Contribution to Hydrogeological Knowledge of the Turonian-Coniacian Aquifer Exploited in the Coastal Sedimentary Basin of Benin-Togo

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Abstract

Our article contributes to improving hydrogeological knowledge of the Turonian-Coniacian aquifer in the Benin-Togo coastal sedimentary basin by determining the geometry, structure, and piezometry of this aquifer in the northern part of the Benin-Togo coastal sedimentary basin. The structure of the Turonian-Coniacian aquifer was determined through geological and hydrogeological correlation of existing logs from thirty-three boreholes on the northern plateaus of the Benin-Togo coastal sedimentary basin. Three cross-sections were created (in Benin and Togo) using the traditional method, combining topographic maps, graph paper, and QGIS 2.18.15. Piezometry was then carried out in three stages: determination of the altitudes of the measurement points (56 wells), calculation of the piezometric levels, and interpolation of the calculated piezometric levels. The piezometric map was produced successively using Excel, Surfer 11, and QGIS 2.18.15.

A total of five layers were identified following the hydrogeological sections carried out. These are the lateritic layer (2 to 15 m from north to south); the sandy layer (extending up to 25 m); the very thick clay layer (60 m in the south, 200 m in the Lama depression, and almost absent in the north); the clayey-sandy layer (varying from 4 to 25 m in some areas); and the limestone layer (embedded in the clay layer, reaching up to 20 m in thickness). The Coniacian-Turonian aquifer outcrops north of the northern plateaus of the Benin-Togo coastal sedimentary basin. As the flow direction is mainly north-south, it can be deduced that the aquifer is recharged by rainwater infiltration in its outcrop areas.

Although the resource is natural, as is its renewal, it is important that the nations that exploit it, including Benin and Togo, reach a consensus on its efficient use in order to avoid any conflict in the future.

Keywords: Turonian-Coniacian, coastal sedimentary basin, groundwater flow, kriging, SRTM

Introduction

Globally, the issue of water supply is becoming increasingly worrying. Groundwater constitutes the largest reserve of liquid drinking water on the planet and has an annually renewable volume through precipitation infiltration of approximately 8 to 10 million km3, or 98 to 99% of the total (Margat, 1989). In recent decades, this freshwater resource has been affected by phenomena linked to climate change (Holman et al., 2012; Seguin et al., 2019) and socio-economic developments (Mérino, 2009), leading to an explosion in water consumption and, inevitably, a deterioration in its quality. In many regions of Africa, such as Benin and Togo, groundwater is the only reliable source of water. Up to 75% of the population uses groundwater as their main source of

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drinking water, which is accessible at low cost (Nijsten, 2018; Mérino, 2009; Penant, 2016). It is also a vital source of fresh water in all tropical regions, providing access to safe water for domestic, agricultural, and industrial purposes close to the point of demand (Kotchoni et al., 2019).

Translated with DeepL.com (free version)Benin and Togo mainly use groundwater to supply drinking water to their populations, as it is generally of better quality than surface water. However, limited knowledge of the hydrogeological characteristics of the land could seriously jeopardise the preservation of these water resources for future generations (Orou-Pété et al., 2021). The Turonian-Coniacian is one of the four major aquifer units in the Coastal Sedimentary Basin (BSC) and is the deepest. It is tapped in the north of the BSC (where it outcrops) with large-diameter wells; in the Lama depression, it is artesian in nature, and in the south of the BSC. With the uncontrolled spread of urban populations linked to demographic growth, it is urgent to control the reservoir in order to manage it efficiently. The objective is to ensure sustainable management of the resource. Management of this deep aquifer inevitably requires hydrogeological characterization.

The objective of the work is to determine the structure, geometry, and piezometry of the Turonian-Coniacian aquifer.

To achieve our objectives, we asked ourselves the following questions/hypotheses:

- The Turonian-Coniacian aquifer is a continuous layer, regardless of the influence of the dip of the plateaus from Benin to Togo.
- What are the likely areas of renewal for this aquifer?
- How does underground flow occur in the Turonian-Coniacian aquifer?
- Is the Turonian-Coniacian aquifer confined or unconfined?

Study area

Location, Climate, Vegetation, and Soils

The Keta Basin in Benin and Togo is located in the tropical zone between the equator and the Tropic of Cancer, between parallels 6° 10' and 7° 75' north latitude and meridians 1° 0' and 2° 48' east longitude. The study area occupies the southern tip of the two countries, with the Mono River forming the border. Known in Togo as the Togolese Coastal Sedimentary Basin, it covers an area of approximately 3,300 km2, or 6% of the national territory (Gnazou et al., 2015). In Benin, it is known as the Benin Coastal Sedimentary Basin and covers an area of approximately 11,476 km2, or 10% of the national territory (Glodji et al., 2019). The Benin-Togo Coastal Sedimentary Basin (BSCB-T) covers a total area of approximately 14,776 km2 and is bounded to the north by the outcrops of its substrate (Panafrican crystalline basement) and extends southwards into the offshore portion under the Atlantic Ocean,

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widening from west to east, from the border between Ghana and Togo to that between Benin and Nigeria.

The Turonian-Coniacian aquifer that is the subject of our study outcrops north of the BSC Benin and Togo on the four northern plateaus of Benin (Kétou, Zagnanado, Abomey and Aplahoué) and the three in Togo (Kouvé, Tchévié and Fogbé).

The region, which has a subequatorial climate, is characterised by two distinct rainy seasons linked to the movement of the Intertropical Front (a longer rainy season from mid-March to July and a shorter rainy season from mid-September to November) and two dry seasons from August to mid-September and from December to mid-March, respectively (Achidi et al., 2012).

The average annual rainfall recorded at the Bohicon weather station in Benin (from 1922 to 2009) is 1,197 mm, with potential evapotranspiration of approximately 1,500 mm/year (Achidi et al., 2012; Amoussou, 2005) cited by (Kpegli et al., 2018).

Rainfall across the basin is not uniform; it decreases significantly from the northeast (1,445 mm in Tabligbo) to the southwest (864 mm in Lomé). The average monthly temperature varies between 25 and 29 °C in Lomé (Gnazou, 2008). Similarly, rainfall gradients vary from west to east between 900 and 1450 mm in southern Benin (Alassane, 2004). Relative humidity is high, ranging between 65% and the average annual temperature is 27°C but can reach 38°C in the dry season and drop to 19°C in the rainy season (Kpegli et al., 2018).

The original vegetation of the study area (in Benin) is characterised by a mosaic of forests and savannahs, but has been largely replaced by secondary grasslands or savannahs due to human intervention. However, isolated tropical forests (original vegetation), most of which are protected for religious reasons, still exist (Adjakidje, 1984); (Adjanohoun, 1989; Houndagba, 2015) cited by (Kpegli et al., 2018). In Togo, it is mostly covered by wooded savannah (Alassane, 2004). The Togolese portion of the study area extends over an ecological zone characterised by Guinean humid savannahs with patches of humid forests.

According to (Volkoff, 1970) and (Lamouroux, 1966), cited respectively by (Alassane, 2004) and (Gnazou, 2008), the soils of the entire Benin-Togo coastal sedimentary basin include ferralitic soils. These are either ferruginous sesquioxide soils or leached soils with concretions on clayey-sandy or sandy-clayey sediments, or vertisols on clayey sediments. The coastal and alluvial zone is covered with either hydromorphic soils, halomorphic soils leached with alkalis, or poorly developed soils on coastal or alluvial sands. They also include tropical ferruginous soils leached at shallow depths.

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The population of the Togo Sedimentary Basin (BSCT) is approximately 1,164,500 inhabitants, according to data from the National Institute of Statistics and Economic and Demographic Studies (INSEED) on the 2010 general population and housing census. The population of the Benin Sedimentary Basin (BSCB) is estimated based on the populations of the various districts covered by the basin. According to the National Institute of Statistics and Economic Analysis (INSAE), it is approximately 5,271,802 inhabitants, RGPH4-2013. The population of the Benin-Togo Coastal Sedimentary Basin (BSCB-T) is around 6,436,300 inhabitants. Economic activities in the basin are dominated by rain-fed agriculture, crafts and trade. Food crops such as maize and cassava are widely grown. Irrigated rice cultivation is also practised in the Kovié, Mission-Tové, Hon, Yovotonou and Ouinhi areas. The BSCB-T is mainly populated by the Evé, Ouatchi, Fon, Goun, Kotafon, Aïzo, Adja, Mina and Xwla peoples, and a few minority groups such as the Yoruba, Haousa and Nago.

Geomorphologically, the Benin-Togo coastal sedimentary basin is organised on either side of the Lama depression, which runs north-northeast to south-southwest, into a series of sloping plateaus cut by river valleys. This basin is drained by the main rivers of the Zio, Haho, Mono, Couffo, Zou and Ouémé.

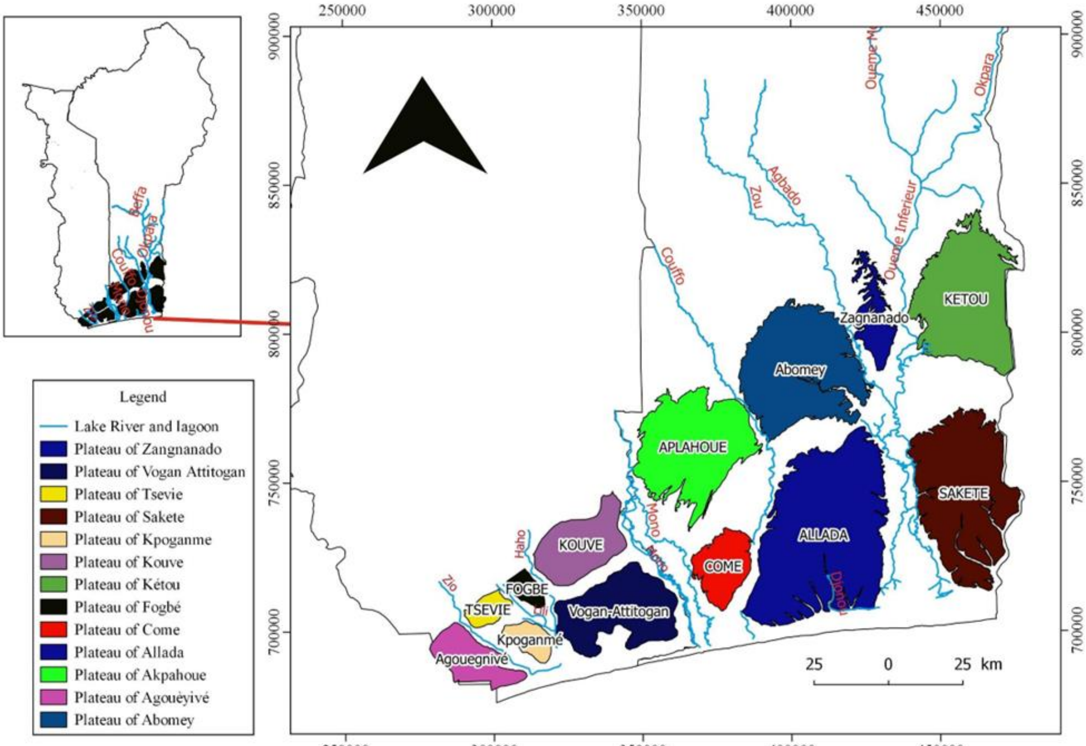

Figure 1: Location of the study area

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Geology and hydrogeology of the Benin and Togo Coastal Sedimentary Basin

From a geological point of view, according to the synthesis of previous studies on the stratigraphy and geology of this basin, reconstructed using seismic, lithological, structural and sedimentological data, as well as numerous hydraulic and petroleum surveys and mineral deposits (Monciardini et al., 1986); (Sylvain et al., 1986); (Johnson, 1987); (Breda, 1987); (Kaki et al., 2001); (Da Costa et al., 2005) and (Oyédé et al., 2006)), the Kéta Basin, which covers Benin and Togo, comprises sedimentary formations (sand, gravel, sandy clay, clay, marl, limestone) dating from the Cretaceous to the Quaternary periods, which have a monoclinal appearance characterised by differential subsidence, increasing towards the south-southeast (Slansky, 1962); (Gnazou, 2015). The sedimentary aquifers of the coastal basin (Kéta Basin) are multi-layer aquifers, which generally have high productivity (Boukari et al., 1994); (Boukari, 1998).

From a hydrogeological perspective, the Coastal Sedimentary Basin contains four aquifers separated by thick aquicludes with low permeability. These are the Quaternary sand aquifer, the Miocene-Pliocene sand aquifer, the Palaeocene limestone aquifer and the Upper Cretaceous (Turonian-Coniacian) sand aquifer. The Quaternary and Miocene-Pliocene aquifers are shallow and can be tapped with large-diameter wells. The Palaeocene and Upper Cretaceous aquifers are deep, but the Upper Cretaceous aquifer (the subject of our study) has the particularity of outcropping in the northern part of the Coastal Sedimentary Basin, where it is recharged.

The Upper Cretaceous aquifer layer resting on the bedrock, fragmented by longitudinal and transverse faults represented by alternating sandy layers of varying thickness, is free-flowing north of the Lama depression (on the northern plateaus) and confined to the south. Its thickness gradually increases from 50 to 60 m in the north to more than 800 m near the coast (Maliki, 1993, cited by Alassane, 2004). In Togo, its thickness varies between 5 and 25 m and is clayey or sandy-clayey in nature. The depth varies between 50 and 120 m in places (Gnazou, 2008).

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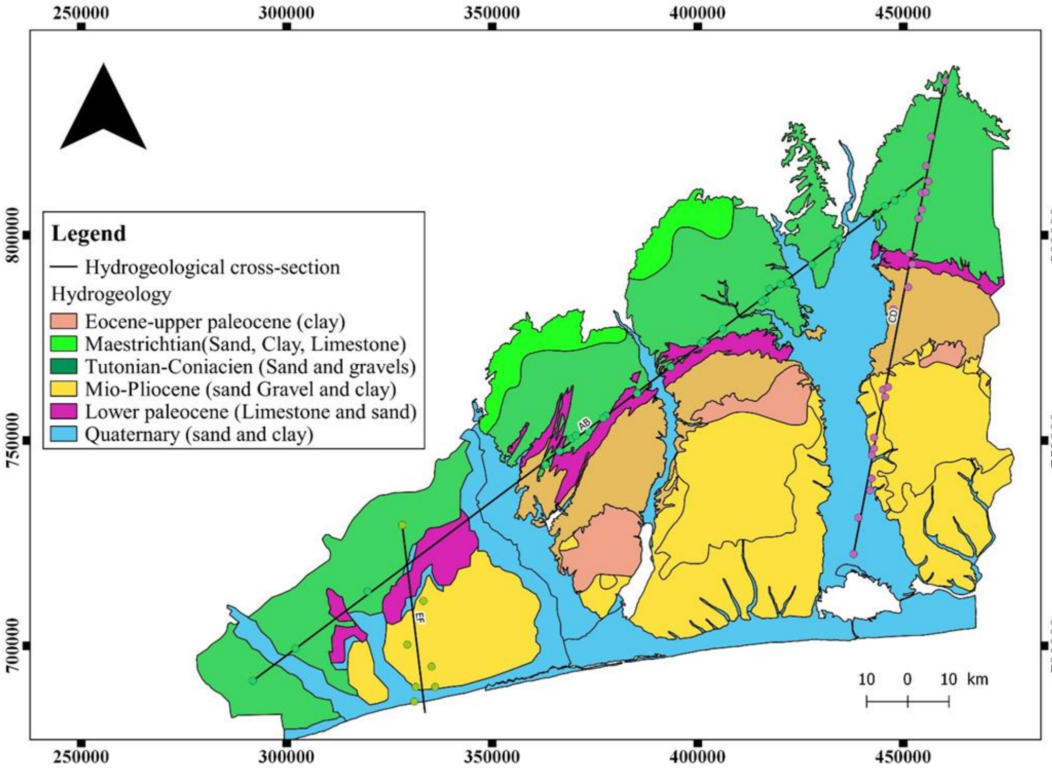

Figure 2: Geology of the Benin-Togo Sedimentary Basin showing the sections to be cut

The Benin and Togo coastal sedimentary basins have been the subject of several geological and hydrogeological investigations. The four aquifer units have been studied by several authors. According to (Dray et al., 1989), it is preferable to exploit the deep, high-quality, well-protected Coniacian Turonian aquifer rather than the surface aquifers, which are prone to frequent contamination problems.

Is this aquifer not being renewed? Where is it recharged? Is it through outcrops or lateral flow?

Our study consists of observing the current behavior of the aquifer, specifying its structure and geometry, and searching for likely areas of resource renewal and its direction of underground flow.

Materials and methods

Data collected and materials used

The data collected initially concerned stratigraphic logs (from boreholes and piezometers), from which those used to produce hydrogeological cross-sections were selected. We then collected topographical maps of the terrain in Benin and Togo from the National

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Geographic Institute (IGN) and the Directorate General of Cartography (DGC) in Lomé, respectively.

We then carried out a field campaign consisting of measuring static levels in 58 large-diameter wells during the high water period (July 2023) in Benin and eight wells in Togo (insignificant for producing a piezometric map) during the same period (July 2023). This piezometric study campaign was carried out over a one-week period to ensure that groundwater levels were comparable. These static levels were used to produce the piezometric map of the aquifer system, which is presented and analyzed below.

During our site work, we used a Garmin GPS (Global Positioning System) to record geographic coordinates in the field, a piezometric probe to measure static levels, Grapher 15 and Excel software for data processing, QGIS 2.18.15 to organize scanned images of lithostratigraphic correlations and hydrogeological sections produced on graph paper, and QGIS and Surfer 11 for map creation and a digital camera for instant photographs.

Méthods

Hydrogeological cross-sections

To determine the structure and geometry of the aquifer captured by the exploitation works, we first carried out a geological identification by creating three (03) cross sections. These are the Benin-Togo (AB), Kouvé-Attitogan (EF), and Kétou Sakété (CD) cross sections (NNE-SSW direction). To produce these sections, the stratigraphic logs from the boreholes were projected in QGIS 2.8.15. Thirty-three (33) drilling logs were used for the three sections: eighteen (18) logs for the Benin-Togo (AB) section, five (05) for the Kouvé-Attitogan section, and ten (10) for the Kétou-Sakété section. To select them, we first sorted the boreholes capturing the Coniacian Turonian in the database of the Directorate General of Water (DGEau), then used those located on or near our various cross-cutting lines from this selection. Next, the topographic profiles and lithostratigraphic correlations between the various stratigraphic logs of the boreholes were drawn on graph paper using the topographic maps mentioned above. The static levels (measured during drilling) were then transferred to the vicinity of the boreholes and, finally, these levels were correlated to obtain the piezometric line of the captured horizon; the sections obtained were scanned, organized, and digitized in QGIS 2.8.15 to be exported as images.

Piezometric surveys

To identify the measuring wells, we started from the data provided by the Directorate General for Water, identifying the wells that capture the Turonian-Coniacian aquifer. Statistical levels (NS) were measured in 56 (fifty-six) wells (large diameter) by first measuring the depth of the water relative to

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the well coping using a piezometric probe, then subtracting the height of the rim. Next, the geographical coordinates (X and Y) were recorded at each well using a GPS device.

The piezometric map were created in three stages: determining the altitudes of the measurement points, calculating the piezometric levels, and interpolating the calculated piezometric levels. We began by determining the altitudes of the measurement points.

The piezometric level is the static level relative to mean sea level (0). As we were unable to level all our measurement points and could not rely on the low accuracy of the Z altitudes recorded by GPS in the field, we determined them using an equation (3) that was established through a correlation between the altitude values of the IGN Benin geodetic markers located within and near the study area, and the altitude values of these geodetic benchmarks extracted from a global 1-arc second SRTM Digital Terrain Model (DTM) (DTM with a spatial resolution of 30m x 30m, downloaded from the website https://ers.cr.usgs.gov/ already mentioned above).

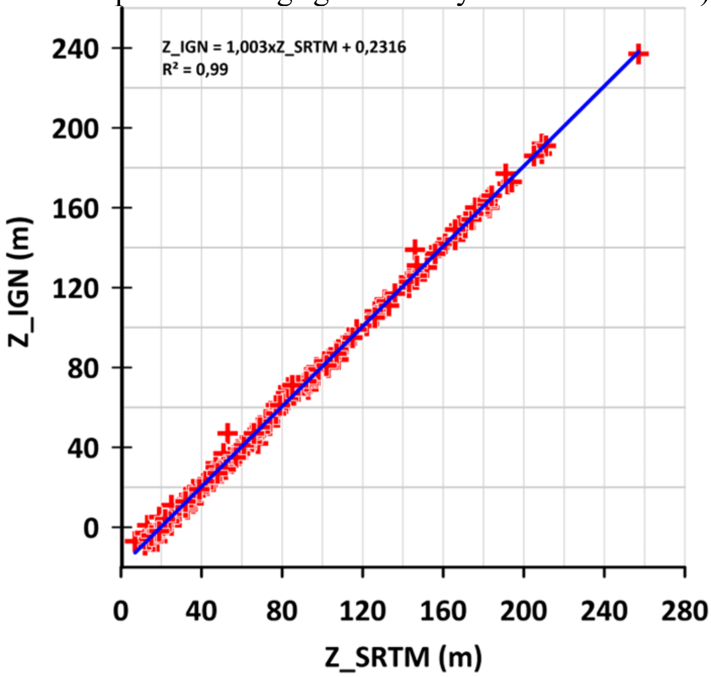

Figure 3: Correlation line between IGN altitudes and SRTM altitudes

We then calculated the piezometric levels (Np) using the formula

$$Np = Z - Ns/sol$$

Equation (1)

Replacing Z with its value in equation (1), we obtained:

$$Np = (1.003 * Z\_MNT + 0.2316) - Ns/sol$$

Equation (2)

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With NP (m): the piezometric level, Z: the estimated altitude of the measurement point; Z_MNT: the altitude of the point from the SRTM 1Arc global DTM source at https://ers.cr.usgs.gov/ and NS: the static level measured relative to the ground.

The advantage of RSR is that it normalizes the root mean square error (RMSE) by the standard deviation of the components concerned (Moriasi et al., 2007). The values of the comparison criteria between the experimental variogram and the modeled variogram are presented in Table 1.

Table 1: Values of parameters for comparing measured piezometric levels and those estimated from the DTM

MNT	NSE	RSR	R^2	Taux de performance du NSE	Taux de performance du RSR
SRTM	0,9978	0,046	0,9982	Satisfaisant	très bien
CGIAR	0,3147	0,82	0,4912	Insatisfaisant	mauvais
GTOPO30	0,8148	0,43	0,22	Satisfaisant	bien

For plotting the iso-value curves, the interpolation method chosen is kriging, as the results can be checked using distance variograms, (Orou pété et al., 2021). According to (Matheron, 1965), cited in (Orou pété et al.,2021), the theoretical variogram is only representative of the empirical variogram in the vicinity of the origin. The power model is the one that best fits our piezometric level values.

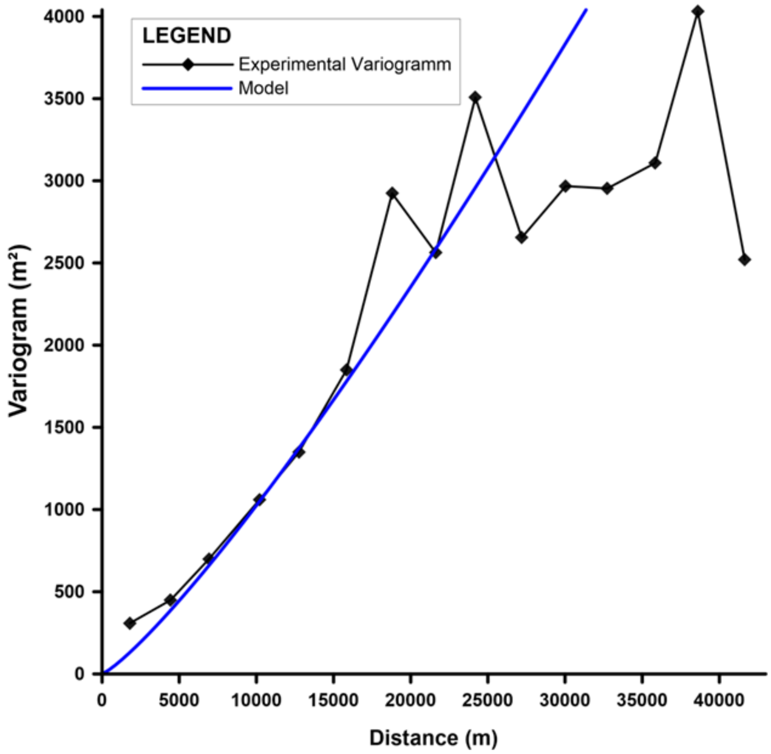

Figure 4: Adjusted distance variograms for piezometric levels

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The formula for the power adjustment model is as follows:

$$\gamma(h) = 1{,}5+bh^{1{,}99}$$ **with b: the slope of the straight line.**

In Togo, this approach could have been applied if we had not been limited by the availability of functional wells. Piezometry was only possible in Benin in this case. Nevertheless, (Gnazou, 2015) addressed the piezometry of the Paleocene aquifer, which seems to reflect, given the relief and dip of the plateaus, the flow of water over the coastal sedimentary basin of Togo.

Results

Geological and hydrogeological identification of the aquifer being exploited

Based on the lithological cross-sections collected from boreholes, three hydrogeological cross-sections were produced in the following directions: South-West to North-East (Togo-Benin); North-North-West to South-South-East (Kouvé-Atitogan); NN East–SS West (Kétou-Sakété). The hydrogeological sections obtained are shown in Figures 5, 6 and 7.

Five (05) more or less continuous layers of different lithology are crossed by the correlated boreholes. They consist of a surface layer of laterite (1 to 7 m), a clay layer dating from the Maastrichtian, sandy layers, a clay-sandy layer, and limestone. The thickness of the layers varies depending on the location of the sections. In the section leaving Benin, the lateritic layer is superficial, ranging from 1 to 7 m, while the clay layer, which gradually thickens in the Lama depression in Benin, narrows north of Kétou and varies between 3 m and 35 m. The sandy layer varies between 3 and 20 m in Togo, 5 to 10 m in the Lama depression in Benin, and outcrops north of Kétou.

For the Kouvé-Atitogan and Kétou-Sakété sections, the clayey-sandy layer is 4 to 25 m thick, the sand up to 10 m, and two limestone levels are encountered (2 to 20 m each). The clay layer reaches a thickness of 150 to 200 m in the south (in the Lama depression) and decreases until it disappears in the north.

The sandy layer (which appears to have two levels in Togo) is a Turonian-Coniacian formation (Cretaceous sand), while the limestone layer between the thick clay layers is a Palaeocene formation.(Monciardini et al., 1986). The sandy layer has a section that outcrops (and is therefore unconfined) to the north of the plateaus and gradually sinks towards the south until it disappears completely under the thick clay layers, making the aquifer confined. The Palaeocene limestone aquifer is confined from south to north of the Coastal Sedimentary Basin.

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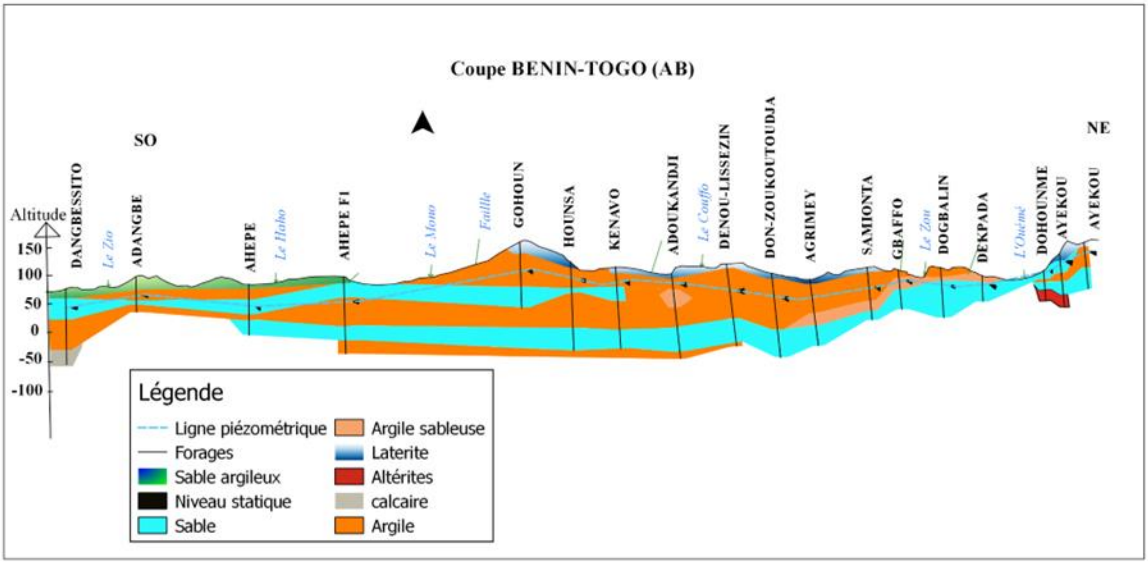

Figure 5: Hydrogeological cross-section of Benin-Togo

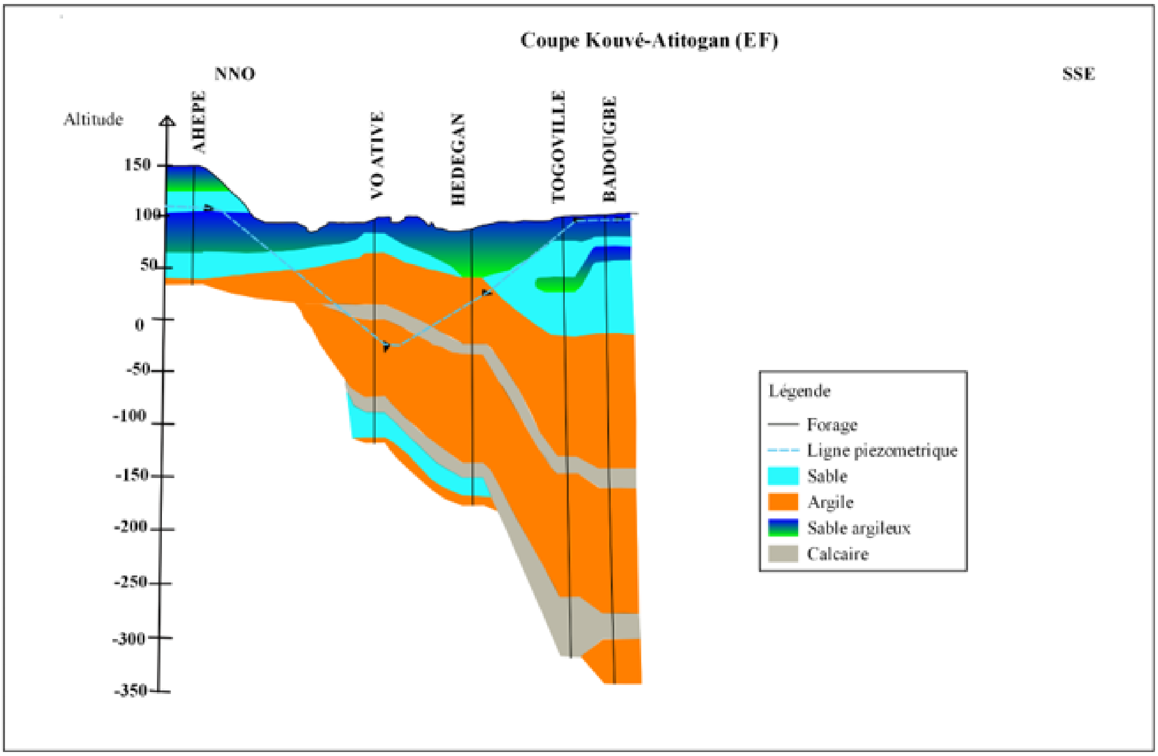

Figure 6: Hydrogeological cross-section of Kouvé-Atitogan

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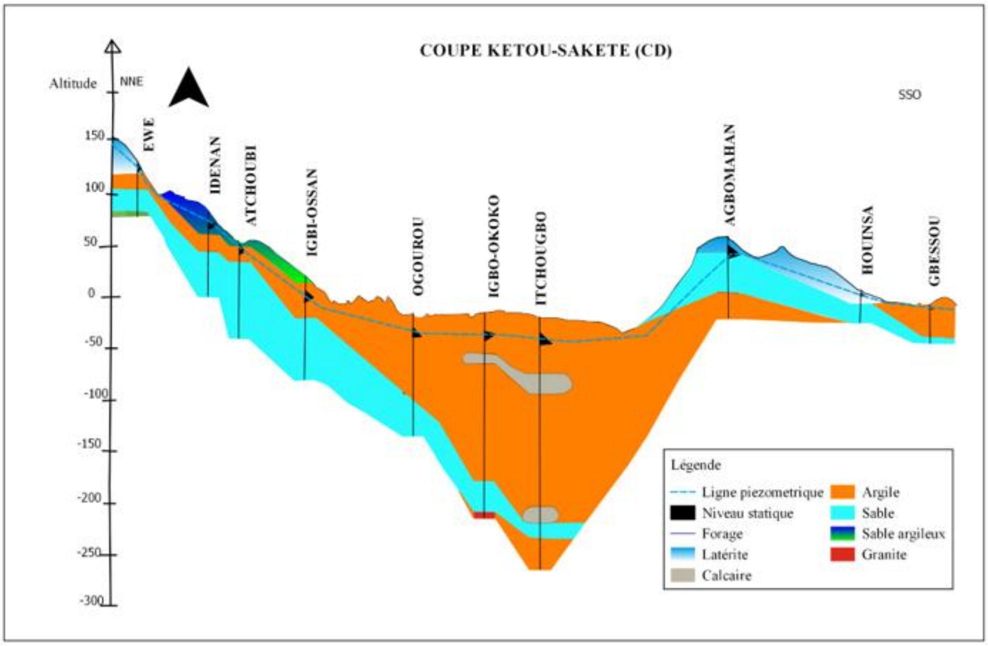

Figure 7: Hydrogeological cross-section of Kétou-Sakété

Piezometry

Piezometric surveys of the aquifer (Figure 8) were only possible for the Beninese part, given the unrepresentative nature of the wells due to their virtual absence in our study area in Togo. The flow directions are multidirectional and differ from one plateau to another. We have a first recharge zone located north of the study area (north of the Kétou plateau) at an altitude of approximately 120 m and a second recharge zone located on the Zagnanado plateau, from where groundwater flows mainly southward. The highest altitude on this plateau is 180 m, compared to 40 m in the depression zone. Observing the direction of flow, groundwater diverges locally on this central plateau towards the Zou and Ouémé river valleys. A recharge zone located northwest of the northern plateau of Abomey, from where groundwater generally flows towards the southeast. The fourth recharge zone is located to the northeast, on the Aplahoué plateau (Kpégli et al., 2018). On these last two plateaus, the highest point is 200 m above sea level.

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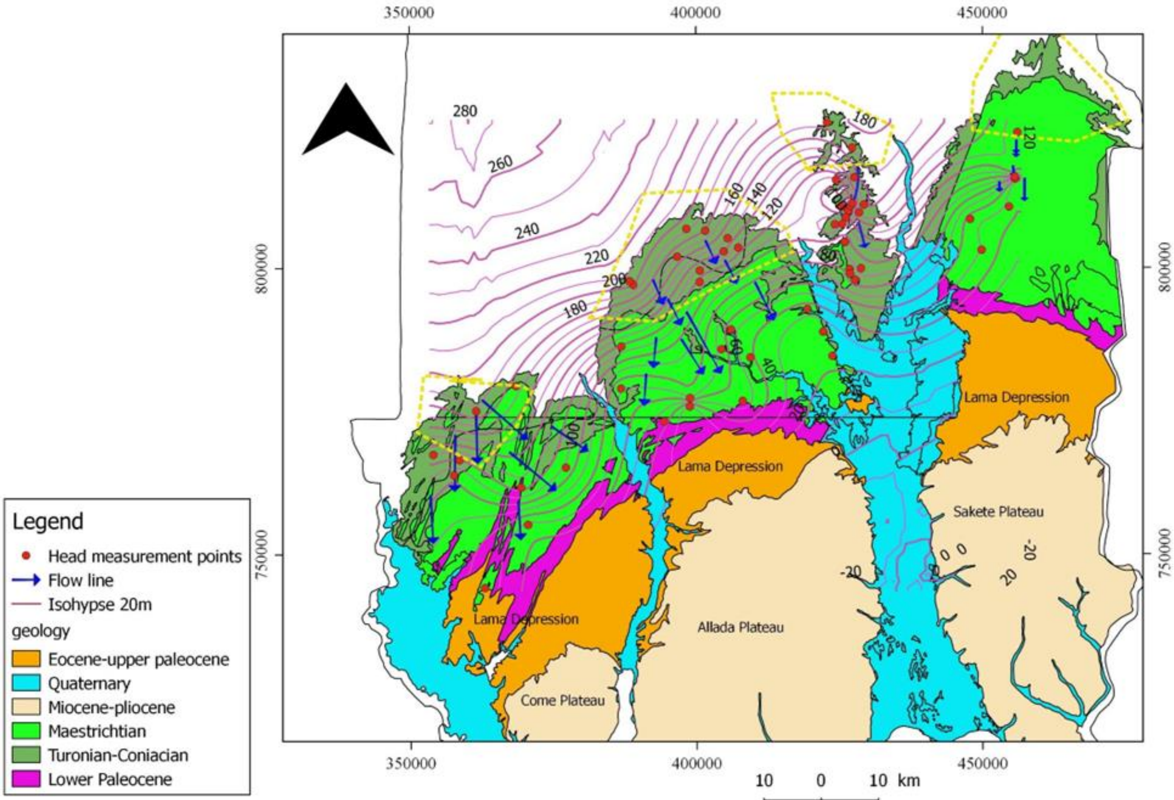

Figure 8: Piezometric map of Turonien Coniacien in Bénin

In the absence of a piezometric map of the Turonian-Coniacian in Togo, the author (Gnazou, 2005) highlighted the direction of underground flow through his study of the Paleocene limestone aquifer (Figure 09). Flow generally occurs from north to south.

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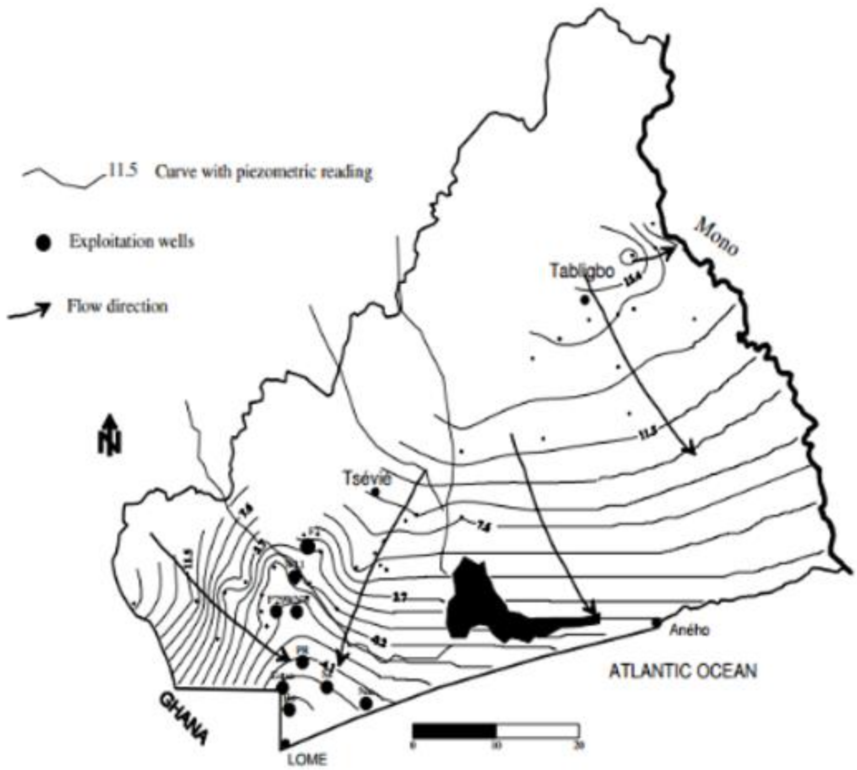

Figure 9: Piezometric map produced by Gnazou in March 2005 showing the general direction of flow in the coastal sedimentary basin in Togo

Discussions

Previous studies, such as those by Slansky (1962), have contributed to the geological study of the Benin-Togo coastal sedimentary basin and show how the layers and facies are structured. Lithostratigraphically, the deposits studied consist mainly of fluvial to marine detrital facies (sandstone, various sands) and sandstone-carbonate rocks (calcareous sandstone, calcareous siltstone). They show several lateral variations in facies and a thickening of all formations from the northern edge towards the center of the basin (Da Costa et al., 2013). The formations in the basin have a slightly inclined structure, marked by a slight dip of 1 to 2° towards the southeast due to plate tectonics (Da Costa et al., 2013).

The Kouvé-Attitogan (Fig. 6) and Kétou-Sakété (Fig. 7) sections crossing the Lama depression reveal the presence of limestone (Paleocene) trapped between thick layers of clay 15 to 30 m thick in boreholes 50 m to over 250 m deep (Gnandi et al., 2009). This zone promotes artesianism, whether gushing or not. In Benin (Fig. 7), Paleocene limestones are found at depths of 150 to 200 m in the north and 300 m in the south (Boukari, 2002).

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Located above the bedrock, the Upper Cretaceous is represented in Togo (Fig. 5 and Fig. 6) by alternating sandy layers of varying thickness and clayey or sandy-clayey layers (Gnandi et al., 2009; Da Costa et al., 2005). The sandy layers, which are the most productive, are often found at depths greater than 50 m in the north (Ahépé). Further south, they are found at depths greater than 200 m in the Vo-Ativé and Hedegan regions (Gnandi et al., 2009). In Benin, its depth varies across the territory, as does its thickness (Kpégli et al., 2018). In the northern region (northern Abomey plateau, Zagnanado plateau, and northern Kétou plateau), hand-dug wells (up to 70 m deep) extend into this main aquifer. In the south, it is impossible to exploit the Upper Cretaceous aquifer using hand-dug wells due to the thick clayey materials covering it and the artesian conditions that prevail for this aquifer in the south. Thus, only deep boreholes exploiting the Upper Cretaceous aquifer are present in the south (Kpégli et al., 2018).

By examining the piezometry, four flow directions are identified (each northern plateau of Benin) (Kpégli et al., 2018). On the BSC in Togo and Benin, water generally flows from north to south. The probable recharge area of the Cretaceous is located north of the northern plateaus of the BSC ((Gnazou 2005) and (Kpégli et al., 2018)).

The piezometric map produced by (Kpégli et al., 2018) from piezometric data from November 2015 reveals flow directions and piezometric values similar to those we obtained with data from July 2023.

Conclusion

Five (05) more or less continuous layers, differing in lithology, are traversed by the correlated boreholes. These consist of a surface layer of laterite, a clayey layer dating from the Maastrichtian, sandy layers, a clayey-sandy layer and limestone.

Limestone (Paleocene) is trapped between thick layers of clay with a thickness of 15 to 30 m in boreholes ranging from 50 m to over 250 m deep (Gnandi et al., 2009). In Benin (Fig. 7), Paleocene limestone is found at depths of 150 to 200 m in the north and 300 m in the south (Boukari, 2002), with a thickness of 10 to 30 m.

The most productive Upper Cretaceous sands in Togo are found at depths of over 50 m in the north and over 200 m in the south. In Benin, its depth varies across the territory, as does its thickness. On the northern plateaus of the Coastal Sedimentary Basin, this aquifer can be tapped with large-diameter wells and can reach depths of up to 70 m. In the south, the impermeable formations that form its roof do not allow it to be captured by wells. It can reach depths of up to 600 m in the south (Boukari, 2002). Its thickness ranges from 50 to 150 m (Géohydraulique, 1985). The dense clay formations in the south of the Lama depression, which cover the Turonian-

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Coniacian and Paleocene aquifers, promote atesianism, whether or not it springs from the boreholes that capture these aquifers.

From piezometric studies, water generally flows from north to south. This leads us to conclude that the aquifer is fed by rainwater infiltration in the outcrop areas north of the northern plateaus of the coastal sedimentary basin. In Togo, most wells have been abandoned and are used as garbage dumps, while others have been motorized to facilitate exploitation of the resource on the northern plateaus. We suggest that a considerable number of wells be constructed to enable stricter monitoring of the water table. The hydrodynamic aspects (estimation of transmissivity, storage coefficient; recharge in terms of quality and quantity) of the Upper Cretaceous should be considered in order to update the available data and thereby contribute more effectively to resource management.

The northern part of the northern plateaus, which constitute the recharge points for the Coniacian Turonian, should be subject to extensive protection. Units to regulate population growth and control activities carried out in these areas must be essential points of reflection for the Beninese and Togolese authorities in order to avoid possible pollution of the aquifer.

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