



## Hydrodynamic Evaluation of the Cretaceous Aquifer in the Northwestern Part of the Coastal Sedimentary Basin of Benin (West Africa)

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ARTICLE DETAILS	ABSTRACT
<p><b>Article History:</b> Received Date: 23/09/2019 Revised Date: 19/10/2019 Accepted Date: 25/10/2019 e-First: 28/10/2019</p> <p><b>Keywords</b> transmissivity, Mono River, Piezometry, Upper Cretaceous aquifer, Benin</p> <p><b>*Corresponding Author</b> (Prudence Dossou Mahutondji)</p>	<p>The main theme of this study is the knowledge of areas favorable to the mobilization of water resources in the Mono catchment area. The use of numerous methods of underground hydrodynamics combined with mapping has allowed us to have an understanding of the areas of high hydrogeological potentiality of the Upper Cretaceous aquifer in this Mono River basin. The evaluation of the hydrodynamic parameters from the Cooper-Jacob line has shown that the transmissivity values at the north of the Cretaceous aquifer of the Mono river catchment are of the order 10<sup>-4</sup> to 10<sup>-5</sup> m<sup>2</sup> / s. These transmissivities are of middle class and show that Cretaceous is sterile at the north of the coastal sedimentary basin. In the center of the aquifer, the transmissivity values obtained are of the order of 10<sup>-3</sup> m<sup>2</sup> / s with the exception of the drilling of the locality Bébéhoué. These transmissivities are of strong class and prove the good productivity of the Upper Cretaceous aquifer. Piezometry of the study area has shown that the direction of the underground flows of the Cretaceous aquifer is North-South in the Mono River watershed.</p>

### 1. Introduction

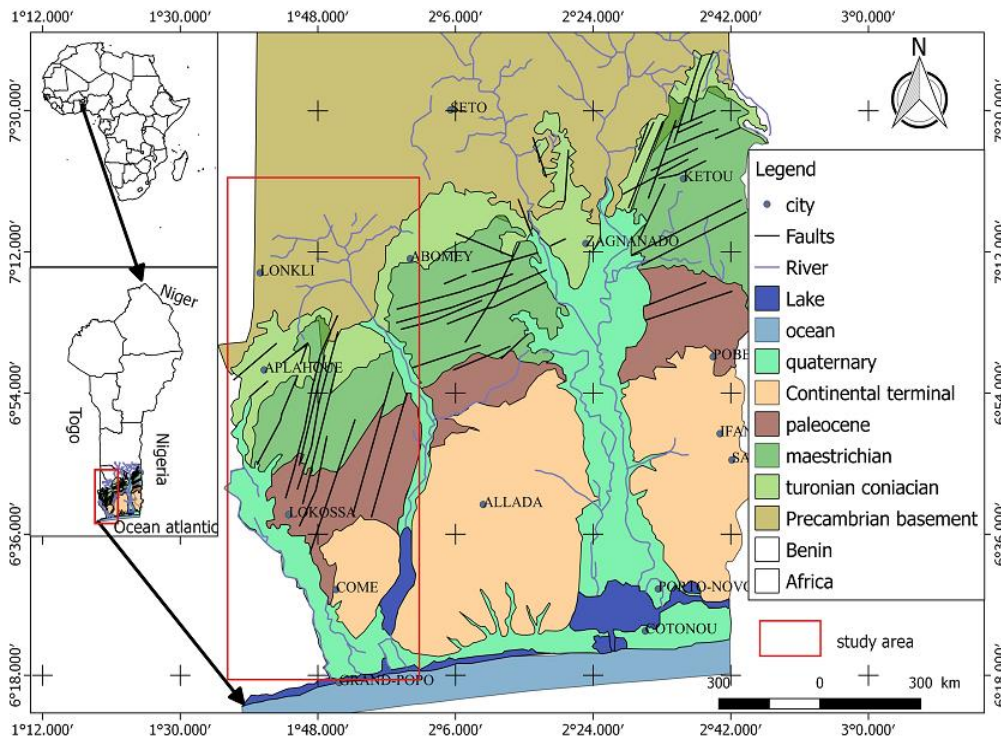
Water is a vital resource for both socio-economic development and ecosystems. In Benin, groundwater reserves are distributed in the geological formations of the sedimentary basins and in the alterites and fractures of the crystalline basement. In the southern part of Benin, the coastal sedimentary basin occupies approximately 10% of the territory and contains about 35% of the country's groundwater resources [1].

The coastal sedimentary basin rests in major unconformity on the crystalline basement (Figure 1). It comprises the Upper Cretaceous, Paleogene, Neogene and Quaternary geological formations that are structured in eight lithostratigraphic units [2], [3], [4]. From a hydrogeological point of view, there are four aquifer levels at the scale of the coastal sedimentary basin (Figure 2). These are, from bottom to top, the aquifers of the Upper Cretaceous, Eo-Paleocene, Mio-Pliocene (Continental Terminal) and Quaternary [5], [6]. From the west to the east of this basin is the watershed of the Mono River, Couffo and Ouémé. Most of the water supply for the populations of the Mono Basin is from the waters of the Upper Cretaceous aquifer [6].

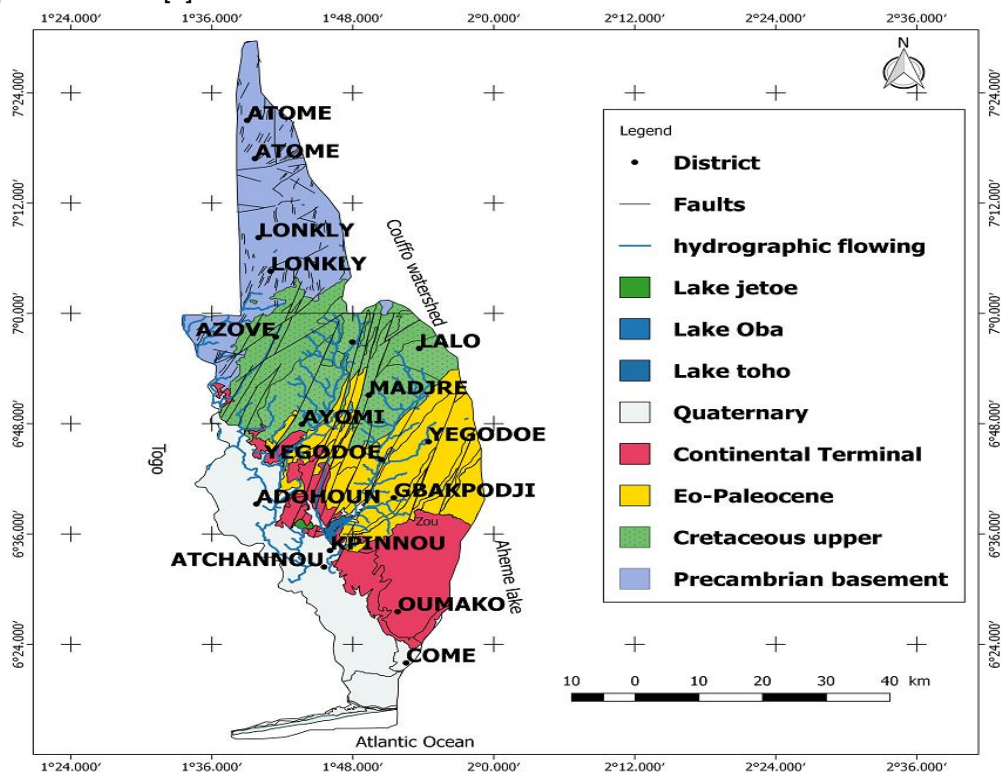
Difficulties associated with groundwater mobilization in this Upper Cretaceous aquifer vary with the geology and the topography [7]. Although the Upper Cretaceous aquifer is present throughout the coastal sedimentary basin, the northern part of this aquifer is bevelled, whereas in the south it is characterized by significant water potential. This difference in the distribution of the water potential of this aquifer raises enormous questions and concerns from the politico-administrative authorities and the populations of this part of the coastal

sedimentary basin. Some drillings are drying up in the North as others are producing abundant water in the South[7]. In the southern part of this aquifer, artesianism is frequent [6] (Figure 2).

The purpose of this article is to explain the causes of the difference in the hydrogeological behavior of the Upper Cretaceous aquifer in the Mono River watershed to be productive in the South and bevel in the North. To do this, the hydrodynamic characteristics of this upper aquifer are studied in its outcrop area, at the scale of the Mono catchment area that covers the study area (Fig. 2). The Mono River watershed is located on the rocks of the coastal sedimentary basin in its southern part and the rocks of the crystalline basement in its northern part [8], [9] (Fig. 2).



**Figure 1.** Geomorphological map of the coastal sedimentary basin of Benin showing the location of the Mono catchment,[10]modified from[2]



**Figure 1.** Hydrogeological map of the Mono catchment in Benin (extracted from the geological sheet at 1/200000 Lokossa-Porto Novo and Abomey-Zangnanado [2]).

## 2. Material and methods

The research methodology adopted for this study aims to characterize the Upper Cretaceous aquifer in order to identify the favorable areas to the mobilization of water resources in the Mono catchment area. It consists essentially of three stages: the collection of long-term pumping test data in the Upper Cretaceous outcrop area, field work for the measurement of static levels of modern wells in the Cretaceous outcrop area and the analysis and processing of the data.

### 2.1. Data collection

As part of this study, six boreholes were studied for the data collection (Figure 4). The collected data relate to long-term (descent) pumping tests carried out in the Upper Cretaceous outcrop area. These are the drawdown ( $s$ ), the duration of the pumping ( $t$ ), the flow rate of the drillings made ( $Q$ ) and the dynamic level ( $ND$ ). These data were collected from the Directorate General of Water (DG-Water).

### 2.2. Field works

Field works started in the month of October and was completed in December 2018. Well identification (Figure 3a) was successful thanks to the coordinates taken at the Directorate General of Water and after, the projection on QGIS. These are modern wells distributed in the Upper Cretaceous outcrop area in the Mono River watershed (Figure 4). Once in the locality, we got informations from the village chief, who leads us to where the well is. To carry out our field research, we used as a differential GPS device to take the geographical coordinates of modern wells, A sound piezometric probe to measure static levels (Figure 3b).



**Figure 3.** Figure showing field equipment: (a) modern well at Ayomi in Dogbo township; (b) piezometric probe

### 2.3. Analysis and data processing

The evaluation of hydrodynamic parameters can be done using long-term pumping test data in order to highlight the hydrodynamic characteristics of the aquifer considered, or with short-term data. The latter makes it possible to have precise and local information on the evaluated work. In this study, long-term pumping test data is used (descent).

The analytical method presented here is the semi-logarithmic graphical method of Cooper-Jacob (1950), (or Jacob's line). It is based on a simplification of the method of Theis (1935). Indeed, we proceeded to:

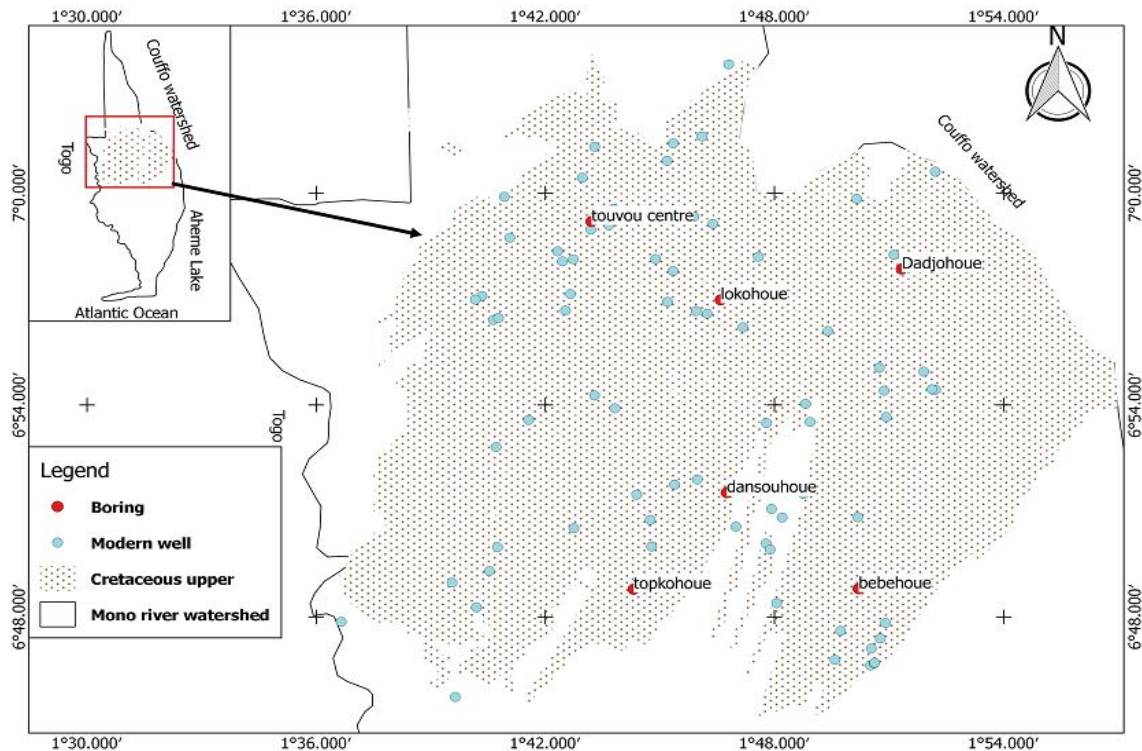
- the input of the data, on a semi-logarithmic graph paper in Excel;
- the drawing of the drawdown curve as a function of time  $s = f(t)$ ;
- a plot of the best-fit line that passes through the majority of these points, ignoring the first data and focusing on the data collected from the middle to the end of the test;
- the determination of  $\Delta s$  (drawdown), which is the difference in water level (in meters) during a logarithmic cycle;
- to the determination of the Transmissivity  $T$  ( $m^2 / s$ ) by relation (1):

$$T = \frac{2.3}{4 \pi \Delta s} * Q \tag{1}$$

With T: Transmissivity, Δs: Jacob's slope and Q: the pumping rate

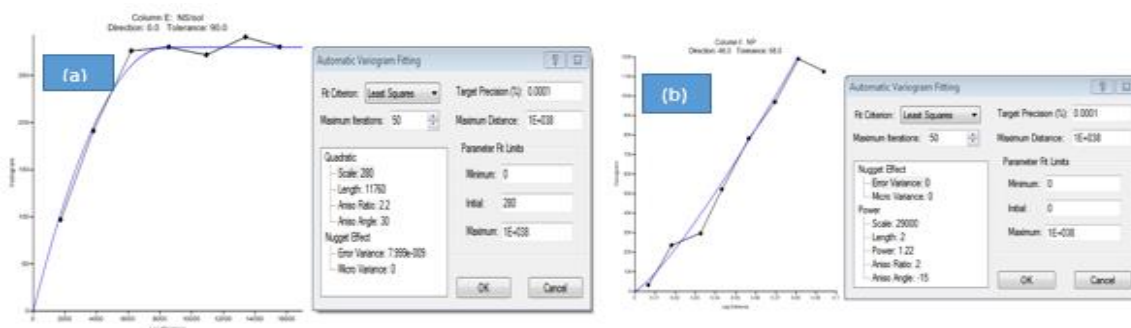
The analysis of transmissivity will be made from the classification of the Inter-African Committee of Hydraulic Studies (C.I.E.H) proposed by [11]:

- low class:  $T < 10^{-5}$  (m<sup>2</sup> / s);
- average class:  $10^{-5} < T < 10^{-4}$  (m<sup>2</sup> / s);
- strong class:  $T > 10^{-4}$  (m<sup>2</sup> / s);



**Figure 4.** Map showing the Upper Cretaceous aquifer, the distribution of boreholes for the study of hydrodynamic parameters and measurement of static well levels.

Static levels collected during the fieldwork are introduced to surf and QGIS to obtain the map of the depth of the Upper Cretaceous nappe in the Mono River basin. The method used is kriging.



**Figure 5.** Variogram of the static level with the adjusted model (a), variogram of the piezometric level with adjusted model (b)

Figure 5 (a) and (b) show that the data are distributed in a normal distribution, centered around the mean. The distribution approaches the quadratic curve (a) and the power curve (b).

The piezometric map is made using static level measurements during field works on the 84 modern wells in the Upper Cretaceous outcrop (Figure 4). The piezometric level is the difference between the altitude of a point considered and its static level measured.

To do this, we used the formula below:

**NP = Z - NS** with, NP: Piezométric level; Z: Altitude; NS: Static level

The altitudes are extracted from the Digital Terrain Model (MNT) using the coordinates of the points of the sampled wells with the QGIS point sampling tool. The choice is focused on the Digital Field Model (source IGN, produced as part of the project carto 1/50000) because of its authenticity and precision. This is a newly developed MNT at a scale of 1 / 50000th with a precision of 2 m. The error is more or less than 0.02 m at each extracted altitude marker. The calculated piezometric levels are introduced in surfer 11 and QGIS in order to obtain the piezometric and static maps after validation with the coefficients of certain statistical parameters such as the NASH and RSR coefficient.

Figure 5 (a) and (b) respectively represent the variograms of the adjusted model of the static and piezometric level. After observing these figures, we see that the model passes through most points. The model chosen for the interpolation of piezometric levels by Kriggeage is the power model. This model adjusted to the raw variogram allowed us to obtain piezometric (2) level values in areas where there are no measurements [12]. For the realization of the piezometric and static maps, the power and quadratic (3) models are used respectively.

➤ Power model

$$\gamma(h) = C_0 + (\alpha - C_0)h^\beta \quad \text{with } \beta \in ]0, 2 [; \text{ This is nugget} \quad (2)$$

➤ Quadratic model

$$\gamma(h) = C_0 + (C - C_0) [ 1 - \exp (-h^2/a^2) ] \quad \text{with } C_0 \text{ nugget ; } C \text{ the landing ; } h \text{ distance} \quad (3)$$

After the visual appreciation of the superposition, the Nash (4) and RSR (5) criteria allowed us to control the adjustment made so that the theoretical variogram better approaches the interesting part of the raw variogram. These are the criteria we used to evaluate the relevance of the adjustment [13]. These criteria are defined as follows:

✓ NSE (Nash coefficient)

$$NSE = 1 - \frac{\left[ \sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2 \right]}{\left[ \sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2 \right]} \quad (4)$$

The adjustment is optimal when the efficiency of Nash coefficient is maximum (close to 1).

✓ RSR (Standard Ration deviation observation)

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[ \sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2 \right]}{\left[ \sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2 \right]} \quad (5)$$

The model is optimal when RSR is less than or equal to 0.70 [13]. This method allows us to identify the best set of parameters (C0, C and a) that characterizes the modeled variogram [12].

Table 1 presents the characteristics of the adjusted variogram of the piezometric level and the static level.

Table 1. characteristics of the adjusted variogram

Treatment	Model	NASH	RSR	R <sup>2</sup>	Appreciation
Piezometric level	Power	0.99	0.02	0.80	Very good
Static level	Quadratic	0.99	0.07	0.03	Very good

### 3. Results

#### 3.1. Summary of the results for the six drillings studied

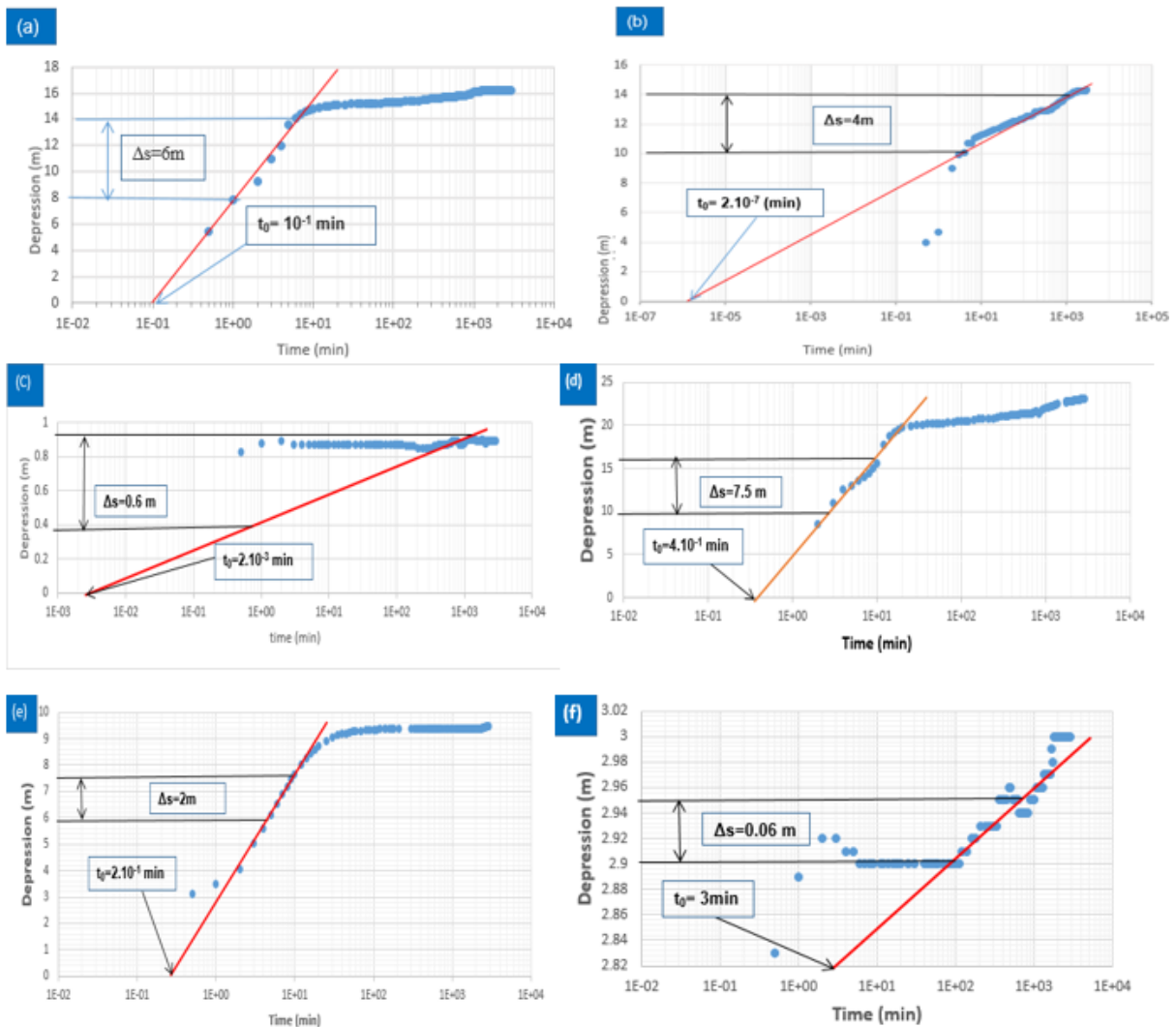


Figure 6. Figure showing the results of the application of the Jacob method to boreholes that capture Upper Cretaceous in the Mono River watershed. (a) Bébéhoué ; (b) Djadjohoué ; (c) Dansouhoué ; (d) Lokohoué ; (e) Touvou-centre ; (f) Tokpohoué.

**Table 2.** Estimated transmissivity values

N° Drilling	Date (test)	Débit (m <sup>3</sup> /h)	Interpretation method	Estimated transmissivity (in 10 <sup>-3</sup> m <sup>2</sup> /s)
Bebehou_M_344	04/ 06/ 14	8.4	Jacob	0.0712
Djadjohoué_M_0097	10/ 06/ 14	12.6		0.1602
Dansouhoué_M_1164	15/ 06/ 14	18.9		1.602
Lokohoué_M_FY_08	21/ 06/ 14	4.72		0.032
Touvou-centre_JM_95-2	24/ 06/ 14	5.04		0.128
Tokpohoué_JM_49	17/ 06/ 14	15.2		12.81

The transmissivity values obtained on the boreholes that are in the north of the aquifer (Djadjohoué, Lokohoué and Touvou-center) are around 10<sup>-4</sup> to 10<sup>-5</sup> m<sup>2</sup> / s (Table 2). According to CIEH, [11], these values belong to the middle class.

The values of transmissivities obtained at the level of the boreholes located in the center and south of the Upper Cretaceous aquifer, that is to say Maiboui, Dansouhoué and Tokpohoué, are around 10<sup>-3</sup> m<sup>2</sup> / with exception to the drilling of Bébéhoué (Table 2). According to CIEH, proposed by [11], these transmissivities belong to the strong class.

### 3.2. Static and Piezometric Level of the Upper Cretaceous Aquifer in the Mono Watershed

Figures 7 and 8 respectively represent the depth maps of the upper Cretaceous surface and piezometric aquifer in the Mono catchment. From Figure 7, it can be seen that the lowest values of the static level (15 to 25 m) are observed in the north and the southwestern edge of the aquifer in the villages of Kodji, Dandjihoué (Aplahoué and Gogounou townships, Dahoué in the Dogbo township). These static level values are indicative of the shallow depth of the crystalline basement in the northern part of the study area. These results are consistent with those obtained in the coastal sedimentary basin [6] which show that the northern part of the Upper Cretaceous aquifer constitutes its recharge zone and generally under the influence of the topography of the zone [7]. The highest values of the static level are observed in the center of the aquifer in the villages of danvlemehoué, Chanvedji, Domi, Bosouhoué, Bitouhoué, Bodjinouhoué, Dakpehoué, and Houhouévigbé in the Djakotomey, Klouékanmey, Dogbo and Toviklin townships with a variation from 35 to 60 m. This suggests that the Upper Cretaceous aquifer becomes thicker as it moves north to south. The lowest values (15 to 10 m) of the static level are observed south-west of the aquifer in depressions located near the Mono River as in the locality of Danhoué and Godohou.

At the opposite of the static level, the piezometric level varies from south to north between 15 m and 200 m (Figure 8). The direction of subsurface flow is generally north-south in the Upper Cretaceous aquifer. At times, the presence of depressions and interruptions changes the direction of underground flow as in the localities of Mamanhoué in Toviklin, Bodjihoué, Tapéhoué and Asahoué. These domes and depressions are observed in the center and east of the aquifer in the Mono River watershed. Artesian drilling is located in this southern portion of the Cretaceous aquifer in the Mono watershed (Figure 2). The low piezometric level values observed in the south of the aquifer in relation to the points of these artesian boreholes show that the manifestations of artesianism are possible in areas of low piezometric level in the Mono River watershed (Figure 2). On the other hand, in the north of the aquifer, piezometry is on average 195 m in areas where the depth of the basement is low. Therefore, artesianism is not possible in areas of high piezometric level in the Mono River watershed.

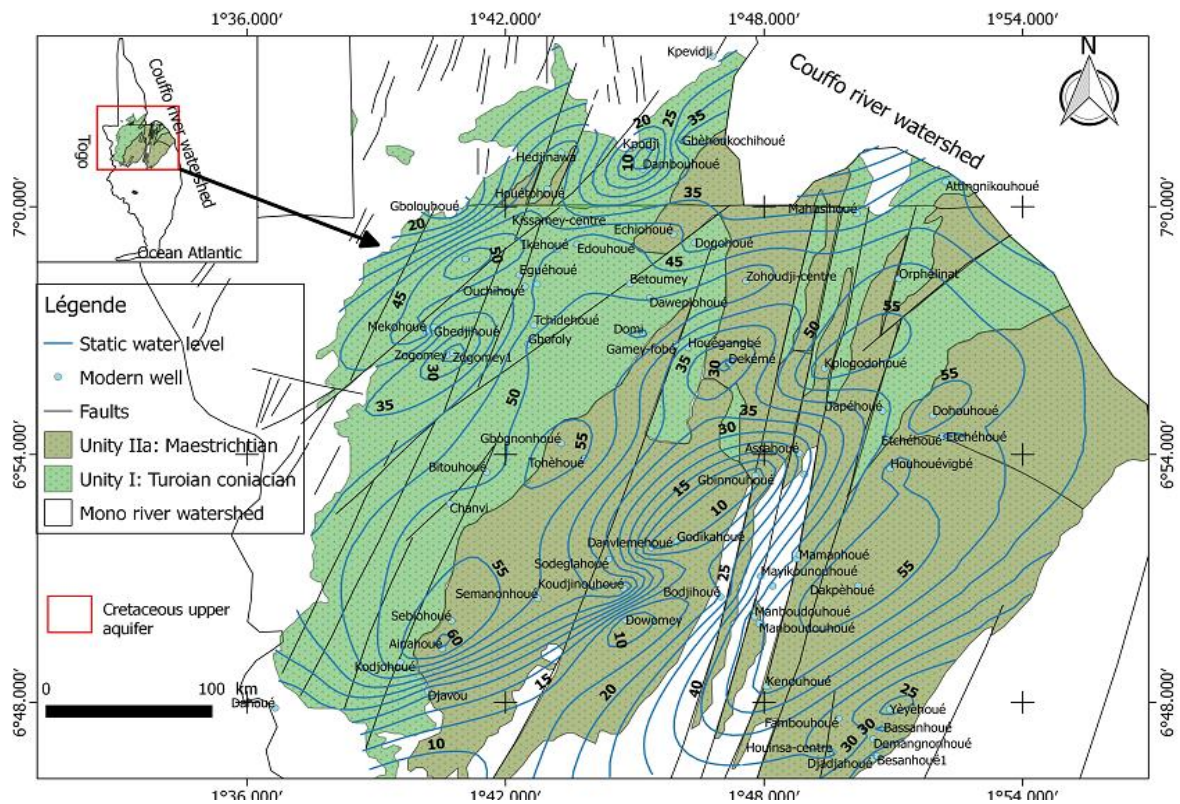


Figure 7. Depth Map of the Upper Cretaceous Water Table in the Mono Watershed

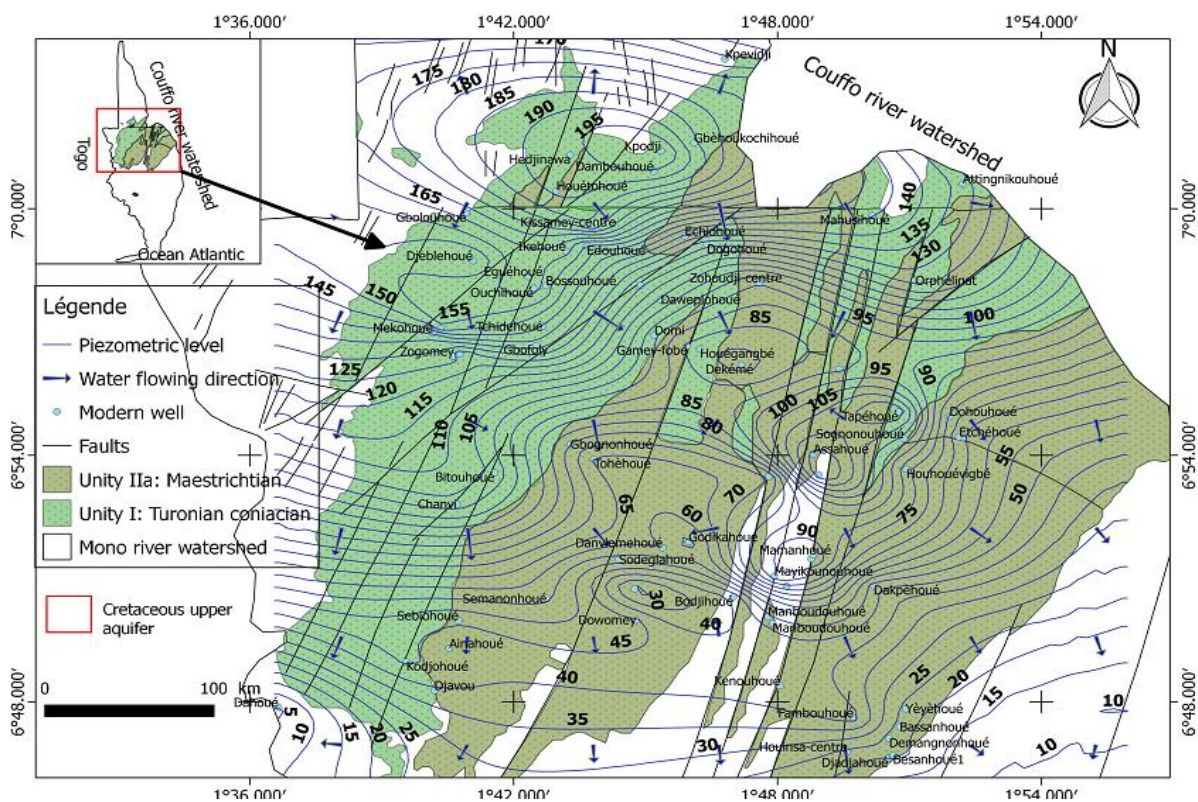


Figure 8. Piezometric map of the upper Cretaceous aquifer in the Mono catchment

#### 4. Discussion

The transmissivity values obtained in the North of the Upper Cretaceous range from  $10^{-4}$  to  $10^{-5}$  m<sup>2</sup> / s. These values belong to the middle class according to CIEH, proposed by [11]. This could explain the dry level of the Upper Cretaceous in its northern part. The Cretaceous is almost sterile in its northern part (the localities of Djadjohoué, Lokohoué and Touvou-center) [6]. According to [14], the hydrogeological formations of the coastal

sedimentary basin slope gently towards the south. As a result, the water and hydraulic potentialities are variable [7]. The West-North part of the sedimentary basin is bevelled while in the south, the hydrogeological reservoirs are in abundance.

According to [15], the transmissivity is the product of the coefficient of permeability and the power of the aquifer. It is defined as the ability of a hydrogeological formation to release water. Recent studies [6] show that the average transmissivity values obtained are due to the geological nature of the Cretaceous sand reservoir and its topography. On the other hand, the values of transmissivity obtained in the south of the aquifer, in the localities of Dansouhoué and Tokpohoué are around  $10^{-3} \text{ m}^2 / \text{s}$ . These transmissivity values are of strong class. This shows the good productivity of the Upper Cretaceous sands. According to [6], these values highlight the good hydrogeological potentialities of Cretaceous. These different results prove that the closer we get to the areas where the Cretaceous is captive (South), the hydrogeological potential becomes important. The southern parts of the Cretaceous aquifer are hydrodynamically favorable areas for the mobilization of water resources. The piezometry of the study area has made it possible to highlight that the direction of the underground flows of the aquifer is North-South. The waters generally flow from high altitudes to low altitudes with direct recharge in the northern part of the aquifer. The low values of the piezometric level observed in the south of the aquifer in relation to the points of these artesian boreholes show that the manifestations of the artesianism are possible in areas of low piezometric level in the Mono River watershed. These results support the research conducted by [6] on Upper Cretaceous artesian boreholes, which states that the artesianism of this aquifer is observable in the low-lying areas of the Lama Depression where the aquifer is located captive.

## 5. Conclusion

This study allowed to use data from pumping tests available on boreholes in the Mono River watershed and the static level to identify areas favorable to the mobilization of Cretaceous water resources in the western part of the coastal sedimentary basin. The areas favorable to the water resource mobilization are located in the southern part of the Upper Cretaceous aquifer. On the other hand, in the northern part, this aquifer which constitutes the main reservoir for the supply is free. As a result, the aquifer bevels in the northern part. To minimize the risk of pollution of this aquifer, we recommend that these areas of medium transmissivity be mapped and protected. This study would propose that the next work of realization of the boreholes in the township respect the scientific standards by capturing the aquifers throughout their thickness. The operating rates of the holes on the plateau are respected.

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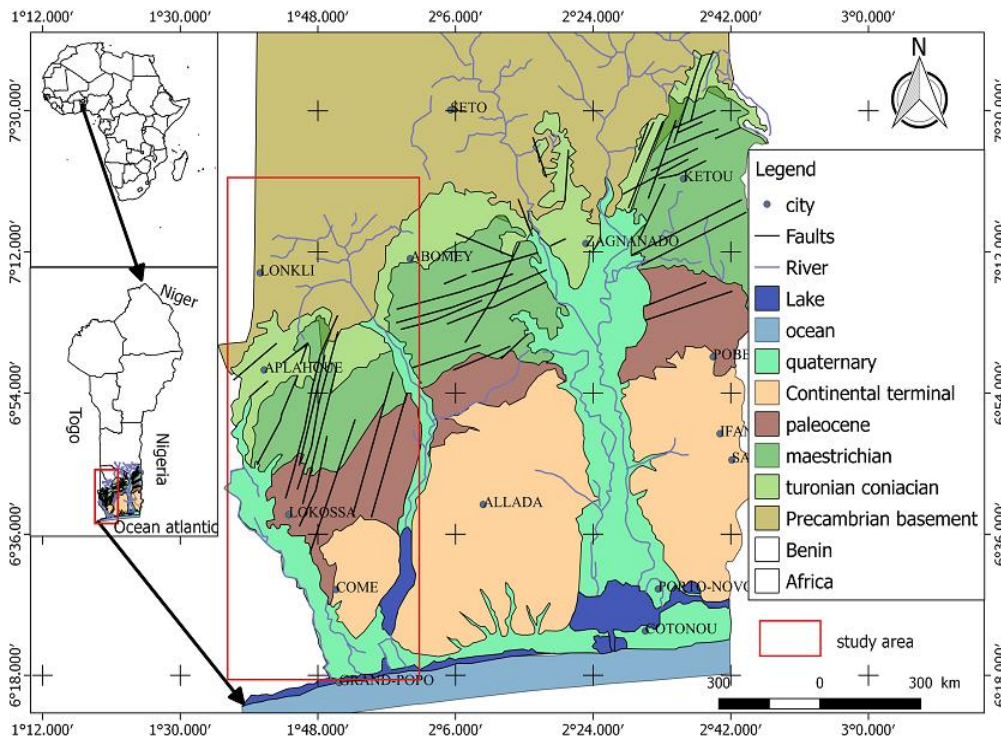
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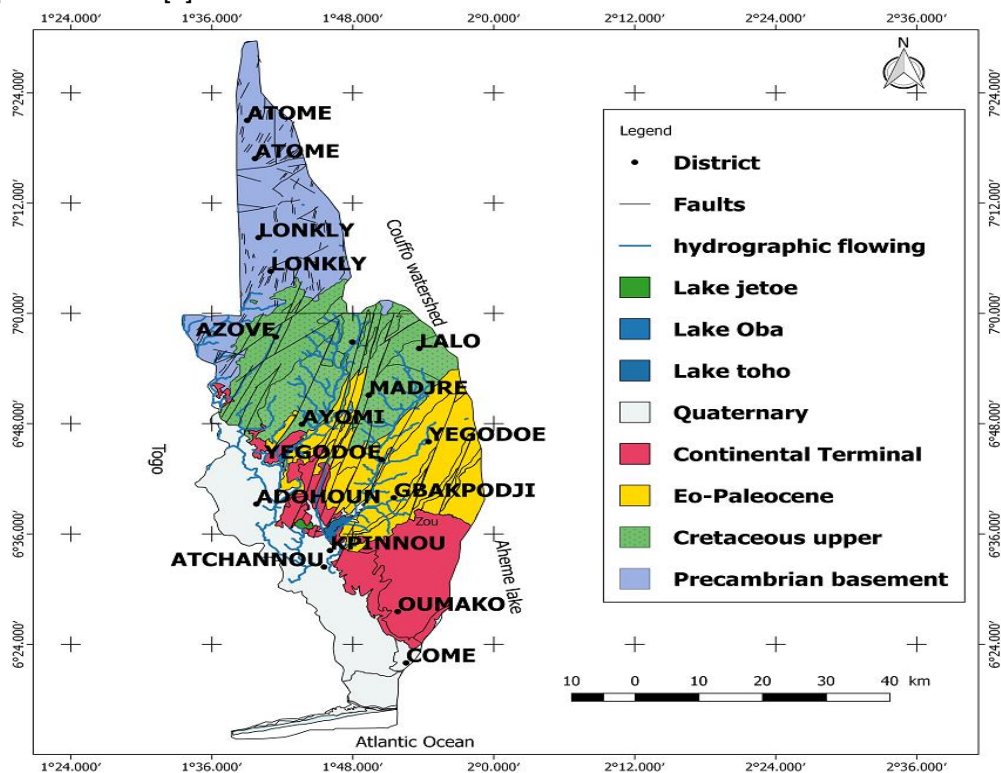
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sedimentary basin. Some drillings are drying up in the North as others are producing abundant water in the South[7]. In the southern part of this aquifer, artesianism is frequent [6] (Figure 2).

The purpose of this article is to explain the causes of the difference in the hydrogeological behavior of the Upper Cretaceous aquifer in the Mono River watershed to be productive in the South and bevel in the North. To do this, the hydrodynamic characteristics of this upper aquifer are studied in its outcrop area, at the scale of the Mono catchment area that covers the study area (Fig. 2). The Mono River watershed is located on the rocks of the coastal sedimentary basin in its southern part and the rocks of the crystalline basement in its northern part [8], [9] (Fig. 2).



**Figure 1.** Geomorphological map of the coastal sedimentary basin of Benin showing the location of the Mono catchment,[10]modified from[2]



**Figure 1.** Hydrogeological map of the Mono catchment in Benin (extracted from the geological sheet at 1/200000 Lokossa-Porto Novo and Abomey-Zangnanado [2]).

## 2. Material and methods

The research methodology adopted for this study aims to characterize the Upper Cretaceous aquifer in order to identify the favorable areas to the mobilization of water resources in the Mono catchment area. It consists essentially of three stages: the collection of long-term pumping test data in the Upper Cretaceous outcrop area, field work for the measurement of static levels of modern wells in the Cretaceous outcrop area and the analysis and processing of the data.

### 2.1. Data collection

As part of this study, six boreholes were studied for the data collection (Figure 4). The collected data relate to long-term (descent) pumping tests carried out in the Upper Cretaceous outcrop area. These are the drawdown (s), the duration of the pumping (t), the flow rate of the drillings made (Q) and the dynamic level (ND). These data were collected from the Directorate General of Water (DG-Water).

### 2.2. Field works

Field works started in the month of October and was completed in December 2018. Well identification (Figure 3a) was successful thanks to the coordinates taken at the Directorate General of Water and after, the projection on QGIS. These are modern wells distributed in the Upper Cretaceous outcrop area in the Mono River watershed (Figure 4). Once in the locality, we got informations from the village chief, who leads us to where the well is. To carry out our field research, we used as a differential GPS device to take the geographical coordinates of modern wells, A sound piezometric probe to measure static levels (Figure 3b).



**Figure 3.** Figure showing field equipment: (a) modern well at Ayomi in Dogbo township; (b) piezometric probe

### 2.3. Analysis and data processing

The evaluation of hydrodynamic parameters can be done using long-term pumping test data in order to highlight the hydrodynamic characteristics of the aquifer considered, or with short-term data. The latter makes it possible to have precise and local information on the evaluated work. In this study, long-term pumping test data is used (descent).

The analytical method presented here is the semi-logarithmic graphical method of Cooper-Jacob (1950), (or Jacob's line). It is based on a simplification of the method of Theis (1935). Indeed, we proceeded to:

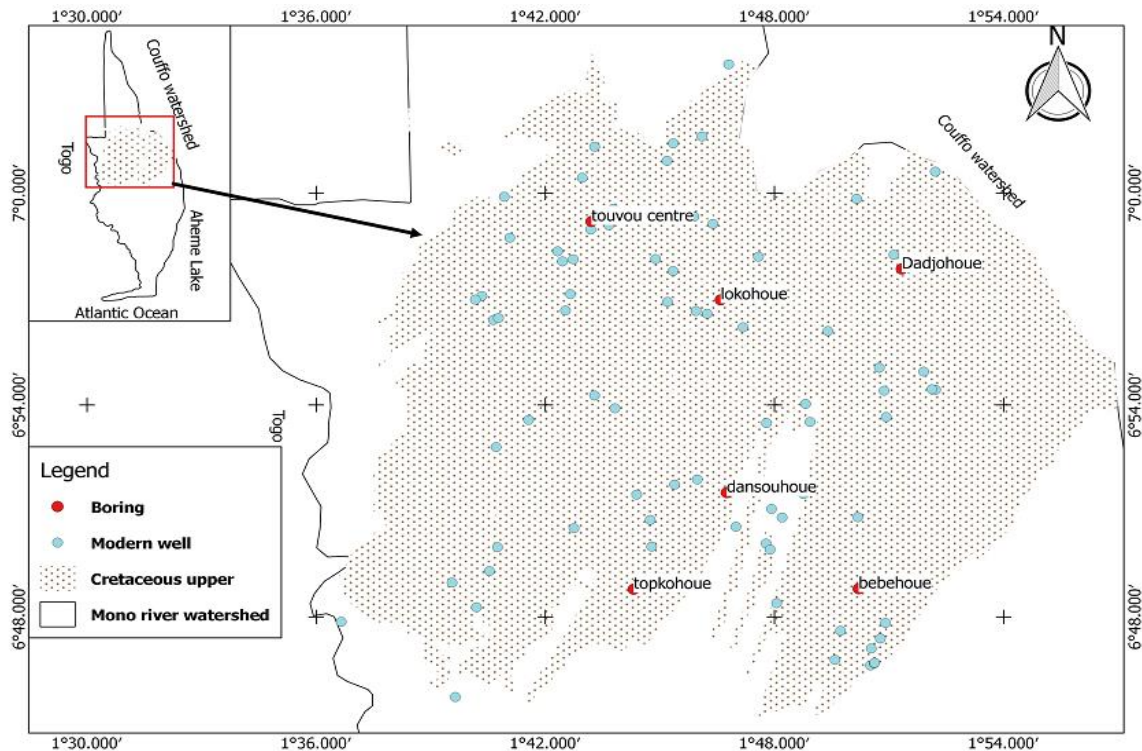
- the input of the data, on a semi-logarithmic graph paper in Excel;
- the drawing of the drawdown curve as a function of time  $s = f(t)$ ;
- a plot of the best-fit line that passes through the majority of these points, ignoring the first data and focusing on the data collected from the middle to the end of the test;
- the determination of  $\Delta s$  (drawdown), which is the difference in water level (in meters) during a logarithmic cycle;
- to the determination of the Transmissivity  $T$  ( $m^2 / s$ ) by relation (1):

$$T = \frac{2.3}{4 \pi \Delta s} * Q \tag{1}$$

With T: Transmissivity, Δs: Jacob's slope and Q: the pumping rate

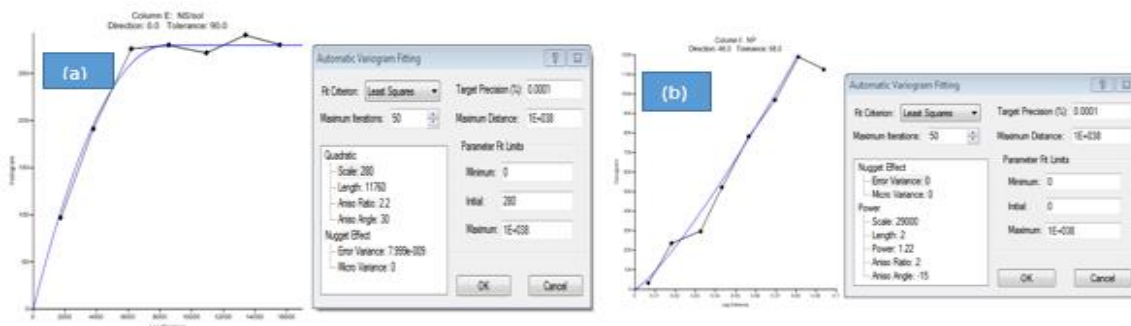
The analysis of transmissivity will be made from the classification of the Inter-African Committee of Hydraulic Studies (C.I.E.H) proposed by [11]:

- low class:  $T < 10^{-5}$  (m<sup>2</sup> / s);
- average class:  $10^{-5} < T < 10^{-4}$  (m<sup>2</sup> / s);
- strong class:  $T > 10^{-4}$  (m<sup>2</sup> / s);



**Figure 4.** Map showing the Upper Cretaceous aquifer, the distribution of boreholes for the study of hydrodynamic parameters and measurement of static well levels.

Static levels collected during the fieldwork are introduced to surf and QGIS to obtain the map of the depth of the Upper Cretaceous nappe in the Mono River basin. The method used is kriging.



**Figure 5.** Variogram of the static level with the adjusted model (a), variogram of the piezometric level with adjusted model (b)

Figure 5 (a) and (b) show that the data are distributed in a normal distribution, centered around the mean. The distribution approaches the quadratic curve (a) and the power curve (b).

The piezometric map is made using static level measurements during field works on the 84 modern wells in the Upper Cretaceous outcrop (Figure 4). The piezometric level is the difference between the altitude of a point considered and its static level measured.

To do this, we used the formula below:

**NP = Z - NS** with, NP: Piezométric level; Z: Altitude; NS: Static level

The altitudes are extracted from the Digital Terrain Model (MNT) using the coordinates of the points of the sampled wells with the QGIS point sampling tool. The choice is focused on the Digital Field Model (source IGN, produced as part of the project carto 1/50000) because of its authenticity and precision. This is a newly developed MNT at a scale of 1 / 50000th with a precision of 2 m. The error is more or less than 0.02 m at each extracted altitude marker. The calculated piezometric levels are introduced in surfer 11 and QGIS in order to obtain the piezometric and static maps after validation with the coefficients of certain statistical parameters such as the NASH and RSR coefficient.

Figure 5 (a) and (b) respectively represent the variograms of the adjusted model of the static and piezometric level. After observing these figures, we see that the model passes through most points. The model chosen for the interpolation of piezometric levels by Kriggeage is the power model. This model adjusted to the raw variogram allowed us to obtain piezometric (2) level values in areas where there are no measurements [12]. For the realization of the piezometric and static maps, the power and quadratic (3) models are used respectively.

➤ Power model

$$\gamma(h) = C_0 + (\alpha - C_0)h^\beta \quad \text{with } \beta \in ]0, 2 [; \text{ This is nugget} \quad (2)$$

➤ Quadratic model

$$\gamma(h) = C_0 + (C - C_0) [ 1 - \exp (-h^2/a^2) ] \quad \text{with } C_0 \text{ nugget ; } C \text{ the landing ; } h \text{ distance} \quad (3)$$

After the visual appreciation of the superposition, the Nash (4) and RSR (5) criteria allowed us to control the adjustment made so that the theoretical variogram better approaches the interesting part of the raw variogram. These are the criteria we used to evaluate the relevance of the adjustment [13]. These criteria are defined as follows:

✓ NSE (Nash coefficient)

$$NSE = 1 - \frac{\left[ \sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2 \right]}{\left[ \sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2 \right]} \quad (4)$$

The adjustment is optimal when the efficiency of Nash coefficient is maximum (close to 1).

✓ RSR (Standard Ration deviation observation)

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[ \sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2} \right]}{\left[ \sqrt{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2} \right]} \quad (5)$$

The model is optimal when RSR is less than or equal to 0.70 [13]. This method allows us to identify the best set of parameters (C0, C and a) that characterizes the modeled variogram [12].

Table 1 presents the characteristics of the adjusted variogram of the piezometric level and the static level.

Table 1. characteristics of the adjusted variogram

Treatment	Model	NASH	RSR	R <sup>2</sup>	Appreciation
Piezometric level	Power	0.99	0.02	0.80	Very good
Static level	Quadratic	0.99	0.07	0.03	Very good

### 3. Results

#### 3.1. Summary of the results for the six drillings studied

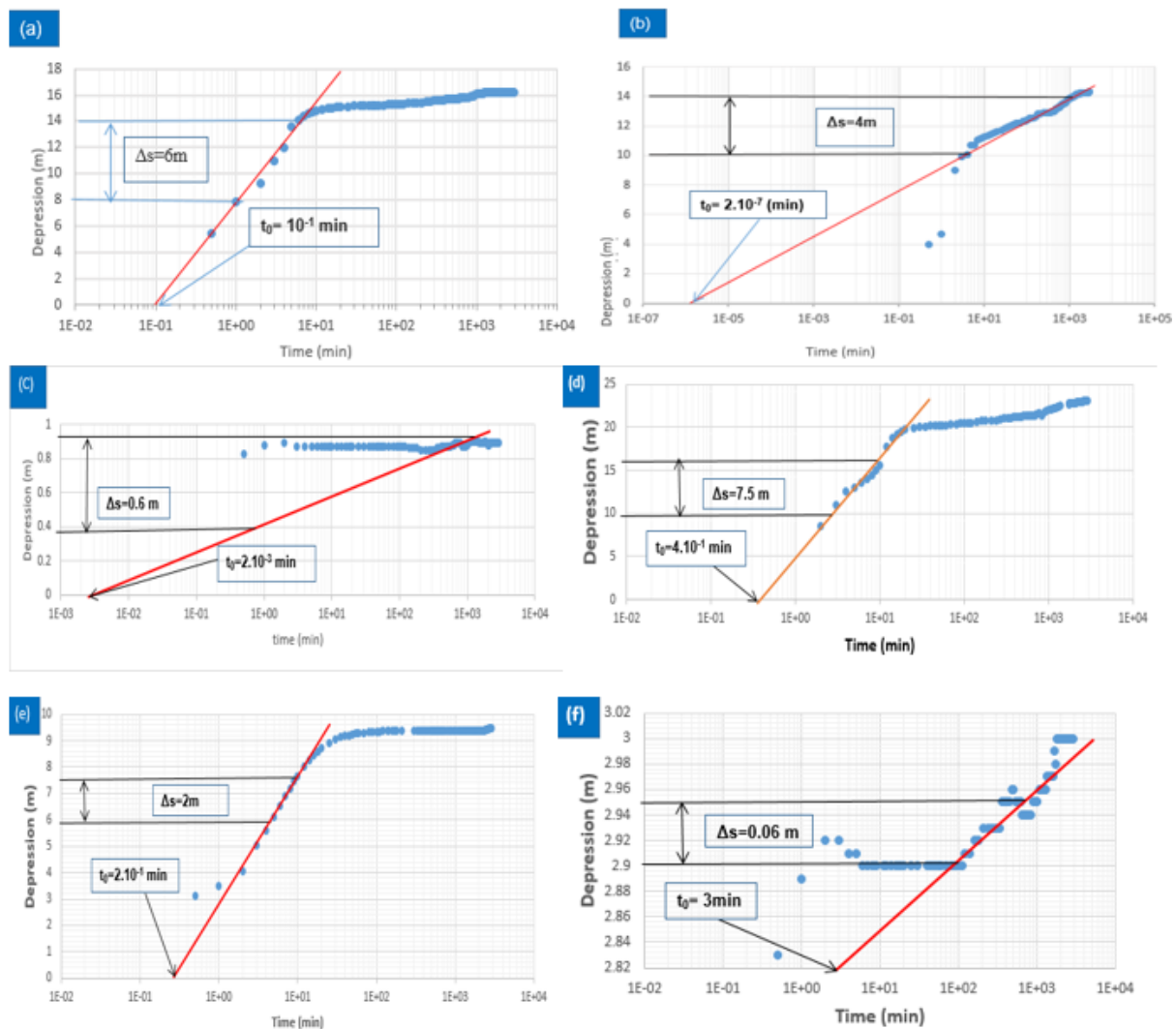


Figure 6. Figure showing the results of the application of the Jacob method to boreholes that capture Upper Cretaceous in the Mono River watershed. (a) Bébéhoué ; (b) Djadjohoué ; (c) Dansouhoué ; (d) Lokohoué ; (e) Touvou-centre ; (f) Tokpohoué.

**Table 2.** Estimated transmissivity values

N° Drilling	Date (test)	Débit (m <sup>3</sup> /h)	Interpretation method	Estimated transmissivity (in 10 <sup>-3</sup> m <sup>2</sup> /s)
Bebehou_M_344	04/ 06/ 14	8.4	Jacob	0.0712
Djadjohoué_M_0097	10/ 06/ 14	12.6		0.1602
Dansouhoué_M_1164	15/ 06/ 14	18.9		1.602
Lokohoué_M_FY_08	21/ 06/ 14	4.72		0.032
Touvou-centre_JM_95-2	24/ 06/ 14	5.04		0.128
Tokpohoué_JM_49	17/ 06/ 14	15.2		12.81

The transmissivity values obtained on the boreholes that are in the north of the aquifer (Djadjohoué, Lokohoué and Touvou-center) are around 10<sup>-4</sup> to 10<sup>-5</sup> m<sup>2</sup> / s (Table 2). According to CIEH, [11], these values belong to the middle class.

The values of transmissivities obtained at the level of the boreholes located in the center and south of the Upper Cretaceous aquifer, that is to say Maiboui, Dansouhoué and Tokpohoué, are around 10<sup>-3</sup> m<sup>2</sup> / with exception to the drilling of Bébéhoué (Table 2). According to CIEH, proposed by [11], these transmissivities belong to the strong class.

### 3.2. Static and Piezometric Level of the Upper Cretaceous Aquifer in the Mono Watershed

Figures 7 and 8 respectively represent the depth maps of the upper Cretaceous surface and piezometric aquifer in the Mono catchment. From Figure 7, it can be seen that the lowest values of the static level (15 to 25 m) are observed in the north and the southwestern edge of the aquifer in the villages of Kodji, Dandjihoué (Aplahoué and Gogounou townships, Dahoué in the Dogbo township). These static level values are indicative of the shallow depth of the crystalline basement in the northern part of the study area. These results are consistent with those obtained in the coastal sedimentary basin [6] which show that the northern part of the Upper Cretaceous aquifer constitutes its recharge zone and generally under the influence of the topography of the zone [7]. The highest values of the static level are observed in the center of the aquifer in the villages of danvlemehoué, Chanvedji, Domi, Bosouhoué, Bitouhoué, Bodjinouhoué, Dakpehoué, and Houhouévigbé in the Djakotomey, Klouékanmey, Dogbo and Toviklin townships with a variation from 35 to 60 m. This suggests that the Upper Cretaceous aquifer becomes thicker as it moves north to south. The lowest values (15 to 10 m) of the static level are observed south-west of the aquifer in depressions located near the Mono River as in the locality of Danhoué and Godohou.

At the opposite of the static level, the piezometric level varies from south to north between 15 m and 200 m (Figure 8). The direction of subsurface flow is generally north-south in the Upper Cretaceous aquifer. At times, the presence of depressions and interruptions changes the direction of underground flow as in the localities of Mamanhoué in Toviklin, Bodjihoué, Tapéhoué and Asahoué. These domes and depressions are observed in the center and east of the aquifer in the Mono River watershed. Artesian drilling is located in this southern portion of the Cretaceous aquifer in the Mono watershed (Figure 2). The low piezometric level values observed in the south of the aquifer in relation to the points of these artesian boreholes show that the manifestations of artesianism are possible in areas of low piezometric level in the Mono River watershed (Figure 2). On the other hand, in the north of the aquifer, piezometry is on average 195 m in areas where the depth of the basement is low. Therefore, artesianism is not possible in areas of high piezometric level in the Mono River watershed.

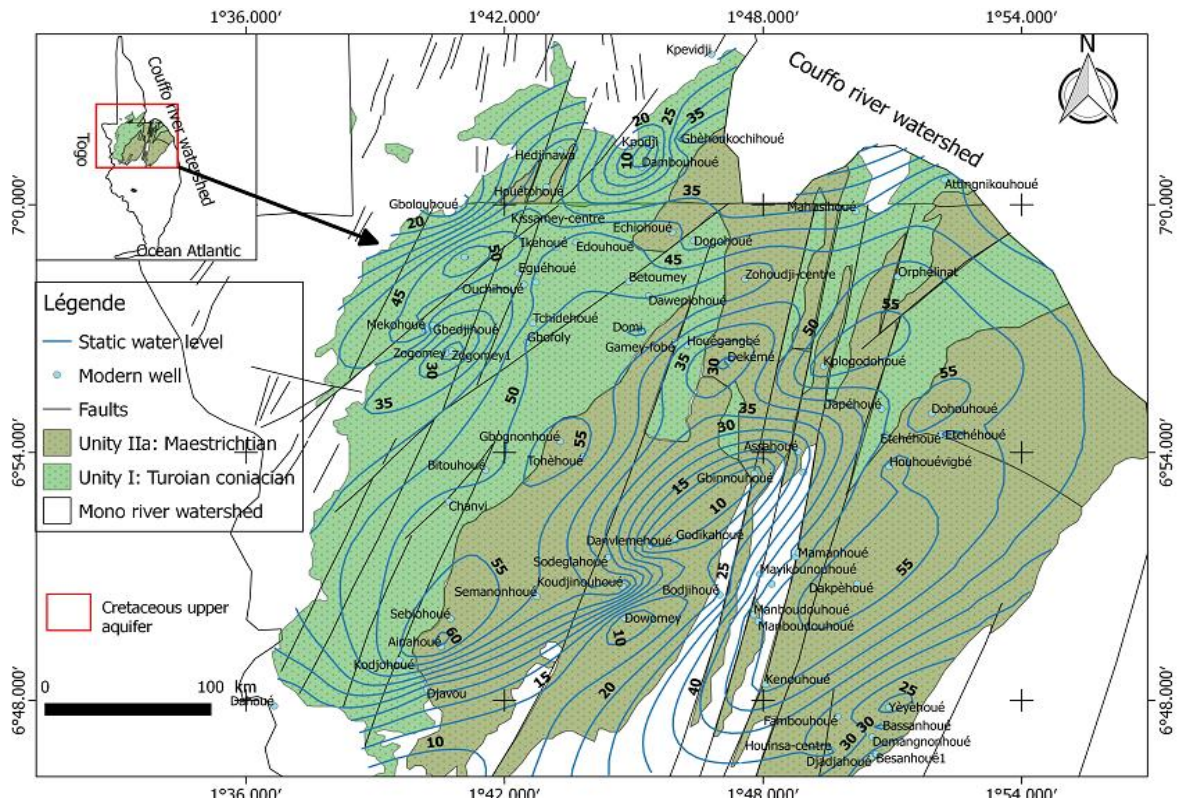


Figure 7. Depth Map of the Upper Cretaceous Water Table in the Mono Watershed

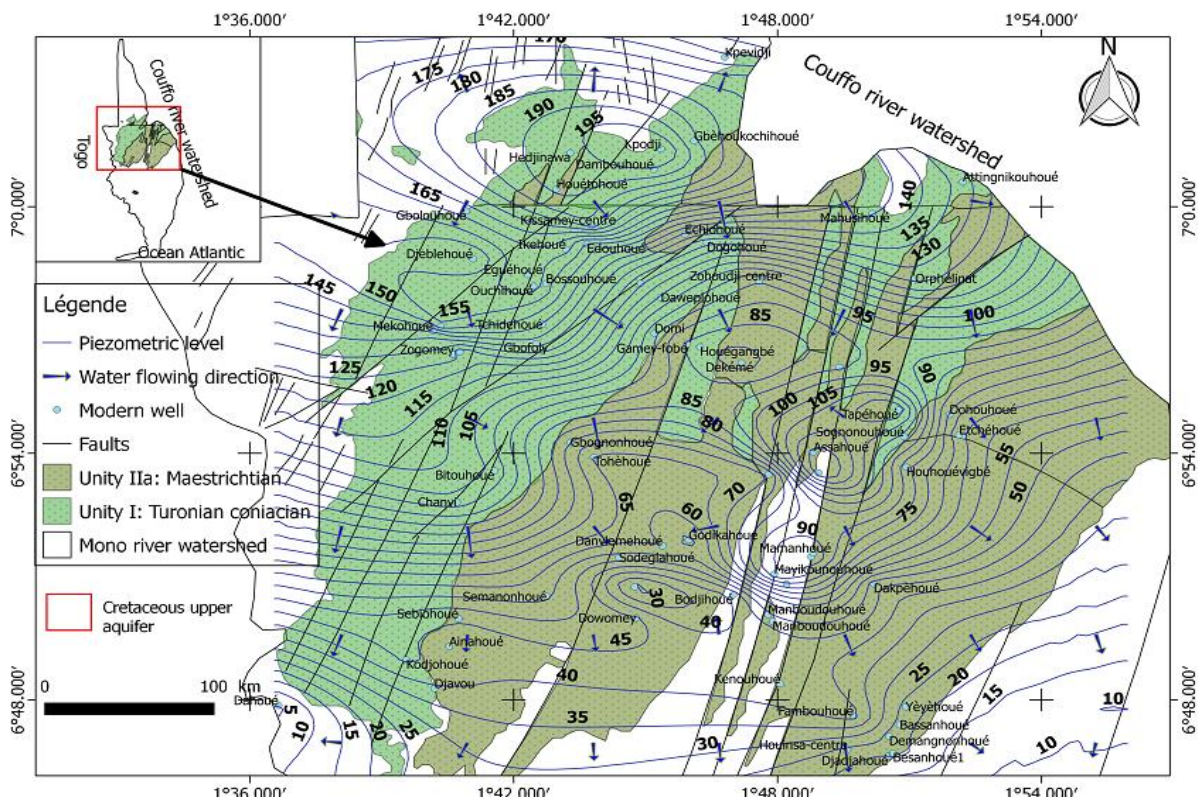


Figure 8. Piezometric map of the upper Cretaceous aquifer in the Mono catchment

#### 4. Discussion

The transmissivity values obtained in the North of the Upper Cretaceous range from  $10^{-4}$  to  $10^{-5}$   $m^2 / s$ . These values belong to the middle class according to CIEH, proposed by [11]. This could explain the dry level of the Upper Cretaceous in its northern part. The Cretaceous is almost sterile in its northern part (the localities of Djadjohoué, Lokohoué and Touvou-center) [6]. According to [14], the hydrogeological formations of the coastal

sedimentary basin slope gently towards the south. As a result, the water and hydraulic potentialities are variable [7]. The West-North part of the sedimentary basin is bevelled while in the south, the hydrogeological reservoirs are in abundance.

According to [15], the transmissivity is the product of the coefficient of permeability and the power of the aquifer. It is defined as the ability of a hydrogeological formation to release water. Recent studies [6] show that the average transmissivity values obtained are due to the geological nature of the Cretaceous sand reservoir and its topography. On the other hand, the values of transmissivity obtained in the south of the aquifer, in the localities of Dansouhoué and Tokpohoué are around  $10^{-3} \text{ m}^2 / \text{s}$ . These transmissivity values are of strong class. This shows the good productivity of the Upper Cretaceous sands. According to [6], these values highlight the good hydrogeological potentialities of Cretaceous. These different results prove that the closer we get to the areas where the Cretaceous is captive (South), the hydrogeological potential becomes important. The southern parts of the Cretaceous aquifer are hydrodynamically favorable areas for the mobilization of water resources. The piezometry of the study area has made it possible to highlight that the direction of the underground flows of the aquifer is North-South. The waters generally flow from high altitudes to low altitudes with direct recharge in the northern part of the aquifer. The low values of the piezometric level observed in the south of the aquifer in relation to the points of these artesian boreholes show that the manifestations of the artesianism are possible in areas of low piezometric level in the Mono River watershed. These results support the research conducted by [6] on Upper Cretaceous artesian boreholes, which states that the artesianism of this aquifer is observable in the low-lying areas of the Lama Depression where the aquifer is located captive.

## 5. Conclusion

This study allowed to use data from pumping tests available on boreholes in the Mono River watershed and the static level to identify areas favorable to the mobilization of Cretaceous water resources in the western part of the coastal sedimentary basin. The areas favorable to the water resource mobilization are located in the southern part of the Upper Cretaceous aquifer. On the other hand, in the northern part, this aquifer which constitutes the main reservoir for the supply is free. As a result, the aquifer bevels in the northern part. To minimize the risk of pollution of this aquifer, we recommend that these areas of medium transmissivity be mapped and protected. This study would propose that the next work of realization of the boreholes in the township respect the scientific standards by capturing the aquifers throughout their thickness. The operating rates of the holes on the plateau are respected.

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