

# Behavior Analysis of the Upper Cretaceous Aquifer Reservoir at the Athieme Outlet, in the Benin Portion of the Mono River Basin

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## Abstract

In recent years, water levels in some of the most heavily tapped aquifers (Upper Cretaceous) in the Beninese Mono River basin have fallen to the point where some boreholes, which used to have a permanent regime, now have a temporary regime, raising questions among the population. This study attempts to answer these questions by analyzing the behavior of the Upper Cretaceous aquifer reservoir at the Athiémé outlet, in the Benin portion of the Mono River watershed. It was based on statistical tests. To this end, the Students' t-test at 95% confidence for linear trend analysis was applied to static data collected from 5 piezometric stations around the Cretaceous aquifer recharge zone, covering the period from 2007 to 2020. Next, Pettitt break detection tests and the Bayesian method of LEE and HEGHINIAN were used to study the homogeneity of the various static levels of the aquifer's wells and boreholes around its recharge zone on these data. The results showed that four (04) of the five (05) piezometric stations used are representative of the hydrodynamic functioning of the aquifer, with the exception of the Volly-Latadji piezometer in Aplahoué. These piezometric stations showed a significant downward trend in static levels until 2020, with a clear break in 2013. Compared with the 2007-2013 sub-period, water levels in the aquifer's catchment structures (wells and boreholes) rose by 23% in the center of the aquifer, 10% in the northeast and south, and 11% in the southwest, between 2014 and 2020. This increase in the aquifer's water resources, which today contrasts with the realities on the ground, raises concerns about the future of the area's groundwater resources, and calls for in-depth reflection on the part of all concerned (decision-makers, craftsmen, scientists...).

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## Keywords

Statistics, Piezometer, Permanent Regime, Homogeneity, Aquifer's Catchment Structures

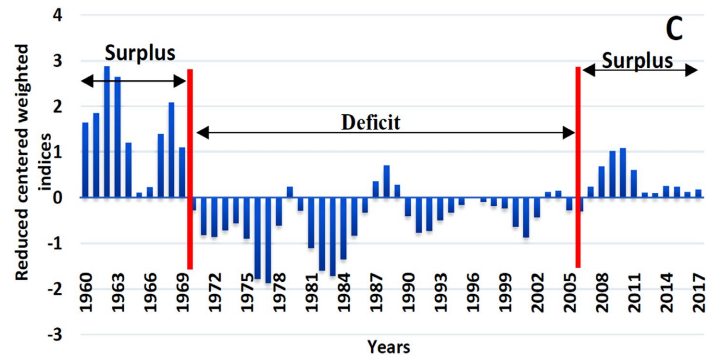
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## 1. Introduction

Freshwater, an indispensable resource for all aspects of life on earth, is nevertheless unevenly distributed across the globe. It accounts for just 3% of the planet's total water volume [1] [2] and is becoming increasingly scarce in many parts of the world. By 2022, around half the world's population had experienced severe water scarcity for at least part of the year, and a quarter faced "extremely high" levels of water stress, using up more than 80% of their total annual renewable freshwater supply [3]. In Africa, for example, 19 out of 22 states surveyed suffer from water scarcity [3]. This situation is set to worsen in West Africa as a result of rapid population growth and the climate change threatening the region, even though the environmental and climatic changes the region has undergone have led some watersheds to behave paradoxically [4]-[7].

In the Beninese portion of the Mono River watershed, water shortages are increasingly being felt in certain aquifers [8], including the Upper Cretaceous, despite the return of wet conditions to this basin since 1988 [9] [10]. Indeed, the Benin portion of the Mono River basin covers part of the coastal basin, including the Upper Cretaceous aquifer, which outcrops and is fed by rainwater [11]-[13]. This coastal basin [14] comprises two main aquifers: the Continental Terminal and the Cretaceous, to which are added the Quaternary and Paleocene aquifers. It accounts for approximately 10% of Benin's surface area and 35% of the country's groundwater resources, and is the most heavily used because it is the most populated [15]. The Upper Cretaceous in the Benin portion of the Mono River basin is the most important confined aquifer [15]. This basin water reservoir, which already mobilized 309 boreholes in 2018 (DGEau, 2018), is currently experiencing a drop in water levels at some catchment structures. In recent years (2008-2018), rainfall in Benin's Mono River basin has been 10% higher than in the 1960-1968 period (Figure 1) [16]. Given its geographical position, this aquifer should logically offer a sufficient guarantee to cover the population's underground needs. However, some of its catchment structures (boreholes and wells), once permanent, are now temporary (Photo 1). Community surveys have revealed a variation in artesian water pressure over the course of the year, and a gradual but relatively slow decrease in water flow at groundwater mobilization structures [17]. In a context where access to water remains a challenge, and the coverage of the various drinking water supply structures, especially in rural areas, remains relatively low, even if efforts are being made by the government supported by partners, this situation of groundwater catchment structures from the Upper Cretaceous aquifer in the Mono river basin in Benin, is not logical and raises concerns among the

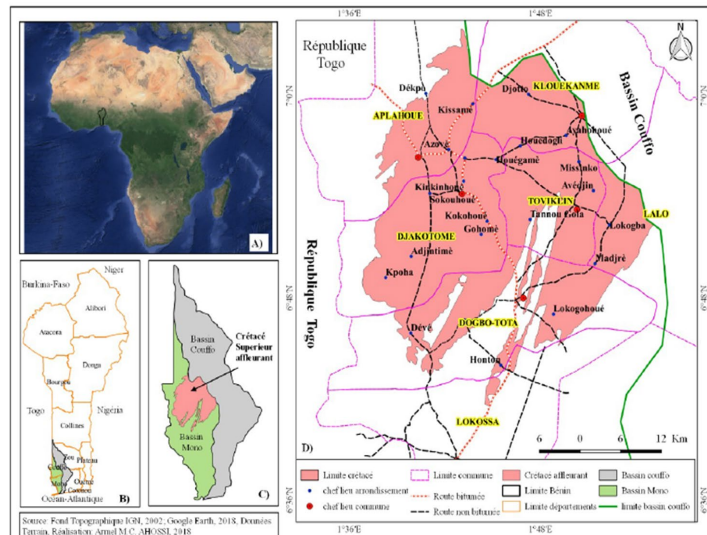
population. Over a recent period (2007-2020), this study analyzes the behavior of the water level in the catchment structures of the Upper Cretaceous aquifer reservoir around its recharge zone, at the Athiémé outlet, in the Benin portion of the Mono River basin, in order to explain the phenomenon. (**Figure 2**)



**Figure 1.** Trends in rainfall patterns in the Beninese Mono River basin from 1960-2018; 10% surplus from 2008-2018 compared with 1960-1969 [16].



**Photo 1.** Photos showing the flow rate of an artesian borehole tapping the aquifer in 2012 and 2018.



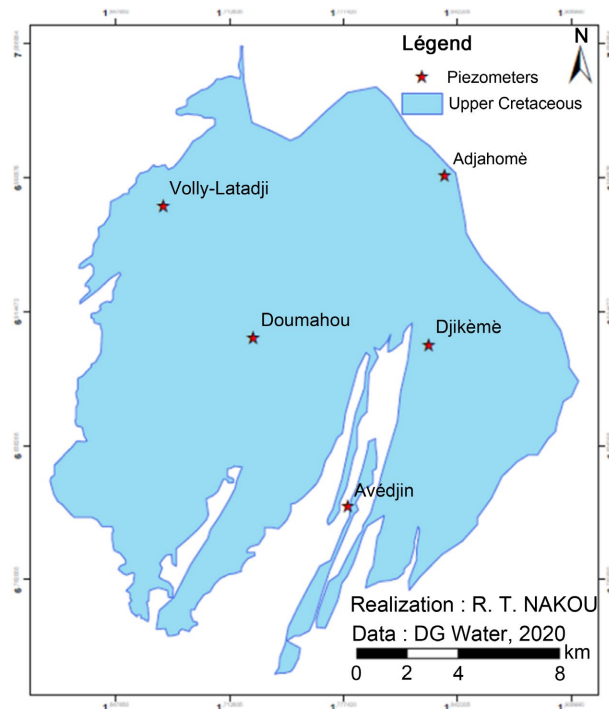
Source: Armel *et al.*, 2020.

**Figure 2.** Upper Cretaceous outcrop in the Mono River basin of Benin.

## 2. Data and Methods

### 2.1. Data

The data used in this study are those from 5 piezometric stations located around the Upper Cretaceous recharge zone at its outlet at Athiémé. These data are available from 2007 and cover the period 2007 to 2020, with a few gaps that have been filled (**Figure 3**).



**Figure 3.** Location of piezometer stations in the Upper Cretaceous reservoir.

### 2.2. Methods

#### 2.2.1. Data Filling

The strong correlation between piezometric data (**Figure 4**) made it easy to fill in the data using analytical linear correlation. This analytical linear correlation between two series is expressed by the equations:

$$\begin{cases} y - \bar{y} = r \frac{\sigma_y}{\sigma_x} (x - \bar{x}) \\ x - \bar{x} = r \frac{\sigma_x}{\sigma_y} (y - \bar{y}) \end{cases} \quad (1)$$

with

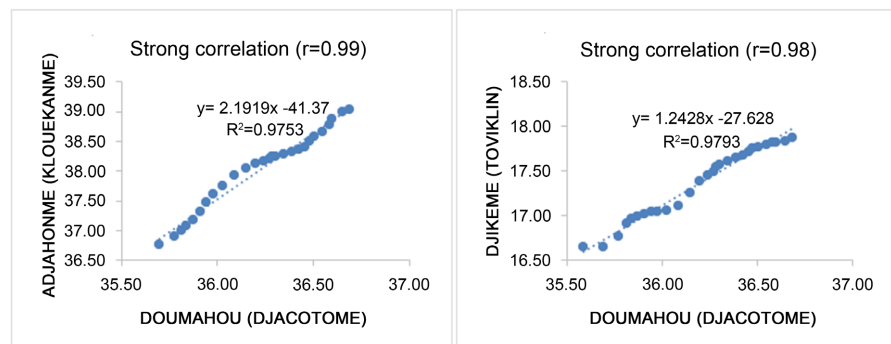
$$\begin{cases} \sigma_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \\ \sigma_y = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1}} \end{cases} \quad n \leq 30 \quad (2)$$

$$\begin{cases} \sigma_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n}} \\ \sigma_y = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n}} \end{cases} \quad n > 30 \quad (3)$$

$\sigma_x$  and  $\sigma_y$  are the respective standard deviations of the series for the reference station and the station under study, and

$$\begin{cases} \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \\ \bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \end{cases} \quad (4)$$

$\bar{x}$  and  $\bar{y}$  are the respective averages of the series for the reference station and the station under study.



**Figure 4.** Strong correlation between the static level of the Djacotomè piezometers and those of Toviklin and Klouékanmè.

### 2.2.2. Statistical Tests

Two static tests have been used to study the temporal stability of data series. These are the Pettitt test [18] and the LEE and HEGHINIAN test [19].

#### 1) Bayesian procedure by Lee and Heghinian [19]

Lee & Heghinian’s [19] method aims to confirm or refute the hypothesis of a change in the mean of the series. It is a parametric approach whose application to a series requires a normal distribution of values. The null hypothesis is that there is no break in the series. The procedure is based on the following assumption:

Let  $\{X_i\}$  be a series of independent normal random variables with constant variance  $\sigma^2$

$$X_i = \begin{cases} \mu + \varepsilon_i & i = 1, 2, \dots, \tau \\ \mu + \delta + \varepsilon_i & i = \tau + 1, \dots, n \end{cases} \quad (5)$$

Lee & Heghinian’s method proposes to determine the a posteriori probability distribution of these two parameters. To do this, we give ourselves a priori distribution of the independent parameters  $\tau$ ,  $\mu$ ,  $\delta$  and  $\sigma$  and, in particular, we assume that the date of rupture follows a uniform probability, *i.e.*, there is exactly as much chance of it occurring at one time or another.

Bayes' formula can be used to update this distribution in the light of observed results: the new "a posteriori" distribution is calculated using the formulae.

- Subsequent distribution of  $\tau$

$$P(\tau | x) = \frac{\sqrt{\frac{n}{\tau(n-\tau)}}}{\sqrt{R(\tau)^{n-2}}} \quad (6)$$

- Subsequent distribution of  $\delta$

$$P(\delta | x) = \sum_{\tau=1}^n P(\delta | x) P(\tau | x) \quad (7)$$

with

$$R(\tau) = \frac{\sum_{i=1}^{\tau} (x_i - \bar{x}_{\tau})^2 + \sum_{i=\tau+1}^n (x_i - \bar{x}_{n-\tau})^2}{\sum_{i=1}^n (x_i - \bar{x}_{\tau})^2} \quad (8)$$

$$\bar{x}_{n-\tau} = \frac{1}{n-\tau} \sum_{i=\tau+1}^n x_i \quad (9)$$

$$\bar{x}_n = \frac{1}{n} \sum_{i=\tau+1}^n x_i$$

$P(\delta | x)$  follows a Student distribution with  $(n-2)$  degrees of freedom and mean  $(\bar{x}_{\tau} - \bar{x}_{n-\tau})$  and variance  $Var = \frac{nR(\tau) \sum_{i=1}^{\tau} (x_i - \bar{x}_{\tau})^2}{(n-2)\tau(n-\tau)}$ .

## 2) Pettitt test [18]

This is a non-parametric test based on ranks (Pettitt, 1979). The sign function is defined as follows:

$$Signe : \mathbb{R} \rightarrow \{-1, 0, 1\}; \begin{cases} signe(x) = 1, \forall x > 0 \\ signe(x) = -1, \forall x < 0 \\ signe(0) = 0 \end{cases} \quad (10)$$

$$\text{Let } u(t) = \sum_{i=1}^t \sum_{j=t+1}^n signe(x_i - x_j) \text{ and } T = \text{MAX} \{ |u(t)|, t=1, \dots, n \} \quad (11)$$

Let  $p$  be the probability that the test statistic  $T$  on the observed series exceeds the value  $k$ :

$$p = P(T \geq k) \approx 2 \exp\left(\frac{-6k^2}{n^3 + n^2}\right) \quad (12)$$

if  $p < \alpha$  then the null hypothesis is rejected at the  $\alpha$  level considered.

## 3. Results

### 3.1. Data Analysis

Analysis of curves A, B, C and D in **Figure 5** shows that all piezometers installed around the recharge zone of the Cretaceous aquifer show a downward trend in static level. Analysis of the linear trends expressed in % per year under the assumption of a slope equal to 0 in Student's t-test shows that this downward trend in the static level of each of the piezometers is significant or non-significant. In

fact, the trend is qualified as significant if the probability  $p$  of the t-test applied to the regression slope is less than 0.05 or 5%, whereas it is not significant when it exceeds the 0.05 threshold. The drop in static level at the Djacotomè and Dogbo piezometers is insignificant. At Toviklin, however, the drop is statically significant (Figure 6). It is 2.30 m/year at Djacotomè (Figure 6(A)), 1.2 m/year at Dogbo (Figure 6(B)) and 5.1 m/year at Toviklin (Figure 6(C)). At Aplahoué, the trend is towards a non-significant rise of 0.4 m/year (Figure 6(D)). This upward trend

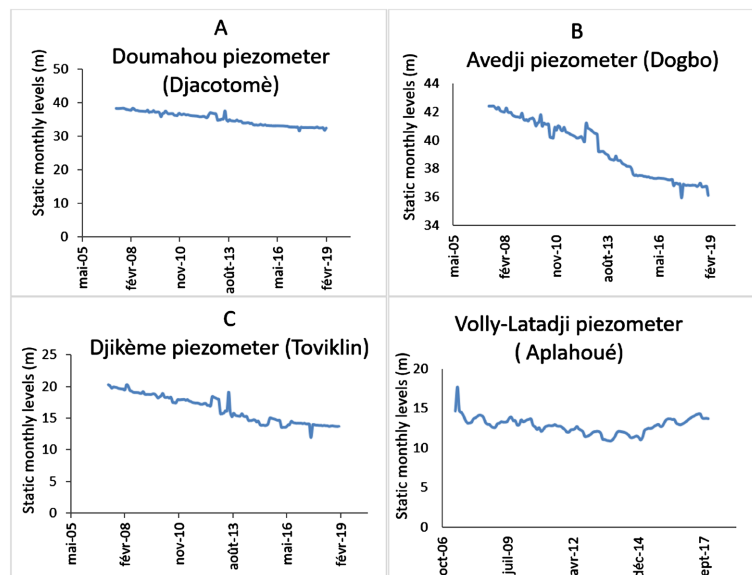


Figure 5. Trends in monthly static levels in 4 piezometers installed around the recharge zone of the Upper Cretaceous aquifer from 2007-2019.

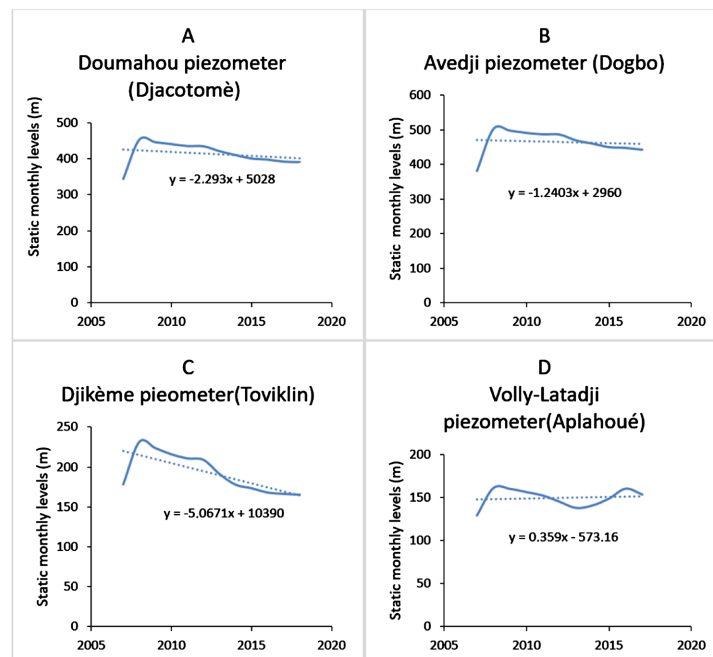
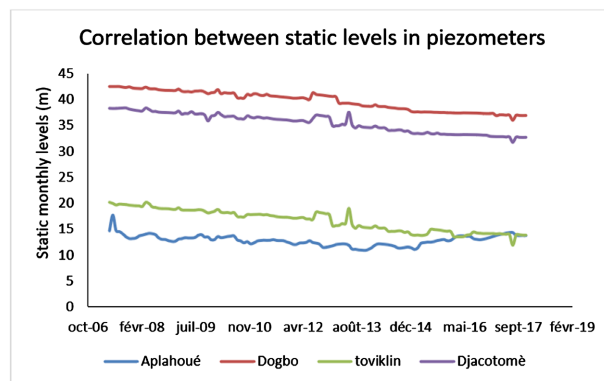
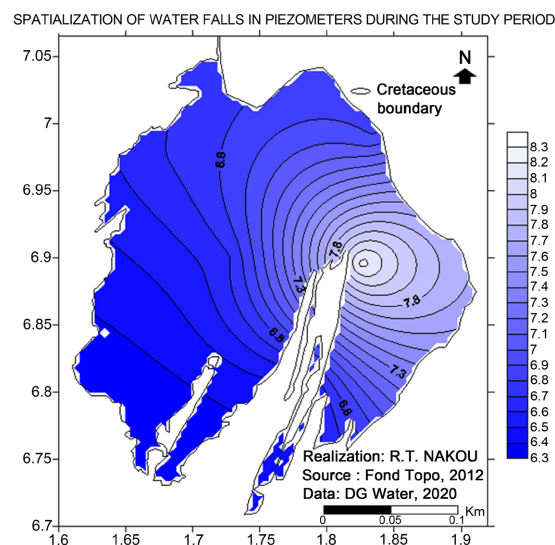


Figure 6. Trends in annual static levels in 4 piezometers installed around the recharge zone of the Upper Cretaceous aquifer from 2007-2019.

in the static level of the Volly-Latadji piezometer at Aplahoué is in contradiction with the others. This contradiction stems from the rise in the static level in this piezometer from the year 2014 onwards, which has continued to the present day (**Figure 7**). Even though the latter is located in the vicinity of the Cretaceous aquifer recharge zone [17], there is no match between its operation and that of the others from 2014 to date. It is not representative of the hydrodynamic functioning of the aquifer. **Figure 8** clearly illustrates the downward trend in static levels in the piezometers of the Upper Cretaceous aquifer over the study period (2007-2020). This figure, which spatializes the difference between maximum and minimum static levels in the piezometers over the study period, shows that all Cretaceous piezometers experienced a drop in static level. This drop ranged from 6.3 m in the north-west and south-west to 8.3 m in the centre-east of the aquifer. The maximum value was recorded in the Toviklin localities, where the Djikémè piezometer registered a maximum value of 8.3 m. The lowest values were recorded in Dogbo and Aplahoué, where the average was 6.3 m. On the aquifer, the average drop recorded was of the order of 7 m. This translates into an average increase of 7 m in the water column of the aquifer's water resources.



**Figure 7.** Correlation between monthly static piezometer levels.



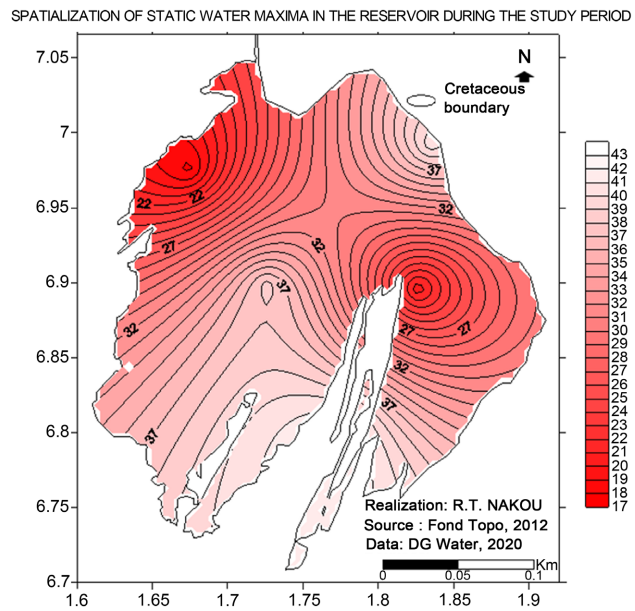
**Figure 8.** Spatialization of differences in static water levels (maxima-minima) in piezometers over the study period (2007-2020).

### 3.2. Analysis of Temporal Stability of Water Levels in Piezometers

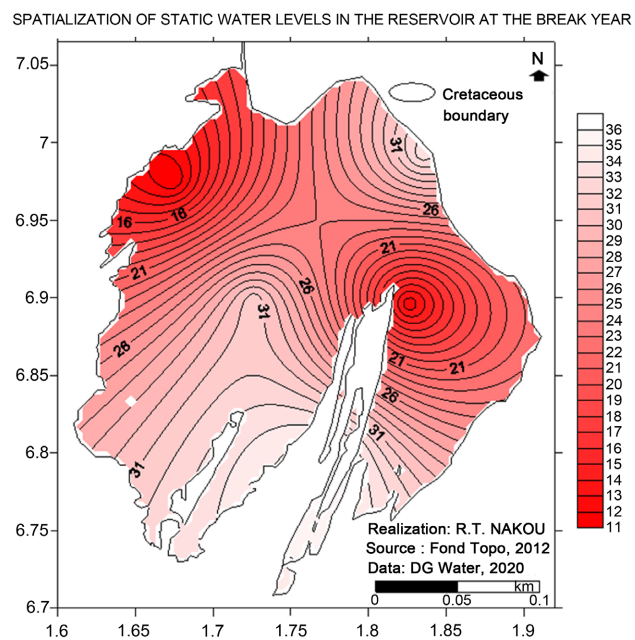
This analysis was made possible by Pettitt's break detection tests and the LEE and HEGHINIAN test. A break is defined as a change in the probability distribution of a time series at a given, usually unknown, point in time [20]. The results of the detection tests are summarized in **Table 1**. Analysis of the results shows that 4 piezometric stations all experienced a break in 2013. This break, which is significant ( $1\% < \text{Péttit test value} < 5\%$ ), reveals two sub-periods over the study period: the sub-period before 2013 (2007-2013) and the sub-period after 2014 (2014 to 2020). Thus, the 2013 to 2020 sub-period shows a static level deficit at all piezometric stations. As a result, water levels in wells and boreholes rose by 23% in Toviklin, 10% in Dogbo and Klouékanmè and 11% in Djacotomè. On the other hand, no break occurred in the data measured at Aplahoué. The absence of a break at this piezometer confirms our analysis that it does not represent the hydrodynamic functioning of the Upper Cretaceous nappe. Furthermore, given the aquifer's geographical position, we should expect an increase in water resources in the area in general. The aquifer is located in the lower Mono River valley in Benin, with its outlet at Athiémé. At this point, the Mono drains a watershed of 21,500 km<sup>2</sup> (86%), with a specific flow rate of 5.34 l/s/km<sup>2</sup> [9]. This outlet is located after the confluence of the main tributaries (Ogou, Anié, Amou and Kra) of the Mono River in Benin [9]. Spatialization of static piezometric maxima over the study period (**Figure 9**) shows that the Cretaceous nappe in the northeast and south experienced the highest static water levels over the period 2007-2020. Indeed, maximum static water levels in the Upper Cretaceous reservoir were recorded in the south at Dogbo (43 m) and in the northeast at Klouékanmè (40 m). These static levels were recorded in 2007. As for static levels in the Upper Cretaceous aquifer at year break (2013) (**Figure 10**), static levels in the aquifer reservoir at this date range from 11 m to 36 m. The lowest values are recorded in the Centre-East of the aquifer and in the North-West in the Aplahoué and Toviklin wells and boreholes, where the Volly-Latadji and Djikème piezometers recorded the lowest values since their installation. In the north-west, for example, the static level is 16 m in Azovè and Kissamè. At the Volly-Latadji piezometer in the extreme north of the Cretaceous, in the Aplahoué localities, the level is 11 m (**Figure 10**). In the south-east

**Table 1.** Statistical tests on static levels of measured piezometers, rupture years and impact after rupture.

Piezometers	LEE Test	Test P value	Pettitt Method	Test P value	Avg (mm) before breakage	Avg (mm) after breakage	Impact in relation to the 2007-2013 period	Type of impact on catchment structures
Djikème (Toviklin)	2013	0.9810	2013	0.0394	19.10	14.66	-23.25%	Increase
Avedji (Dogbo)	2013	0.9010	2012	0.0314	41.558	37.578	-9.58%	Increase
Doumahou (Djacotomè)	2013	0.9505	2013	0.0394	37.614	33.44	-11.09%	Increase
Volly-Latadji (Aplahoué)	-	-	-	-	-	-	-	-
Adjahomè (Klouékanmè)	2013	0.9501	2013	0.0391	37.74	34.118	-9.59%	Increase



**Figure 9.** Spatialization of static maxima in the aquifer reservoir over the study period.



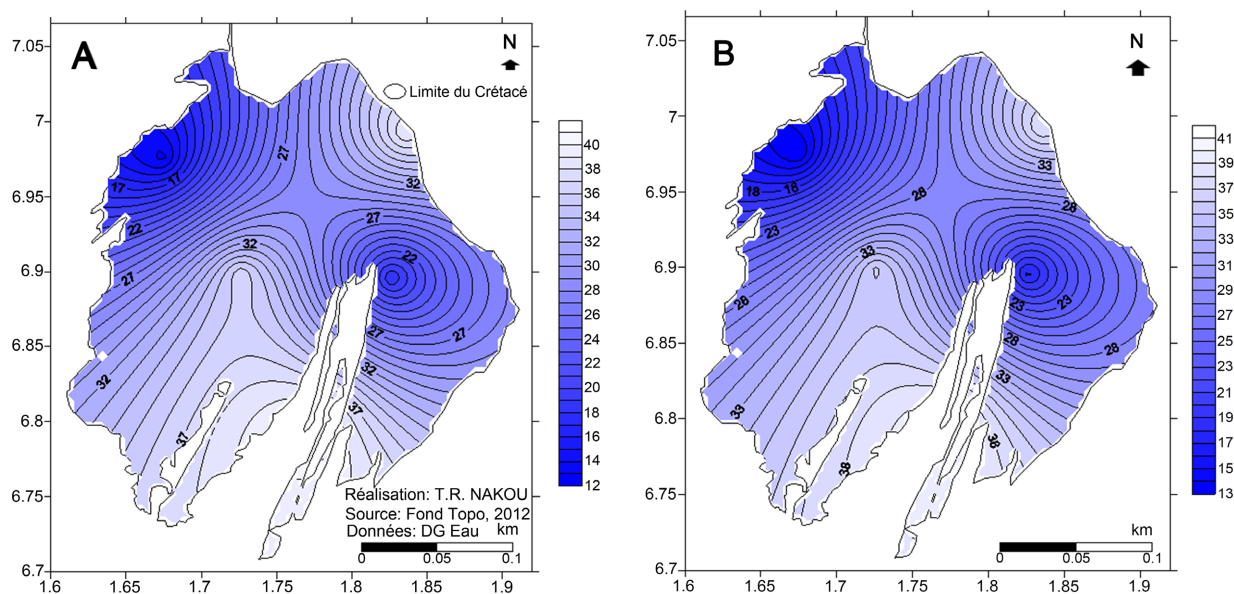
**Figure 10.** Spatialization of static levels in the aquifer reservoir in the year of rupture.

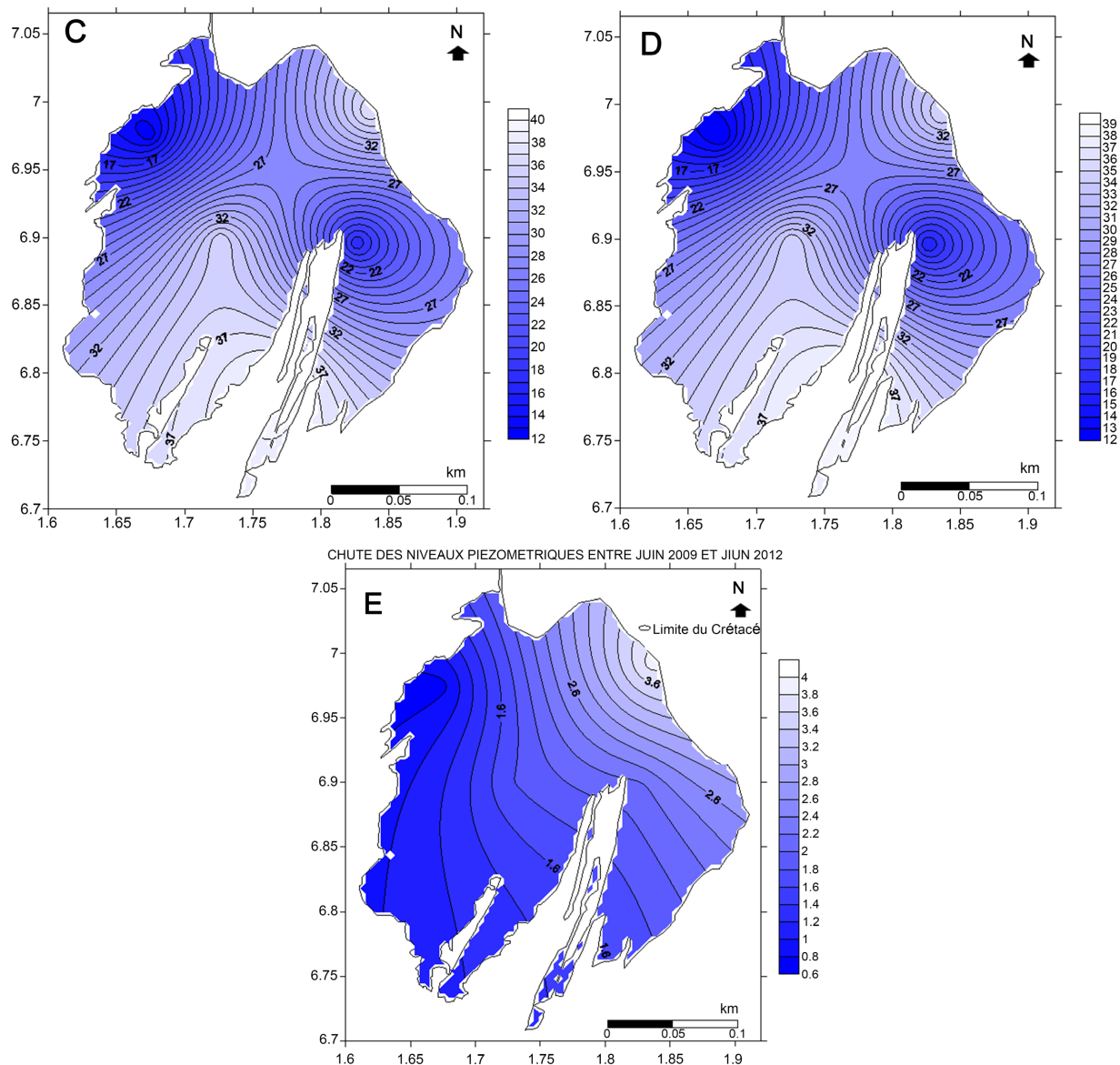
Cretaceous, static levels measured in wells and boreholes fall from 21 m at Avèdji, to 13 m in the Toviklin localities and 12 m at the Djikème piezometer. These results show that the central-eastern and north-western parts of the aquifer received more water that year.

### 3.3. Analysis of Static Levels in Piezometers in the Upper Cretaceous Aquifer

The climatic assessment carried out in the Benin sub-basin of the Mono River by

Amoussou [9] and by Nakou *et al.* [16] revealed two important months in the basin. June is the month of maximum infiltration of water into the sub-basin's underground reservoirs, and February is the month of maximum depletion of the sub-basin's groundwater reserves. The Upper Cretaceous aquifer, which outcrops the Benin River sub-basin to the northeast where its recharge zone is located, reçoit rainwater by infiltration [17]. Maps A, B, C and D in **Figure 11** respectively spatialize the static levels in the aquifer's piezometers during the month of June in 2009, 2010, 2011 and 2012. Map E in the same figure shows the drop in static levels from June 2009 to June 2012. Analysis of maps A, B, C and D reveals a similar trend in static levels in piezometers in the Upper Cretaceous aquifer. Over the months of June 2009 and 2011, static levels in the Cretaceous aquifer ranged from 12 m in the north-west and centre-east to 40 m in the south and north-east of the aquifer, with an average of 29.50 m over the entire aquifer. In 2010, static levels during the month of greatest infiltration in the Cretaceous aquifer ranged from 13 m in the northwest and central-east to 41 m in the south and northeast, with an average of 29 m over the entire aquifer. The month of June 2012 recorded 12 m in the North-West and Centre-East and 39 m in the South and North-East of the aquifer, with an average of 27.40 m over the entire aquifer. There was a 2.1 m drop in the static water level over the average (difference between 29.50 m and 27.40 m) during this short period. This phenomenon is illustrated on map E of the same figure (**Figure 11**). This map, which depicts the drop in static levels in piezometers in the Upper Cretaceous aquifer from June 2009 to June 2012, shows the significance of the phenomenon in the aquifer. Indeed, this 2.1 m drop in static level reflects a 2.1 m increase in water resource levels in the aquifer over this period. This increase in water resources (rise in piezometric levels) is much more pronounced in the extreme north-east of the aquifer. This zone has seen more infiltration during the Upper Cretaceous.





**Figure 11.** Spatialization of static levels in piezometers during the month (June) of maximum water infiltration in the Upper Cretaceous reservoir.

#### 4. Discussion

Water levels in wells and boreholes in the Upper Cretaceous aquifer showed a clear break in 2013, revealing two sub-periods (2007-2013 and 2014-2020). The 2007-2013 period saw less water entering the aquifer than the 2014-2020 period. This situation of the aquifer's water resources could be linked to the rainfall regime of the Benin sub-basin of the river, which has experienced two disruptions. The first was in 1968 [9] [16] and the second in 2007 [16], revealing three sub-periods (1960-1968, 1969-2007, 2008-2018). Compared with the 1960-1968 sub-period, the 2008-2018 period saw a rainfall surplus of 10% [16]. We logically expect an increase in groundwater resources in the Upper Cretaceous aquifer over this recent study period. However, the aquifer's catchment structures experienced

lower water inflows over the 2007-2013 period, before picking up again from 2014 onwards. This situation of groundwater resources during periods of excess rainfall is thought to be linked to the 1969-2007 sub-period, which had a 21% deficit in rainfall compared with the 1960-1968 period [16], which had a negative and prolonged impact on the aquifer's groundwater resources until 2013 (year of rupture), when the aquifer's catchment structures experienced low water levels. Indeed, over the period 1969-2007, the impact of rainfall changes on aquifer recharge in the Benin sub-basin of the Mono River is 84.25% of the recharge deficit, *i.e.*, 4 times [16]. The same result had already been obtained by E Amoussou [21] on the Mono-Ahémé-Couffo complex. In the context of integrated water resource management (IWRM), the author showed by analyzing the variability of runoff and sediment dynamics in the Mono-Ahémé-Couffo watershed over the 1961-2000 period that the rainfall deficits of the 1970s and 1980s multiplied runoff deficits by a factor of 4, resulting in a recharge deficit in the complex. In Côte d'Ivoire, work by Goula *et al.* [22] showed that the hydrological impact of rainfall scarcity was 2 times more intense in the N'zi basin: 49% from 1969-2004 versus 27% in the N'zo basin from 1970-1993. This phenomenon, which seems to have been widespread during this period in all Sudano-Guinean basins, where the drop in runoff coefficients is probably linked to a reduction in groundwater resources, is a consequence of the droughts of the 70s and 80s that hit the region [23], causing many rivers and reservoirs to dry up or run off less. In addition, during this period, particularly between 1969 and 1986, the basin saw a regression of more than 60% in forest formations and wooded savannahs [9], all of which are significant factors in the decline of water resources in the aquifer.

Over the study period and compared with the 2007-2013 sub-period, water levels in the aquifer's catchment structures rose by 23% in the center of the aquifer, 10% in the northeast and south and 11% in the southwest between 2014 and 2020. This situation in the aquifer is a logical consequence of the rainfall and hydrological regimes that have affected the Beninese Mono River basin over the past decade. Indeed, the Beninese Mono River basin has seen a return to wet conditions in recent years. This return to wet conditions began in 2007, when the basin's rainfall regime broke for the second time [16]. However, this increase in the aquifer's water resources contrasts with the reality on the ground, where water levels in wells and boreholes are steadily falling in some parts of the aquifer. This ongoing situation in the aquifer, against a backdrop of high demand for water in the basin, is a cause for concern.

## 5. Conclusion

This study characterizes the behavior of water levels in wells and boreholes in the Upper Cretaceous aquifer reservoir around its recharge zone at the Athiémé outlet. The high correlation between piezometers enabled data to be filled in using linear regression. Analysis of the linear trends expressed in % per year under the assumption of a slope equal to 0 in Student's t-test revealed clear trends in water

measurements in the piezometers installed around the aquifer recharge zone. Finally, the homogeneity of water levels in the aquifer's wells and boreholes around its recharge zone was studied using breakpoint tests. The trend in water levels in wells and boreholes in the communes of Dogbo, Toviklin, Djacotomè and Klouékanmè shows an upward trend, with a significant break recorded in 2013 at all piezometers representative of the hydrodynamic functioning of the aquifer. Compared with the period 2007-2013, water levels in the aquifer's catchment structures rose by an average of 14% in the period 2013-2020. This increase in water resources contradicts the realities on the ground. It would be advisable to investigate the causes of the decline in groundwater resources in the Upper Cretaceous aquifer in order to propose mitigation measures.

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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