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Hydrogeological Characterization and Approach to a Conceptual Model of the Aquifer of the Cuvette Basin, Republic of Congo

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Abstract

The continuous aquifers of the Congolese Cuvette basin constitute the seat of significant water tables reversibly supplying the Congo River basin as well as the water tables they drain. Consisting mainly of sandy-clayey-sandstone formations, these aquifers contain groundwater which is the main source of drinking water supply for communities in this sector of the departments Cuvette and Cuvette-Ouest. The need for water being more and more acute, these aquifers have been subjected to drilling operations in order to supply drinking water to these populations. The information obtained from these operations is data which made it possible to obtain information relating to the lithology, the hydrogeological parameters of these aquifers and information on the depth and on the lateral variations of the water table. The purpose of this present work is to contribute to the hydrogeological characterization of the aquifer of the Cuvette basin in the departments of Cuvette and Cuvette-Ouest via data from the analysis of the technical sheets of drillings carried out by the ASPERBRAS Company, collected at the Ministry of Major Works and territory planning. This characterization was made using Visual MODFLOW Flex 2015.1 software coupled with Surfer 10 software and Rock Works 17 software. The hydrogeological interpretation of the data shows that this aquifer, whose constitution is essentially made up of sands, clayey sands and clay, is continuous, porous and free. This composition gives the aquifer of Cuvette basin a heterogeneous character. In addition, a piezometric map was produced in order to indicate the direction of the water flows which turned out to be from west to east towards the lowest areas occupied by the valleys of the rivers and rivers. The conceptual model shows that the depth of the aquifer deceases considerably from the Cuvette-Ouest towards the Cuvette.

Keywords

Cuvette Basin, Hydrogeology, Aquifer, Piezometric Map, Conceptual Model

1. Introduction

In equatorial and humid tropical regions, surface water resources are very abundant, but their accessibility and quality mean that they are used less than groundwater resources, which are very valuable to the populations. Groundwater resources are essential for sustainable economic and population growth ([1]). Compared to surface waters, groundwaters require more investigation effort because they follow a given geological structure ([2] [3]). This structuring is the engine of the dynamics of water flows, hence the importance of knowing it and defining it well for easy research. Groundwater is found in most geological formations, in sediments and rocks forming an underground reservoir or aquifer in which groundwater can be stored and transmitted ([3] [4]). Furthermore, groundwater availability depends on the hydrogeological context, which can be highly variable even within a single lithological formation ([2] [4]).

Over the past decade, in the Republic of Congo, the increase in groundwater demand has led to the installation of several drinking water supply boreholes throughout the country. Then, some of these boreholes were declared dry after some pumping time. This is how interest arose in better characterizing the nature of the aquifers of Congolese Cuvette basin in the departments of Cuvette and Cuvette-Ouest.

In addition, previous work sufficiently shows that the Congo has not yet carried out a complete assessment of its water resources and therefore suffers from a huge deficit in terms of hydrogeological knowledge ([5]). Previous studies did not provide enough information to acquire a mastery of the hydrogeological characteristics of the aquifers of the Cuvette basin in the Cuvette and Cuvette-Ouest departments, which would have facilitated our understanding of the functioning of Congolese Cuvette basin aquifers ([6]). The data available on the hydrogeological situation of the Cuvette and Cuvette-Ouest departments reveal that the aquifer in these sectors is porous, continuous, permeable, and widespread ([6] [7]).

However, recent studies have provided information on the lithology, piezometry and water quality in the area ([7]). In addition, scientific progress in recent years has repeatedly demonstrated that modeling is the simplified way to represent the reality on the ground ([8]). Reliable groundwater modeling is necessary for successful management of groundwater resources ([9]). In addition, scientific progress in recent years has repeatedly demonstrated that modeling is the simplified way to represent the reality on the ground ([8]). Two options are generally involved in building a geological model. These are conceptual and numerical models. In accordance with our database, we opted for the construction of a conceptual model. Building a conceptual model of an area helps simplify field problems so that the system can be analyzed more effectively ([10]). However, before starting to build a groundwater model, it is essential to create lithological and stratigraphic models of the area, providing information on the texture of the formations, the rock materials, the thickness of the strata, the ages and the spatial variation of physical properties over the region of interest ([11]).

The lithology provides valuable information on the dominant rock types in the region and their physical and geochemical properties. It can also provide important information to predict the origin of groundwater and its former environment of deposition ([11] [12]). The influence of rock lithology on the development of the drainage network and the shape of the basin has been reported by Mukherjee and Jha ([13]). A lithologic model can give a general overview of the spatial distribution of the main geological formations in an area. Additionally, it facilitates a more accurate discrimination of different stratigraphic units vertically and hence a more realistic conceptual groundwater model ([13]). Over the past four decades, several techniques have been developed to predict rock lithology, such as interpretation of seismic data ([14] [15]), physical well logs and geochemical data ([16]), and, recently, remote sensing data ([17]). Software development over the past decades has provided powerful tools to create and visualize 3D models at different resolutions in a reasonable timeframe, providing comprehensive subsurface information even in areas with complex geology ([2]).

It is on this basis that this paper proposes to initiate this study in order to contribute even a little to the mastery of knowledge on the hydrogeological characteristics of the aquifers of the Cuvette basin in the departments of Cuvette and Cuvette-Ouest and to serve as a decision-making aid tool during the search for and exploitation of groundwater resources (installation of adequate hydraulic structures and capture of the groundwater table).

To do this, this paper aims to provide a fairly clear and detailed knowledge of the hydrogeological characteristics of the aquifer and to set up a conceptual model of the aquifer of Cuvette basin in the departments of Cuvette and Cuvette-Ouest. To achieve this goal, Rockworks.17 software coupled with Visual MODFLOW Flex 2015.1 software, which is often used in groundwater-focused studies ([18]), was used for this purpose.

2. General Context of the Study Area

2.1. Geographical Location of the Study Area

The study area is located in the center of the Republic of Congo-Brazzaville, more precisely in the Congolese Cuvette basin which is presented as an immense basin of 196,689 km^2 where several rivers converge ([19]). In this vast ensemble, our study (**Figure 1**) only concerned the departments of Cuvette and Cuvette-Ouest.

The study area is bounded to the north by the department of Sangha, to the northeast by the department of Likouaka, to the west, it is bounded by Gabon

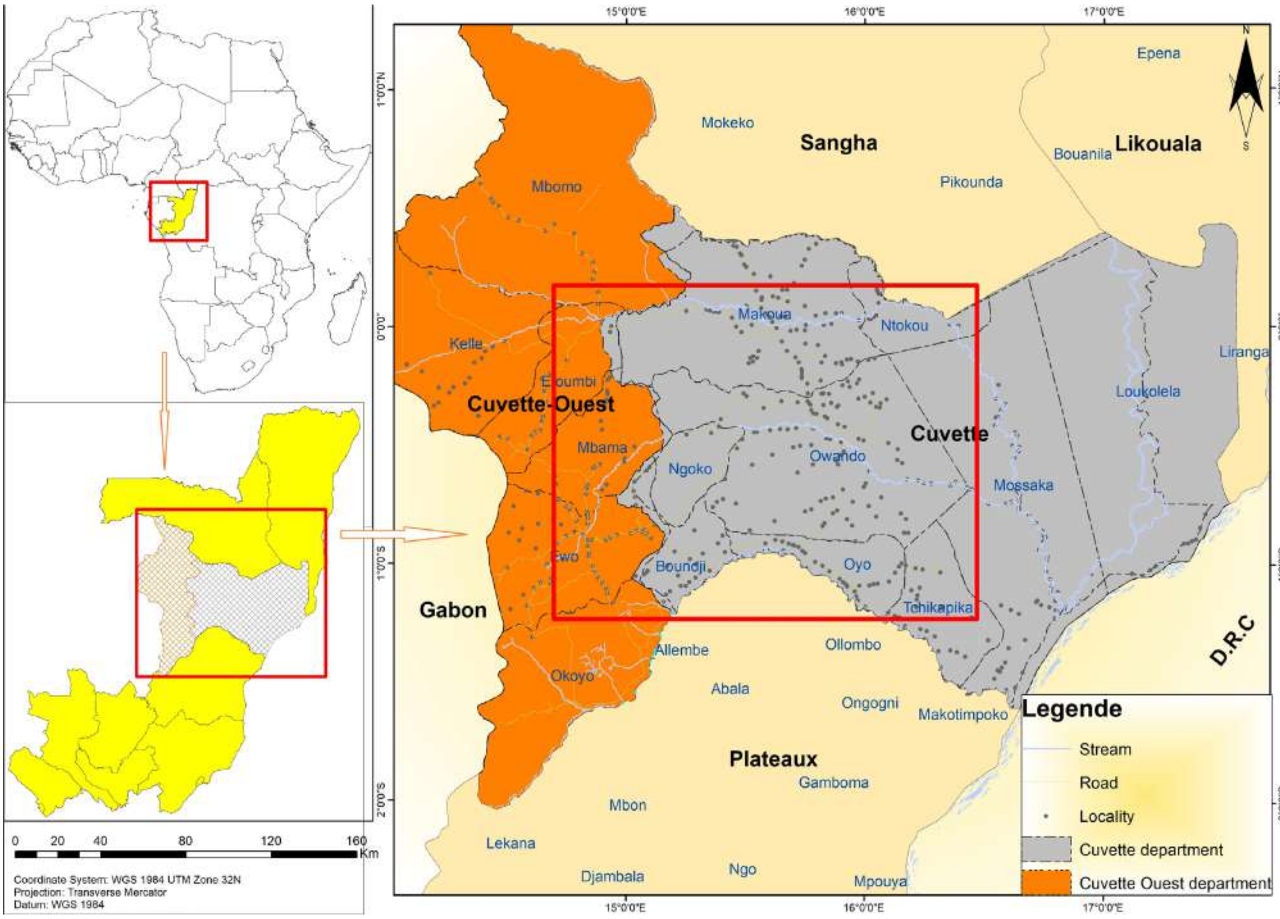


Figure 1. Portion of the map of the Republic of the Congo showing the location of the study area. Insert: Insert: The map position of the Republic of Congo through that of Africa then the map position of the study area through that of Congo.

and to the east by the Congo River and to the south by the department of Plateaux (**Figure 1**).

2.2. Climatology

Our study area comprising the departments of Cuvette and Cuvette-Ouest highlights two types of climates: the equatorial climate and the humid tropical climate. These climatic nuances are largely dependent on the intertropical convergence and also on the type of relief found in the area ([20]).

The equatorial climate: It is characterized by relatively modest rainfall (1600 to 1800 mm) 50% of which comes from evaporation and local evapotranspiration generated by the large forest mass. A recession is more or less marked in Loukolela, Mossaka, Makoua, owando in January and also in July in Mbomo. April and May; October and May; are the wettest months with 200 to 250 mm (**Figure 2(a)**).

January and July are less watered with 50 and 80 mm. The dry season is almost non-existent and is between December and January with very low rainfall irregularity (10% to 15%). The average annual temperature is close to 25˚C to 26˚C (**Figure 2(b)**) with a low annual amplitude (1˚C to 2˚C).

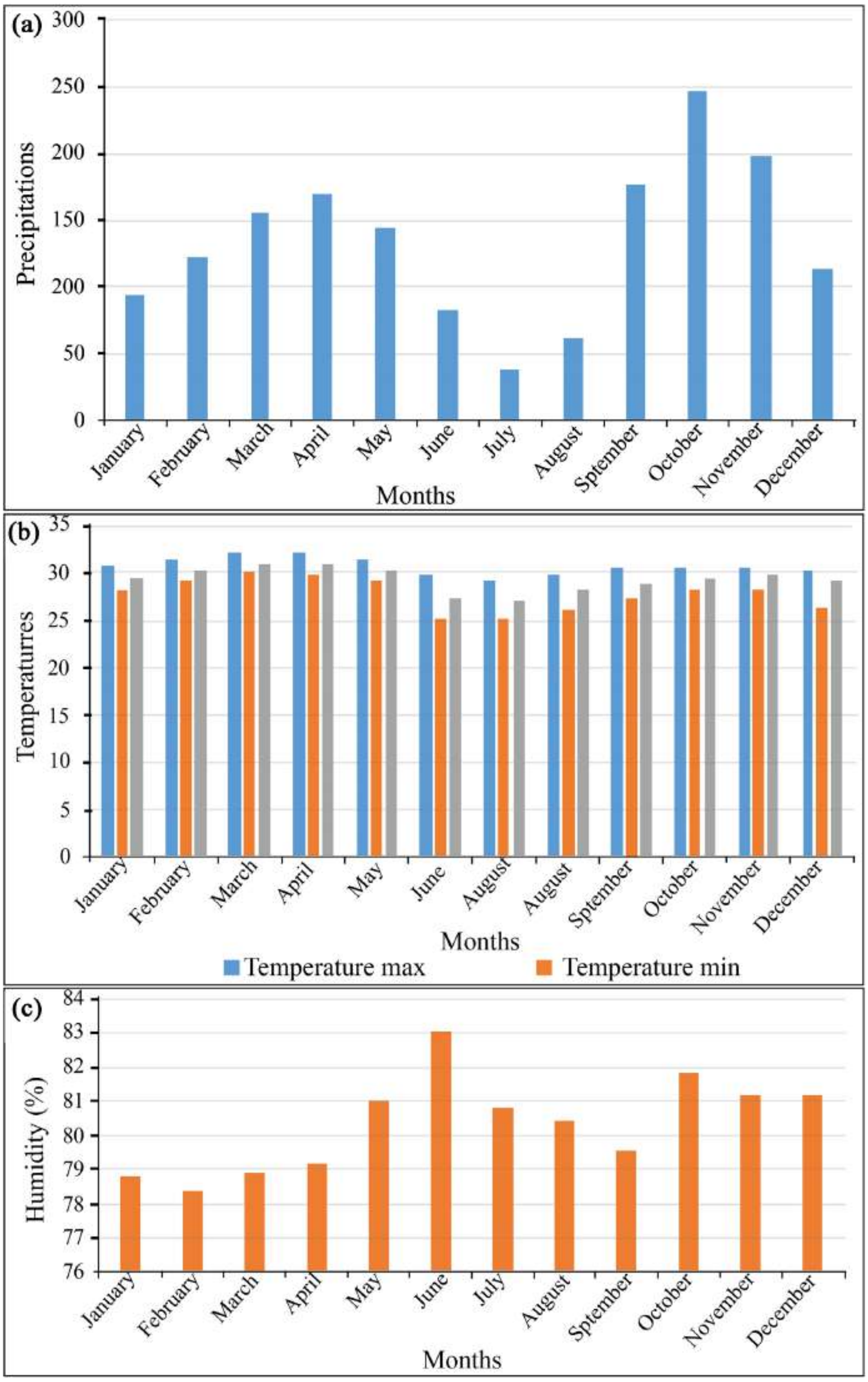


Figure 2. Histograms showing the climatological characteristics of the study area. (a) Average monthly rainfall at Makoua station (1987-2017); (b) Monthly temperatures at Makoua station (1987-2017); (c) Mean monthly relative humidity at Makoua station (1987-2017).

Figure 2(b) shows the evolution of monthly temperatures recorded in the Makoua station. Average temperatures vary between 29˚C and 30˚C from February to April with a maximum of 32˚C and a minimum of 25˚C. The relative humidity of the air is constantly high (**Figure 2(c)**). **Figure 2(c)** illustrates the average relative humidity recorded at the Makoua synoptic station. It shows that the study area is sufficiently watered with more than 97% humidity all year round. The study area is subject to two climatic nuances: the subequatorial climate and the equatorial climate ([21]).

Humid tropical climate**:** It is present in the sector of the western basin where a relief of northwest plateaus and hills predominates, in particular the south of Mbomo, Kellé, Ewo and Okoyo. This climate is characterized by abundant rains of the order of 1200 to 1600 mm of water per year, the annual distribution of which highlights a division of the seasons. A long rainy season from October to May interspersed with a short dry season between January and February and a more sensitive dry season from June to September. Annual temperatures in this area vary between 23˚ and 26˚C. In sum, such a climate justifies the abundance of groundwater in the area.

2.3. Hydrographic Network

The hydrographic network is mainly represented by the Congo River and its tributaries. These drain the western and northern part of the Congo River watershed. Their confluences are located along a section of 600 km, in an overall North-South direction, upstream of Brazzaville ([22]). The hydrographic network presents a remarkable convergence. A wide range of tributaries narrows towards the Congo: Likouala-aux-Herbes, Sangha, Likouala-Mossaka, Alima. They flow into the river for less than 100 km, via a series of braided deltas; dozens of arms intertwine where the waters flow in one direction or the other, depending on the level of the respective floods ([23]).

In the study area, we find the following sub-basins ([24]) (**Figure 3(a)**):

- The Sangha sub-basin with more than 240,000 km^2 in area.
- The Likouala-Mossaka sub-basin with an area of nearly 60,000 km^2.
- The Alima sub-basin with an area of 20,300 km^2.

2.4. Geological and Hydrogeological Context

2.4.1. Geological Background

The geology of the study area (**Figure 3(b)**) shows from top to bottom the following formations:

1) Plio-Pleistocene cover formations comprising: a clayey-sandy series made up of sandy clays of a red hue; clayey, sandy and loamy alluvium; surface formations comprising more or less yellow clays, ferruginous gravel levels and weathered rock levels. The thickness of these cover formations is not well known but it is at least several tens of meters ([25]).

2) The Plateaux series of Tertiary age, whose thickness is not known, divided into two:

- the series of Batéké Plateaux made up of essentially sandstone and sandy continental formations which extend into vast plateaus with a characteristic semi-desert aspect, to the north of Brazzaville, between the alluvium of the Congo River to the east and the old series that they overcome to the west.

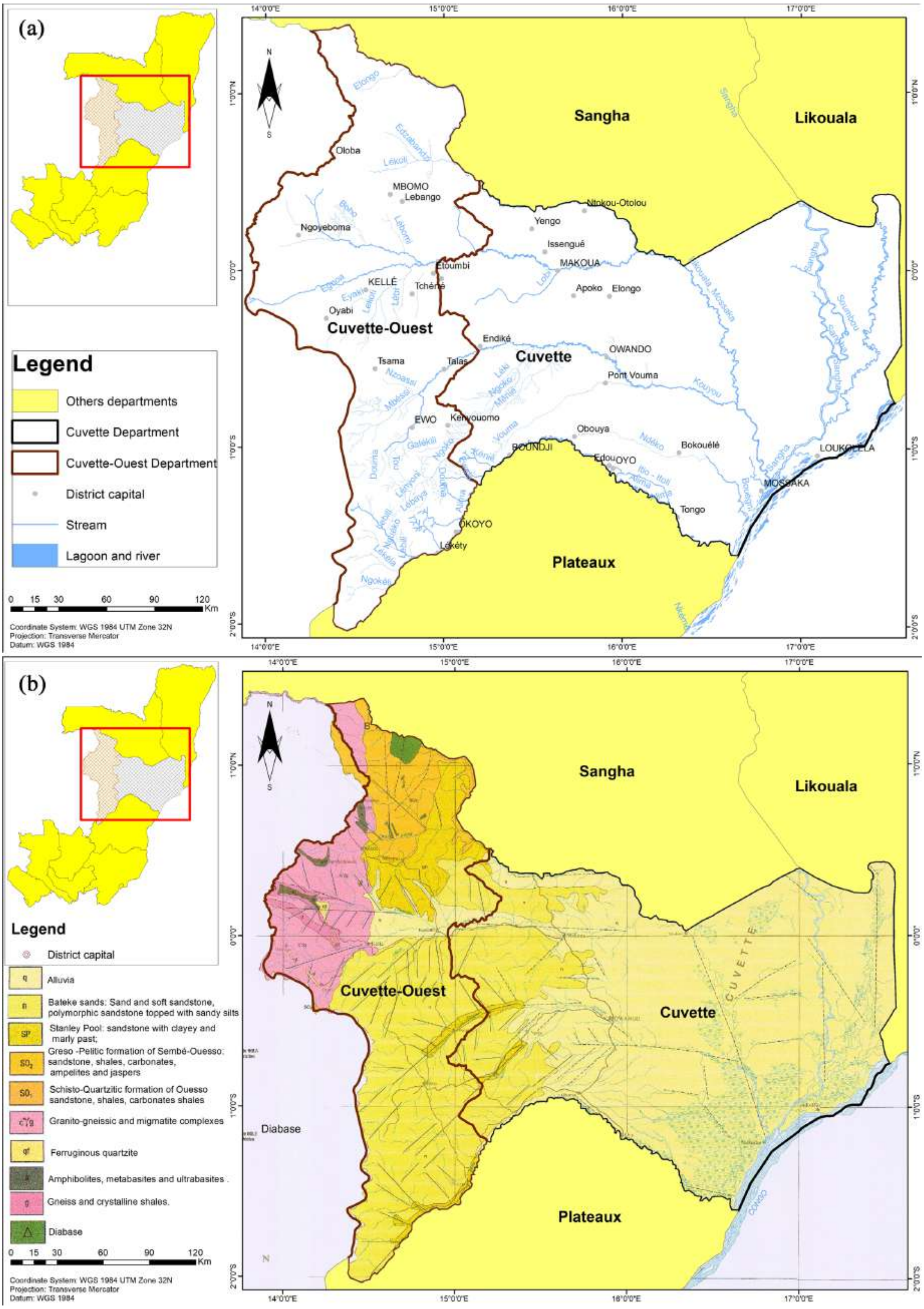


Figure 3. Portion of maps showing (a) the hydrographie of the study area modified from Moukoko and Samba-Kimbata ([24]) and (b) the geology of the study area, modified from the geological map of Congo ([25]).

The upper layers, called sandy silts, of Neogene age (Ba 2) overlie a set of soft, fine-grained polymorphic sandstones, Paleogene (Ba l). The total power of this series is 300 to 400 meters ([25]);

- the Plateaux de Bambio series borders the alluvial deposits of the Congolese basin to the North. These are silicified sandstones, beige sands and sandy silts.

3) The Secondary formations directly overlie the Precambrian formations of the basement. The Secondary is represented here by the Stanley-Pool series which includes:

- in the Upper Jurassic, argillites with sandstone past.
- in the middle and lower Cretaceous, compact white sandstones locally indurated and soft kaolinic sandstones with crossed stratification.

The Stanley-Pool series of Upper Jurassic to Cretaceous age is made up of fossiliferous clays and marls (SP1), overlain by kaolinic soft sands and sandstones with large intersecting stratifications (SP2) and kaolinic white sands of SP3 ([25]).

- The sandstone-pelitic series, of Mesoproterozoic age, outcrops to the northwest of our study area. It begins with conglomerates and coarse sandstones then ends with pelites with whitish aspects at the base which are in turn surmounted by brown and black, micaceous and pyritic pelites ([26]).
- The furrows of the Kellé zone, of Archean age, outcrop in the northwestern part of the study area. They consist of gneiss, garnet leptynites; ortho-amphibolites which are most often associated with ultrabasic rocks which clearly correspond to ancient basic lavas, as well as soapstones and actinolites; the quartzite bars are also represented there ([26]) (**Figure 3(b)**).

2.4.2. Tectonic

The eastern half of the Cuvette department would form a vast depression, comparable to a subsidence zone where the total thickness of the sedimentary series would reach 6000 m above the Precambrian basement ([26]). The aeromagnetic survey carried out in 1980 by the CGG for Hydro-Congo made it possible to follow under the recent covers, a certain number of deep fractures and to define a certain number of basins where the thickness of the sediments above the magnetic basement can reach 4000 m from North to South ([24] [26]):

- Impfondo basin.
- Liranga Basin.
- Owando-Gamboma Basin.
- Mbé-Odziba Basin.

Some data from the Airmag sometimes confirms the observation of the hydrographic network: the rectilinear lines of the watercourses probably reflect neotectonics in relation to deep structures ([24]).

2.4.3. Hydrogeological Context

The hydrogeological context depends on the geology of the study area. The Congo has 4 hydrogeological units:

- the coastal sedimentary basin: 6000 km^2.

- the continental lands of the Congolese basin: 224,000 km^2.
- the old sedimentary series: 68,000 km^2.
- crystalline and crystallophyllian rocks of the lower Precambrian: 44,000 km^2 ([24]).

The first two sets are essentially formed of loose sedimentary rocks with interstice porosity. They constitute generalized aquifers. The last two, on the other hand, are essentially formed of compact rocks, granites and metamorphic rocks. They constitute discontinuous aquifers with fissure porosity ([24]).

Regarding the limits of our study area, two hydrogeological contexts stand out:

- The continental lands of the Congolese Basin.
- The old sedimentary series (specifically, the schisto-sandstone formations outcropping in the north of the country) ([26]).

3. Materials and Methods

3.1. Datasets

Data from 243 boreholes (**Figure 4**) were used for lithological and stratigraphic modeling, including detailed description of lithology and depths.

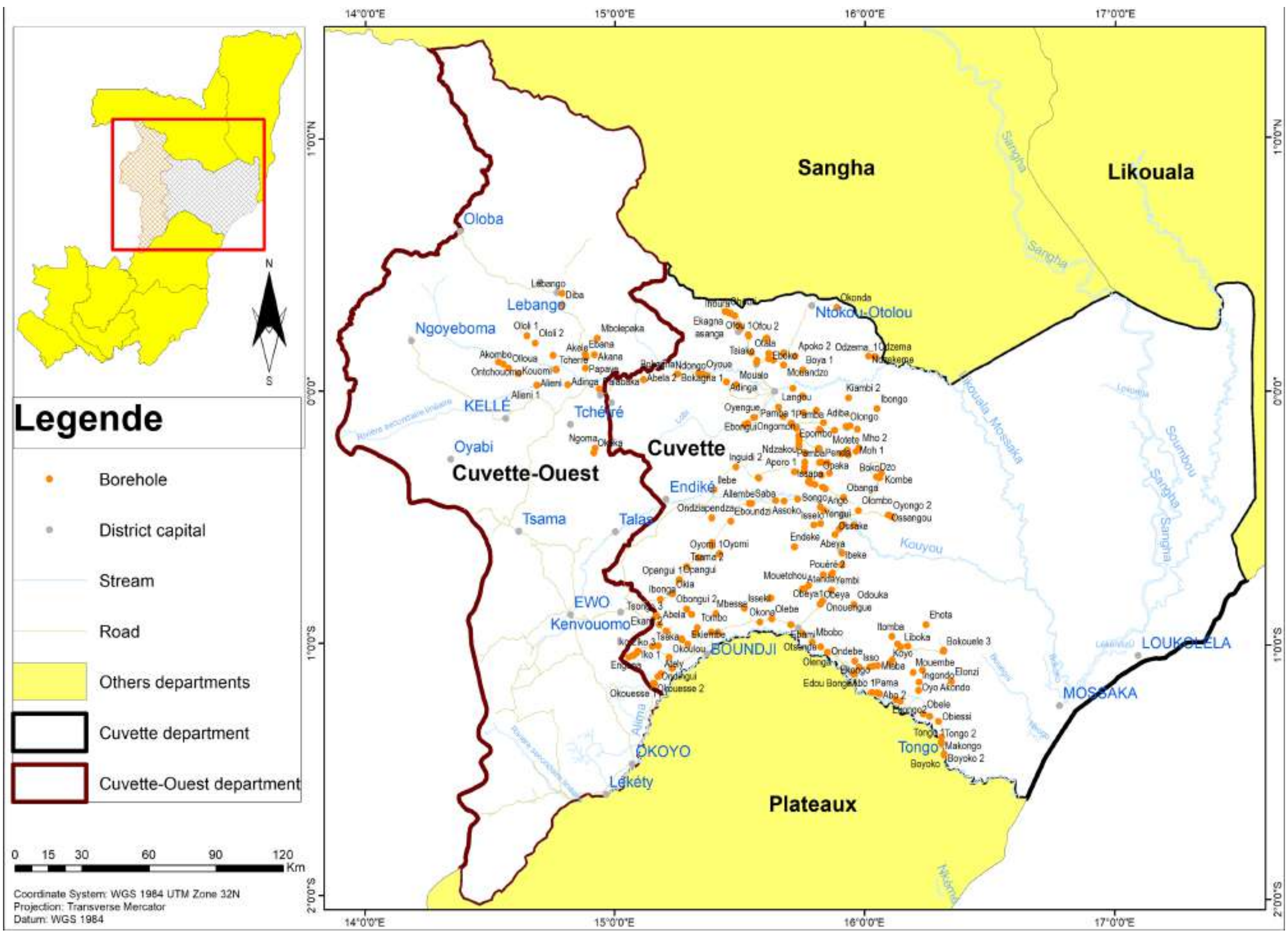


Figure 4. Drilling point location map.

Figure 4 shows the selected borehole locations. The total depths of the boreholes vary from 30 to 220 m. All drilling data was provided by the Congolese Ministry in charge of Major Works and the company Asperbras Congo.

In addition, the geological map at 1/1,000,000 from Desthieux ([25]) and sections at different scales were used to calibrate the final models. The piezometric data consists of time series of groundwater levels with sampling at 243 well sites Table 1.

Table 1. Representative list of drill point coordinates.

HOLE/Village	Longitude (X)	Latitude (Y)	Altitude (m)	Static level
Mbesse	544,811.1261	9,902,860.056	378	−3.25
Adinga	549,449.7467	10,004,175.73	372	−5.73
Atekou 1	590,790.7972	9,983,388.07	375	−22.88
Atekou 2	591,013.3613	9,983,182.344	375	−17.18
Embouli 1	557,610.1343	9,985,433.973	351	−7.95
Okokohoko	584,415.8701	9,968,701.869	372	−25.7
Tsiako	563,028.8098	10013543.69	386	−28.44
Tsama 2	531,844.0423	9,923,337.239	347	−4.10
Atanda	584,282.3804	9,913,772.736	325	−4.25
Boko	617,748.9404	9,962,364.243	345	−15.54
Ihimbou	581,175.0695	9,952,962.546	334	−8.2
Yengui	591,455.0514	9,942,269.688	359	−18
Edou Illanga	606,444.0795	9,876,499.01	332	0
Elondji	613,368.6287	9,879,622.649	320	0
Kali-Otoko	625,692.9347	9,889,752.232	319	−2.1
Liboka	627,108.1537	9,888,354.47	349	−2.1
Mbobo	587,810.4007	9,890,478.694	334	0
Miaba	616,951.1877	9,880,275.539	313	0
Okona	564,405.7337	9,899,191.334	349	−5.65
Boundji Asté	640,037.6364	9,858,173.694	288	0
Elonzi	649,618.0177	9,873,327.989	308	0
Illanga	636,832.018	9,878,370.142	308	0
Ololi 1	460,549.9464	10,024,360.08	407	−5.94
Ololi 2	464,336.3848	10,021,154.68	442	−27.51
Palabaka	492,878.401	10,001,050.04	409	−39
Tcherre	473,361.9496	10,009,502.57	421	−36.3
Ontchouomo	447,913.4924	10,012,788.09	443	−39.06
Okeka	490,476.7254	9,973,082.807	424	−21.54
Ebana	486,566.587	10,016,324.66	468	−44.48

Geological modeling was carried out using RockWorks software ([27]), while ArcGIS version 10.1 ([28]) was used for post-processing of spatial data. The RockWorks program uses different types of algorithms to interpolate the 3D distribution of geological units. Therefore, the results would not simulate the actual outcrop distribution in reality. In addition, the digital geological map (polygon files), formation boundaries and lineaments (polylines) were used to calibrate the final models. The 3D hydrogeological simulation was carried out using the Visual MODFLOW Flex 2015 software ([8] [29]).

3.2. Data Preparation

The lithological succession, depths and elevations have been transformed into data sheets. The formations have been subdivided into depths based on their lithologic types and background information. Drilling data was imported into the RockWorks database, including all model geometry, coordinates, lithology and stratigraphy information. In addition, spatial information (shapefiles, surface geological boundaries and faults) was imported into the software and saved in the polylines/polygons database.

3.3. Lithological Model

The lithology of the stratigraphic formation in the study area was described using a 3-D lithologic model made using the lithologic modeling option of RockWorks.17 ([30]). First, the lithological types of the different geological formations were identified from the lithological column of the selected boreholes. These have been stored in **Table 2** of lithological types from the RockWorks.17 database ([30]). **Table 2** includes detailed information about the rock material, pattern, color, and order in the pattern from top to bottom. The solid model was made from the drilling database (spatial information, depths and lithological types). Lateral extrusions, advanced midpoint random correlations and outlier interpolation algorithms were used in the full voxel mode modeling option available in RockWorks.17 ([30]).

3.4. Preparation of the Piezometric Map

The piezometric map relating to the year of data collection was drawn up from the elements of the kriging equation applicable to the depth of the layers. Kriging being a geostatistical technique of spatial modeling, has made it possible, from dispersed data of the depths of the layers, to obtain a homogeneous representation of these. Kriging therefore made it possible, using the depth values, to estimate the spatial distribution of the static levels of the aquifer to create a piezometric map. The kriging technique has the advantage of taking into account the distances between the wells for which the depth is to be estimated. The statistical kriging method is based on the assumption of spatial autocorrelation of the data. Concretely, this means that two data close in space tend to have similar characteristics. Then, the results obtained from the kriging

Table 2. Representative data of lithologic information from the various boreholes in the study area.

HOLE/Village	Longitude (X)	Latitude (Y)	Altitude (m)	Lithology	Depth (m)
Mbesse	544,811.1261	9,902,860.056	378	Brown medium fine sand	0 - 9
				Yellowish fine sand	9 - 13.5
				Greyish medium sand	13.5 - 22.5
				Light greyish fine sand	22.5 - 27
				Brick-red sandy silty sand	27 - 31.5
				Reddish fine sand	31.5 - 49
				Brick-red sandy silty sand	49 - 54
Adinga	5494.497467	10,004,175.73	372	Yellowish fine sand	0 - 24
				Coarse pinkish sand	24 - 48
				Reddish clay sandstone	48 - 62
Atekou 1	590,790.7972	9,983,388.07	375	Yellowish fine sand	0 - 18
				Fine orange sand	18 - 42
				Reddish sandy clay	42 - 96
				Fine pinkish clay sand	96 - 130
Embouli 1	557,610.1343	9,985,433.973	351	Greyish fine sand	0 - 24
				Greyish medium coarse sand	24 - 48
				Pinkish fine sand	48 - 111
Okokohoko	584,415.8701	9,968,701.869	372	Yellowish fine sand	0 - 18
				Fine orange sand	18 - 48
				Pinkish fine sand	48 - 125
Tsiako	563,028.8098	10,013,543.69	386	Yellowish sandy clay	0 - 18
				Orange sandy clay	18 - 48
				Reddish sandy clay	48 - 98
Edou Illanga	606,444.0795	9,876,499.01	332	Yellowish fine sand	0 - 48
				Greyish sandstone	48 - 90
				yellowish clay sand	90 - 114
				Yellowish fine sand	114 - 169
Elondji	613,368.6287	9,879,622.649	320	Greyish fine sand	0 - 54
				Brown sandy clay	54 - 120
				Reddish lateritic clay	120 - 170
Liboka	625,692.9347	9,889,752.232	319	Medium brown sand	0 - 31.5
				Greyish clay	31.5 - 40.5
				Fine to medium greyish sand	40.5 - 58.5
Miaba	616,951.1877	9,880,275.539	313	Blackish fine sand with organic matter	0 - 42
				Fine brown clay sand	42 - 155

technique were imported into the Visual MODFLOW Flex software ([8]) which provides the tools to create three-dimensional conceptual and numerical models.

3.5. Groundwater Conceptual Model

The results of the stratigraphic model of the Cuvette basin in the departments of Cuvette and Cuvette-Ouest were used to build the conceptual groundwater model. These include the topographic surface, and the stratigraphic horizons of the formations. Data from different sources were used in the conceptual model, such as spatial data, shapefiles (rivers, boundary area) and observation and pumping wells. All layers are referenced to the UTM WGS84 zone 33N projection system. Surfer software was chosen as the pre- and post-processor to build the groundwater flow models and supports many groundwater models including MODFLOW.

The US Geological Survey (USGS) MODFLOW ([31]) is a modular, three-dimensional, finite-difference groundwater flow model that is widely applied in groundwater modeling and used in the present work. Visual MODFLOW Flex 2015 ([8]) was used to model the area. The lithological model of the study area was exported to MODFLOW to represent the different layers with their topography and thicknesses. The MODFLOW model grid has been adjusted to match the dimensions of the lithologic model. The model grid was constructed in 80 rows by 70 columns with a grid spacing of 1000 m, and vertically the model was divided into 37 slices of 5 m each to coincide with the dimensions of the lithologic model.

4. Results and Discussions

4.1. Hydrogeological Characteristics of the Aquifer System

4.1.1. Lithologic Description and Location of the Aquifer

Case of the Embouli 1 village

The lithological data of the Embouli 1 village show, from bottom to top over a depth of about 100 m, a succession of layers of fine sand with an average thickness of about 63 m, medium to coarse sand with an average thickness of about 24 m and finally fine sand towards the top with an average thickness of 24 m (**Figure 5(a)**). The drilling carried out in the locality of Embouli 1 reveals that the aquifer of this locality is in the layer of fine sand and at a depth of 63 m (**Figure 5(a)**).

Case of Yengui village

Here, after drilling operation, the lithology shows from bottom to top over a depth of about 100 m, a clayey layer has passed sandstone with an average thickness of about 61 m representing the aquifer level; then comes a level of fine clayey sand with an average thickness of about 30 m and finally a clayey level with an average thickness of 24 m (**Figure 5(b)**).

Case of Atekou village 1

The lithological description made in the Atekou 1 locality after the drilling,

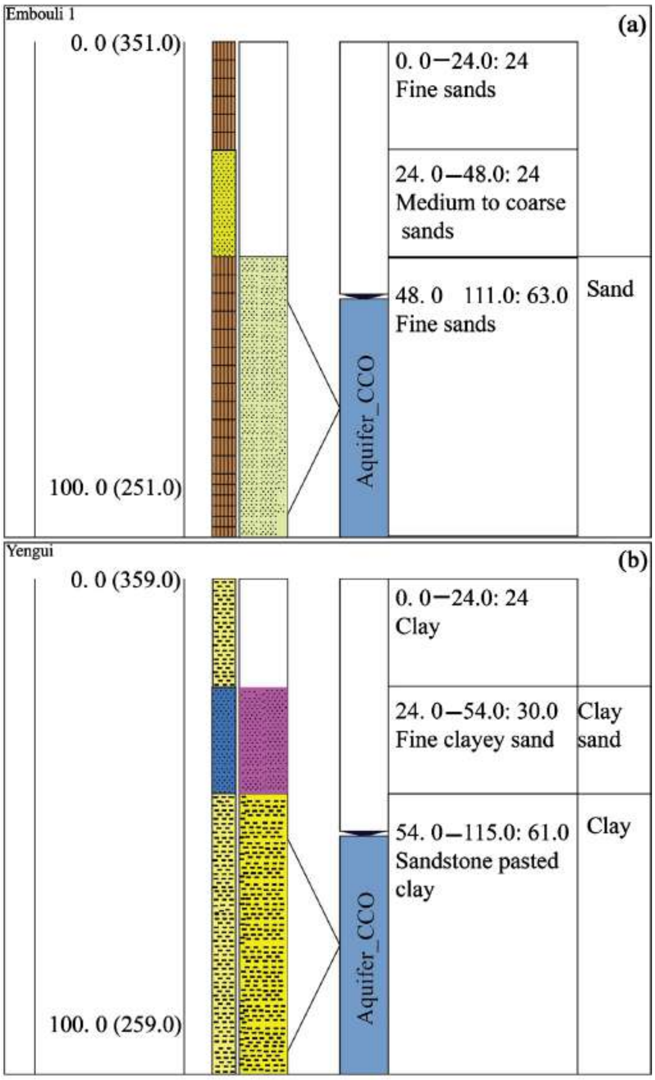


Figure 5. The lithostratigraphic logs of (a) Embouli 1 and (b) the Yengui Village.

shows from bottom to top over a depth of about 100 m, a sandy-clayey layer with an average thickness of about 34 m, representing the aquifer level; then comes a clayey-sandy level with an average thickness of about 54 m; then a level of medium sand with an average thickness of about 24 m and finally a level of very fine sand with an average thickness of 18 m (**Figure 6(a)**).

Case of the Atanda village

At the level of the Atenda village, the lithological description (**Figure 6(b)**) reveals that from bottom to top over a depth of about 50 m: a layer of fine sand with an average thickness of about 54 m, representing the aquifer level; then comes a clayey-sandy level with an average thickness of about 14 m; finally, a level of fine sand with the presence of organic matter with an average thickness of 23 m.

4.1.2. Aquifer Geometry: Data from Lithostratigraphic Sections

During this study, four lines (**Figure 7**) of lithostratigraphic sections were carried

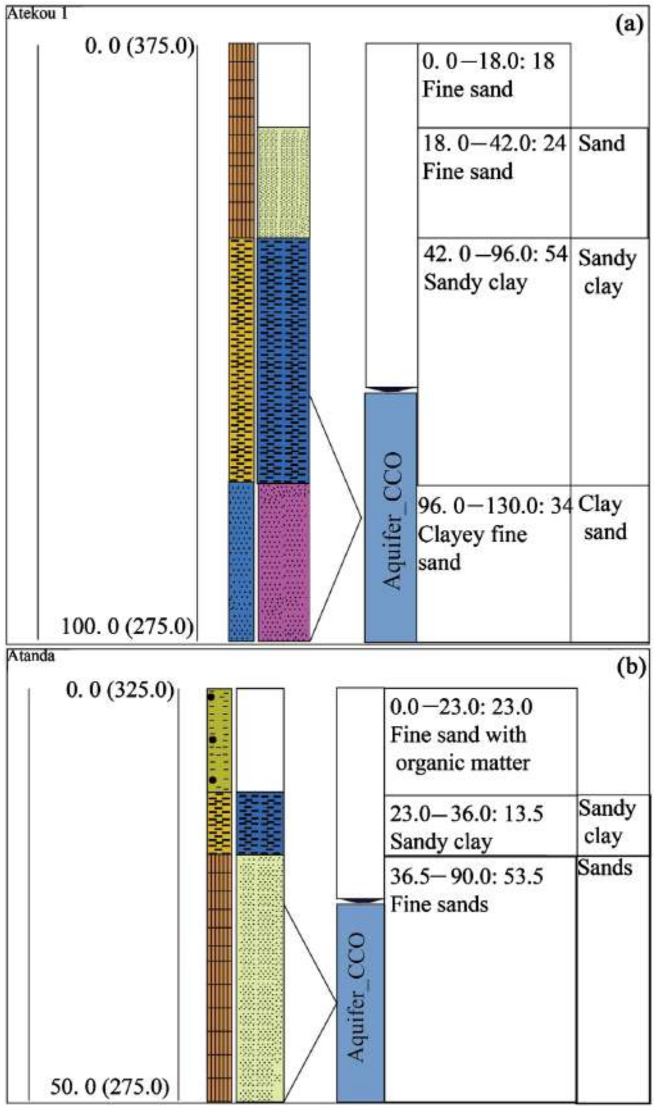


Figure 6. The lithostratigraphic logs of (a) the Atekou and (b) Atanda Village.

out with the aim of locating and determining the morphology of the aquifer.

These sections make it possible to follow the evolution of the geometry of the aquifer system and to examine the lateral changes of the lithological facies as well as the thicknesses of the reservoir levels in the departments of Cuvette and Cuvette-Ouest. These lines are as follows (**Figure 7**):

- Section line that goes from Ololi 2 to Boya 1.
- Section line which goes from Ololi 1 to Indinga.
- Section line that goes from Okeka to Elonzi.
- Section line that goes from Tsama 2 Boundji-Atse.

1) Section line that goes from Ololi 2 to Boya 1

The sandy-clayey level of this line is present everywhere in the Ololi 2 - Boya 1 sector important at this stage (**Figure 8(a)**).

This model leads to significant local variations in the thickness of the sandy layers, most often in the form of a syncline, hosting the main aquifer (**Figure 8(b)**)

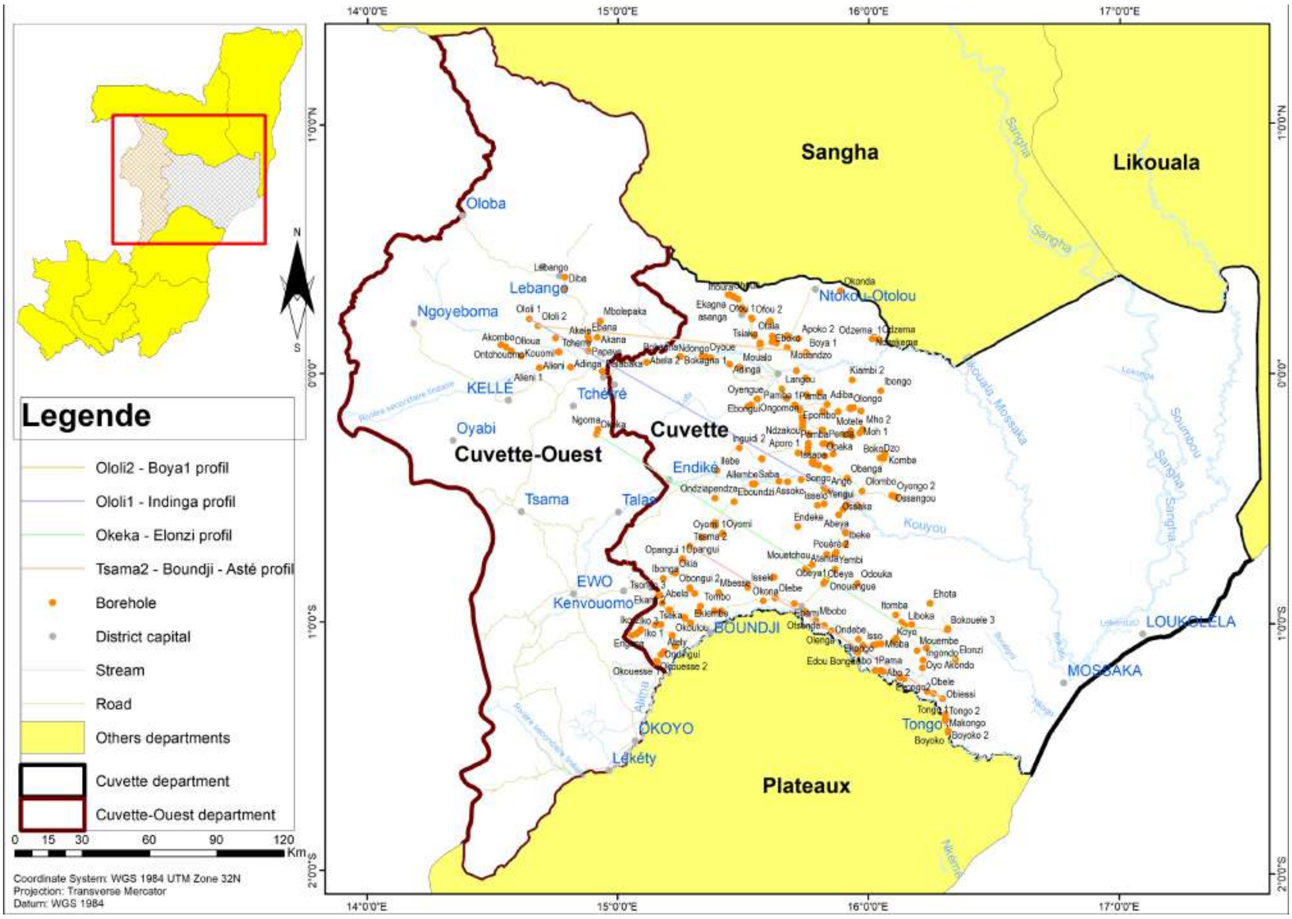


Figure 7. Location map of lithostratigraphic sections.

of this sector from Ololo 2 to Boya 1. Despite the presence of the clayey level, from a local point of view, this can constitute a good aquifer accessible by wells during drilling operations. Furthermore, fluvial erosion during recent eras of geological history has also cut deeply into the clayey-sandy level.

2) Section line that goes from Ololi 1 to Indinga

Just like the section profile of the Ololi 2 Boya 1 sector, the profile of the Ololi 1 section at Indinga suffered significant erosion during the setting up of the sandy and lateritic levels. On the other hand, the sandy-clayey level presents a linear continuity with variation of thickness. However, according to the litho-stratigraphic section, shreds of sandstone and clayey-sandy levels are preserved respectively on the sides of the alluvial valleys and at the top of a small anticline (Figure 9(a)) when they are not eroded. In addition, the clayey-sandy level overhangs the sandy-clayey and lateritic levels located very close to Ololi 1.

The aquifer of the Ololi 1 sector in Indinga (Figure 9(b)) is hosted by the sandy-clayey and clayey layers -sandy, where it is in the form of an anticline very close to the village Ololi 1 and in the form of a syncline all along the section going towards the village Indinga. The aquifer in the Ololi 1 sector at Indinga, despite a fairly large proportion of clays in their level, turns out to have good hydrodynamic characteristics due to the presence of a very high proportion of

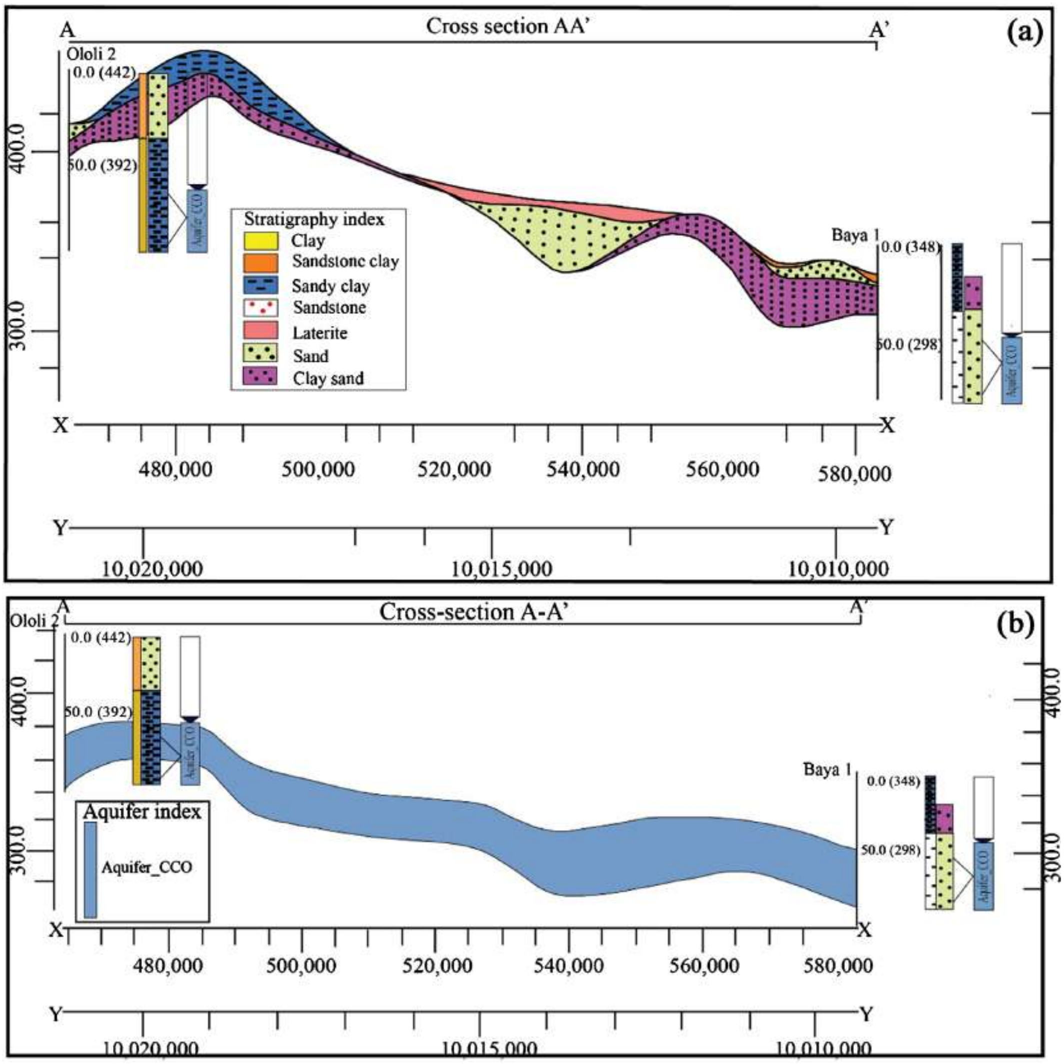
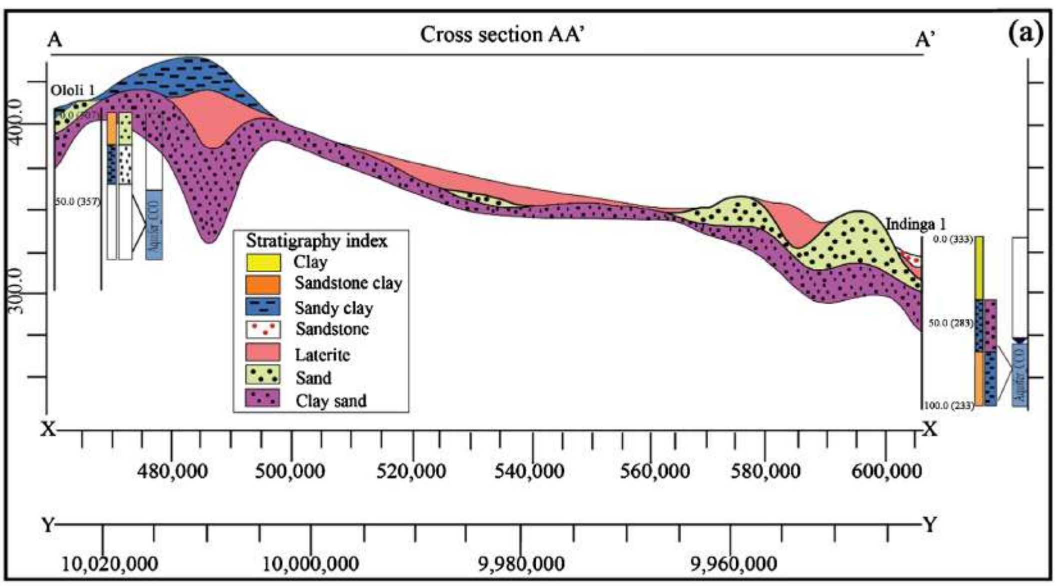


Figure 8. (a) Lithostratigraphic section and (b) aquifer section of Ololi 2 – Baya 1.



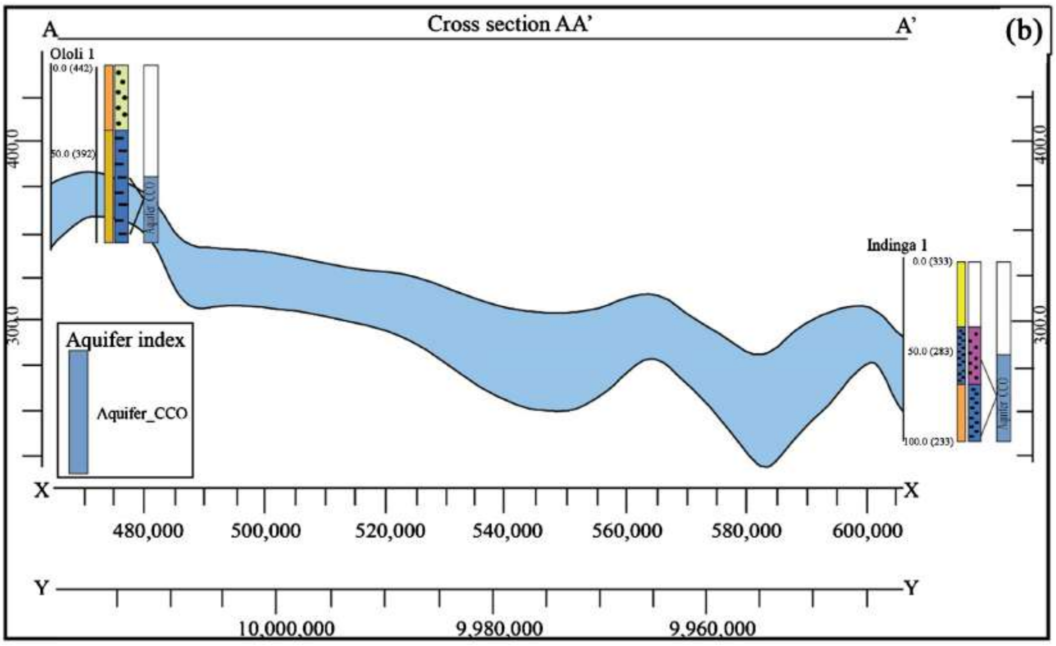


Figure 9. (a) Lithostratigraphic section and (b) aquifer section of Ololi 1 – Indinga.

coarse sand which thus makes it very good the productivity and permeability of structures. In addition to this information, there is also a piezometric level with a shallow depth of around 60 m in places.

3) Section line that goes from Okeka to Elonzi

The section profile from Okeka to Elonzi (**Figure 10(a)**), presents a discontinuity of layer like those of the two preceding profiles reflecting a significant erosion during the installation of the clayey-sandstone layer.

The sandy-clayey layer also presents a discontinuity with the sandy layer which in turn is in the form of a lens characterizing its placement in the channels. The same is true for the lateritic, sandstone and clayey-sandy layers which also appear in the form of lenses indicating their placement in the channels. The aquifer in this sector is generally in the form of a syncline located at the level of the sandy and clay-sandstone layers (**Figure 10(b)**). The contact of the two aquifer levels of the Okeka sector in Elonzi is noted by a lens located between the sandy layer and the clayey-sandstone layer, which are in communication precisely when approaching the village of Elonzi (**Figure 10(b)**). The aquifer in the Okeka sector in Elonzi is captured at fairly varied depths ranging from the surface, near the Okeka village, to the foothills of Elonzi at more than 100 m.

3) Section line that goes from Tsama 2 to Boundji-Atse

Section of the profile of Tsama 2 at Boundji-Atse (**Figure 11(a)**), shows that the clayey-sandy layer overlies the sandy-clayey layer between Tsama 2 and Boundji-Atse, showing the lateral variations in thickness and the sandy, sandstone, and clayey-sandy layers in the form of lenses intercalated between the two along the entire length of the profile. The sandy and clayey-sandstone layers which present continuity with lateral variation in thickness, host the aquifer of

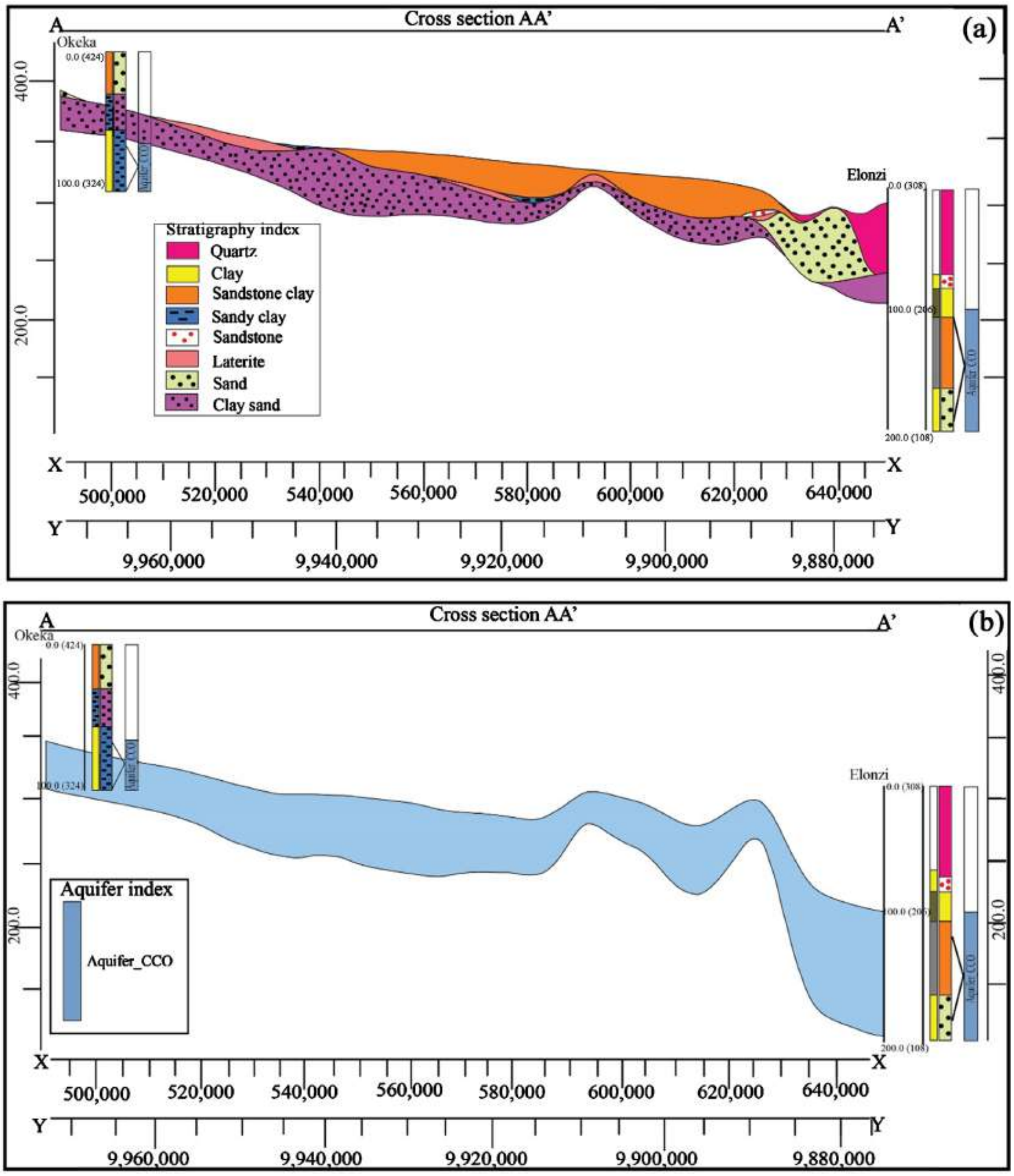


Figure 10. (a) Lithostratigraphic section and (b) aquifer of Okeka-Elonzi.

the Tsama 2 sector in Boundji-Atse which is in the form of anticline and syncline (Figure 11(b)).

The interpretation of this section illustrates the lateral change of facies and thicknesses of the two aquifer levels. The clay-sandstone level is thicker, continuous and of sandstone constitution with a low proportion of clay, ranging from Tsama2 village to Boundji-Atse. The sandy level which appears as a lens and a little deeper than the clay-sandstone level towards the village of Tsama 2. The thickness of this clay-sandstone level becomes less and less important in the central part of the section (line) and then increase towards the Boundji-Atse village (Figure 11(a)). These variations in the thickness of the aquifer level in both cases are linked to the sedimentation conditions, which depend on the folding of

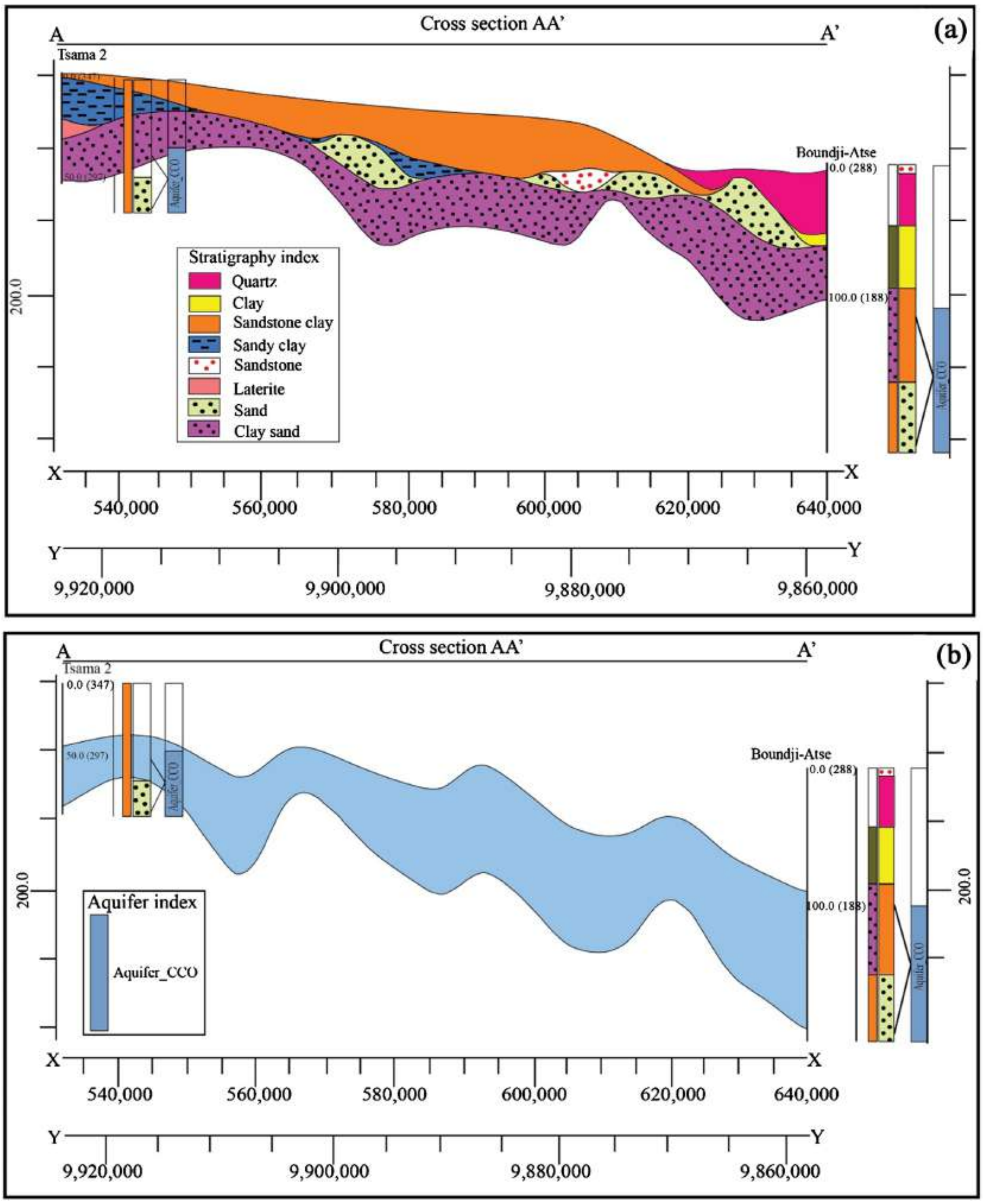


Figure 11. (a) Lithostratigraphic section and (b) aquifer section of Tsama 2 - Boundji-Atse.

the bedrock.

The lens morphology of the sandy level brought them into contact with the more or less permeable clay-sandstone level. This thus allowed hydraulic continuity between the two adjacent levels (**Figure 11(a)**).

4.2. Piezometric Levels of the Study Area

Figure 12(a) below represents the piezometric map of the study area relating to the year of data collection by the Asperbras Company during the installation of the boreholes in 2015. This shows that all the arrows converging towards the

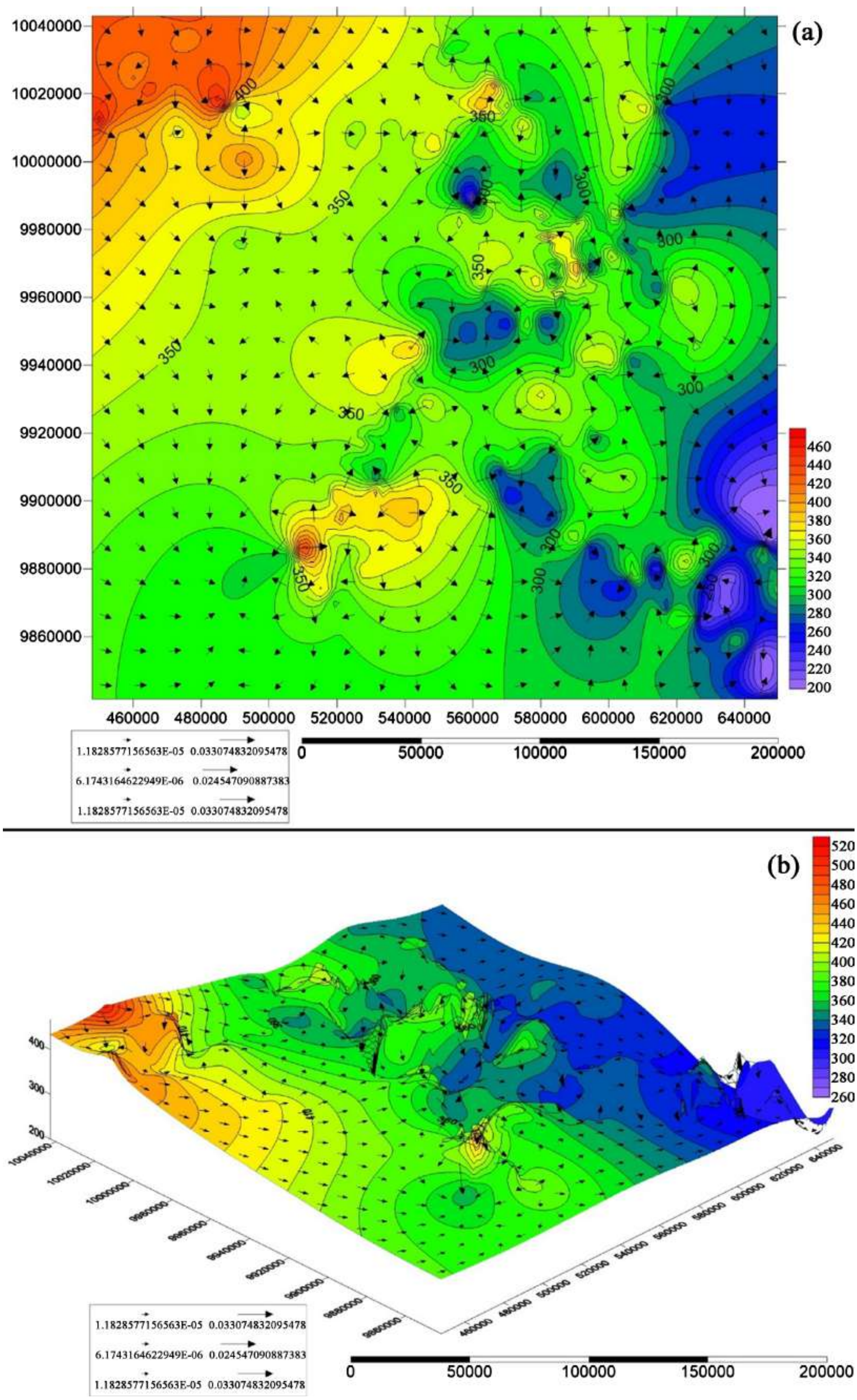


Figure 12. Piezometric map of the study area (a) in 2D and (b) in 3D.

lowest static level.

At the Cuvette-Ouest level the arrows generally converge in the direction of the Cuvette but on the other hand, we notice that at the Cuvette level the arrows diverge more. Static levels throughout the eastern part of the study area are between 0 and 10 m depth relative to mean sea level and at altitudes ranging from 200 to 470 m. On the other hand, the static level has considerably increased from East to West towards the West Cuvette.

The piezometric map of the departments of Cuvette-Ouest and Cuvette, extracted from the 3D geological model, shows that the thickness of this formation varies between 240 and 310 m with a majority of values between 300 and 320 m (**Figure 12(b)**). The average thickness is about 310 m above the basin department. The most important is mainly observed at the eastern ends of the department of the Cuvette where it reaches more than 350 m (**Figure 12(b)**). The department of Cuvette-Ouest recorded thickness values greater than 400 m, among the strongest in the geological model.

4.3. Approach to the Hydrogeological Model of the Aquifer in the Departments of Cuvette and Cuvette-Ouest

The 3D geological visualization model of the depth layers of the Cuvette and the Cuvette-Ouest was produced from the interpolation of the geological data collected in the end-of-borehole reports from 243 water wells. The interpolation of these data using the Visual MODFLOW Flex software ([8]), makes it possible to characterize and visualize the three-dimensional geometry of the departments of Cuvette-Ouest (CO) and Cuvette (C), to where the term "3D geological model of the departments of Cuvette-Ouest and Cuvette. If the Visual MODFLOW Flex software does not make it possible to visualize the volumes, it does on the other hand make it possible to edit sections for illustration of the layer of the roofs of the wells of the boreholes (**Figure 13(a)**), of the statistical level of the wells (**Figure 13(b)**) and the depth of location of the water table (**Figure 13(c)**). Three surfaces allowing to characterize the 3D geometry of the departments of Cuvette-Ouest and Cuvette were thus obtained. They represent the morphology of the roof and the wall of the Cuvette-Ouest and Cuvette departments as well as its thickness (**Figure 13(a)** and **Figure 14**).

Overall, the 3D geological model of the Cuvette-Ouest and Cuvette departments shows that this aquifer forms a large asymmetrical syncline, molded on the deep morphology of the basin of the Congolese basin, the depth of which increases from west to east, that is to say that our aquifer is much thicker at the level of the Cuvette department (170 m) than at the level of the Cuvette-Ouest department (85 m). This model shows that the aquifer is continuous and free throughout the extent of our study area (**Figure 14**). This is in accordance with the geology of this study area and with the results of the work of ([24]). This model shows that the static level of the wells is located at a depth between 10 and 40 m (**Figure 13(c)**).

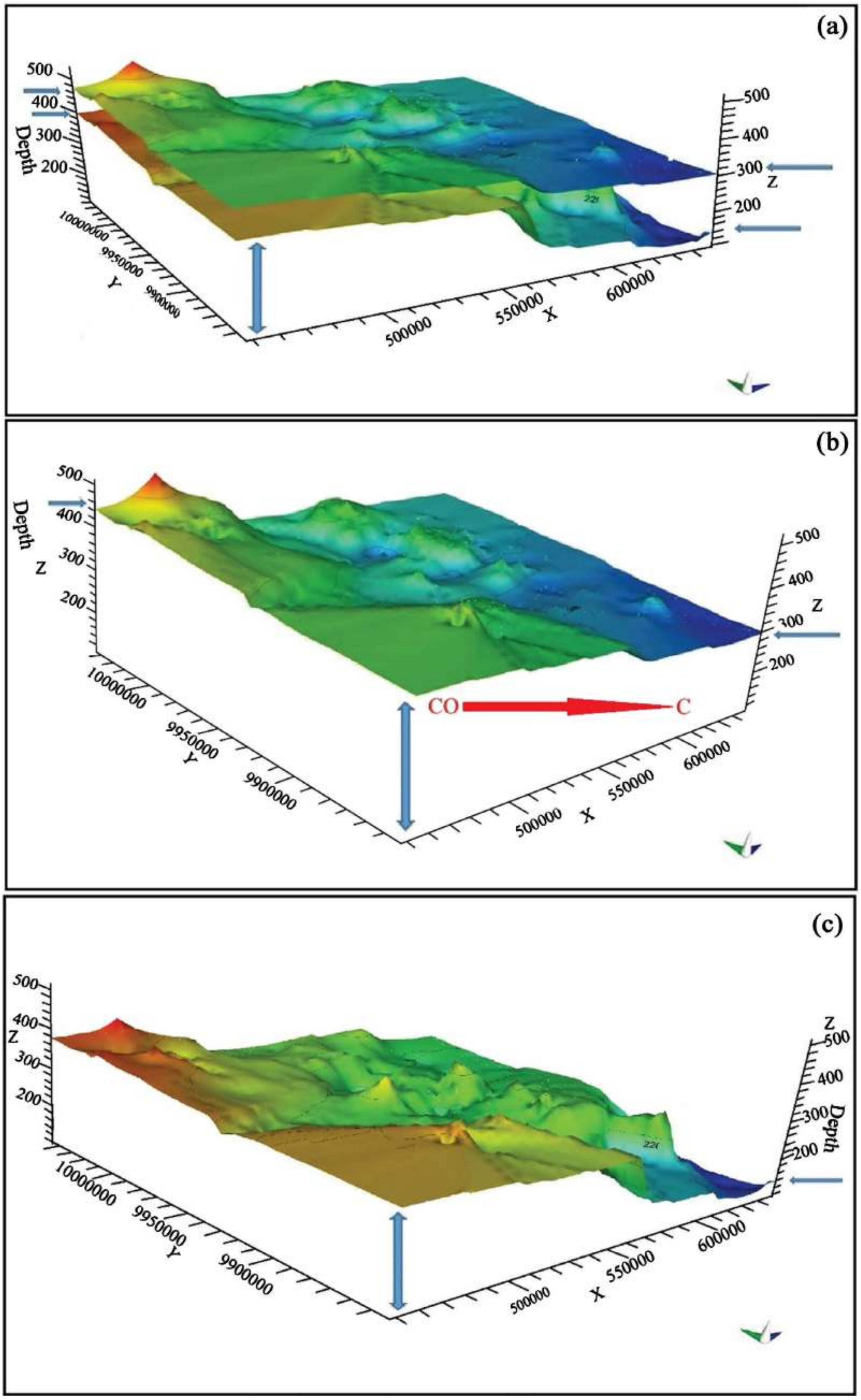


Figure 13. 3D figures show (a) borehole roof and base illustration, (b) well statistics level and (c) depth of groundwater location.

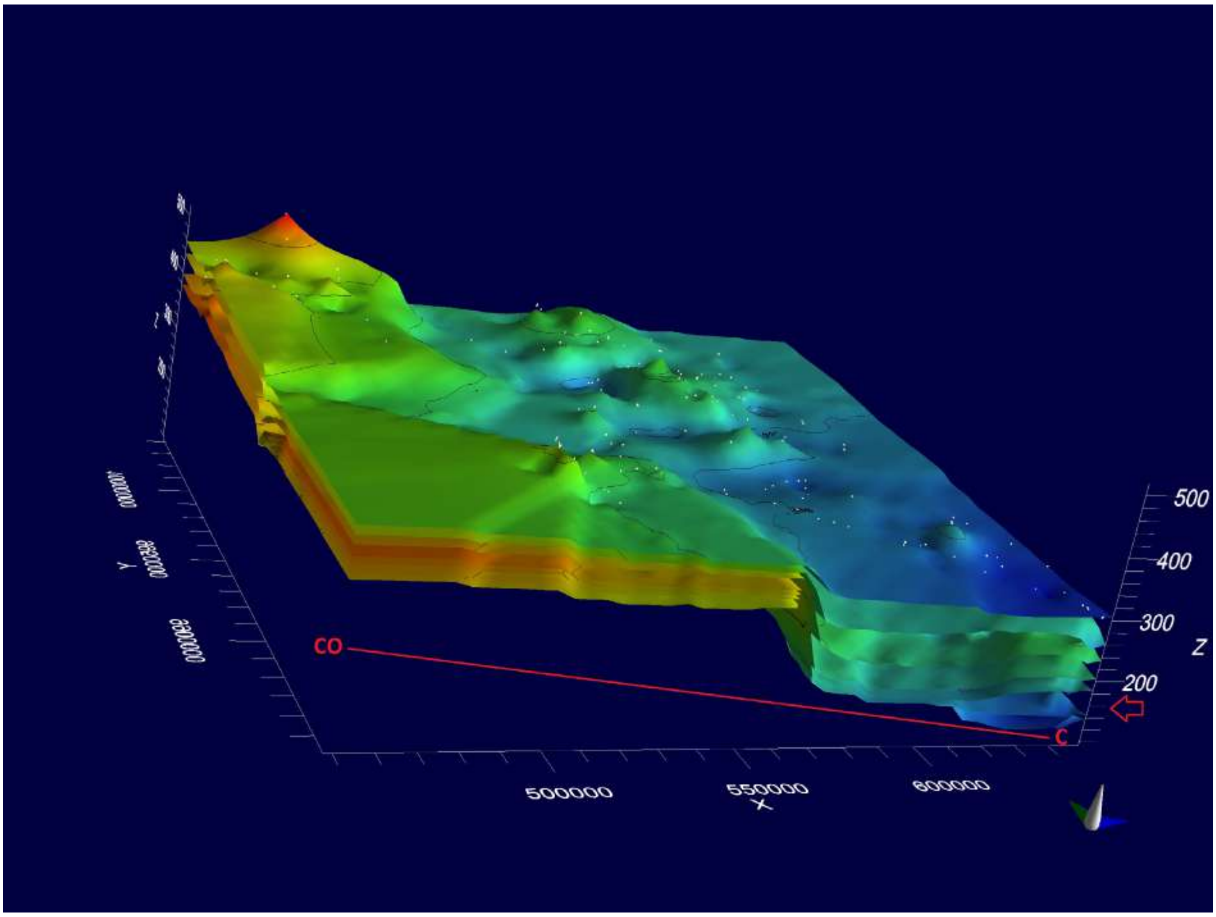


Figure 14. Hydrogeological modeling approach showing the depth of the water table in the department of Cuvette and Cuvette-Ouest.

To estimate the depth of the roof and that of the wall of the water table and then deduce the thickness, it was necessary to carry out a 3D geological visualization model of the different layers crossed by the boreholes from the drilling data. It emerges from this model that the elevation of the roof of this formation appears between 430 m and 150 m under the departments of Cuvette-Ouest (CO) and Cuvette (C) deepening from west to East (**Figure 13(a)** and **Figure 14**). In the basin department, on the other hand, the boreholes reach values of 150 m to 200 m maximum depth (**Figure 14**).

At first glance, the piezometric maps and those of depth extracted from the 3D geological model show that between the department of the basin and that of the western basin, the department of the basin is indeed the favorable zone for hydrogeological exploration. This represents almost two-thirds of the eastern part of the model (**Figure 14**). Observation made, it is noted that the layers of the geological formations located in the department of the Cuvette appear thicker and deeper than those located at the level of the department of the Cuvette-Ouest.

5. Conclusions

The study of the aquifer is seen as a powerful tool for the assessment, development and management of groundwater resources. A combination of lithostratigraphic sections and piezometric maps was used to develop a conceptual hydrogeological model of the Congolese Cuvette basin aquifer in the departments of Cuvette and Cuvette-Ouest. The conceptual hydrogeological model was designed using MODFLOW Flex 2015.1 software to characterize the geometry of the aquifer and to understand the direction of groundwater flow in the Congolese Cuvette basin.

Lithostratigraphic sections were designed using Rock-Works.17 software using data resulting from perforated boreholes across the Congolese Cuvette basin. These sections showed a vertical variation of the lithological layers according to the following arrangement from bottom to top: clay - clayey sand - sand and which gives the aquifer a heterogeneous character. They also showed that the thickness of the geological layers traversed during the drilling varies considerably from the Cuvette-Ouest towards the Cuvette. This aquifer is generally located in sandy to clayey formations which constitute a generalized and porous aquifer.

The piezometric map shows us that the water flows from a place with a strong hydraulic gradient towards an area with a weak hydraulic gradient. In this case, we can say that the water flows from the Cuvette-Ouest towards the Cuvette. This may be due to the morphology of the terrain because compared to the relief of the Cuvette, the relief of the Cuvette-Ouest is high.

The geometry of the aquifer is presented through a 3D model showing its different overlapping layers. The general direction of groundwater flow is from west to east that is to say from Cuvette-Ouest (CO) to Cuvette (C). The rocks that contain these groundwater layers constitute a large free aquifer in constant communication with the rivers and rivers as indicated by the flows which are all oriented towards the low areas where the rivers and rivers flow.

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Conflicts of Interest

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

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