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Characterization of Climate Change and Aquifer Recharge in Three Localities in the South-West of Côte d'Ivoire

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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

Located in the southwestern part of Côte d'Ivoire, the study area's economic activity is rainfall-dependent agriculture and facing climate change impact on water resources. This study aims to improve the resilience of water users based on a better understanding of the recent manifestation of climate change. Specifically, it is to determine the episodes of rainfall variability and estimate the effective rainfall and groundwater recharge. The hydro-climatic database for this study covers more or less the period from 1977 to 2021. The characterization of rainfall variability was highlighted by the calculation of rainfall indices, while effective rainfall and recharge values were determined using the ESPERE (Estimation of Effective Rainfall and Recharge) software according to different mathematical methods. Using the non-parametric Pettitt test was possible to detect years with significant rainfall breaks. Thus, there was an alternation of deficit and surplus periods at different scales in the three localities. However, a break in the rainfall pattern occurred in 1989 in San Pedro,

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whereas this event took place a year later, in 1990, in the other two localities. The effective rainfall and annual recharge closely followed the rainfall evolution in the three localities at different scales. This acquired knowledge of hydrological and hydrogeological rainfall, dynamics can be used to better educate the resilience and climate change adaptation habits of the populations in the southwest region of Côte d'Ivoire.

Keywords: Climate change; climatic break; aquifer recharge; effective rainfall; ESPERE.

1. INTRODUCTION

Climate change refers to a change in the state of the climate that can be identified using statistical tests by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer [1]. And so, dry seasons becoming more frequent, higher temperatures than usual, very short rainy seasons in previous dry periods, droughts, and floods, among other consequences, attributed to climate change, are considered the main threats to human development in our generation [2]. All this variability in the weather has the consequence existence of an increasing or decreasing trend in a hydrological time series which can be induced either by climatic factors (precipitation case), [3,4] or through changes in land use and catchment characteristics (runoff case). Along the same line, the demand for groundwater is rapidly increasing with population growth, while climate change is imposing additional stress on water resources [5]. Climate change influences groundwater systems in several ways [6,7]. The most direct climate change effect on groundwater is related to the groundwater recharge as climate change can alter rainfall amounts and patterns. In terms of the hydrological cycle, climate change can affect the amounts of soil infiltration, deeper percolation, and hence groundwater recharge. Also, rising temperature increases evaporative demand over land [8] which limits the amount of water to replenish groundwater. By contrast, the anthropogenic effects on groundwater resources are mainly due to groundwater pumping and the indirect effects of irrigation and land use changes [9]. Therefore, it will be important to analyze the effect of climate change on aquifer recharge. In this study, we will focus our analysis on three localities in the southwest of Côte d'Ivoire (San-pedro, Tabou and Taï). During the last years, numerous research studies [10,11] have used different methods to better understand of recent manifestation of climate change. Our contribution is therefore to characterize the recent manifestation of climate change and assess effective rainfall and groundwater recharge. This characterization of rainfall variability was highlighted by the calculation of rainfall indices, while effective rainfall and recharge values were determined using the ESPERE (Estimation of Effective Rainfall and Recharge) software according to different mathematical methods. Using the non-parametric Pettitt test was possible to detect years with significant rainfall breaks. This study aims to improve the resilience of water users based on a better understanding of the recent manifestation of climate change. Specifically, it is to determine the episodes of rainfall variability and estimate the effective rainfall and groundwater recharge.

1.1 Study Area

Extends within the 4°35' and 6°40'parallels of northern latitude and the 7°40' and 6°20' meridians of eastern longitude, the study area covers Taï, Tabou and San-Pedro zone (Fig. 1) which has a surface area of approximately 16502 km². It is essentially drained by the San Pedro river and its tributaries (Palapod, Ménégbé, Kré) and the Brimay, Néro, and Dodo rivers. The climate is characterized by two rainy seasons and two dry seasons. The average annual rainfall recorded from 1977 to 2020 is 1730 mm for San Pedro (rainiest months: may-jully and September –November), Tabou 1616,7 mm (rainiest months: April and August) and Tai 902,2 mm (rainiest months: March and July).

The study area belongs to the Proterozoic domain of Côte d'Ivoire. Petrographically, it is made up of crystalline and crystallophyllous rocks: gneisses, migmatites, granites, granodiorites and mica schists (Fig. 1). Tectonically and structurally, this region is characterized by poly deformation consisting of flattening and ductile shear mechanisms with retrograde metamorphism. Two major deformations have affected this part of the country, according to the work of Papon and Lemarchand [12] and Yacé [13]: i) tangential tectonics characterized by the applicative style and the identification of isoclinal folds with sub-vertical axial planes, ii) brittle tectonics characterized by numerous fractures of local to regional extent. The various successive tectonic events in this region have resulted in well-developed fracturing.

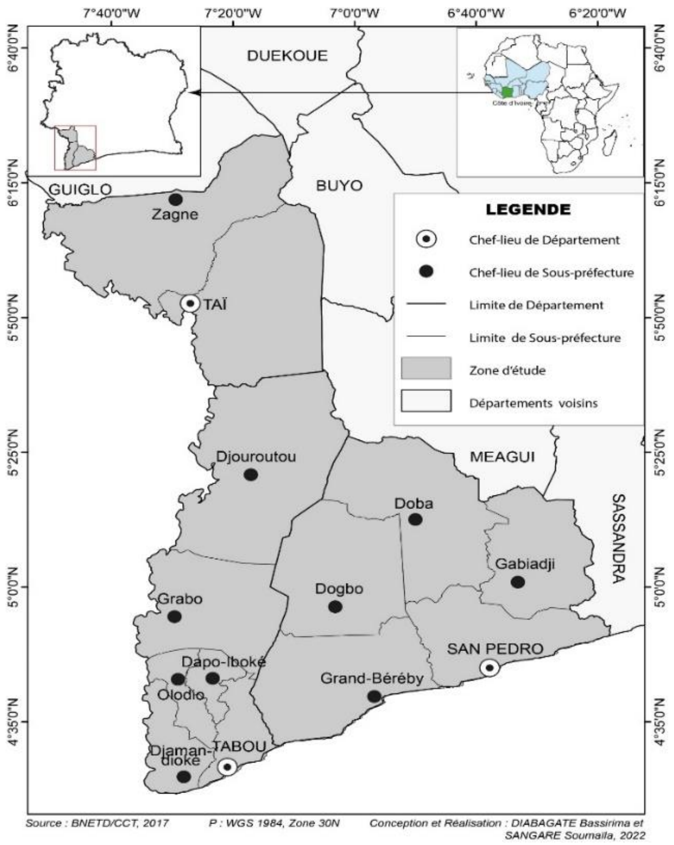


Fig. 1. Geographical location of the study area

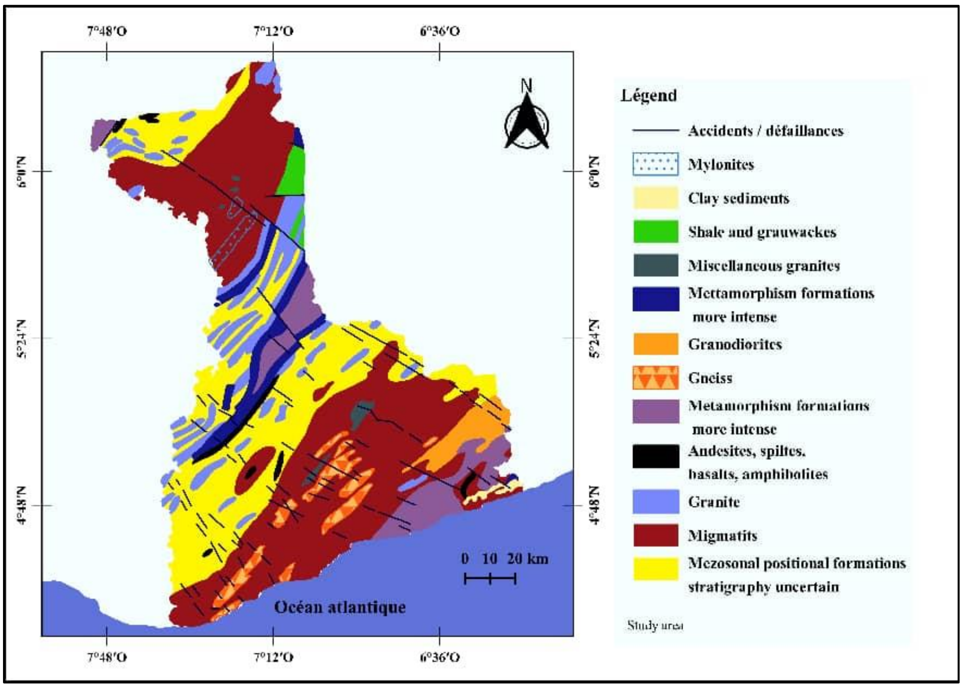


Fig. 2. Simplified geological map of the study area

2. MATERIALS AND METHODS

2.1 Data Used

Hydroclimatic (precipitation and temperature) data were used for this study. The hydroclimatic data were provided by SODEXAM (aeronautical and meteorological, operations and development center).

The precipitation records of the meteorological station of San-Pedro showed significant gaps for certain months and/or even years. Unfortunately, this station is the only one located in the southwest part of the study area. The missing data were completed to facilitate the analysis and ease the interpretation of the results. According to Nicholson, et al., [14] missing or erroneous data of a station can be estimated based on the values of nearby stations if they are subject to the same weather conditions and located in the same geographic zone.

The software ESPERE version 2 is a Microsoft Excel spreadsheet designed by the French Geological Survey to estimate effective rainfall and aquifer recharge through simultaneous calculations with up to ten different methods [15]

2.2 Spatiotemporal Variability of Rainfall

2.2.1 Rainfall index or Nicholson method

It is used to determine the number of deficit and surplus years. Thus, it is used to identify wet, normal, and/or dry periods from the rainfall dataset. This rainfall index was computed using Equation 1 below [16].

$$\boldsymbol{Ii} = \frac{(X_i - X_m)}{\sigma} \qquad (Eq1)$$

Where

Xi is the precipitation for the year,
X_i is the average precipitation of the study period and **σ** is the standard deviation of the annual rainfall that occurred during the study period. Negative values indicate a rainfall deficit during the period and positive values define excessive rainfall amounts.

2.2.2 Break in precipitation

According to Lubès-Niel et al., [17], a break is defined by a change in the probability law of the random variables, of which successive realizations define the studied chronological series. To highlight climatic breaks, several methods were previously used: The Pettitt test [18], the Bayesian method (Lee and Heghinian 1983), and Hubert's segmentation method [19]. The use of these statistical methods is justified by their robustness. Based on the literature [20-22], we choose to use Pettitt test to detect statistical breaks in the precipitation levels during the period considered. These statistical methods were applied to our data by utilizing Khronostat software (Version 1.01). which was developed by the mixed research unit for Hydro sciences of Montpellier [16].

2.2.2.1 Pettitt test method

The Pettitt test [18] is based on the ranking *ri* of the *yi* values. The ranks *ri* are obtained by ordering the data in crescent order, so that the smallest one gets ranked 1 and the highest gets the n-rank. The U_k is then obtained as:

$$U_k = 2\sum_{i=1}^{k} r_i - k(n+1);\ k = 1,2,\ldots,n \quad (eq2)$$

If a break occurs in the year K, then the U_k is:

$$U_k = max_{1\le k\le n}|U_k| \qquad (eq3)$$

2.2.3 Aquifer recharge through modelling with Turc, Thornthwaite, Edjitano and Michel [15]

Aquifer recharge and effective rainfall were estimated by using ESPERE software version 2. This Microsoft Excel worksheet application

Table 1. Hydrological stations Characteristics. (Meteo. = meteorological; Long. = longitude; Lat. = latitude; Obs. = observation)

Station type	Localities	Geographical coordinates		Measured data	Obs. period	Time serie
		Long. E	Lat. N			
Meteo	San-pedro	6°38'	4°44'	Precipitation	1977-2020	Monthly
				Temperature	1991-2020	
	Tabou	7°37'	4°42'	Precipitation	1977-2020	
				Temperature	1991-2020	
	Taï	7°27'	5°52'	Precipitation	1977-2020	
				Temperature	1991-2020	

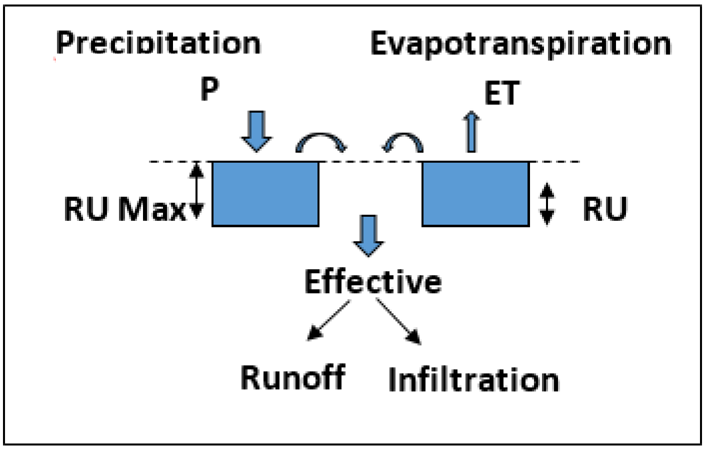


Fig. 3. Diagram of balance sheet

allows to apply several commonly used methods to estimate groundwater recharge rapidly and simultaneously. According to available data of the study area, we applied and compared the results of one empirical method (Turc) and two slightly water budget methods (Thornthwaite, Edjitano) (Fig. 3).

3. RESULTS AND DISCUSSION

3.1 Climate Change Characterization

3.1.1 Rainfall trends and variability break

Analysis of rainfall data using Nicholson rainfall indexes is presented in Fig. 4. This figure highlights wet years (i.e. with positive values of Nicholson index) and dry years (i.e. with negative values index) that occurred in the study area.

Two (2) tendencies emerged when analyzing the Nicholson rainfall index graph at San Pedro, a surplus wet period from 1977 to 1984 and a dry period from 1985 to 2020. The Pettitt statistical test method applied to the time series reveals a break occurred into precipitations in the year 1989, (Fig. 5). Three (3) main climate periods occurred at Taï. The normal one from 1977 to 1988 was followed by a long dry period from 1989 to 2008 and a wet period from 2009 to 2020, two (2) breaks were noted. The first one occurred in 1990 and the second in 2007 when rainfalls started increasing again. The periods 1991–1988 and 1989–2020, respectively, correspond to the wet periods and dry periods at Tabou. The significant break occurred in the year 1990 according to the result of the Pettit statistical test method applied.

The dry period resulting from the decrease in rainfall pattern in the years 1990 was also observed by Gnamba et al., [23], and Kpan et al., [24] in the north and the coastal area part of Côte d'Ivoire. Moreover, several studies identified an important decrease in rainfalls after the year 1970 in Côte d’Ivoire [20], especially in the West, the Center, and the South-west [25-28]. According Goula et al., (2006b) and Kouassi [27], these breaks led to rainfall deficit

3.2 Aquifer Recharge and Effective Rainfall

3.2.1 Effective rainfall estimation

Under the ESPERE model, temperature and rainfall data are used to determine effective rainfall. Thus, Thornthwaite, Turc and Edijatno & Michel's methods simulations allowed us to estimate the annual effective rainfall before and after breaking into three localities.

Table 2. Alternation of different phases and breaks detected within the precipitation series recorded at the measuring stations

Station	Periodic trend within the series			Break
	Wet period	Normal period	Dry period	Pettitt
San-pedro	1977-1984	-	1985-2020	1989
Taï	2009-2020	1977-1988	1989-2008	1990 ; 2007
Touba	1977-1988	-	1989-2020	1990

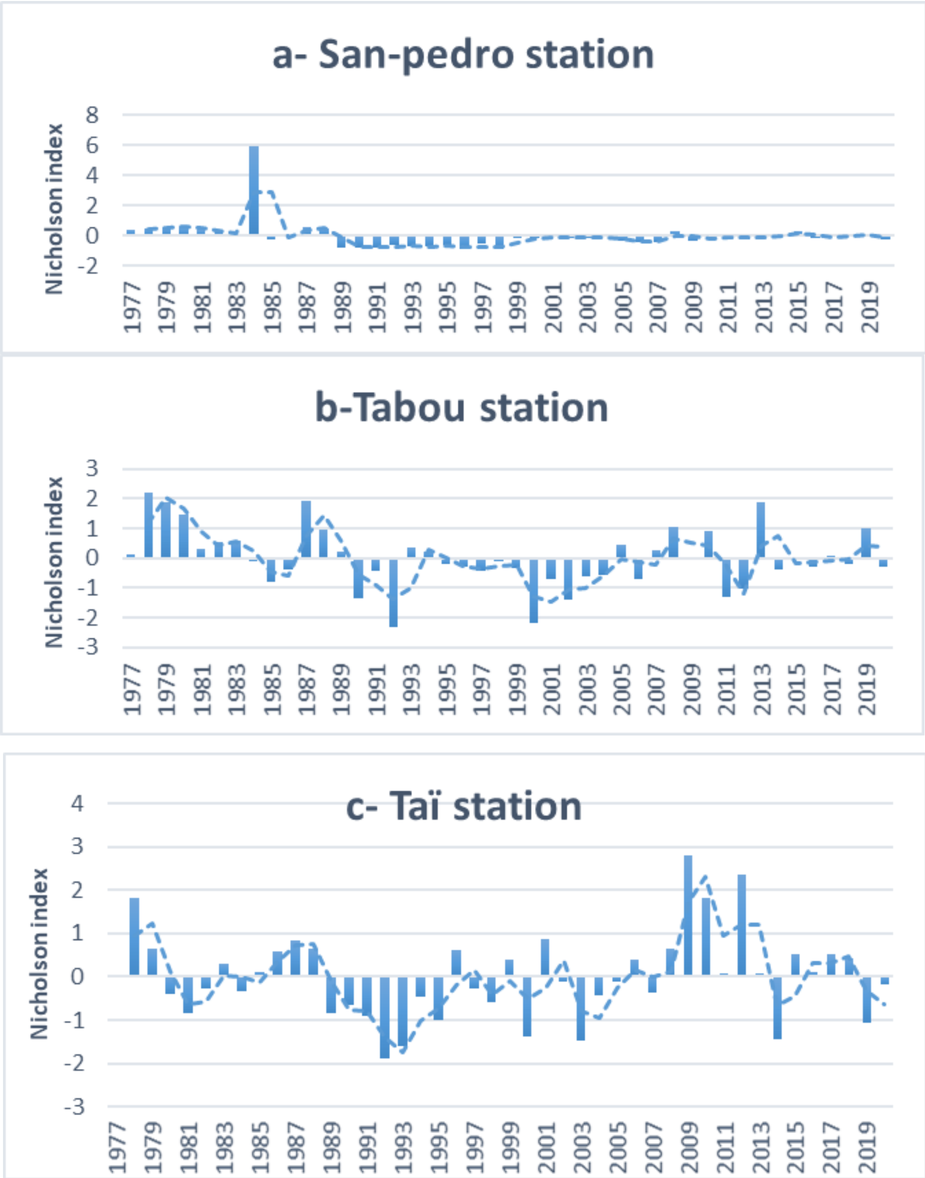


Fig. 4. Variation of Nicholson rainfall index in the south-west

This modeling solution reveals that:

*In San Pedro, effective rainfall changes from 411 mm before the break to 484.9 mm after the rainfall break using the Thornthwaite method. However, the Turc method shows that effective rainfall moved from 422 mm before the break to 498.1 mm after the break and the Edijatno & Michel method's effective rainfall change from 316 mm before breaking to 478.9 mm after the break (Fig. 6 and Table 3).

*In Tabou effective rainfall changes from 884.9 mm before the break to 509.4 mm after the rainfall break using the Thornthwaite method. However, the Turc method shows that effective rainfall moved from 807.6 mm before the break to 541.3 mm after the break and the Edijatno & Michel method's effective rainfall changed from 958.5 mm before the break to 586.5 mm after the break (Fig. 6 and Table 3).

*In Taï effective rainfall changes from 1026.8 mm before breaking to 444.8 mm after rainfall break using the Thornthwaite method. However, the Turc method shows that effective rainfall moved from 957.6 mm before the break to 492.2 mm after the break and the Edijatno & Michel method effective rainfall changed from 1075.2 mm before the break to 492.5 mm after break (Fig. 6 and Table 3).

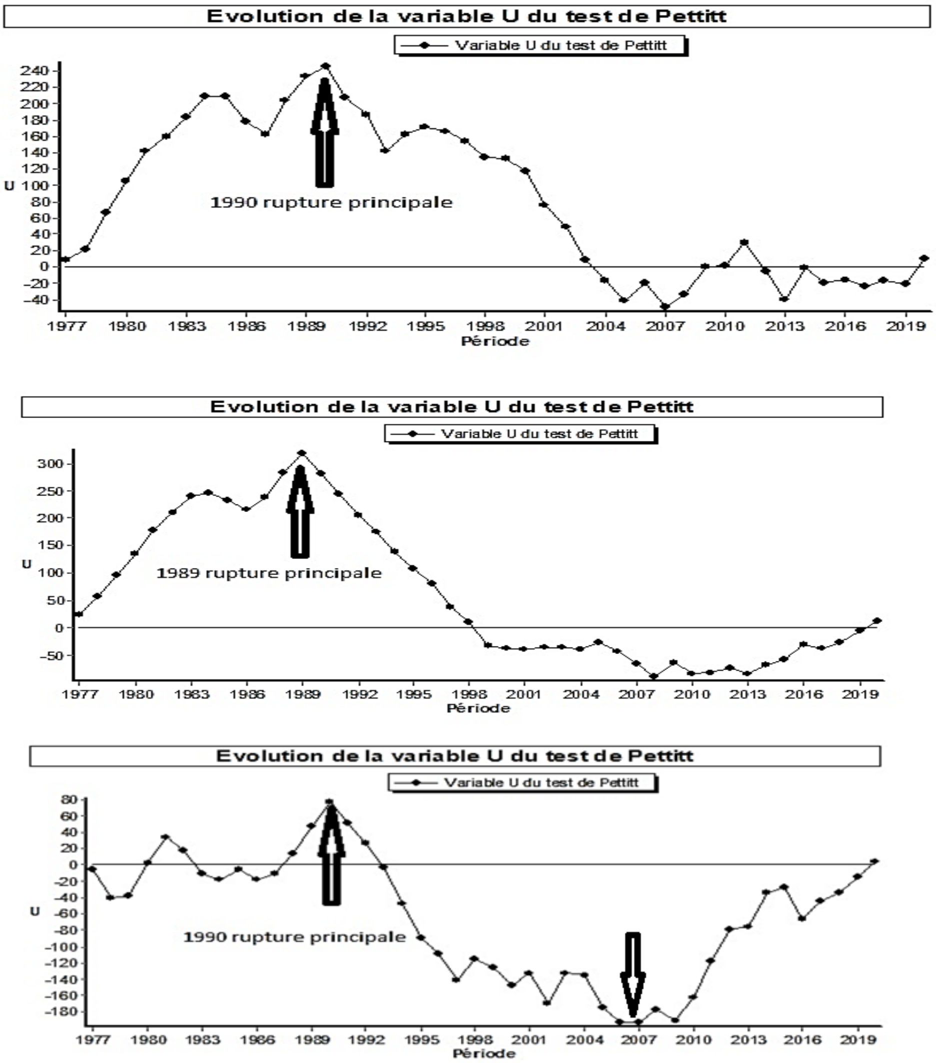
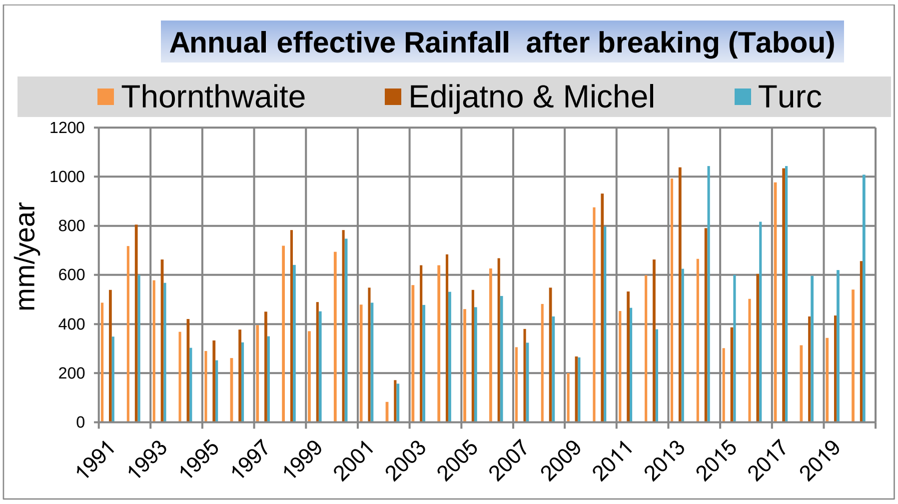
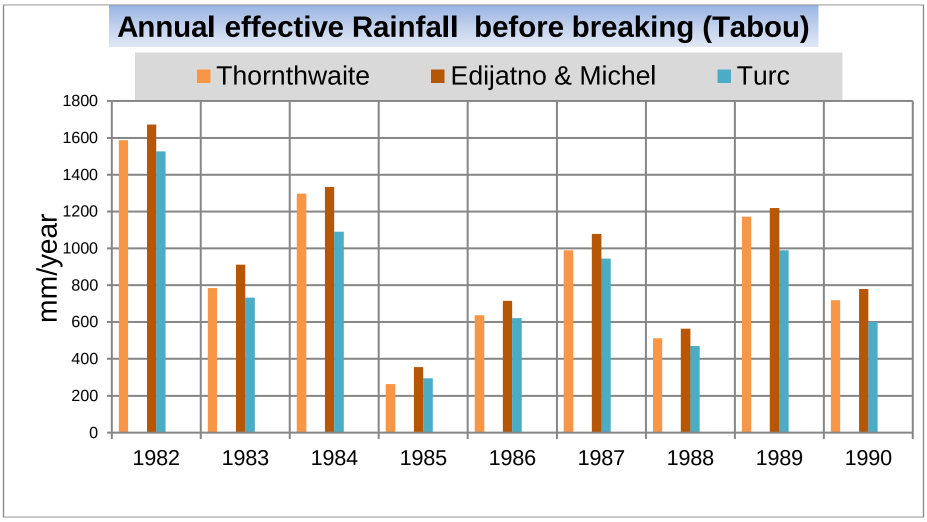
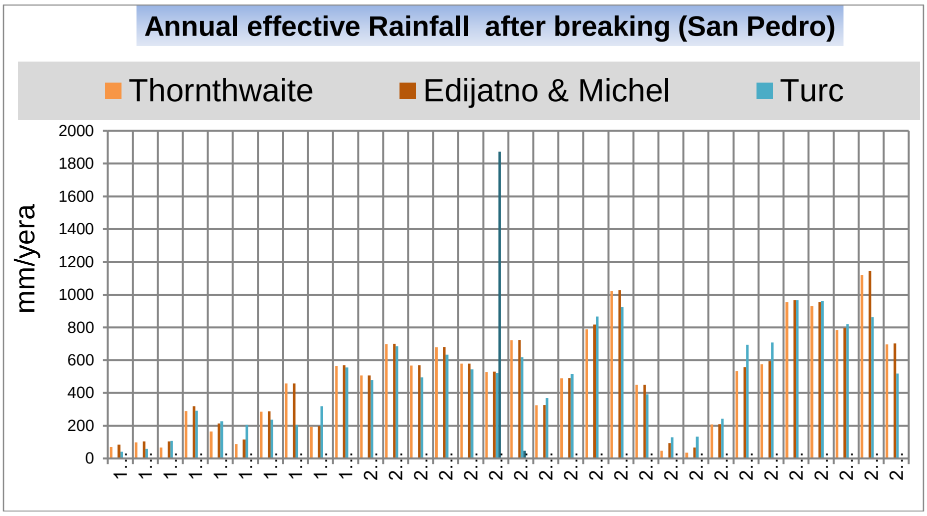


Fig. 5. Variation of Pettitt U variable and rainfall from 1977 to 2020




Annual effective Rainfall before breaking (Tabou)
Thornthwaite
Edijatno & Michel
Turc
mm/year
1800
1600
1400
1200
1000
800
600
400
200
0
1982
1983
1984
1985
1986
1987
1988
1989
1990


Annual effective Rainfall after breaking (San Pedro)
Thornthwaite
Edijatno & Michel
Turc
mm/yera
2000
1800
1600
1400
1200
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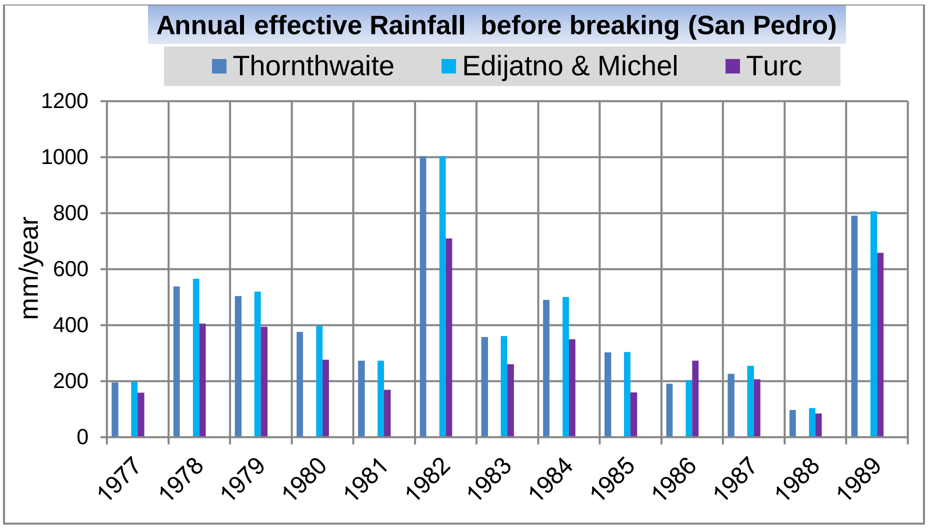
800
600
400
200
0


Annual effective Rainfall before breaking (San Pedro)
Thornthwaite
Edijatno & Michel
Turc
mm/year
1200
1000
800
600
400
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1977
1978
1979
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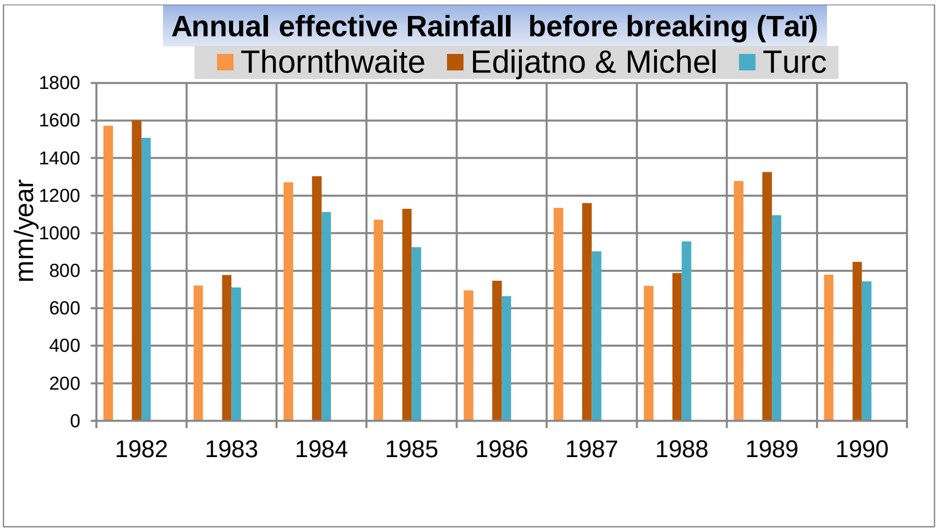


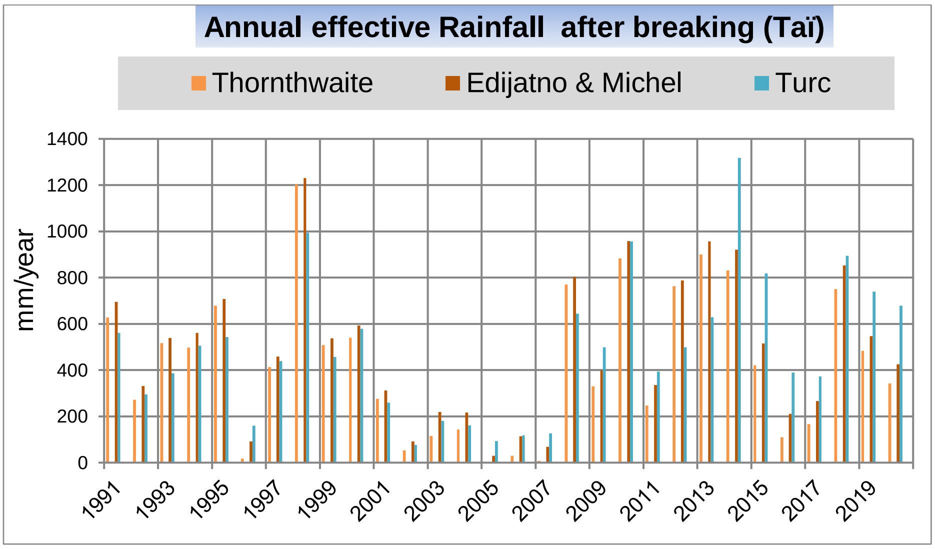


Fig. 6. Effective rainfall estimated under ESPERE modeling

3.2.2 Aquifer recharge estimation

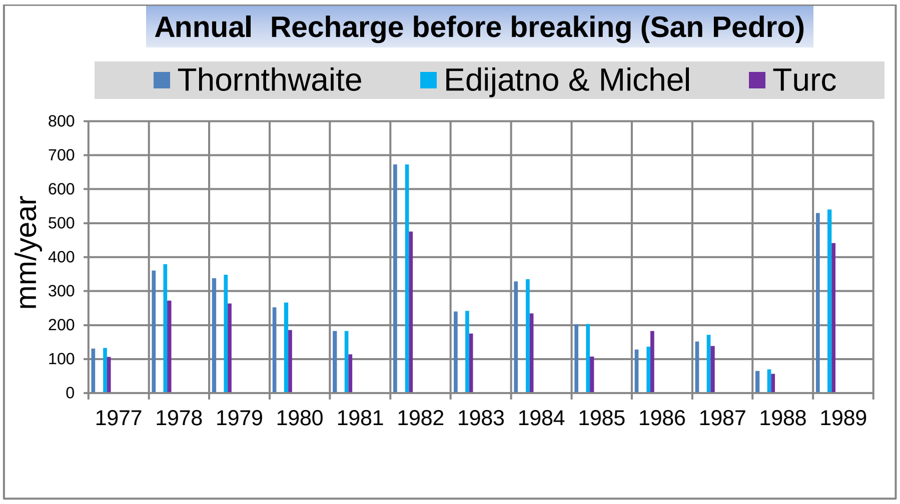
Recharge estimation through ESPERE modeling takes into account some parameters such as evaporation with transpiration and river discharges, in addition to temperature and rainfall entry data. Chronical filter methods such as Wallingford, Chapman, Edijatno & Michel and Eckhardt included in the ESPERE package were used to estimate annual aquifer recharge. The results reveal that:

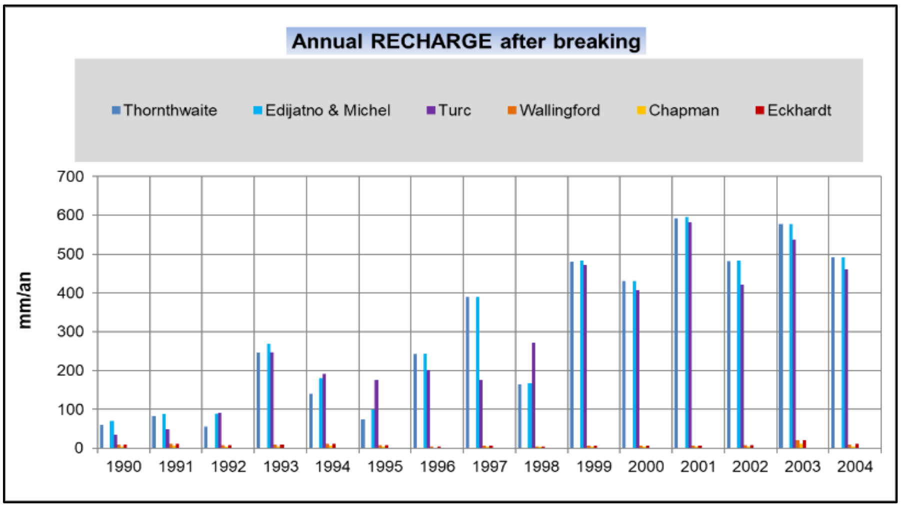
*In San Pedro, the Thornthwaite method highlights that recharge moves from 275 to 325 mm by year while the Turc method estimate recharge from 212 to 321 mm by year and Edijatno & Michel method estimate recharge from 283 to 334 mm by year (Fig. 7 and Table 3).

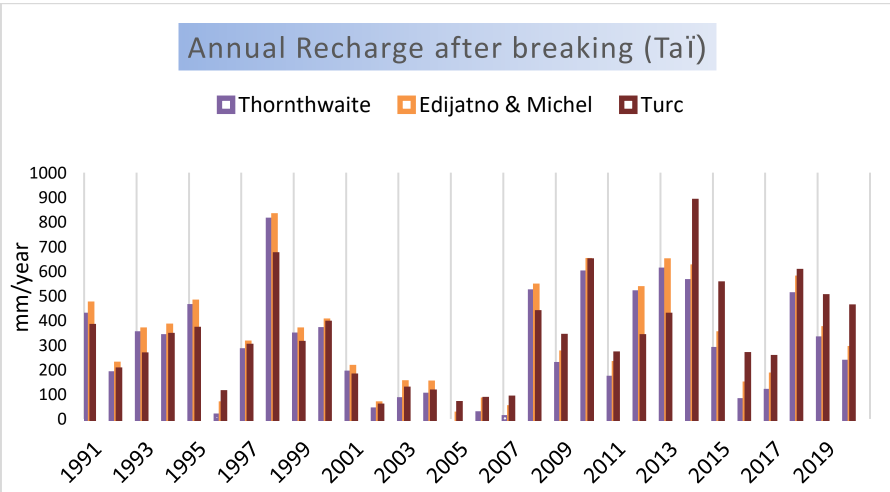
*In Tabou, the Thornthwaite method highlights that recharge moves from 592.9 to 341.3 mm by year while the Turc method estimates recharge from 541.1 to 361.7 mm by year and Edijatno & Michel method estimates recharge from 642.2 to 392.9 mm by year (Fig. 7 and Table 3).

*In Taï, the Thornthwaite method highlights that recharge moves from 688 to 298 mm by year while the Turc method estimates recharge from 641.6 to 329.7 mm by year and the Edijatno & Michel method estimates recharge from 720.4 to 330 mm by year (Fig. 7 and Table 3).

In previous works, the authors showed that it was the gross rainfall that inevitably affected aquifer recharge. Given the results obtained in this work, which highlight the strong dependence between effective rainfall and aquifer recharge, it is important to point out that effective rainfall is a real factor in the evolution or regression of aquifer recharge. This is in line with the studies carried out by Omer Z. et al., [29].







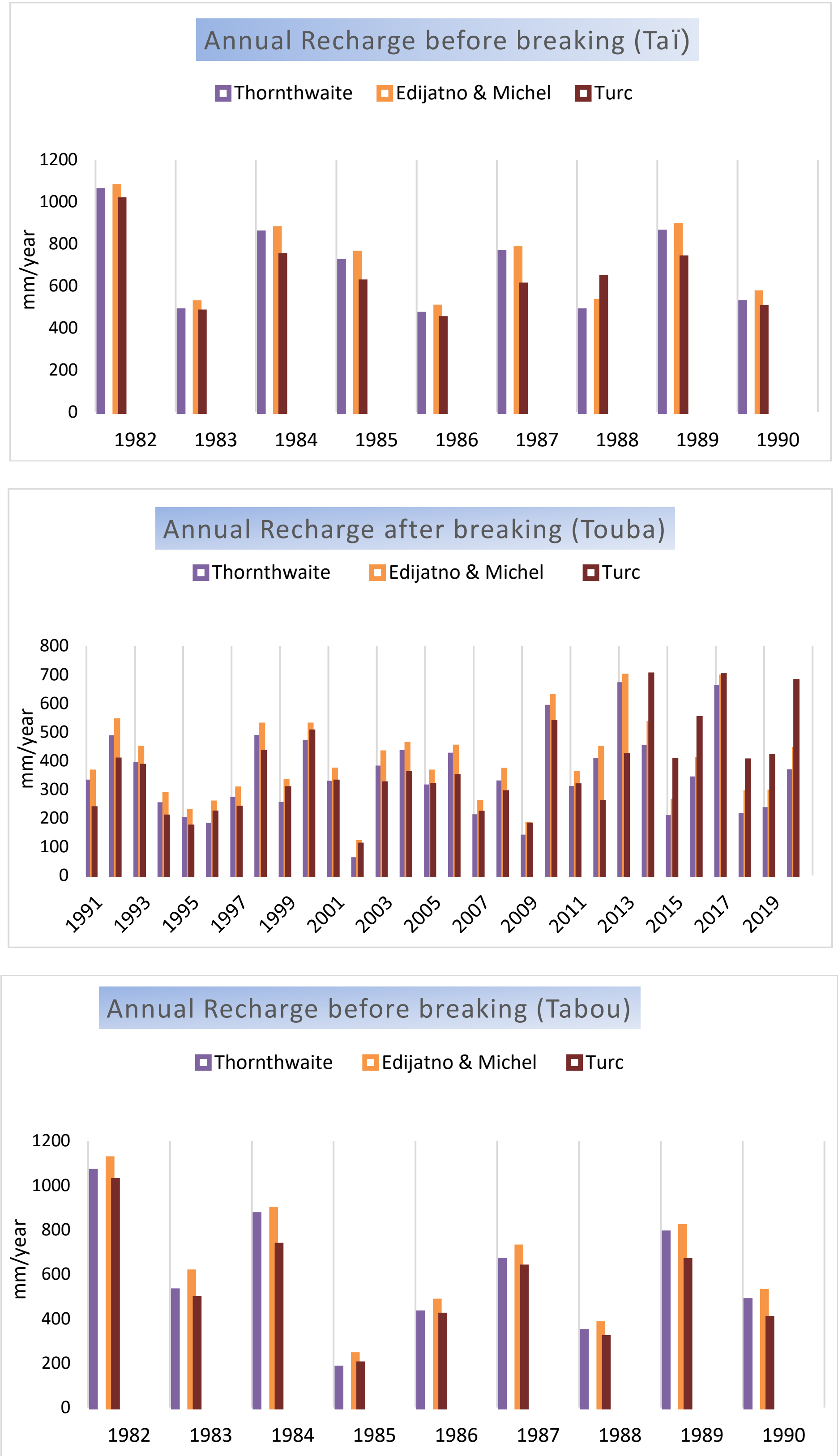


Fig. 7. Recharge estimated through different methods before and after break in ESPERE model

Table 3. Aquifer recharge and Effective rainfall estimation using different methods

Locality	Period	Methods	Effective rainfall	Aquifer recharge
San-pedro	**Before break**	Thornthwaite	411	275
		Turc	422	212
		Edijatno & Michel	361	283
	After break	Thornthwaite	484.9	325
		Turc	498.1	321
		Edijatno & Michel	478.9	334
Tabou	**Before break**	Thornthwaite	884.9	592.9
		Turc	807.6	541.1
		Edijatno & Michel	958.5	642.2
	After break	Thornthwaite	509.4	341.3
		Turc	541.3	362.7
		Edijatno & Michel	586.5	392.9
Taï	**Before break**	Thornthwaite	1026.8	688
		Turc	957.6	641.6
		Edijatno & Michel	1075.2	720.4
	After break	Thornthwaite	444.8	298
		Turc	492.2	329.7
		Edijatno & Michel	492.5	330

In previous works, the authors showed that it was the gross rainfall that inevitably affected aquifer recharge. Given the results obtained in this work, which highlight the strong dependence between effective rainfall and aquifer recharge, it is important to point out that effective rainfall is a real factor in the evolution or regression of aquifer recharge. This is in line with the studies carried out by Omer Z. et al., 2020.

4. CONCLUSION

This study evidenced the characteristics of rainfall variability with significant breaks in three localities of Côte d'Ivoire, It also highlighted the evolution of the aquifer recharge values estimated before and after rainfall breaking, Globally, climate change proofs evidenced a short surplus humid period followed by a long deficit rainy period, Aquifer recharge strictly followed effective rainfall everywhere, Particularly, the resilience building at Tai locality, is the western part, is the best one and must be replicate as the climate adaptation example.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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