaus whose altitudes are less than 350 m. It is covered with savannahs composed of large grassland areas and sparse trees with a transition tropical climate of south Sudanese type with two seasons (a dry season and a rainy season). Only peripheral areas of rivers have denser vegetation. Vegetation is also marked by vast expanses of tecks, mango trees, and shea trees. The main plantations are millet, sorghum, rice, cotton, cashew as well as vegetable market gardeners. Geologically and hydrogeologically, the study area consists of the crystalline and crystallophyll basement with alterites and cracks aquifers.

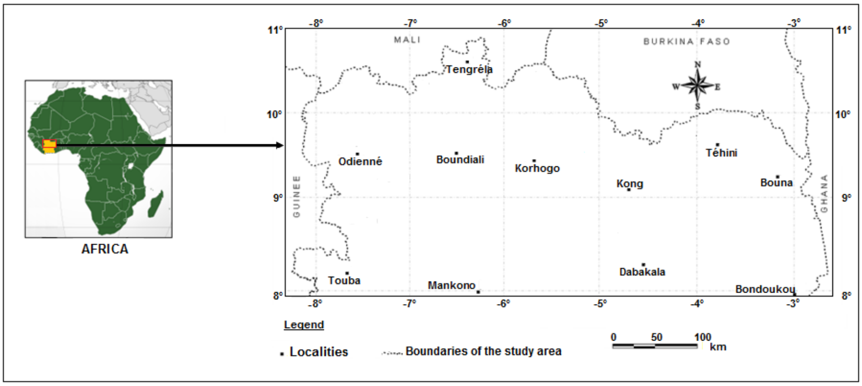

Figure 1: Location map of the study area

MATERIALS AND METHODS

Data and materials

Average annual rainfall data over four decades (1961-1970, 1971-1980, 1981-1990, and 1991-2000), used in this study, were compiled using total annual rainfall provided by the Society of Development Aeronautical and Meteorological Operation (Table 1). These rainfall data come from 19 selected rainfall stations, which are geographically well distributed over the study area (Fig. 2). These rainfall stations also have homogeneous and almost uninterrupted rainfall data over 1961-2000 period. Indeed, analysis of the spatial variability of rainfall, such as several authors (Paturel et al., 1997 and 1998; Bigot et al., 2005), requires a large number of rainfall stations with long-term rainfall measurements. The GIS software MapInfo 7.5 and Surfer 8.0 were used to produce the various maps of spatio-temporal fluctuations of average annual rainfall over 1961-2000 period, following each decade.

Table 1: Average annual rainfall by decade for 19 selected rainfall stations over 1961-2000 period

Rainfall Stations	Geographic coordinates		Average rainfall (mm)			
	Longitudes	Latitudes	1961-1970	1971-1980	1981-1990	1991-2000
Bondoukou	2°47'00"W	8°03'00"N	1157.77	1121.15	1031.28	1053.3
Bouna	2°59'00"W	9°16'00"N	1049.5	966.6	1000.6	958.99
Boundiali	6°28'00"W	9°31'00"N	1564.7	1528.3	1253.39	1303.2
Dabakala	4°26'00"W	8°23'00"N	1264.24	926.7	900.22	967.63
Dembasso	4°24'00"W	9°41'00"N	1227.62	1050.36	1081.6	1238.7
Ferkessédougou	5°13'00"W	9°35'30"N	1278.92	1117.74	843.37	819.48
Katiola	5°06'00"W	8°08'00"N	1271.24	1093.71	868.89	1119.3
Korhogo	5°37'00"W	9°26'00"N	1378.2	1259.9	1291.66	1216.3
Kouto	6°25'00"W	9°54'00"N	1423.87	1177.57	1132.54	1216.1
Madinani	6°57'00"W	9°37'00"N	1499.4	1392.93	1312.24	1391.0
Minignan	7°50'00"W	10°00'00"N	1935.98	1401.48	1256.36	1348.2
Mankono	6°11'00"W	8°30'00"N	1170.78	1140.08	1102.42	1136.7
Niakaramandougou	5°17'00"W	8°40'00"N	1127.92	1053.81	984.65	1071.6
Odienné	7°34'00"W	9°30'00"N	1606.31	1544.78	1222.49	1392.2
Ouangolodougou	5°09'00"W	9°58'00"N	1185.94	1001.72	1007.78	903.84
Sianhala	6°51'00"W	10°12'00"N	1358.82	1123.4	1158.81	1374.3
Tafiré	5°09'00"W	9°04'00"N	1073.08	1053.81	1000.78	979.66
Tengréla	6°24'00"W	10°29'00"N	1393.24	1056.96	1047.49	1070.7
Touba	7°41'00"W	8°17'00"N	1287.78	1268.13	1138.89	-

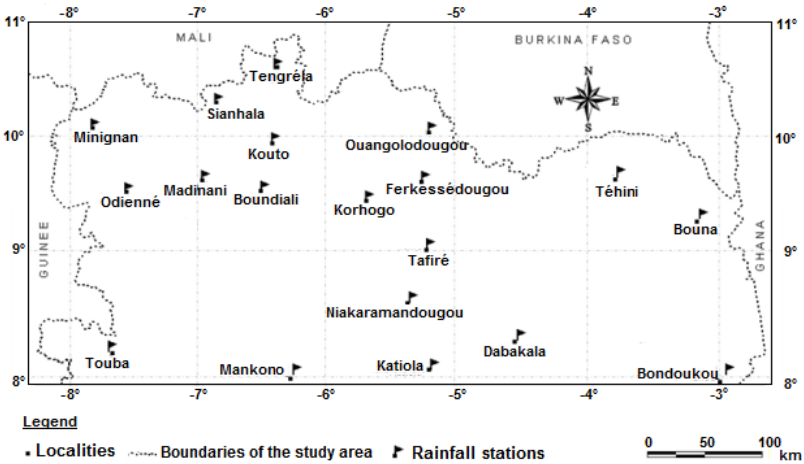

Figure 2: Location map of selected rainfall stations

Methods

Method for mapping and qualitative analysis of rainfall variability

The average annual rainfall per decade is spatialized by kriging, highlighting evolution of rainfall isohyets using the geographic coordinates of the rainfall stations. This step leads to the conception of rainfall isohyet maps or rainfall isohyet network per decade. The rainfall isohyets are defined in a step of 100 mm (Benoit, 1977). Between two rainfall isohyets, the distribution of rainfall is assumed to be uniform, so the spatial extent or influence of a rainfall isohyet is quantified by the area between isohyet (i) and isohyet (i+100) (IUCN-BRAO et al., 2003). Obtained area is attributed to average isohyet ([i+(i+100)]/2) or ((2i+100)/2) to constitute a data grid of covered area per average rainfall isohyet per decade. This makes it possible to appreciate the spatio-temporal fluctuations of rainfall in the study area. These rainfall fluctuations indicate a decrease or an increase in rainfall. Covered area data by rainfall isohyets for a given decade are used for analysis of spatio-temporal regressive or progressive rainfall fluctuations. These fluctuations are followed preferentially from East to West. A regressive fluctuation in rainfall isohyets will be significant as they move towards in West and disappear from the study area and vice versa.

Method for quantitative analysis of rainfall variability

At the temporal scale, 1961-1970 decade included in 1950-1970 period, which is known to be humid in West Africa (Janicot and Fontaine, 1993; Bamba et al., 1997), was chosen in this study as the "reference decade" or "climatic benchmark" period. The spatial structure of the rainfall isohyets of other decades is therefore compared to that of the rainfall isohyets of the reference decade to highlight rainfall progression or regression. Rainfall progression or regression is perceived by an increase or decrease in covered areas by the rainfall isohyets according to the four considered decades. Thus, for a good understanding of the spatio-temporal dynamics of the rainfall isohyets, the rainfall isohyet (1200 mm) which is closer to average value of average rainfall of four decades (1196.77 mm), is chosen as the "reference isohyet", unlike the rainfall isohyet (1300 mm) used by (Bigot et al., 2005). The quantitative analysis of rainfall variability consisted to:

- Determine covered areas by average rainfall isohyets per decade to assess progression or regression of rainfall. This step led to identification of persistent rainfall isohyets and analysis of decadal fluctuations in their coverage rate;

- Exploit covered areas by these rainfall isohyets, which made it possible to define rainfall isohyet classes by taking into account average rainfall recorded at selected various stations over four considered decades. Thus, three rainfall isohyet classes were constituted for analysis of the variation in the rate of covered area per rainfall isohyet class:

- [800-1150 mm] for low rainfall isohyets (IfP) ;
-]1150-1450 mm] for medium rainfall isohyets (ImP);
-]1450-1750 mm] for high rainfall isohyets (IFP).

- Characterize general pattern of rainfall isohyets, which allowed an evaluation of available water resources through the calculation of average rainfall per decade (LeDec) according to isohyet method (Chuzéville, 1990). These water levels are obtained from the formula of Eq. (1) as follows:

$$Le_{Dec} = \frac{1}{S}\sum_{i=1}^{i=n}\left(S_i \times P_i\right) \qquad (1)$$

Where, Le_{Dec} is decadal average water level (m), P_i is rainfall amounts (m) between isohyets i and i+1, S_i is covered area (m²) between isohyets i and i+1, S is total area (m²) of the study area and n is total number of isohyets.

RESULTS AND DISCUSSION

Results

Qualitative analysis of spatio-temporal fluctuations in rainfall

The spatio-temporal fluctuations maps in average rainfall per decade over 1961-2000 period are shown in Fig. 3. Analysis allows to appreciate the spatial dynamics of rainfall, which is expressed by the displacement from East to West of rainfall isohyets. This shift corresponds to a strong spatial regression of rainfall during the first three decades. This regression is manifested by the gradual disappearance of certain high rainfall isohyets

(1300, 1400, 1500, 1600, and 1700 mm) in West in favor of low rainfall isohyets (900, 1000, and 1100 mm) which appear in East. Indeed, the reference decade (1961-1970), which was recognized as wet, had the highest rainfall isohyets (1600 and 1700 mm), which will migrate towards West and disappear from 1971. During 1971-1980 decade, the reference isohyet (1200 mm) tended to move towards West, indicating a clear and significant perception of rainfall regression. The 1981-1990 decade was the driest in Sudano-Sahelian environment, during which the extreme west of the study area remained under influence of the reference isohyet (1200 mm), which was increasingly oriented towards West. A slight increase in rainfall was observed in the last decade (1991-2000), illustrated by a redeployment of the reference isohyet (1200 mm) towards East. This same decade was marked by reappearance of the rainfall isohyet (1300 mm), which had been virtually non-existent during the previous decade, and slight recoil of 900 and 1000 mm rainfall isohyets, which had already occupied the eastern part of the study area.

Analyse quantitative de la régression spatio-temporelle de la pluviométrie

The decadal fluctuations in coverage rate of persistent rainfall isohyets are shown in Fig. 4. Analysis shows the persistent rainfall isohyets that have been identified:

- Rainfall isohyets 1050mm and 1150mm, by their decadal coverage rate, are highly expressive of the overall rainfall decline. These rates decreased from 32% to 11% for 1150 mm rainfall isohyet from 1961-1970 decade to 1991-2000 decade and from 37% to 20% for 1050 mm rainfall isohyet from 1971-1980 decade to 1991-2000 decade;
- 1250 mm rainfall isohyet shows an irregularity in its area coverage which regresses from 23% to 10% during the first two decades with an increase to about 24% and then decreases to 9% following the last two decades;
- 1350 mm rainfall isohyet, on the other hand, clearly illustrates the spatial regression of rainfall during the first three decades and the weak recovery of last decade. In fact, from about 14% in the reference decade (1961-1970), the coverage rate of this rainfall isohyet (1350 mm) decreased to about 4% from 1981 to 1990 and increased to 17% in the last decade.

The decadal fluctuations in covered area rate by rainfall isohyet class are shown in Fig. 5. Analysis shows that over four decades, the high rainfall isohyet class ([1450-1750 mm]) is only observed in the first two decades. On the other hand, isohyets classes with low IfP ([800-1150 mm]) and medium ImP ([1150-1450 mm]) rainfall are present over four decades, but in different proportions. These rainfall isohyet classes show that the decline in rainfall was very pronounced during two decades (1971-1990 period). In fact, covered area by all the low rainfall isohyets increased from 31% between 1961 and 1970 to 72% during 1981-1990 decade.

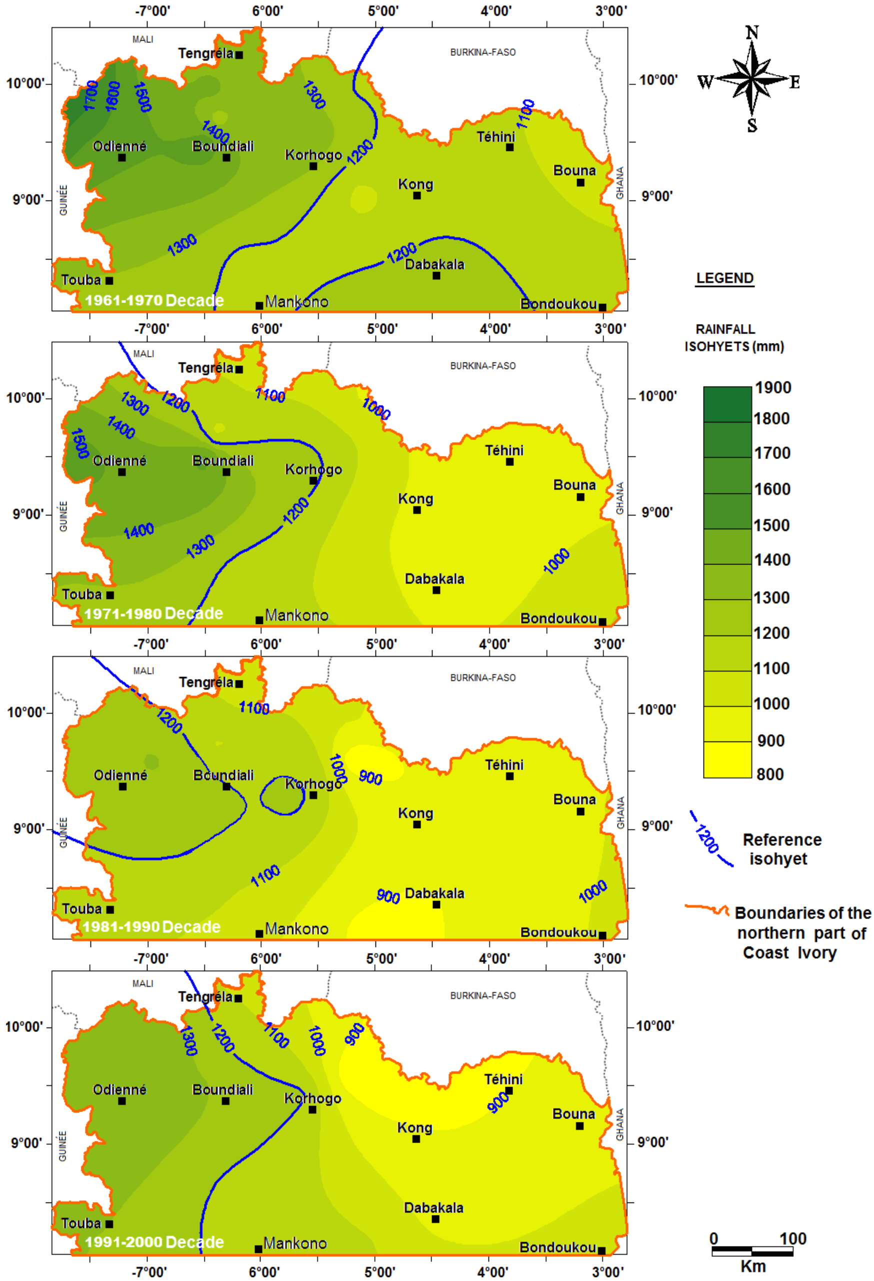

Figure 3: Maps of the spatial dynamics of rainfall isohyets by decade over 1961-2000 period

This increase was at expense of the high rainfall isohyets class, which decreased from 19% coverage between 1961 and 1970 to 3.69% during 1971-1980 decade. The coverage rate of the medium rainfall isohyet classes (ImP) also decreased from 1961 to 1990. In the last decade, this rate has increased, proof of a probable resumption of rainfall reported earlier.

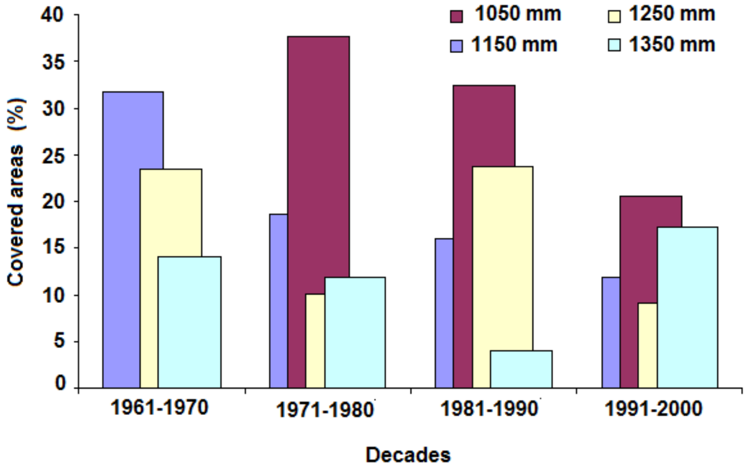

Figure 4: Decadal fluctuations in the coverage rate of the persistent rainfall isohyets

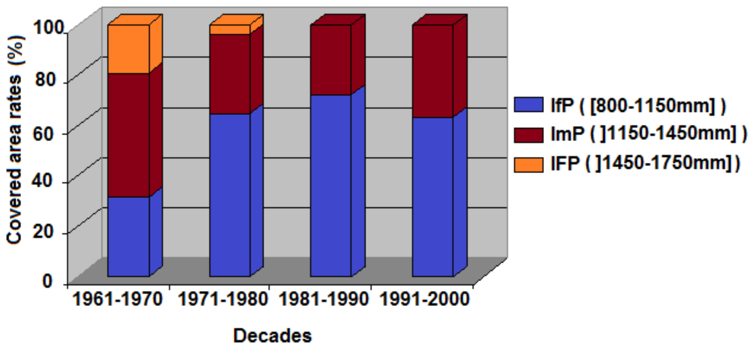

Figure 5: Variation in coverage area rates by the rainfall isohyet classes

Average variation in rainfall over the four decades is shown in Fig. 6. Analysis shows that precipitated average water level has fluctuated according to the decadal dynamics of rainfall isohyets. The rainfall amounts (1694.45 mm) significantly decreased from 1961-1970 decade to 1981-1990 decade (1469.82 mm). However, an increasing trend in average water level seems to occur in 1991-2000 decade with 1525.66 mm of recorded water level. Average water level (1694.45 mm) of the reference decade (1961-1970), considered as the reference value, allowed to highlight the rainfall deficits in comparison with average water levels of considered other decades. Table 2 presents the statistics of average water level fluctuations and rainfall deficits on a decadal scale. Analysis shows that recorded rainfall deficit in 1971-1980 decade (-123.01 mm) almost doubled in 1981-1990 decade (-224.62 mm). However, in 1991-2000 decade, this deficit has improved by 33.76% or a recovery of about 56 mm of water level. Despite this contribution, precipitated average water level on a decadal scale remains deficient compared to the period of good rainfall experienced by the whole region during the reference decade (1961-1970). This observation is explained by the trend line in Figure 6, whose slope is negative (-60.798) with a correlation coefficient (R^2) equal to 0.67.

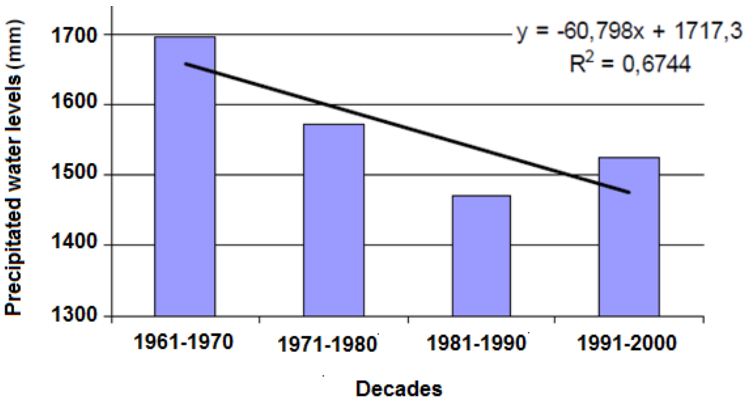

Figure 6: Variation of average rainfall on a decadal scale for 1961-2000 period

Table 2: Statistics of precipitated average water levels and rainfall deficits on a decadal scale for 1961-2000 period

Decades	Le_{Dec} (mm)	Le_{Dec} - Le_{Ref} (mm)	Observations
1961-1970	1694,45	0	-
1971-1980	1571,43	-123,01	Déficit
1981-1990	1469,82	-224,62	Déficit
1991-2000	1525,66	-168,79	Déficit

Le_{Ref} is precipitated average water level during the reference decade (1961-2000) and Le_{Dec} is precipitated average water level during other decades.

DISCUSSION

The qualitative analysis of spatio-temporal variability of rainfall revealed a generalized decrease in rainfall during the first three decades (1961-1970, 1971-1980, and 1981-1990), resulting in the migration of rainfall isohyets in an East-West direction and the disappearance of isohyets with high rainfall. This rainfall regression has also been demonstrated over the entire Ivorian territory by (Bigot et al., 2005), who showed a migration of isohyets towards West and South over 1950-1996 period. Already, (Servat et al., 1999) had demonstrated a trend of rainfall isohyets shifting towards South and South-West in West Africa, from 1950s to 1980s, in agreement with the studies of (Bodian et al., 2011) at thirty-year and ten-year scales. Indeed, although rainfall has generally declined in the study area, it remains higher in West than East. The rainfall recovery reported during 1991-2000 decade is weak and concerns the western part of the study area, with only the reappearance of the rainfall isohyet (1300 mm), a precursor sign of a trend towards a relative and very timid return of rainfall. This observation was also made by (Khoualdia et al., 2014) over the period 2001-2007 in Medjerda watershed and by (Nouceur and Laignel, 2015) over 2002-2004 period in North-Eastern Quarter of Algeria, which used methods based on rainfall indices.

The quantitative analysis of spatio-temporal variability of rainfall, based on the persistent average rainfall isohyets (1050, 1150, 1250, and 1350 mm) and rainfall isohyet classes, also confirms the same trend of decadal regression of rainfall and its low return indicated to the last decade. In fact, the rainfall decrease is perceived by the progressive extension of covered areas by low rainfall isohyets from East to West from 1961 to 2000. As a result, the water resources were poorly supplied, thus disrupting water-related activities. The decade (1981-1990) was the driest with a rainfall deficit of -224.62 mm, compared with -123.01 mm and -168.79 mm for 1971-1980 decade and the last decade, respectively, in which a relative rainfall recovery was observed. Overall, a persistent decrease in rainfall following 1971-1980, 1981-1990, and 1991-2000 decades compared to the reference decade (1961-1970) should be noted as observed by (Faye et al., 2015) in Upper Senegal River Basin. The decline in rainfall in the study area had a negative impact on agricultural activities and water-related development projects. That is why it is essential to adopt strategies to adapt to this decline in rainfall in order to meet the requirements of sustainable development.

CONCLUSIONS

The dynamics study of spatio-temporal variability of rainfall over 1961-2000 period, showed a gradual regression of rainfall from 1961-1970 decade to 1981-1990 decade. During this period, the high rainfall isohyets shift and disappear in West in favor of the low rainfall isohyets that appear and extend to East of the study area. A reversal of the downward trend in rainfall, attributable to a semblance of rainfall recovery, was observed during 1991-2000 decade. This finding was also justified by the analysis of persistent rainfall isohyets which showed a preponderance of the coverage rates of 1050 mm (37 to 20%) and 1150 mm (32 to 11%) rainfall isohyets and an increase in the coverage rate of the 1350 mm rainfall isohyet at 17% in the last decade. Analysis of rainfall variability by rainfall isohyet class also showed a predominance of low rainfall isohyet class (IfP = [800-1150 mm]) which reached its maximum coverage rate of 72% in 1981-1990 decade. The decade (1981-1990) was the driest with a rainfall deficit of -224.62 mm compared to -123.01 mm in 1971-1980 decade and -168.79 mm in the last decade (1991-2000) marked by a weak rainfall recovery. It is therefore necessary to monitor this spatio-temporal evolution of rainfall in order to adapt water-related development projects to prevailing rainfall context.

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