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Characterization of the Hydrological Balance and Assessment of the Recharge of Fractured Aquifers in the Context of Climatic Variability in Siguiri

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Climate change in the Siguiri prefecture is having a considerable impact on the water balance. With the aim of determining the hydrological balance and the quantity infiltrated into the aquifers, groundwater resources can be assessed. To carry out the study, we focused our analyses on climatic parameters (rainfall, temperature), which led to the determination of groundwater recharge in the aquifers. We found an average temperature of 26°C, with a maximum temperature of 39°C in April. The minimum temperature from December to January was 13°C. Rainfall during the dry

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season (November, December, January, February, March and April) was 54 mm. The average rainfall during the wet season (May, June, July, August, September, October) is 1142 mm. The imbalance in the water balance is explained by the amount of water infiltrated (41 mm or 3% of rainfall). This value, which represents a volume of 717.5 million m3 per year, is deemed sufficient to meet the needs of the population of Siguiri (695,449 inhabitants with a growth rate of 3%). Groundwater resources have been affected by rainfall deficits and variability in groundwater levels over the last forty (40) years (1980-2020) in the various localities in the study area. Precipitation water runs off (90%) more than it infiltrates (3%) into the aquifer horizons of the Siguiri prefecture, making access to drinking water difficult during the dry season for the population of Siguiri.

Keywords: Balance; water; Siguiri; precipitation; aquifers; population.

1. INTRODUCTION

Variations in climatic parameters relating to rainfall and temperature over the last forty years (1980-2022) in the Siguiri area have had an impact on the water balance [1,2]. The ratio established between the quantity of water that infiltrates into the aquifer horizons and the surface water that runs off is of different proportions [3]. More water runs off than seeps into the Niger river basin at Siguiri [4]. The level of the River Niger at Siguiri is gradually falling, to the point of drying up in some of its river valleys. In such situations, the groundwater that ensures the regularity of the flow is subject to very significant variations because of variations in climatic parameters but also because of the difference resulting from the fracturing of the aquifers. The aim of this study is to characterize the parameters of rainfall and temperature and to understand the nature of the equilibrium between the quantities of water that precipitate in relation to those that evaporate or leave the boundary of the aquifer horizons of the Niger sub-basin at Siguiri. This study will enable us to understand the agrometeorological factors and to establish the seasonal patterns of variation in groundwater resources through the characteristic elements for determining the water balance. The main aim of the study is to manage groundwater resources and overcome the difficulties of access to drinking water in the study area.

2. DATA AND METHODOLOGICAL APPROACHES

2.1 Presentation of the Study Area

2.1.1 Geographical and geological context

The Siguiri prefecture borders the Republic of Mali and is administratively bounded by the prefectures of Kankan, Kouroussa, Dinguiraye and Mandiana (Fig. 1). Siguiri covers an area of 17,500 km2, or 18.25% of the 95,884.23 km2 of Upper Guinea. The population of the Siguiri prefecture is estimated at 862 357, with a growth rate of 3% [5]. The study area is located in the north-east of Guinea, between the coordinates of 11° and 12°51 north latitude and 9° and 11° west longitude. The geological formations identified in the Siguiri area (Fig. 1) are characteristic of a sedimentary basin [6]. The study area belongs to the Siguiri-Kankan basin, which is essentially composed of pelitic schists, limestones in the north-west and monzogranites of Palaeo-Proterozoic age in the south of the study area [7]. Rocks of Middle Proterozoic age are sandstones, conglomerates and sediments in the Taoudeni basin in the north-west along the line A-B of the Fig. 1 [7]. Alluvial formations of Quaternary age are found along the main rivers [7].

2.1.2 Hydrological and hydrogeological context

The hydrographic network in the Siguiri area is dense (Fig. 2) and is represented by three rivers: the Niger, the Tinkisso, the Bakoye and their tributaries. In the Siguiri area, we have identified basement aquifers, which are discontinuous and fractured, overburden aquifers (alterites) resulting from the weathering of basement rocks, and alluvial aquifers, which are found along the main rivers [8].

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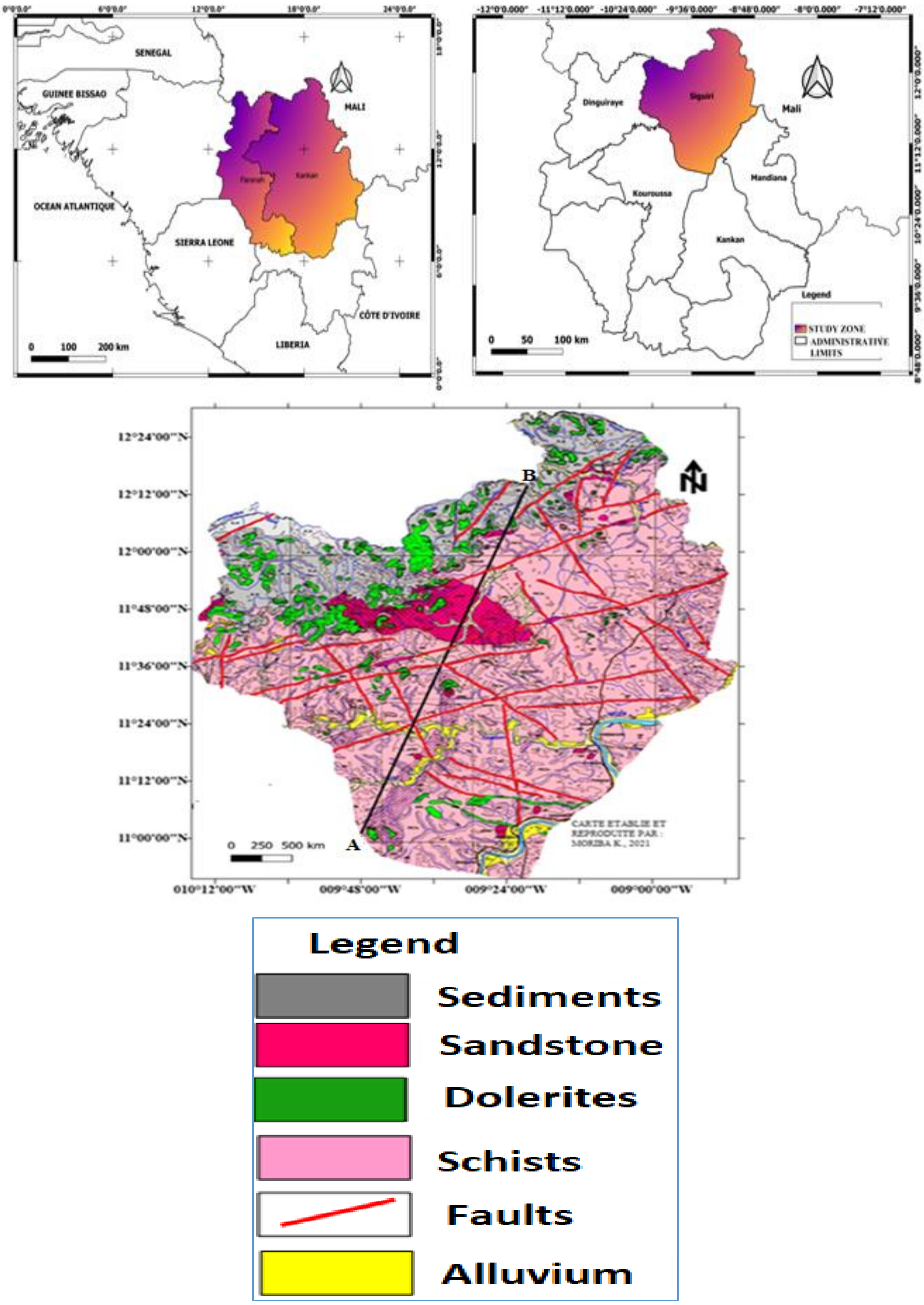

Fig. 1. Location map of the study area

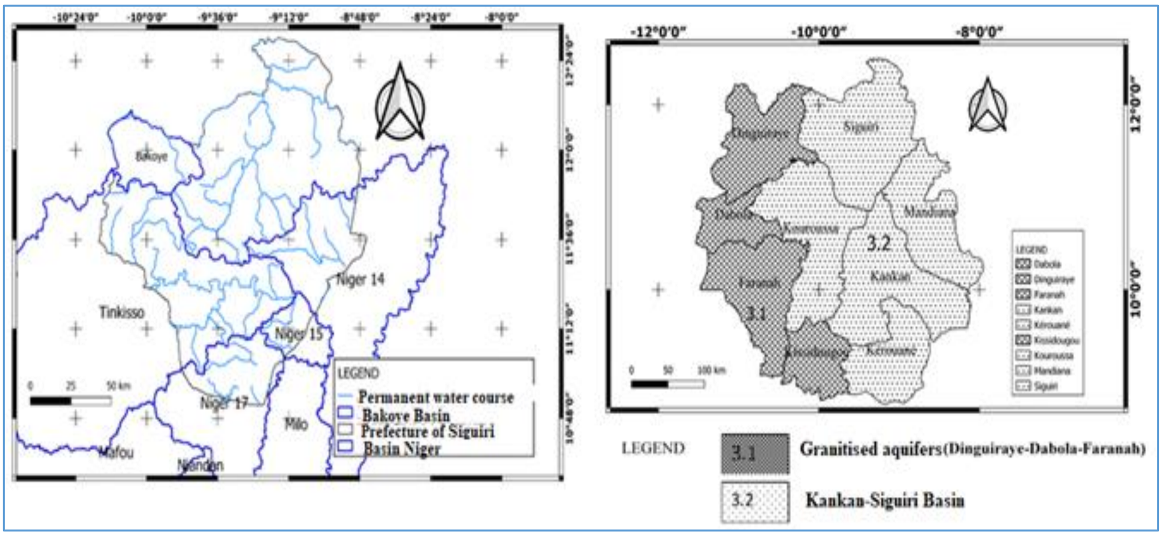

Fig. 2. Sub-catchment areas of the River Niger in the Siguiri prefecture

2.2 Climatological Data

2.2.1 Rainfall data

The rainfall data consist of monthly and annual rainfall data collected from the National Meteorological Department of Guinea.

The rainfall data concern six (6) stations: Siguiri (1961-2020) and Dinguiraye, Mandiana, Kankan, Kouroussa and Faranah for the period 1981-202.

Due to a lack of rainfall stations, rainfall data for the sub-prefectures of Siguiri were downloaded from the website: (https://power.larc.nasa.gov/data-access-viewer).

2.2.2 Temperature data

We used temperature data from the Siguiri station and stations in Dinguiraye, Mandiana, Kankan, Kouroussa and Faranah. As there are no rainfall stations in the sub-prefectures, we downloaded the temperature data from the website (https://power.larc.nasa.gov/data-access-viewer).

2.3 METHODOLOGY

2.3.1 Study of monthly and interannual variability of climatic parameters

The calculation of the annual mean and monthly mean can be expressed by relations 1 and 2 [9].

$$M_m = \frac{1}{N}\sum_{i=1}^{n} Xi\,j \qquad \text{(Eq.1)}$$

Where M ij is the average value of the climatic parameter concerned in year i and month j; i varies from 1 to n years and j varies from 1 to 12 months; N is the total number of years in the chronicle concerned.

$$Mint = \frac{1}{12}\sum_{j=1}^{12} M_j \qquad \text{(Eq.2)}$$

Mint, interannual average of the climatic parameter in question; M_j, monthly average of the climatic parameter in month i.

2.3.2 Analysis of climatological data using the Pettitt and Buishand tests

Rainfall data from the Tiguibery station in Siguiri were analysed using KhronoStat software [10] in order to detect any breaks linked to non-stationarity.

PETTIT break tests [11] and BUISHAND statistics [12,13] are applied in this study to analyse rainfall. The choice of these tests is explained by their widespread use in catchment hydrology studies in West and Central Africa [14,15,16,17,18].

2.3.3 Assessment of recharge using the Thornthwaite balance method

Thornthwaite Potential evapotranspiration (ETP) [19] is calculated using the following formula (Equation 3). The unknown elements are determined using the relations (Equation 4; Equation 5; Equation 6).

$$PET=1,6\left(\frac{10t}{I}\right)^{a}F(\lambda) \quad \text{(Eq. 3)}$$

Where: t: average temperature over the period in question (°C)

I: Annual thermal index

$$\mathbf{I}=\sum_{m=1}^{12} i \quad \text{(Eq. 4)}$$

$$i=\left(\frac{T}{5}\right)^{1,514} \quad \text{(Eq. 5)}$$

a: complex function of the index I

$$a=6,75.10^{-7}I^{3}-7,71.10^{-5}I^{2}+1,792.10^{-2}I+0,49239 \quad \text{(Eq. 6)}$$

F" (λ) is the correction factor which is a function of the latitude of the location under consideration and is given by Riquier [20].

2.1.2.4. Calculation of ETR using Turc's formula (1961)

Turc's [21] formula is valid for all types of climates. It is a function of precipitation and temperature 7.

$$ETR=\frac{P}{\sqrt{0,9+\frac{P^2}{L^2}}} \quad \text{(Eq.7)}$$

Where: ETR: real evapotranspiration, in (mm); P: annual precipitation, in (mm); L: a parameter calculated as a function of temperature according to formula 8: $L=300+25T+0.05T^3$ (Eq. 8)

with T: average annual temperature in °C.

2.3.4 Calculation of effective rainfall (Peff)

The method for calculating effective rainfall consists of 4 steps:

1) Determination of an ETP chronicle corresponding to the maximum quantity of water that a plant cover can return to the atmosphere.

2) Evaluation of a maximum soil water reserve (Rmax) which, in this conceptual model, represents the water capacity of a reservoir symbolising the soil-vegetation combination.

The maximum water reserve has a major influence on evapotranspiration. For the sake of convenience, this maximum reserve is generally assimilated to the useful reserve (UR), or readily usable reserve (URR), of soils as defined by agronomists.

3) Estimation of the actual evapotranspiration (ETR) chronicle using Turc and Thornthwaite's chained balance method for a defined time step [22]. The conditions for determining the AET are established using relations 9; 10; 11; 12 and 13.

• if P ≥ ETP alors ETR = ETP

• if P < ETP alors :

 if P + ΔRU ≤ ETP, ETR = P + ΔRU ; Eq. (9)

 if P + ΔRU > ETP, ETR = ETP; Eq. (10)

With 0 ≤ RU ≤ Rmax (often with 50 ≤ Rmax ≤ 200 mm)

4) The water balance finally gives us the effective rainfall value for each calculation level:

- If P ≥ ETP and if RU = Rmax then Peff = P - ETR Eq. (11)

- If P ≥ ETP and if RU < Rmax then Peff = P - ETR - (Rmax - RU) Eq. (12)

(Recharging the useful reserve)

- If P < ETP then Peff = 0 Eq. (13)

2.3.5 Estimation of effective infiltration in the study area

The runoff coefficient (Cr) is the ratio between the height of water that has run off a given surface (also called "net rainfall") and the height of water that has precipitated ("gross rainfall"). This is the formula for the runoff coefficient in relation 14.

$$R\ (\%)=\frac{Peff}{Pm} \quad \text{Eq. (14)}$$

Where: Cr is the runoff coefficient. Peff defines the net or effective rainfall and Pm is the average rainfall for the study area.

The balance diagram is expressed by the following fundamental equation (Equation 15):

$$P=ETP+R+I \pm \Delta S \quad \text{Eq. (15)}$$

According to this relationship, the rain that falls on a catchment or sub-catchment has four destinations: evapotranspiration (ETP), runoff (R), groundwater recharge or infiltration (I) and soil storage (ΔS).

Because we do not know about the more complex exchanges between groundwater and surface water, we substitute the (R+I) with that of effective rainfall (ETP) and we accept that for very long periods of time, variations in stocks (ΔS) can be considered as zero [23] and the equation is simplified to that of relationship 16.

$$P=ETP+R+I;\ mm \qquad \text{Eq. (16)}$$

2.3.6 The volume of infiltrated water

This is calculated using relation 17 noted by: $V=I \times S$; m^3 Eq. (17)

Where V: Volume of water infiltrated in m^3; I: Infiltration in mm, S: Surface area of the study zone in m^2.

2.3.7 Average annual recharge by rainfall (1981-2021) at the scale of the Siguiri prefecture

We considered runoff coefficient values and effective rainfall to compare runoff periods with years of high infiltration. A graph shows the annual and interannual variations in effective rainfall compared with runoff.

3. RESULTS

3.1 Presentation of the Results of the Study of Climatic Parameters

The average monthly and annual characteristics relating to the amplitude, maximum and minimum of temperature and rainfall are shown in Table 1.

3.1.1 Temperature

We present temperature data (period 1980-2020) for the prefecture of Siguiri. The average annual temperature is 26°C. The maximum monthly temperature is reached in April-March with a value of 39°C. The lowest temperatures occur in December and January, with values of 13°C. The average temperature range is 16°C. Figure 3a shows two thermal seasons.

-A dry season from November to April, when monthly temperatures are higher than the annual average;

-a wet season from May to October, with average temperatures (27, 28°C) higher than the annual average (26°C).

Interannual variations in air temperature show a steady rise throughout the period 1980-2020. At the Siguiri station (Fig. 3b), the temperature remained below 26°C before 1990 and above 26°C after 1986. In 1988, the temperature reached a defined average of 26.5°C before fluctuating until 2012, when it reached 25.38°C (Fig. 3b). From 2013 onwards, the value rises significantly to 27.58°C and remains below the average of 26.46°C or above the average set at 25.50°C, from 27.58°C (2016) to 25.86°C (2020) in Fig. 3b.

3.1.2 Monthly variation in rainfall (period 1981-2020)

The variation in rainfall in Fig. 4a extends from May to October. The other months of the year (November, December, January, February, March, April) belong to the dry season (Fig. 4a). In August, the amount of rainfall (321.79 mm) is highest in Siguiri (Fig. 4b). It rained heavily in July (252.04 mm) and September (233.29 mm) in this study area (Fig. 4a).

3.1.3 Annual variation in rainfall (1981-2020)

Over the past 40 years, rainfall has evolved in a jagged pattern. The graph (Figure 4b) shows years in which rainfall either exceeded or remained below the average value (1195.43 mm).

The average rainfall in Siguiri over the 40-year period (1981-2020) is 1195.43 mm. The years 1994 (1661.9 mm) and 2011 (1799.1 mm) were years of high rainfall in the study area (Fig. 4b). The years 1993 (862.2 mm) and 2013 (808.6 mm) recorded the lowest rainfall (Fig. 4b). It should be noted that rainfall in 1983 (997.2 mm) and 1984 (1171.14 mm) was at the lower end of the average value (Fig 4b).

There was a fall in rainfall from 1981 (1237 mm) to 1983 (997.2 mm) before an increase to 1986 (Fig. 4b). The other phase of decreasing rainfall amounts occurred between 1986 (957 mm) and 1989 (888.2 mm) before there were increases during 1990 (1287.8 mm) and 1992 (1171.14 mm). The drop in rainfall (Fig. 4b) in 1993 (862.2 mm) was followed by an increase in 1994 (1661.9 mm). From 1998 (1171.14 mm) to 2009 (1397.8 mm), rainfall fluctuated around the average (1171.14 mm). Rainfall, which peaked in 2011 (1799.1 mm), fell to 808.6 mm in 2013.

The change in rainfall is remarkable in 2014 (1171.14 mm) and remains around the rainfall average until 2016 (1171.14 mm). In Fig. 4b, the increase in rainfall seen in 2017 (1280.9 mm) is followed by a drop in rainfall in 2018 (931.9 mm). The increase in rainfall is rising around the current average of 1204 mm in 2020 (Fig. 4b). The phenomenon of inter-annual variability in rainfall modules is given by the coefficient of variation. The values of the coefficient of variation vary from 0.00 to 3.32, which for certain rainfall data indicates an irregularity around the average (1195.43 mm).

3.1.4 Break tests

The Pettitt test in Fig. 5a and the Buishand test in Fig. 5b confirm the non-stationarity of the rainfall series for the Siguiri area. The break dates are located in two periods corresponding to the year 2010, with rainfall from 1984 to 2008 showing an upward trend from 2011 to 2020 during wich period the annual average merges with the year (1204.4 mm). The irregularity of the rainfall series in the Siguiri area is remarkable for 23 of the 40 possible years. In all 23 years, rainfall amounts were below average.

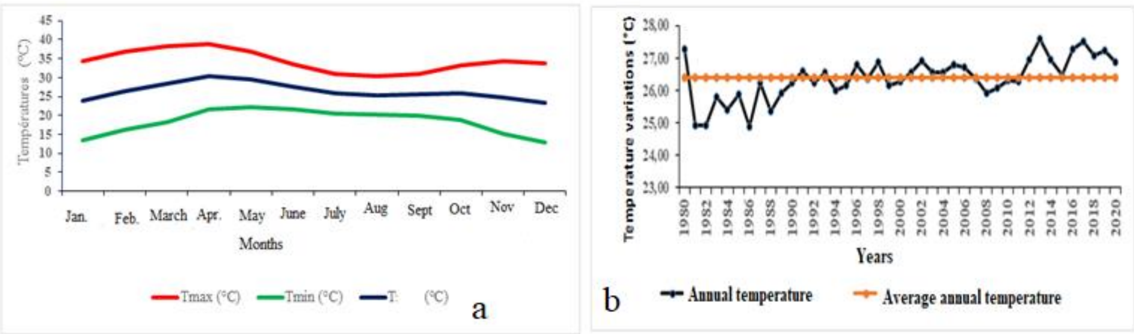

Fig. 3. Monthly (Figure 3a) and inter-annual (Figure 3b) temperature variations in Siguiri (1980-2020 period)

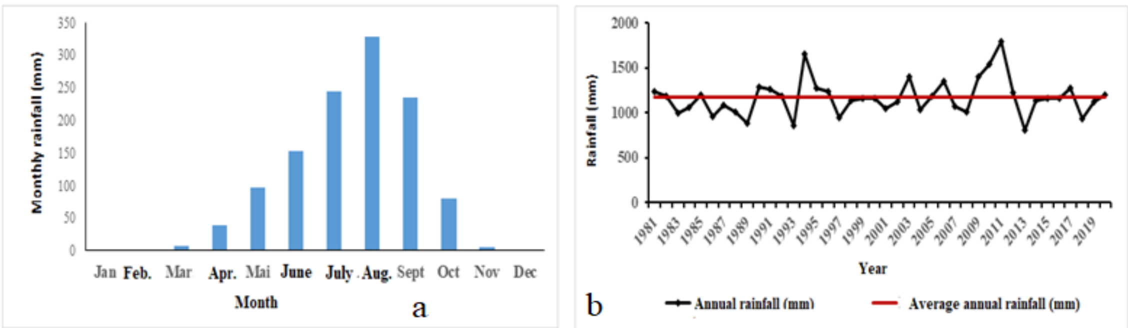

Fig. 4. Monthly (Figure 4a) and annual (Figure 4b) variations in rainfall at Siguiri (period 1981-2020)

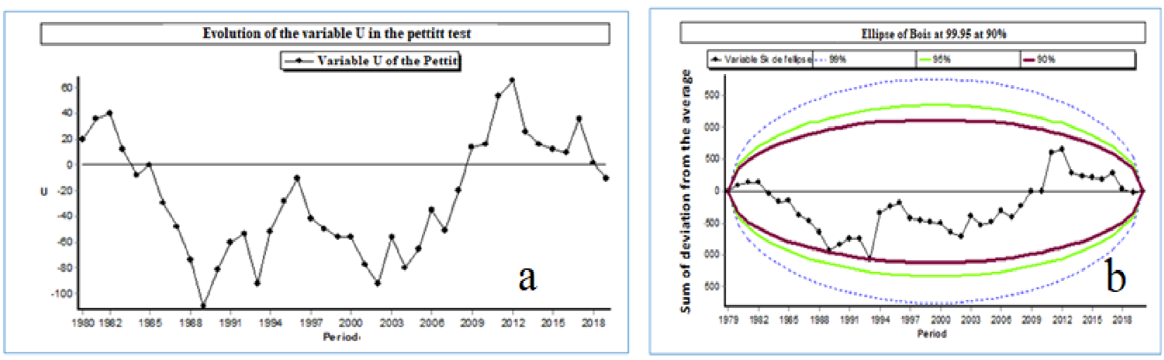

Fig. 5. Pettitt statistical test (Figure 5a) and Bois Ellipse (Figure 5b) on annual rainfall

Table 1. Statistics on climatic parameters measured at the Siguiri station (1980-2020 period)

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Annual Average**
T(°C)	24	26	28	30	30	28	26	25	26	26	25	23	26
P (mm)	0,3	1,7	6,7	39,9	97,8	153,8	244,4	328,4	236,1	81,2	5,2	0	1195,43

3.1.5 Seasonal climatic variations in the study area

The graphical interpretation of climatic (rainfall, temperature) and agrometeorological (evapotranspiration) parameters reflects the climatic variations in the Siguiri area. The relationship between rainfall, evapotranspiration and temperature defines seasonal conditions in the study area (Fig. 6). Rainfall varies from 98 mm in May to a maximum of 328 mm in August (Fig. 6). From August onwards, rainfall fell by 236 mm, and from October to December rainfall was on a downward trend (Fig. 6). From January to May, evapotranspiration increased in line with the rise in temperature (Fig. 6).

3.2 Hydrological Balance of the Study Area

3.2.1 Monthly and seasonal balances

Table 2 summarises the water balance for the study area.

3.2.2 Presentation of effective rainfall results and volume infiltrated into aquifers

Average annual rainfall is 1195.5 mm. Calculation of evapotranspiration using Thornthwaite's method gives 1071 mm, i.e. 90% of rainfall. The remaining 10% is split between runoff and infiltration. The average flow in the study area is estimated at 177 m3/s. This value, taken in relation to the surface area of the river basin (67,600 km2), gives us 83 mm per year, representing 7% of precipitation. The 3% will constitute the quantity of water contributing to the recharging of the water table on the scale of the prefecture (17,500 km2). The results of the calculations of the elements of the water balance using Thornthwaite's method are presented in Table 3.

Average infiltration in the Siguiri area over the period is estimated at 41 mm, or 3% of rainfall (Table 3). This represents a volume of 717.5 million m3 per year (Table 3).

3.2.3 Aquifer recharge under the influence of climate change

Aquifer recharge at the expense of effective rainfall is shown in Fig. 7. In interpreting the data obtained, we will, on each occasion, compare the quantities of water infiltrated into the aquifers with the runoff water within the limits of the study area**.**

The year 1981 was marked by a high level of infiltration (1237 mm) to a greater or lesser extent than groundwater infiltration (Fig. 7). From 1982 (1183 mm) to 1989, runoff was much greater than groundwater infiltration (Fig. 7). During the years 1990 (39 mm) and 1991 (1269 mm), effective rainfall exceeded the quantities of water estimated for runoff (Fig. 7). Between 1992 (1191 mm) and 1993 (862 mm) infiltration was lower than runoff (Fig. 7). The years 1994 (1912 mm), 1995 (1275 mm) and 1996 (1242 mm) recorded high infiltration values compared with runoff values (Fig. 7). From 1997 (942 mm) to 2002 (1121 mm), more rainwater ran off than infiltrated into the aquifer horizons (Fig. 7).

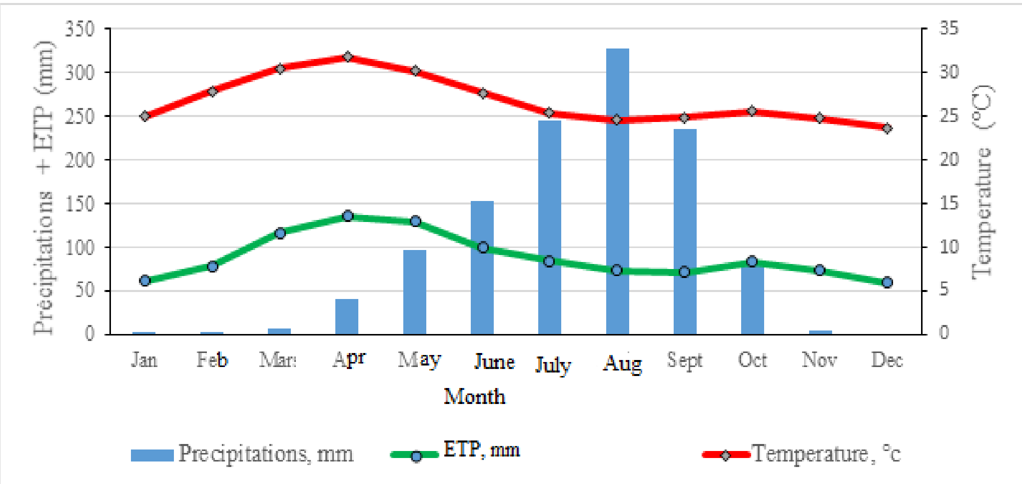

Fig. 6. Umbro-thermal diagram for the study area (1981-2020)

Table 2. Average water balance for the Siguiri area for the period 1981-2020

Paramètres (mm)	Jan.	Feb.	Mar	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Total (mm)
ETP	62,1	80,8	125,3	148,0	138,4	106,6	84,9	72,9	68,7	71,0	59,9	51,9	1071
P	0,3	1,7	6,7	39,9	97,8	153,8	244,4	328,4	236,1	81,2	5,2	0,0	1196
ETR	100,3	101,7	106,7	139,9	138,0	106,6	84,9	72,9	68,7	71,1	59,9	52,0	1103
Flow	0	0	0	0	0	47	161	255	0	0	0	0	463
P+ΔRU	0,3	1,7	6,7	39,9	97,8	160,0	344,4	428,4	336,1	181,2	105,2	50,0	1752
ΔFU (ETR-P)	100,0	100,0	100,0	100,0	40,2	-47,2	-159,5	-167,4	-167,4	-10,2	54,7	52,0	-5
ΔRU	0,0	0,0	0,0	0,0	0,0	60,0	100,0	100,0	100,0	100,0	100,0	50,0	610
Agricultural deficit (ETP-ETR)	-38,2	-20,9	18,6	8,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-32
Balance surplus (P-ETR)	-100	-100	-100	-100	-40,23	47,21	159,47	255,47	167,37	10,15	-54,73	-51,95	93

NB: ΔRU-variation of usable reserve; ΔFU -easily usable reserve

Table 3. Recapitulation of the hydrological balance in the Siguiri area from 1980-2020

Method	P (mm)	ETP (mm)	ETR (mm)	R+I (mm)	R (mm)	I (mm)	Volume infiltrated $10^6 m^3$
Thornthwaite	1195	1071	992	124	83	41	717,5

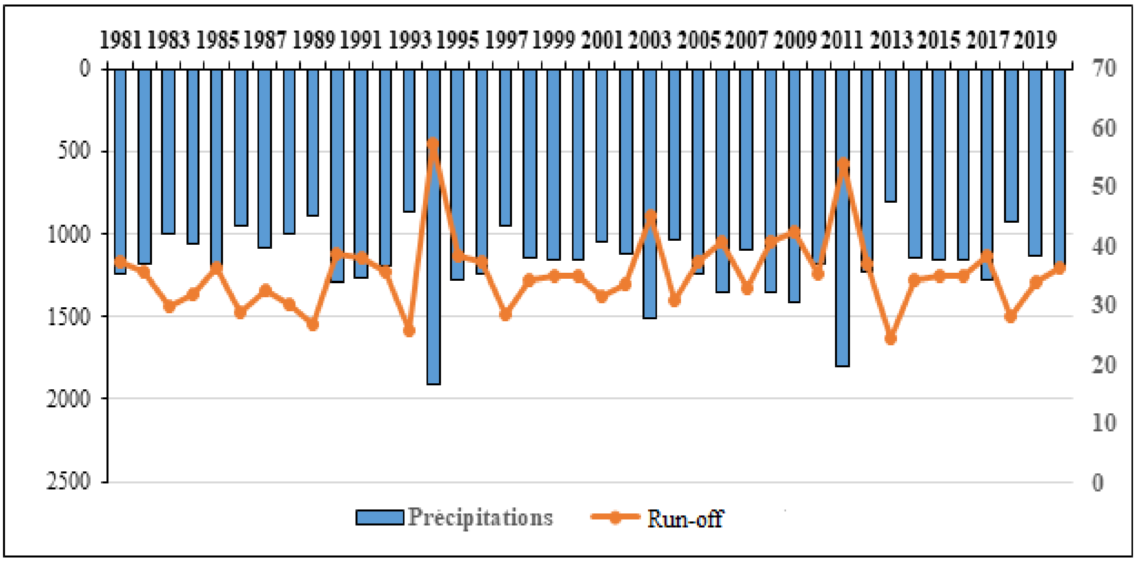

Fig. 7. Relationship between precipitation and runoff in the Siguiri area (1981-2020)

The years 2004 (1032 mm) and 2011 (1799 mm) were marked by high groundwater infiltration (Fig. 7). Between the two years, i.e. 2004 and 2011, there was an alternation between years of runoff and infiltration (Fig. 7). Runoff dominates infiltration from 2013 (809mm) to 2016 (1159mm), as is the case between 2018 (932mm) and 2020 (1204mm) in Fig. 7.

4. DISCUSSION

West Africa has been facing chronic drought since the early 1970s [24]. The drought observed for more than twenty years in the Sahelian countries is also felt further south in regions of Africa with more humid climates [17]. The drop in rainfall recorded in West Africa is having an impact on river regimes and hence on the availability of water resources, the key to the success of many development projects [17]. In the Siguiri area, the monthly and annual balances vary from month to month and season to season. For example, we found that from January to May, rainfall amounts (P) are respectively lower than the corresponding ETP values. In this case, evapotranspiration is equal to precipitation, i.e. ETR= P. The balance deficit (ETP-ETR) can vary from -38.2 to 18.6 mm for the months considered. From June to October, rainfall (P) exceeds ETP (P>ETP). It is during this period that we record a balance surplus known as effective rainfall (P-ETR), which is equal to 47.21 mm in June, 159.47 mm in July, 255.47 mm in August, 167.37 mm in September and 10.15 mm in October. This surplus, which contributes to replenishing soil reserves (RFU), is equal to 100 mm in July. It represents Thornthwaite's "water surplus". This is excess water that will run off into surface watercourses, flood plains and aquifer fractures [19]. The surplus available for the Siguiri area is evident in the months of June (47 mm), July (161 mm) and July (255 mm). From November to December, rainfall of 59.9 mm is less than the ETP of 51.9 mm. In this case, ETR = ETP. This is a situation in which soil saturation falls and a balance of -51.95 mm and -54.73 mm is observed. The end of November is the start of the major dry season, which marks the period when plants have a high-water requirement [25].

Climatic variability is the most important factor in the rate of aquifer recharge, and rainfall is the dominant component in the water balance in a catchment [26]. Rainfall intensity and volume play an important role in aquifer recharge [27]. In

Benin, the amount of water infiltration into aquifer horizons varies from 660 mm to 930 m. The N'zi-Comoé region (Côte d'Ivoire) receives an average of 1154.71 mm of rainfall per year, and the amount of water likely to infiltrate to recharge aquifers is 105.61 mm, or 9.15% of rainfall [28].

5. CONCLUSION

The prefecture of Siguiri is suffering the effects of hydro-climatic variability on the hydrological and hydrogeological balance. The gradual decline in rainfall and hydrometric regimes over the past 20 years has had a significant impact on the daily lives of the population. The population is increasingly faced with problems of access to drinking water in all climatic seasons. The rainfall series is variable, with breaks in the series as the climate in the study area warms up. Under the influence of hydro-climatic variability, we note an imbalance between the quantities of water brought into the Siguiri sub-basin and the quantities leaving within the limits of this sub-basin.

In approaching this study, we wanted to explain how the processes of climatic and hydrological evolution can have an impact on the quantity of water infiltrated into the subsoil of the Siguiri boundary. The study showed that the amount of water that can infiltrate aquifers is 41 mm, or 3% of rainfall (1195 mm). In the Siguiri area, rainwater runs off (83 mm) more than it infiltrates (41 mm).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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