Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2024, 11(12):125-140**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Impacts of Climate Change on Water Resources in the Republic of Congo by Application of the Maillet Model: Case of the Sangha (Ouesso) and Kouilou-Niari (Sounda) Watersheds over the Period 1961-2020.

Christian Ngoma Mvoundou[1], Guy Blanchard Matété Moukoko[1], Harmel Obami-Ondo[1], Podo Mahamat Matar[2], Christian Armand Anicet Tathy[1,3]

[1]Laboratory of Mechanics, Energy and Engineering, Higher National Polytechnic School, Marien Ngouabi University, Brazzaville, Congo.
[2]Department of Geosciences, Faculty of Exact and Applied Sciences, University of Ndjamena (Chad).
[3]Department of Exact Sciences, Higher Teacher's Training School, Marien Ngouabi University, Brazzaville, Congo.
E-mail: christiangomh@gmail.com

Abstract: The application of Maillet's law on the hydrological behavior of certain basins in the Republic of Congo, namely: the Sangha watershed at the Ouesso hydrological station and the Kouilou-Niari watershed at the Sounda hydrological station, revealed conclusive results. The objective of this study is to assess the impacts of climate change on groundwater resources in Ouesso and Sounda using the Maillet model. The assessed drying coefficients vary on average between $3.40.10^{-3}$ d^{-1} in Sounda and 5.60. 10^{-3} d^{-1} in Ouesso at the monthly time step on the one hand and 3.50. 10^{-3} d^{-1} in Ouesso and $3.70.10^{-3}$ d^{-1} in Sounda at the annual time step on the other hand. This phenomenon of drying up of the aquifers was observed in September 1978 at the Sounda station and in April 2012 at the Ouesso station, over the period 1961-20202. These two stations being located at the start and on the other side of the equator present different climatic behaviors, which influence the quality of the results. The results obtained show a contribution of resources in the aquifers from 1978 in Sounda and from 2012 in Ouesso, i.e. an average increase of +7.13 % in Sounda and +86.36 % in Ouesso and highlight a draining, much faster in Ouesso after 2012 and much slower in Sounda after 1978, of the aquifers feeding the basic underground flows of these basins. A shortening of 24 days with an average of 5 days of the dry period after 1978 and of 9 days with an average of 6 days of the dry period after 2012 was highlighted respectively in Sounda and Ouesso over the period 1961-20202. The volumes of water mobilized by aquifers fluctuate on average between 10311.0 m^3 in Sounda and 21144.3 m^3 in Ouesso, i.e. a decrease means on average of the order of -49203.63 m^3 in Sounda and -32844.47 m^3 in Ouesso, respectively before and after the drying up. These results highlight a decrease in the volumes of water resources mobilized by aquifers after 1978 in Sounda and 2012 in Ouesso and suggest a considerable decline in groundwater resources under the influence of climate change.

Keywords: Climate change; Groundwater resources; Maillet model; Watershed; Kouilou-Niari; Sangha; Sounda; Ouesso; Republic of Congo.

1. Introduction

Sustainable development requires, among other things, meeting the vital needs of populations. Water is recognized as essential for all forms of life, namely humans, animal and plant [1]. Therefore, there is no need to be a scientist to realize that the planet is seriously affected by the effects of climate change. The oceans, seas, rivers, forests and even the air are in a worrying state of degradation. Indeed, one of the greatest challenges facing humanity today is global warming, which corresponds to a gradual increase, predicted or observed, in the temperature of the surface of the globe, which is one of the consequences of the radiative forcing caused by anthropogenic emissions [2]. Africa is at the forefront of the regions concerned by the issue of the impact of climate fluctuations on water resources [3]. Several studies conducted in Africa, particularly in Central and West Africa, have shown a decrease in groundwater flows following the decrease in rainfall events ([2], [4], [5], [5], [7], [8] and [9]). The analysis of the manifestations of climate variability and its relationship with the variability of water resources, especially groundwater, is today a problem of development and sustainable management of water resources. The seriousness of the problems of water resources, both surface and groundwater, being intimately linked to those of climate and hydrology on a global scale, leads to a globalization of observations techniques and analysis methods. In order to better diagnose and design adapted and effective strategies to deal with this problem, several relevant tools such as the Mallet model, reduced centered data, etc. are used.

Integrated and sustainable management of these resources is a pressing imperative to better understand the impacts of climate, such as droughts and floods, on our ecosystems. In this context, exceptional droughts and floods can be fuelled by global warming. These climatic extremes can also be defined by the impact that an event has on society, resulting in loss of human life, or large economic losses. The issue of the management of water resources, especially groundwater, is one of the issues currently being raised by climate change. In other words, the question is whether current climate variability affects groundwater resources. The quantitative analysis of these impacts on water resources, or rather groundwater, is of paramount interest when we know that in most of our rural African regions, particularly in the Republic of Congo, the populations are supplied exclusively with drinking water from groundwater by means of boreholes, springs or wells that capture groundwater and are themselves subject to climatic hazards. The results of such an analysis can be useful as an aid to decision-making related to the impacts of climate change on water resources. The impacts of climate variability can differ from one region to another, so we conducted our study, to better understand this problem, in the Kouilou-Niari basin in the southwest and in the Sangha basin in the northwest.

The objective of this study is to assess the impacts of climate change on groundwater resources in the Sangha and Kouilou-Niari watersheds, respectively at the Ouesso and Sounda hydrological stations. This study aims to provide decision-makers with the necessary tools for decision-making and to put in place water resources management policies adapted to the climatic context and the sustainable development of these two watersheds. This study is based on the hypothesis that the effects of climate change observed in recent decades have led to a decrease in aquifer reserves. The methodology was based on Maillet's model and consisted of analysing the variations in the depletion coefficients and the volumes of water mobilised by the aquifers on either side of the drying up year, which is constituted as the year of depletion of the aquifers and therefore of the rupture of the underground reserves in these watersheds, over the period 1961-2020.

2. Data and methods

Data

Presentation of the study area

The study area concerns two hydrological units located at the beginning and others from the equator with climatic conditions as different in terms of manifestations, namely: the Kouilou-Niari watershed (Sounda) and the Sangha watershed (Ouesso). The Kouilou-Niari basin at Sounda, located in the southwest of the Republic of Congo (Figure 1a), lies between latitudes 2° and 5° S and longitudes 11°45′ and 15° E, with an area of about 60000 km2. The Kouilou-Niari River, 690 km long, changes its name according to the deferential areas: called N'douo in the Batékés Plateaus (upper course: northern zone), it becomes Niari in the Niari valley in (middle course: central zone) and becomes Kouilou (lower course: southern zone) crossing the Mayombe through a succession of narrow gorges (Sounda), a name it retains until its mouth on the Atlantic Ocean. It occupies nearly 17 % of the country's surface area by size and represents the second hydrological lung of the country [1]. Its modulus averaged 911.7 m^3/s at its outlet in Sounda, over the period 1961-2020. On the other hand, the Sangha basin at Ouesso, located in the north-west of the Republic of the Congo (Figure 1b), and is located between three countries: the Republic of Congo, the Central African Republic and the Republic of Cameroon. It covers an area of nearly 213,000 km^2 and occupies nearly 6 % of the Congo River Basin by size and is between longitudes 11°51′ and 16°44′ East and latitudes 1°37′ and 6°40′ N [10]. The 781 km long Sangha River originates in Cameroon and then flows through the Central African Republic and the Republic of Congo to the confluence with the Congo River. Its modulus averaged 1502.7 m^3/s in Ouesso over the period 1961-2020. The Sangha River flows through the region of Africa that is mostly covered by the great rainforest. Its hydrometric station in Ouesso occupies nearly 3 % of the country's total area by its size and represents the third economic lung of the Republic of Congo in terms of resources.

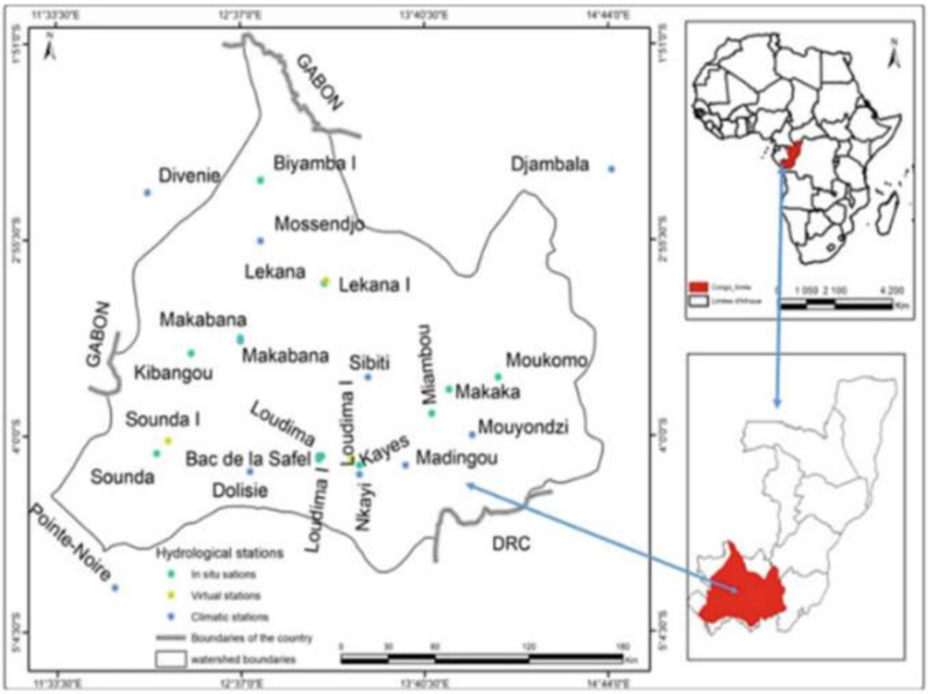
The Kouilou-Niari basin is characterized by a humid tropical climate and extends over different microclimates ranging from the savannah region in the north to the forest area in the south of the basin; Its relief is mainly made up of plains and plateaus. There is also mountain ranges made up of hard rocks that resist erosion in the Chaillu massif and in the Mayombe forest. The humid tropical climate, which prevails in the area, is characterized by the existence of two rainy seasons alternating with two dry seasons of unequal length [1]. Its humid tropical regime is characterized by a moderate volume of rainfall, with annual rainfall between 816.8 mm and 1771.3 mm. The relief of the basin is relatively homogeneous, it is intimately linked to the geological nature of the soil and in general not very hilly. The Kouilou-Niari basin is covered by forest vegetation with high rainfall, which is still under-exploited despite anarchic deforestation which promotes the penetration of water into the water table. The main geological formations of the basin are organized as follows: to the north, there are limestone formations (schisto-limestone series), micaceous feldspathic sandstones, quartzo-schist; in the centre, we note the presence of quartzites, quartzophylades and schists which constitute for geologists, the quartzo-schist series and finally in the south, 50 km from the mouth with the Atlantic Ocean, we note the presence of coastal formations (Cretaceous and Eocene) represented by sandstones and sands [1].

The Sangha basin in Ouesso is subject to an equatorial climate. It is characterized by heavy rainfall, it rains almost all year round. The annual rainfall of the basin in Ouesso varies between 1393 and 2327 mm per year, the dry season extends from March to May, known as the MAM season, i.e. March-April-May. Upstream of Ouesso, the Sangha watershed is made up of a Precambrian schisto-quartzitic complex with intrusions of various kinds: intrusive dolerites, tillitic complexes, etc. [11]. Downstream of Ouesso, the rocks are made up of Quaternary alluvium from the Congolese Basin. The soils of the basin, as everywhere else, are ferralitic. The Sangha basin is essentially covered by a dense and humid equatorial forest, except for the north of the basin which is covered almost by wooded savannahs [12]. The Sangha forest is full of a wide variety of species of large trees. This forest is a loose forest of large trees dominating a low stratum of bushy appearance, very dense [13]. The different hydroclimatic parameters that characterize the two watersheds, symbolizing the study area, are recorded (Table 1) and rendered in graphical form (Figure 2a, 2b, 2c and 3a, 3b, 3c).

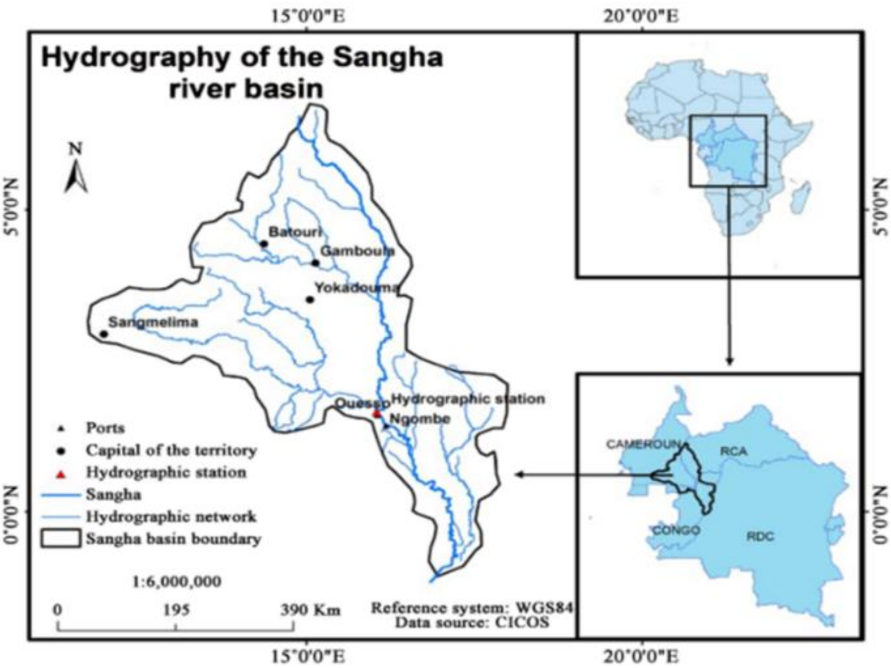
Table 1: Statistics of the hydroclimatic parameters of the study area over the period 1961-2020 (Kouilou-Niari Basin in Sounda and Sangha Basin in Ouesso)

Variables	Hydroclimatic parameters		
	Discharge (m^3/s)	**Rainfall (mm)**	**Temperature (°C)**
Kouilou-Niari basin in Sounda			
Maxi	3303,5	446,9	28,4
Mini	201,0	2,0	18,0
Average	911,7	110,2	25,4
Median	852,7	112,7	26,1
Ecartype	452,1	95,9	1,9
Cv in (%)	49,6	87,0	7,3
Years (damp/dry)	28/32	30/30	34/26
K3	1,11	1,14	1,01
Sangha Basin in Ouesso			

Maxi	4098,7	456,2	27,0
Mini	361,8	2,0	22,4
Average	1502,8	141,0	24,7
Median	1264,3	137,3	24,6
Ecartype	844,2	76,5	0,7
Cv in (%)	56,2	54,3	3,0
Years (damp/dry)	24/36	27/33	31/29
K3	1,14	1,08	1,01

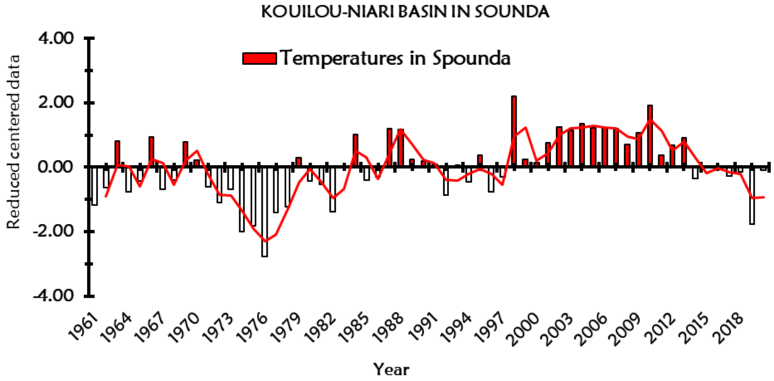


(a)

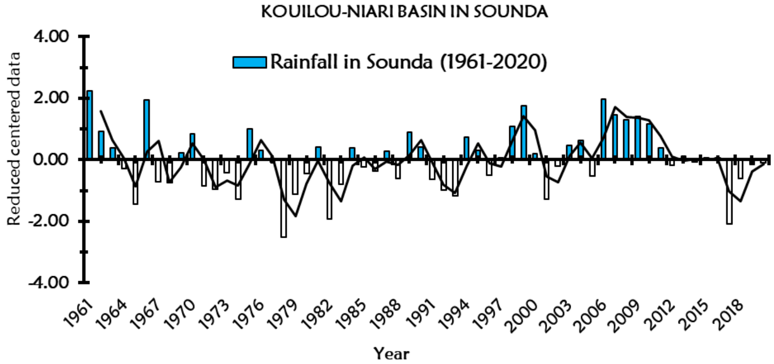


(b)

Figure 1: Location of the study area: a) Kouilou-Niari basin in Sounda b) Sangha basin in Ouesso.



(a)



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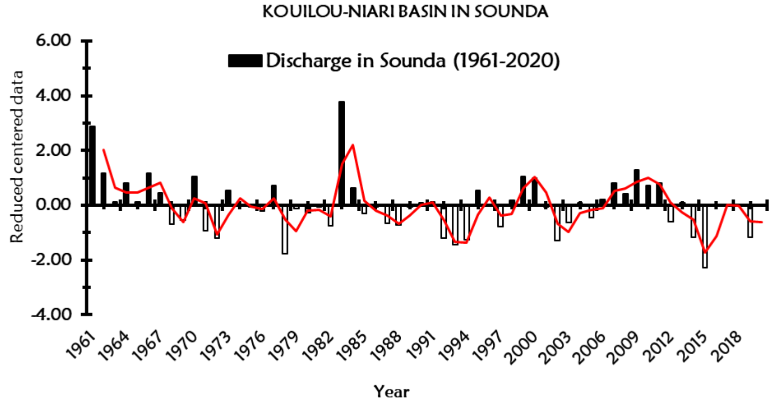
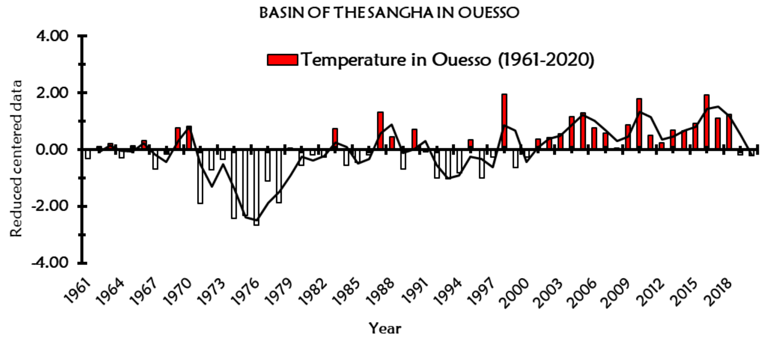
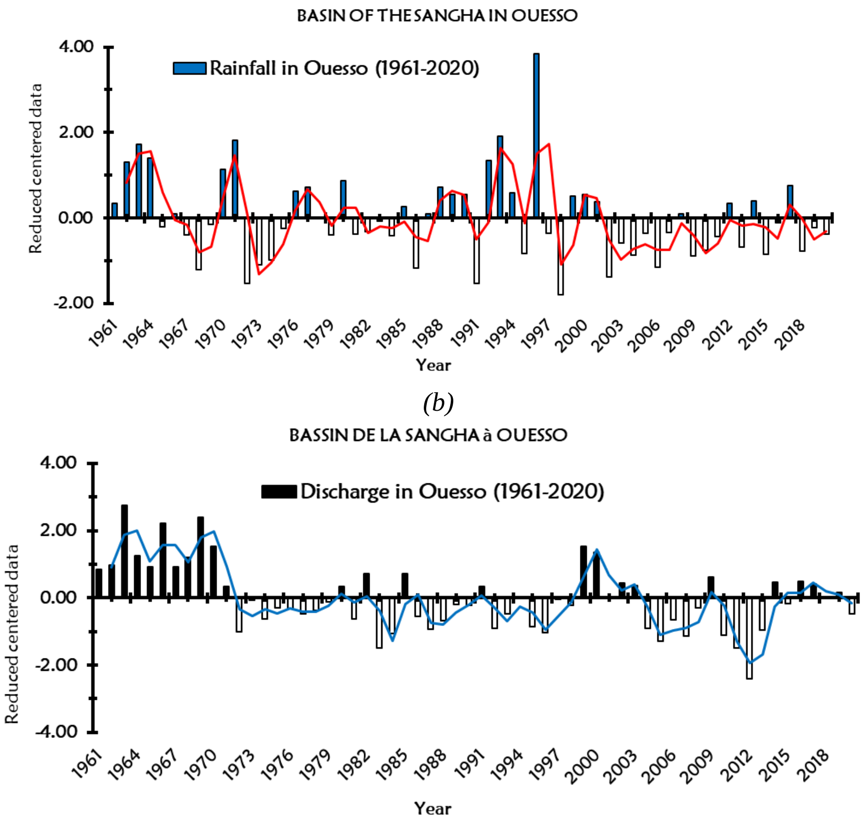


(c)

Figure 2: Evolution of the hydtoclimatic parameters of the study area in Sounda: a) Temperatures; b) Rainfall and c) Discharge.



(a)



(c)

Figure 3: Evolution of the hydtoclimatic parameters of the study area in Ouesso: a) Temperatures; b) Rainfall and c) Discharge.

Study data

The hydroclimatological data used in this study are at monthly intervals and concern two stations located at the beginning and others from the equator in the Republic of Congo. These data come from the hydrological service databases of the IRD (formerly ORSTOM), the work of Tchicaya [14], the work of Molinier et al. [15] and the IRSEN (Institute for Research in Exact and Natural Sciences) in Brazzaville, for the Sounda hydrological station. On the other hand, for the Ouesso station, these data come from the database of the Common Service for the Maintenance of Waterways of the Republic of Congo (SCEVN). The climate data used in this study are also monthly time, they come from the database of the meteorological service of the National Civil Aviation Agency (ANAC) of the Republic of Congo. These different data cover a hydroclimatological period of nearly sixty (60) from 1961 to 2020.

Methods

The methodology used in this study, which makes it possible to assess the impacts of climate change on water resources, especially groundwater, using the Maillet model, was only possible by determining the drying up coefficient, the duration of the drying up and the volume of water mobilized in the aquifers. This study was carried out over a hydrovlimatological period of nearly sixty (60) years, from 1961 to 2020. This methodology used consists of three steps: 1) collection of hydrovlimatic data at the stations of Sounda (Kouilou-Niari basin) and Ouesso (Sangha basin); 2) processing of these different data and 3) modeling by statistical approach using the Maillet model. These data are supposed to undergo various classic statistical tests. These analyses characterize the behavior of the underground flows at these two stations.

- **Drying Coefficient**

Dry-up is a hydrogeological event where the flow of a river is in a decreasing phase. During this phase, known as the emptying of groundwater, the flow of the watercourses is reduced to the flow of the aquifers. This drying up phase results from a lack of rainfall, it occurs after a flood phase. Drying up is also the decrease in the flow of water, which is happening exponentially, more and more slowly. Drying up represents "the phase of flow of a watercourse or other source corresponding to the regular decrease in flow in the absence of any meteoric input and human intervention" [16]. The calculation of the dry-off coefficient is based on the Maillet model which is used in much scientific work ([1], [4], [8], [17], [18], [19], [20] and [21]). This work has shown the relevance of drying up in the hydrological cycle, especially the underground flows, of a watershed. In this approach, the drying up curve gives the appearance of the emptying of aquifers and therefore of underground reservoirs. Maillet's model admits that in the low-water regime (absence of precipitation), the drying up corresponds to the exponential decrease in flow as a function of time. In other words, it is the period during which the emptying of groundwater is the only contribution to the flow of watercourses in a basin. According to Olivry et al. [22], the drying up coefficient makes it possible to assess the state of water "inflows" that would contribute to the apparent modification of the rainfall/flow relationships observed in river basins. It thus makes it possible to compare the evolution of surface water and aquifer storage in order to better understand the behaviour of the drain reservoir. The depletion coefficient (k) depends on the physical and geometric characteristics of the aquifer. The depletion coefficient is determined by Maillet's formula represented by equation (1):

$$Q_t = Q_0 e^{-kt} \qquad (1)$$

Taking the natural logarithm member by member, we find:

$$k = -\frac{1}{t}\ln\left(\frac{Q_t}{Q_0}\right) \qquad (2)$$

The minus sign (-) in equation (2) denotes draining, so this equation can be written as:

$$k = \frac{1}{t}\ln\left(\frac{Q_t}{Q_0}\right) \qquad (3)$$

with:

- k : drying up or emptying coefficient (d^{-1});
- Q_t: minimum monthly flow rate (m^3/s) at time **t**;
- Q_0 : minimum monthly flow rate of the series (m^3/s) at **t** = 0 given;
- t: time elapsed since the initial moment at **t**=0 (d).

This Maillet model defines the drying curve as the moment of emptying and recharging of underground reservoirs. Maillet's drying coefficient (k) was obtained by solving equation 4, which is defined as follows **[23]:**

$$\frac{e^{-kt}}{k} + \frac{V}{Q_0} - \frac{1}{k} = 0 \qquad (4)$$

- **Duration of dry-off**

From equation 4, the expression T of the dry-off period, expressed in days i.e. (J) and defined as the sequence **([8]** and **[20])**:

$$T = \frac{1}{k} \qquad (5)$$

avec:

- k : drying up or emptying coefficient (d^{-1});
- T: Dry-off duration in (d).

- **Volume of water mobilized by aquifers**

The quantity of water available in underground reservoirs corresponds exclusively to the dynamic volumes (V) mobilized by all the aquifers in the basin. This volume of water mobilized is given by equation 6 **([18]** and **[23]):**

$$V_{mobilized} = \int_0^{+\infty} Q_0 e^{-kt}\, dt \qquad (6)$$

Integrating equation **6** into time, we find:

$$V_{mobilized} = 86400\frac{Q_0}{k} \qquad (7)$$

with:

- $V_{mobilized}$: Volume of water mobilized by all aquifers (m^3).

This Mallet model determines the law of low water frequency, by retaining for each year the smallest monthly flow observed. The drying coefficients (k), which characterize the slope of the line, vary from one station to another. The dry-off curves are drawn from the minimum monthly flow. To do this, we start from the smallest minimum flow of the hydrological cycle (Q_0) and we report the minimum monthly flows measured on the abscissa until they cancel each other out, then rise significantly to justify the recharge of the aquifers. These curves correspond to the periods during which the flow decreases more or less regularly, known as emptying, and those during which the flow also increases more or less regularly, known as recharge (uninfluenced regime), i.e. in the absence of precipitation.

3. Results and Discussion

Results of the study

The Maillet model, studied in this article, made it possible to determine and assess at these two stations the temporal evolution of the drying coefficient coefficient, the duration of the drying up and the volume of water mobilized by the aquifers under the effect of climate change. The various results obtained during this study were recorded (Tables 2 and 3) and represented in graphical form (Figures 4, 5 and 6), at annual time steps.

Table 2: Statistical results of the test variables of the Maillet model in the study area on the period 1961-2020 (Kouilou-Niari Basin in Sounda and Sangha Basin in Ouesso).

Period	Sounda station				Ouesso station			
	Low water m³/s	Drying coefficient $10^{-3}.d^{-1}$	Volume of water mobilized 10^3 m³/s	Duration of drying up day	Low water m³/s	Drying coefficient $10^{-3}.d^{-1}$	Volume of water mobilized 10^3 m³/s	Duration of drying up day
January	510,3	30,1	6,688	3,3	499,0	10,4	34,871	9,6
February	499,0	32,5	6,189	3,1	437,0	06,7	53,607	14,8
March	550,0	32,5	6,190	3,1	374,3	01,1	54,810	15,2
April	536,0	32,7	6,148	3,1	**361,8**	**0,0**	**0,00**	**0,00**
May	557,2	32,9	6,111	3,0	517,9	11,6	31,262	8,6
June	348,0	18,3	10,986	5,5	696,1	21,8	16,581	4,6
July	280,0	10,7	18,797	9,4	762,3	24,0	15,045	4,2
August	206,0	0,80	25,359	12,6	768,3	24,3	14,891	4,1
September	**201,0**	**0,0**	**0,00**	**0,00**	1147,9	38,5	9,399	2,6
October	206,0	0,80	25,359	12,6	2053,5	56,0	6,459	1,8
November	558,0	34,0	5,906	2,9	1939,6	56,0	6,463	1,8
December	567,8	33,5	6,000	3,0	1069,7	35,0	10,344	2,9

Table 3: Statistical results and characteristics of the test variables of the Mallet model on the period 1961-2020 (Kouilou-Niari basin in Sounda and Sangha basin in Ouesso).

Characteristics	Sounda station				Ouesso station			
	Low water m³/s	Drying coefficient $10^{-3}.d^{-1}$	Volume of water mobilized 10^3 m³/s	Duration of drying up day	Low water m³/s	Drying coefficient $10^{-3}.d^{-1}$	Volume of water mobilized 10^3 m³/s	Duration of drying up day
Sum	5019,4	259,0	123,732	61,6	10627,4	285,0	25,373	70,1
Maxi	567,8	34,0	25,359	12,6	2053,5	56,0	54,810	15,2
Mini	201,0	0,0	0,0	0,0	361,8	0,0	0,0	0,0
Average	418,3	22,0	10,311	5,1	885,6	24,0	21,144	5,8
Median	504,6	31,0	6,190	3,1	729,2	23,0	14,968	4,1
Ecartype	156,3	15,0	8,267	4,1	577,2	19,0	18,360	5,1
Cv in (%)	37,4	67,30	80,2	80,2	65,2	81,4	86,8	86,8

Drying coefficient

To better understand the impacts of climate change on the groundwater resources of the Kouilou-Niari basin in Sounda and the Sangha basin in Ouesso, this study focused on the drying up coefficient. The dry-off coefficients were determined at both monthly and annual steps over the study period (1961-2020). During this period, the evolution of the dry-off coefficient was first observed over two sub-periods (1961-1990 and 1991-2020), and then over the entire study period (1961-2020) only at monthly time steps (Figure 4a and 4b). This drying up phenomenon did not occur in the same months throughout the two sub-periods as well as at the two stations in the study area. In the Kouilou-Niari basin in Sounda, this drying up phenomenon occurred in September 1978 for the 1961-1990 sub-period and then early in August 2015 for the 1991-2020 sub-period. In the entire Kouilou-Niari basin in Sunda, over the period (1961-2020), it occurred in September 1978. On the other hand, in the Sangha basin in Ouesso, the drying up first took place in March 1989 for the 1961-1990 sub-period before occurring in April 2012 for the 1991-2020 sub-period. This phenomenon was finally observed in April 2012 over the period 1961-2020, in the entire basin.

As these two stations are located at the start and from the other, their positions in relation to the equator have a great influence on the quality of the results. The results obtained reflect the influence of climate on water resources, especially groundwater, in these basins over the entire study period (1961-2020). This drying up phenomenon does not manifest itself in the same way depending on the annual calendar. It occurs during the dry season from June to September (JJAS season) which corresponds to the low water season for the Sounda resort. On the other hand, for the Ouesso station, it is observed during the low water season from March to May (MAM season) which corresponds to the dry season. The results obtained are recorded (Tables 4, 5 and 6) and graphically translated (Figures 4a and 4b and 5) to highlight changes in the flow of aquifers in the basin.

Table 4: Statistical results of minimum flows in the study area by period (Kouilou-Niari Basin in Sounda and Sangha Basin in Ouesso).

Month	Kouilou-Niari basin in Sounda			Sangha basin in Ouesso		
	Period					
	1961-1990	1991-2020	1961-2020	1961-1990	1991-2020	1961-2020
January	668,8	510,3	510,3	619,8	499,0	499,0
February	637,0	499,0	499,0	451,2	437,0	437,0
March	557,0	550,0	550,0	374,3	395,3	374,3
April	536,0	536,0	536,0	473,9	361,8	361,8
May	573,0	557,2	557,2	555,5	517,9	517,9
June	353,0	348,0	348,0	754,4	696,1	696,1
July	285,0	280,0	280,0	919,4	762,3	762,3
August	235,0	206,0	206,0	803,6	768,3	768,3
September	201,0	235,0	201,0	1147,9	1195,9	1147,9
October	206,0	266,0	206,0	2232,4	2053,5	2053,5
November	558,0	558,0	558,0	2302,5	1939,6	1939,6
December	822,1	567,8	567,8	1179,5	1069,7	1069,7

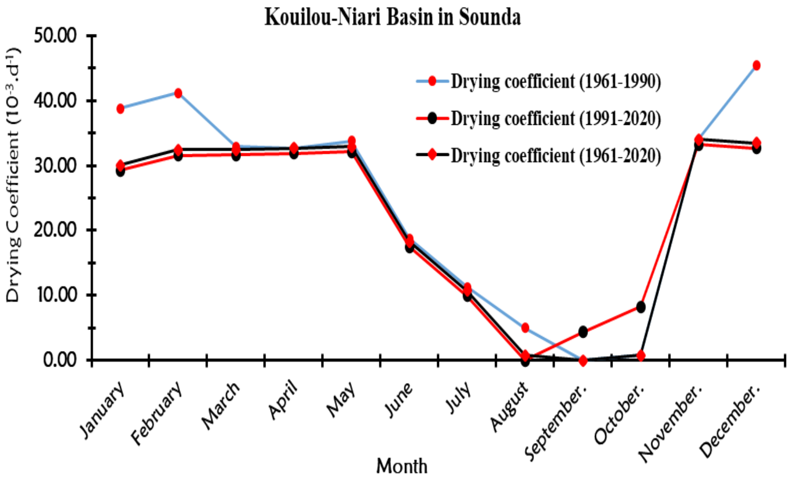
Table 5: Statistical results of the drying coefficients in the study area by period at 10^{-3} d^{-1} (Kouilou-Niari basin in Sounda and Sangha basin in Ouesso).

Month	Kouilou-Niari basin in Sounda			Sangha basin in Ouesso		
	Period					
	1961-1990	1991-2020	1961-2020	1961-1990	1991-2020	1961-2020
January	38,78	29,26	30,05	16,27	10,37	10,37
February	41,20	31,60	32,48	6,67	6,75	6,75
March	32,88	31,68	32,47	0,00	2,86	1,10
April	32,69	31,88	32,69	7,86	0,00	0,00
May	33,79	32,10	32,89	12,74	11,57	11,57
June	18,77	17,48	18,30	23,36	21,82	21,82

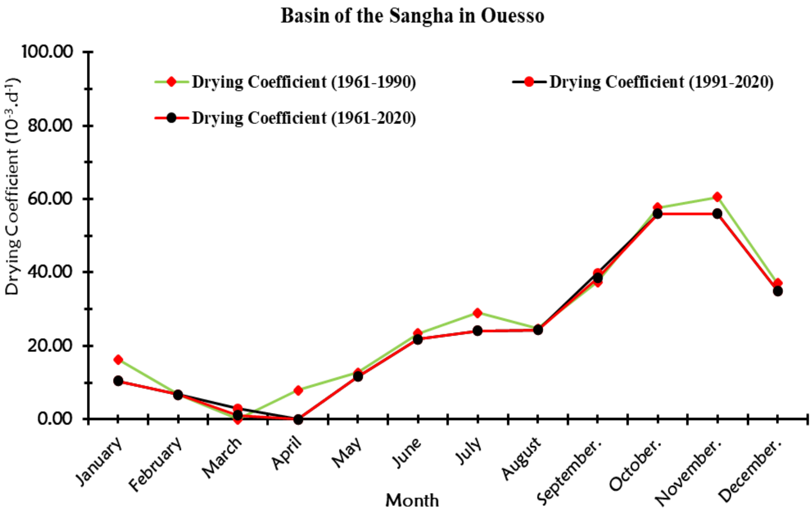
July	11,26	9,90	10,69	28,99	24,05	24,05
August	5,04	0,00	0,79	24,65	24,29	24,29
September	0,00	4,39	0,00	37,35	39,86	38,49
October	0,79	8,25	0,79	57,60	56,01	56,01
November	34,04	33,22	34,04	60,56	55,97	55,97
December	45,44	32,71	33,50	37,03	34,97	34,97

Table 6: Statistical results of the mean drying coefficients before and after rupture (Kouilou-Niari basin in Sounda and Sangha basin in Ouesso).

Basin	Period	Average drying at $10^{-3}.d^{-1}$	Rate of increase (%)
Kouilou-Niari at Sounda	1961-1978	21,2	+7,02
	1979-2020	22,8	
Sangha at Ouesso	1961-2012	4,6	+86,23
	2013-2020	33,4	



(a)

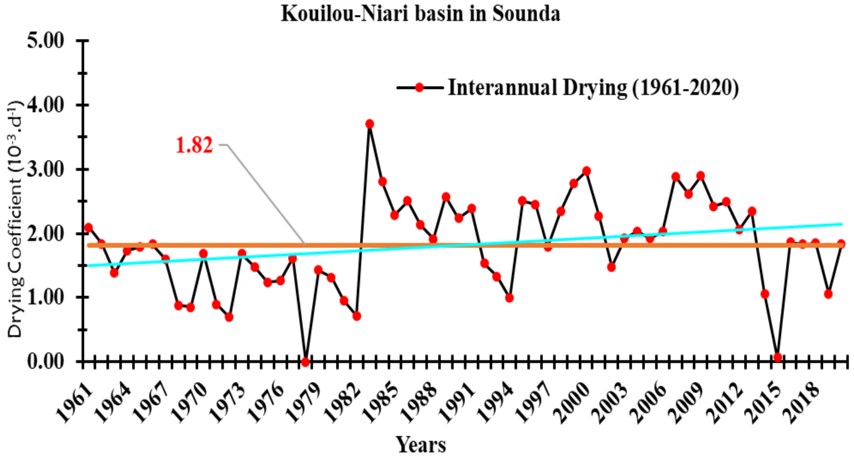


(b)

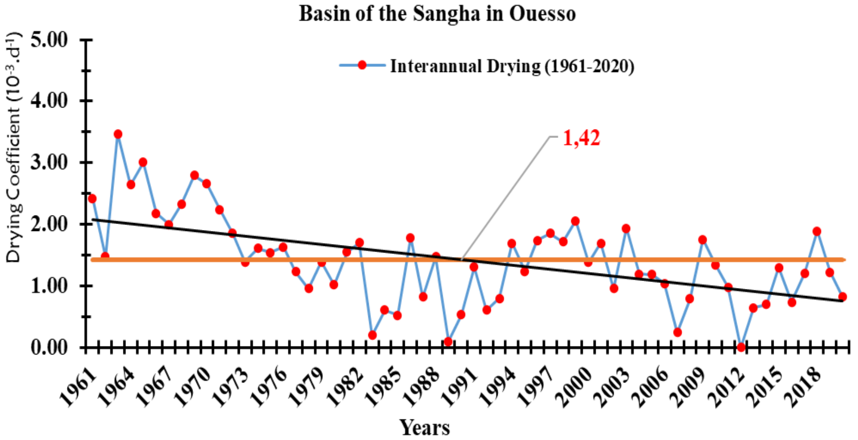
Figure 4: Monthly and period-specific evolution of drying coefficients in the study area: a) Kouilou-Niari basin in Sounda and b) Sangha basin in Ouesso.

In addition, the results of the drying up obtained at these two stations, at the annual time step, are represented graphically (Figures 5a and 5b). These results show a slightly upward trend in the Kouilou-Niari basin in

Sounda and a downward trend in the Sangha basin in Ouesso, over the period 1961-2020. In other words, in the Kouilou-Niari basin, the drying up is above the normal for the seasons, which means that the aquifers are in surplus in Sounda and in deficit in Ouesso because the drying up is below the normal for the seasons (Figures 5a and 5b).



(a)



(b)

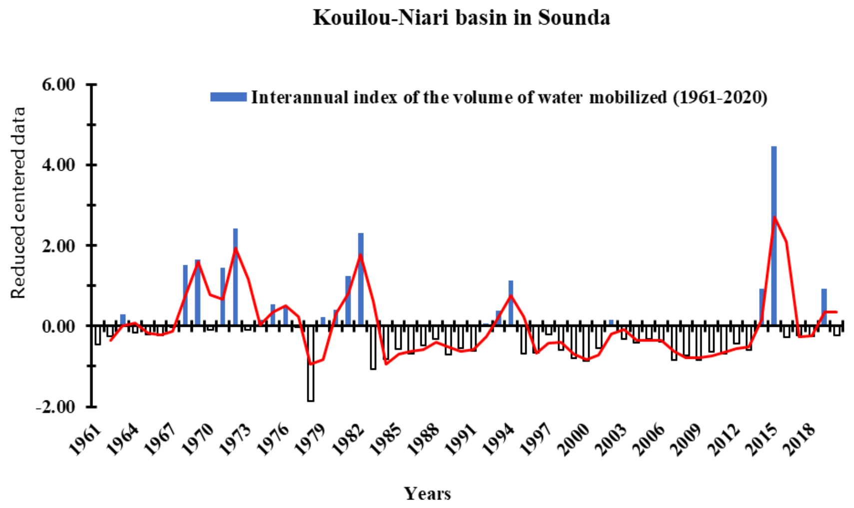
Figure 5: Evolution annuelle des coefficients de tarissements dans la zone d'étude: a) Bassin Kouilou-Niari à Sounda et b) Bassin de la Sangha à Ouesso.

Volume of water mobilized by the acquiferes

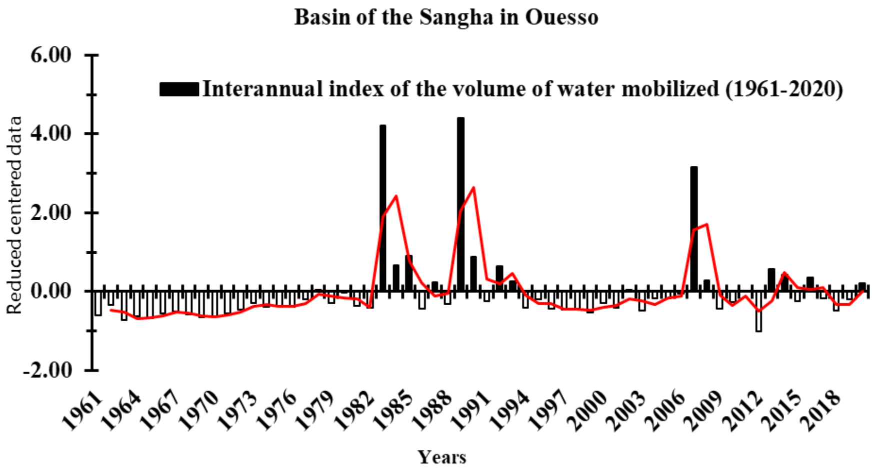
The analysis of the volumes of water mobilized by the aquifers determined at the level of each station in terms of water reserves contained in the groundwater. In other words, it made it possible to evaluate the loading and emptying time of aquifers at each station, over the period 1961-2020. The volumes of water mobilized by the calculated aquifers are recorded (Table 7) and graphed at the annual time step (Figures 6a and 6b).

Table 7: Résultats statistiques des volumes d'eau mobilisés avant et après rupture (Bassin Kouilou-Niari à Sounda et Bassin de la Sangha à Ouesso).

Basin	Period	Volumes of water mobilized à 10^3 m^3	Rate of reduction (%)
Kouilou-Niari at Sounda	1961-1978	8,649	-1,32
	1979-2020	3,726	
Sangha at Ouesso	1961-2012	14,329	-0,30
	2013-2020	11,044	



(a)



(b)

Figure 6: Annual evolution of the volumes of water mobilized in the study area: (a) Kouilou-Niari basin in Sounda and b) Sangha basin in Ouesso.

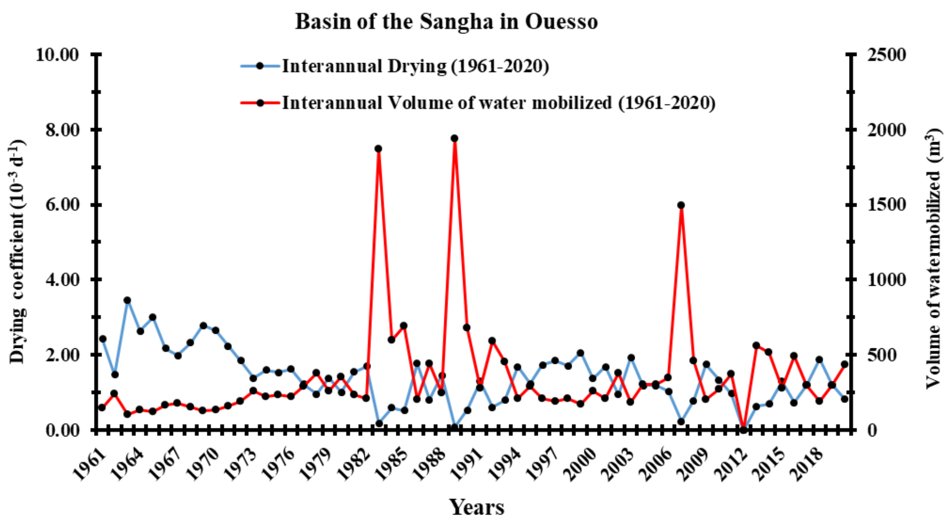


Figure 7: Annual evolution of the volumes of water mobilized and the drying coefficient in the study area: a) Kouilou-Niari basin in Sounda and b) Sangha basin in Ouesso.

The results represented graphically (Figures 7a and 7b), at the annual time step, show a comparative evolution of the depletion coefficients and the volumes of water mobilized by the aquifers. It follows from these results that the volumes of water mobilized are inversely proportional to the drying coefficients.

Duration of aquifer drying

As the duration of dry-up is inversely proportional to the rate of aquifer emptying, the calculations made were determined before and after the rupture, i.e. the drying-up, on the data of these two hydrometric stations and during the period 1961-2020. The results obtained have been synthesized (Table 8). These results show that the drying time varies according to the hydrologic of each watershed and depends on the drying up of each station. The dry period before 1978 in Sunda ranges from 3 to 13 days. After 1978, it fluctuated between 3 and 13 days, which corresponds to the duration of groundwater recharge for the Sounda station. On the other hand, for the Ouesso station, the drying up period before 2012 fluctuates between 10 and 15 and after 2012, it varies from 2 to 9 days, which corresponds to the duration of groundwater recharge for the Ouesso station. A shortening of the dry period ranging from nearly 5 and 10 days respectively after 1978 and 2012 for the Sounda and Ouesso stations is highlighted, over the period 1961-2020. The results obtained from the drying period are recorded (Table 8).

Table 8: Statistical results of drying periods before and after rupture (Kouilou-Niari Basin in Sounda and Sangha Basin in Ouesso).

Basin	Period	Drying duration in day	Rate of reduction (%)
Kouilou-Niari at Sounda	1961-1978	43	-1,26
	1979-2020	19	
Sangha at Ouesso	1961-2012	40	-0,29
	2013-2020	31	

Discussion of the results

The drying up coefficients evaluated from the hydrometric stations of Sounda and Ouesso, during this study over the period 1961-2020, vary between 0.8 and 32.710^{-3} d^{-1} before 1978 and between 0.8 and 34.010^{-3} d^{-1} after 1978 at the Sounda station. On the other hand, at the Ouesso station, these depletion coefficients fluctuate between 1.1 and 10.410^{-3} d^{-1} before 2012 and between 11.6 and 56.010^{-3} d^{-1} after 2012. These results show that the drying off coefficients increased by +7.02 and +86.23 respectively in Sounda and Ouesso. In other words, the emptying of the aquifers at these stations follows an exponentially decreasing drying up law, which is all the easier to study the more marked the dry season is [4]. The analysis of these developments, at a monthly time step, shows that the drying up occurs over the period from January to September, i.e. 9 out of 12 months of the year, in the Kouilou-Niari basin in Sounda. On the other hand, in the Sangha basin in Ouesso, it takes place between January and April, i.e. 4 out of 12 months of the year. The analysis of the evolution of the drying coefficients, at the annual time step over the period 1961-2020, shows that they vary greatly from one year to the next before the break and slightly after the break. The variations are smaller, the average values around the rupture oscillate between 21.2 and 22.810^{-3} d^{-1} at the Sounda station and between 4.6 and 33.410^{-3} d^{-1} at the Ouesso station. Several studies carried out on different watercourses in Côte d'Ivoire by (Savané et al. **[18]** ; Saley, **[19]** and Fadika et al. **[24]**), gave results almost in the same order of magnitude, for example of the order of 5,710^{-3} d^{-1} on the Cavally at Flampeu; from 4,010^{-3} d^{-1} on Kahin to N'zo (Sassandra); from 3.610^{-3} d^{-1} on the Drou at Man (Sassandra) by Savané et al. **[18].** The different results are in the order of 10^{-3} as is the case of our present study and converge towards the evidence of a significant drying up of aquifers under the effect of climatic variability manifested by a decrease in rainfall and an increase in evapotranspiration following the monotonous increase in temperature in the study area, over the period 1961-2020. However, the results obtained evolve in opposite directions between the two stations, which could be explained by their positions in relation to the equator. The divergence in results could be due to the low water seasons from one station to another that define the dry phase.

The drying up coefficients in the Kouilou-Niari basin in Sounda show a slightly upward trend, as in the Niger watershed in Benin **[8].** While it is decreasing in Ouesso in the Sangha basin. This significant change is observed at different dates in the two stations in the study area, given the response time of the hydrological system due to precipitation. In hydrology, the evolution of vegetation cover also influences the quality of the results, such as the trends observed on the drying coefficients of these two hydrometric stations. Indeed, the degradation of the vegetation cover has repercussions on the water and even underground resources of the environment. The evolution of land use can strongly influence the quality of the results in hydrology, such as the drying coefficient in the case of this study. In the watersheds of our study area, changes in vegetation cover change are no exception to anthropogenic activities due to the practice of traditional slash-and-burn agriculture. In Africa, especially in tropical regions, the phenomenon of drying up has also been described by several authors such as Vissin **[8]**, Amoussou **[20]**, Olivry et al. **[22]** and Mahé et al. **[25]**. For example, the work carried out by Olivry et al. **[22]** shows that from 1969 onwards in Bani in Douna, the increase in the drying up coefficient corresponded to an earlier and faster emptying of groundwater.

The duration of the drying up observed in the study area, in these two watersheds, varies between 19 and 43 days in general, before and after the drying up over the period 1961-2020. The calculated dry period varies from one station to another and has a significant reduction from the date of the dry period. This variability in drying-up could be explained by the distribution of rainfall events during the year and by the importance of rainfall in the dry season and which supports low water levels **[26].** Indeed, low-water flows depend on the state of recharge of the aquifers at the end of the rainy season and on the law of drying up of the river. The variation in the duration of dry-off could also be explained by a decrease in the number of rainy days. These different observations provide an idea of the temporal behaviour of rainy day frequencies, which are a factor in the trend to explain the impact of climate variability on rainfall patterns **[27].** The speed of the drying up and the low volumes of water mobilized lead us to say that the aquifers that feed the basins are in aquifers of low permeability and small size **[26].** Indeed, in fractured formations of watersheds, the presence of groundwater is conditioned by the existence of fractures, hence the presence of discontinuous aquifers that contain water in small proportions.

The volumes of water mobilized by the aquifers vary between 8.649 and 3.72610^3 m^3 before and after 1978, with a reduction rate of -1.32 %, at the Sounda station. On the other hand, at the Ouesso station, the volumes mobilized by the aquifers fluctuate between 14,320 and 11.04410^3 m^3 before and after 2012, with a reduction rate of -0.30 %. The volumes of water mobilized by aquifers are therefore experiencing a decrease linked to the reduction in rainfall observed from the end of the 1970. The long-term depletion of baseflow inputs is linked to a reduction in the volume of water in aquifers. Indeed, there is a considerable decrease in the underground reserves that normally supply rivers during periods of low water. These variations in the volumes of water mobilized suggest a decline in groundwater reserves. It would then explain the high extent of the recent drought on the drop in flows. The conclusions of the work of Savané et al. **[18]**, Saley **[19]** and Goula et al. **[26]**, based on the same methodological approach used in this study, show that a marked decline in the volumes mobilized by aquifers has been observed since 1970 on Ivorian rivers. The results obtained during this study are therefore consistent with those obtained by previous authors and show the small quantities of water discharged into watercourses by groundwater.

The analysis of the drying-up in the study area is carried out on the basis of the results obtained at these two hydrometric stations and there is a variation in the drying-up coefficient at the level of the watercourses throughout the study period, with in particular higher values obtained in the two basins, in terms of the rate of increase, between +7.02 % and +86.23 %. These variations in results could be explained by major anthropogenic removals at certain locations during dry periods. Indeed, the study area has many forest dams in most of it and coincides with the most unfavorable area from the hydroclimatic point of view. These dams therefore affect the normal hydrological behaviour of the study area, better known as the basin.

The study of the drying up and the volumes of water mobilized by aquifers confirms that the low contribution of basesoil flows, due to the reduction of inputs to groundwater, is a long-term phenomenon. This increasing decrease in groundwater reserves observed in the study area is the result of cumulative rainfall deficits observed and the degradation of the vegetation cover, which generally leads to a rapid drying up of the water tables.

4. Conclusion

The depletion coefficients evaluated during this study in the study area, which are better in the two watersheds precisely at the hydrometric stations of Sounda and Ouesso, over the period 1961-2020, gave convincing results.

These depletion coefficients vary between 21.2 and 22.810^{-3} d^{-1}, before and after the dry year, 1978 for the Sounda station. On the other hand, for the Ouesso station, this phenomenon occurred in 2012 and they fluctuate between 4.6 and 33.410^{-3} d^{-1}, these values were obtained before and after the dry year. These results show an increase in the drying up coefficient of +7.02 % at the Sounda station and +86.23 % at the Ouesso station after the drying up, in other words a much faster emptying of the aquifers feeding the base flow, at the level of the stations. A shortening of the dry-off period from 9 to 24 days with an average of 5 to 6 days after drying-off was highlighted. These results showed significant reductions of -1.26 % and -0.29 % in terms of dry periods before and after drying-off. In addition, the volumes of water mobilized by aquifers, obtained in this study, fluctuate between 3.726 and 8.64910^{3} m^{3} before and after 1978 in Sounda and between 11.044 and 14.32910^{3} m^{3} before and after 2012 in Ouesso. With reduction rates of -1.32 % in Sounda and -0.30 % in Ouesso in terms of the volumes of water mobilized. These results highlight a decrease in the volumes of water mobilized by aquifers after drying up. These variations in the volume of water mobilized by aquifers suggest a considerable decline in groundwater resources under the influence of climate change.

Acknowledgements

The authors of this study would like to thank the Meteorology Directorate of the National Civil Aviation Agency (ANAC) and the Economic Interest Group and the Joint Waterways Maintenance Service (GIE-SECVN) Congo-CAR for providing the data necessary to carry out this work. They also thank the instructors whose criticisms and suggestions have helped to improve this article.

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