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Hydrogeological Characterization of Continental Terminal and Oligo-Miocene Aquifers in the Tambacounda-Kaffrine Zone (Senegal)

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Abstract: This study aims to make a hydrogeological characterization of the aquifers of the Continental Terminal and the Oligo-Miocene. To do so, an analysis is conducted on the basis of hydrogeological parameters from 172 boreholes, 10 of which are used for groundwater levels and flows analysis. The results of the statistical analysis of the hydrogeological parameters show that the average flow rate is 42.29 m^3/h, the average specific flow rate is 5.96 m^3/h/m, and the average transmissivity is 0.024 m^2/s. These values highlight the high productivity of aquifers from the Continental Terminal and the Oligo-Miocene. The results of piezometry showed that water flows from the south center to the northwest of Tambacounda where the largest depression is located and could even be the outlet of the system. The groundwater fluctuations between low water level and high water level seasons reveal a rise in the piezometric surface of the aquifers at the scale of the study area.

Key words: Aquifer, productivity, piezometry, Continental Terminal, Oligo-Miocene.

1. Introduction

The countries of Sahelian Africa such as Senegal have been experiencing chronic climate disturbances for the past ten years, which severely threaten the availability of water resources. Recurrent droughts occurred these recent years: indeed in the 1970s, 1980s and 1990s rainfall decreased by about 40% [1, 2]. In the center of the country which is not sufficiently supplied by rainfalls, the aquifers are deeply depressed and desertification is progressing in the most disadvantaged areas [3]. Under such conditions, the control of water mobilization becomes a major concern. Senegal certainly has rivers with high discharge (more than 26 billion m^3 per year), but to date, vast areas, formerly crossed by watercourses, have become almost completely devoid of surface water as a result of drying up of rivers [4].

Faced with the non-permanence of surface water, the future of groundwater, which is widely used, is a major concern. In some regions of the country, pumping rate exceeds the renewal capacities (aquifers of the Quaternary sands of Cape Verde and the Palaeocene limestones of Sébikhotane).

This over-pumping has also increased the phenomenon of saline intrusion, particularly in the Sine Saloum valleys and in the deltas of Casamance and the Senegal River. In addition, groundwater recharge is limited as the uncontrolled urbanization of large urban centers (such as Dakar) has reduced the areas of water infiltration. The recharge deficit of aquifers from rainfall was 13% and 27% respectively

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during the 1970s and 1980 [5, 6].

Among Senegal's groundwater resources are the Continental Terminal and Oligo-Miocene aquifers, which cover a large part of the country and are experiencing a water level decreasing (from 20 to 25 m in 25 years at the horst of Ndiass). In 2015, there were an estimated 207 boreholes exploiting these aquifers in the Tambacounda and Kaffrine regions. In these regions, the situation is particularly worrying. Studies carried out on the southern edge of the Ferlo, located between these two regions, have predicted an overall water balance deficit because infiltration during the rainy season is consumed by evaporation during the dry season [7]. It results from all these climatic and anthropic factors mentioned, a degradation of the balance between aquifers and the ecosystem which is difficult to assess in particular for the regions of Tambacounda and Kaffrine.

Since the sustainability of the water resource depends on its adequate management, it is necessary to assess the functioning and the hydrodynamic properties of the aquifers under intense exploitation and rainfall decline. To do so, the Department of Water Resources Management and Planning [4] has set up a measurement and observation program on all the country's aquifers with the aim of monitoring the quantitative and qualitative evolution of surface and groundwater resources [8]. This study is carried out in this context and aims at contributing to better quantitative management of groundwater resources in the Tambacounda-Kaffrine zone. Specifically, the study will consist to characterize the hydrodynamic behaviour of the Continental Terminal and the Oligo-Miocene aquifers.

2. Study Site

2.1 Location

The study area is located in regions of Tambacounda and Kaffrine which have a cumulative area of 53,887 km ²or 28% of the area of Senegal. It is limited by the region of Matam in the North and North-East; the regions of Kaolack, Falick and Kolda in the West; those of Louga and Diourbel in the North and by the region of Kedougou in the South. The study area is also bordered by the Republic of Mali to the East, by Mauritania to the North-East and by the Republic of Gambia to the West and South-west (Fig. 1).

2.2 Climate and Hydrography

The climate type of the study area is sudano-sahelian with a short rainy season, from June-July to October, and a long dry season of 8 to 9 months. This situation is due to the dynamics of the general atmospheric circulation prevailing in West Africa. Rainfall experiences inter-annual variability. The study area lies between the 450 and 800 mm isohyets. Temperatures are generally high, with significant variations. They oscillate between 26 and 39 ℃ with a monthly average of 29 ℃ and a daily average duration of sunshine of 11 h.

The Tambacounda region is watered by a very important hydrographic network consisting of the Senegal River, the Falémé, the Gambia River as well as several tributaries and backwaters which drain approximately 30 billion m^3 of water each year [9].

2.3 Geology and Hydrogeology

Senegal is characterized by two major geological and structural units:

- The Senegalese-Mauritanian coastal sedimentary basin made up of layers of variable thickness of sands, clays and limestones which extend over 1,400 km from Mauritania to Guinea Bissau. The Kaffrine region and a large part of the Tambacounda region are located in this set;
- The ancient bedrock, representing less than 1/5 of the territory, is made up of plutonic and metamorphic rocks in the eastern part of Senegal.

Hydrogeological, hydrodynamic and geophysical studies carried out on the Senegalese sedimentary basin have identified four (4) major aquifer systems, including the superficial aquifer system which is located above the more consolidated deposits of the intermediate aquifer system (Eocene and Paleocene) and the deep aquifer system (Maastrichtian). Its thickness varies from 0 to 150 m and the depth of the water table can range from a few meters to 72.5 m.

The aquifer system of the study area (Fig. 2) groups vertically from top to bottom the following aquifers:

- The Continental Terminal aquifer: it contains a water table in the sandy and sandy clay formations. It is the water table which is mainly exploited by village wells and supplies almost all of them in the study area.
- The Oligo-Miocene: the structure of this aquifer is complex because it is often difficult to distinguish from the Continental Terminal and appears in the form of several superimposed sandy or clayey horizons, two or three in number.

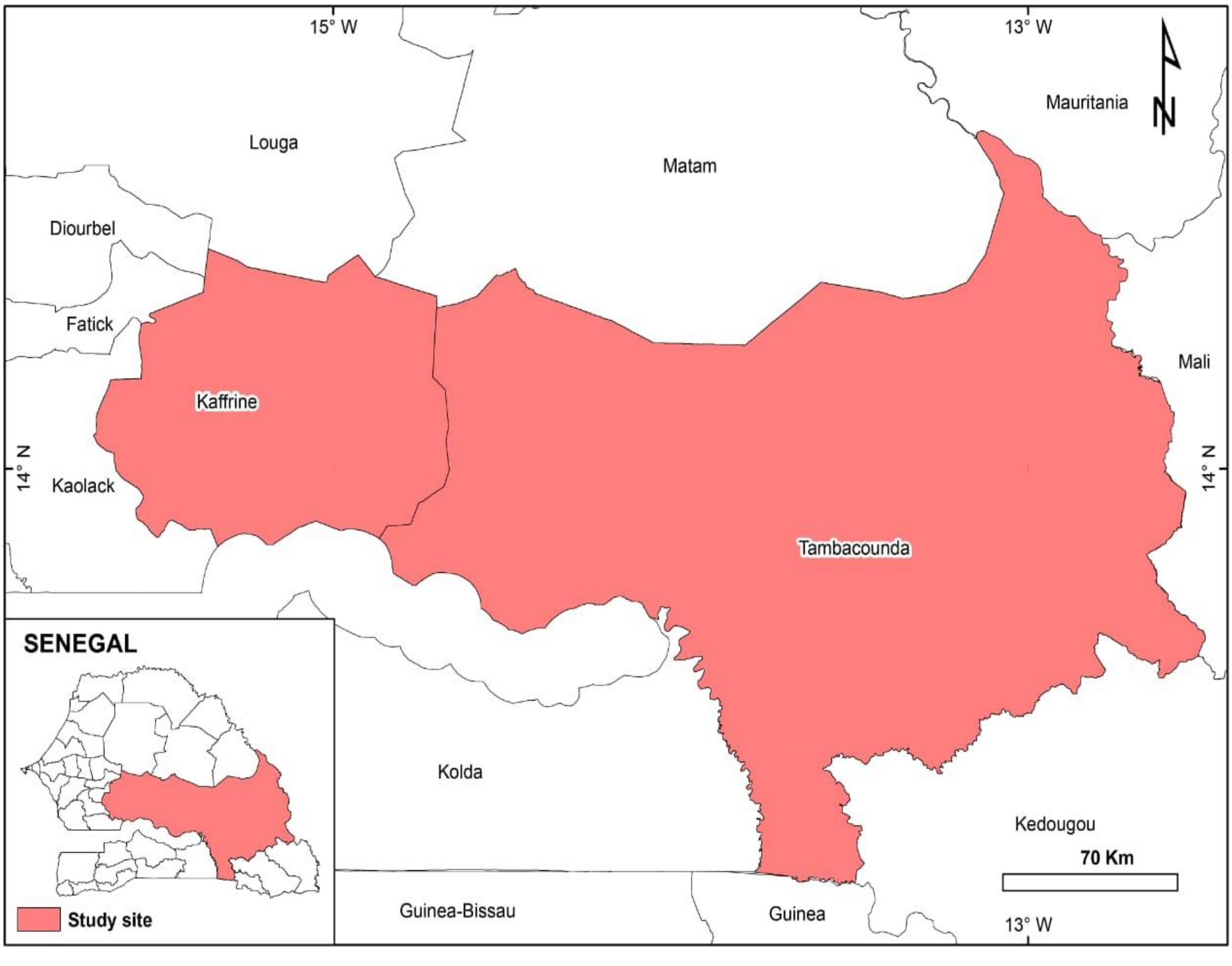


Fig. 1 Localization map of the study site.

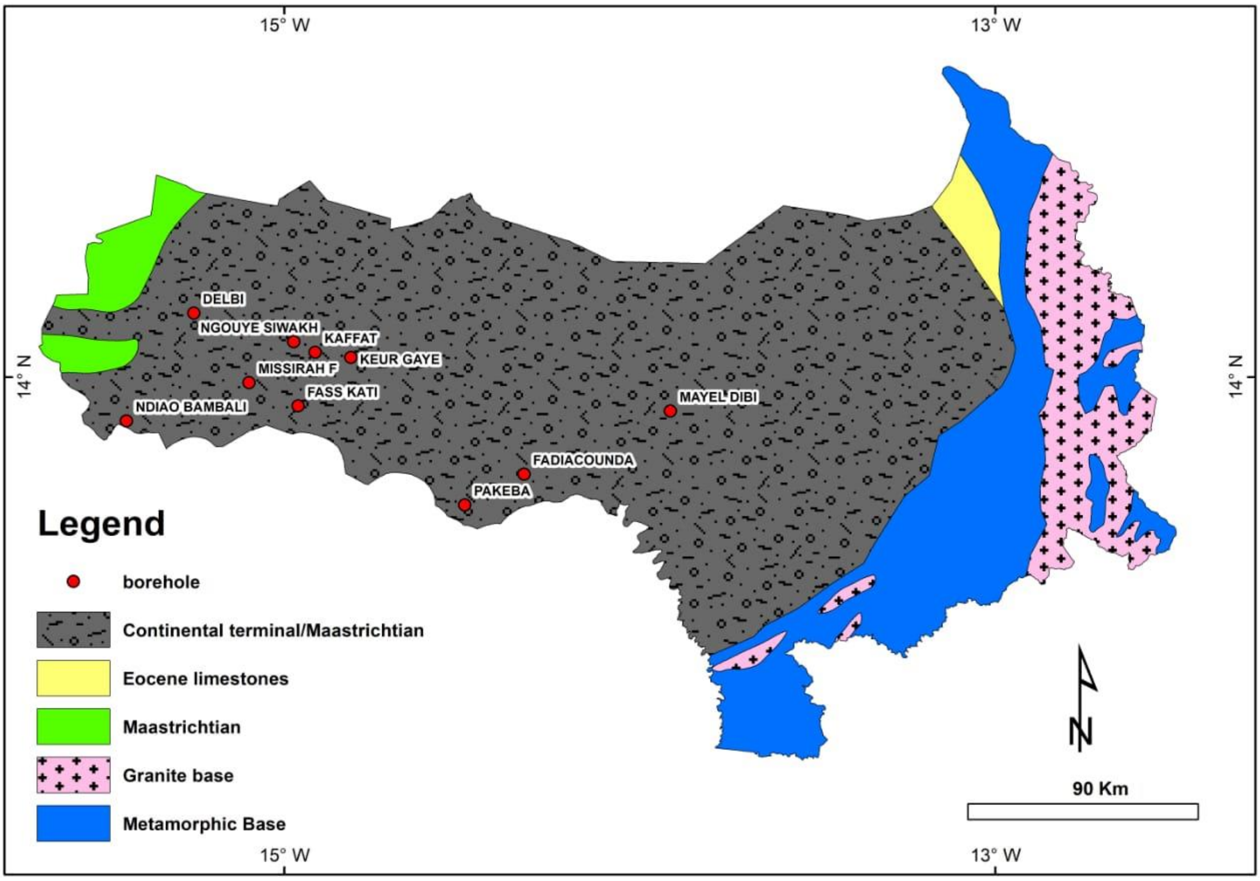


Fig. 2 Hydrogeological map of the study site.

3. Materials and Methods

3.1 Assessment of the Terminal Complex Aquifer Productivity

Data sets from 162 boreholes and wells were collected at the DGPRE (Directorate of Management and Planning of Water Resources of Senegal). The following data were considered or calculated for the study of the terminal complex (Continental Terminal and Oligo-Miocene) aquifer productivity: the total depth of the borehole/well, the alteration thickness, the static level, the flow rate (Q), the specific flow rate (Qs) and the transmissivity (T).

First, an elementary statistical analysis was carried out on the basis of these parameters. Then the flow rate, the specific flow rate and the transmissivity values were compared with values given by the Comité Interafricain d'Etudes Hydrauliques (CIEH) classification [10] (Tables 1-3).

Table 1 Rate (Q) classification by CIEH.

Intervals	Class
$0 < Q < 1$ m^3/h	Very low rate
$1 < Q < 2.5$ m^3/h	Low rate
$2.5 < Q < 5$ m^3/h	Average rate
$5 < Q < 10$ m^3/h	High rate
$Q > 10$ m^3/h	Very high rate

Table 2 Specific flow rate (Qs) classification by CIEH.

Intervals	Class
$Qs < 0.1$ m^3/h/m	Field of rural hydraulics
0.1 m^3/h/m $< Qs < 0.36$ m^3/h/m	Field of small agricultural hydraulics
0.36 m^3/h/m $< Qs < 1$ m^3/h/m	Field of agricultural hydraulics
$Qs > 1$ m^3/h/m	Field of urban hydraulics

Table 3 Transmissivity (T) classification by CIEH.

Intervals	Class
$T < 10^{-5}$ m^2/s	Low
10^{-5} m^2/s $< T < 10^{-4}$ m^2/s	Medium
$T > 10^{-4}$ m^2/s	High

3.2 Study of Piezometry

Ten (10) boreholes were used for the piezometry study. Indeed, these boreholes are intended to ensure the piezometric monitoring of the study area.

The piezometry is represented by the hydraulic head defined by the Eq. (1):

$$H = z + \frac{P}{\rho g} \quad (1)$$

where H is the hydraulic head, z is the elevation of the body of water, P is the pressure, ρ is the density of water, g is the acceleration due to gravity.

This hydraulic head is calculated in relation to a reference plan which is in our case the sea level, so the hydraulic head is obtained by the Eq. (2):

$$H = Z - SL \quad (2)$$

with H, the hydraulic head or piezometric height, Z, the altitude of the borehole and SL the static level.

3.2.1 Data Treatment

Piezometric data that were collected using the DGPRE database ranged from 1980 to 2018. However, data were not all usable so we processed and sorted them. Each measurement point was plotted on the geological map of Tambacounda and Kaffrine to find out if it was located exactly on one of the aquifers studied.

Then it was checked whether for each hydrological year, measurements were taken on all the piezometers in the study area. On the 13 measurement points that capture the Oligo-Miocene aquifer, after treatment, 10 were selected because the monitoring is regular for these boreholes.

The piezometric maps produced are then based on these 10 monitoring locations during the year 2018. Two maps are drawn: one is related to the high water level season and the second is related to the low water level season.

Fig. 3 illustrates the localization of the boreholes which have been considered for the drawing of the piezometric map.

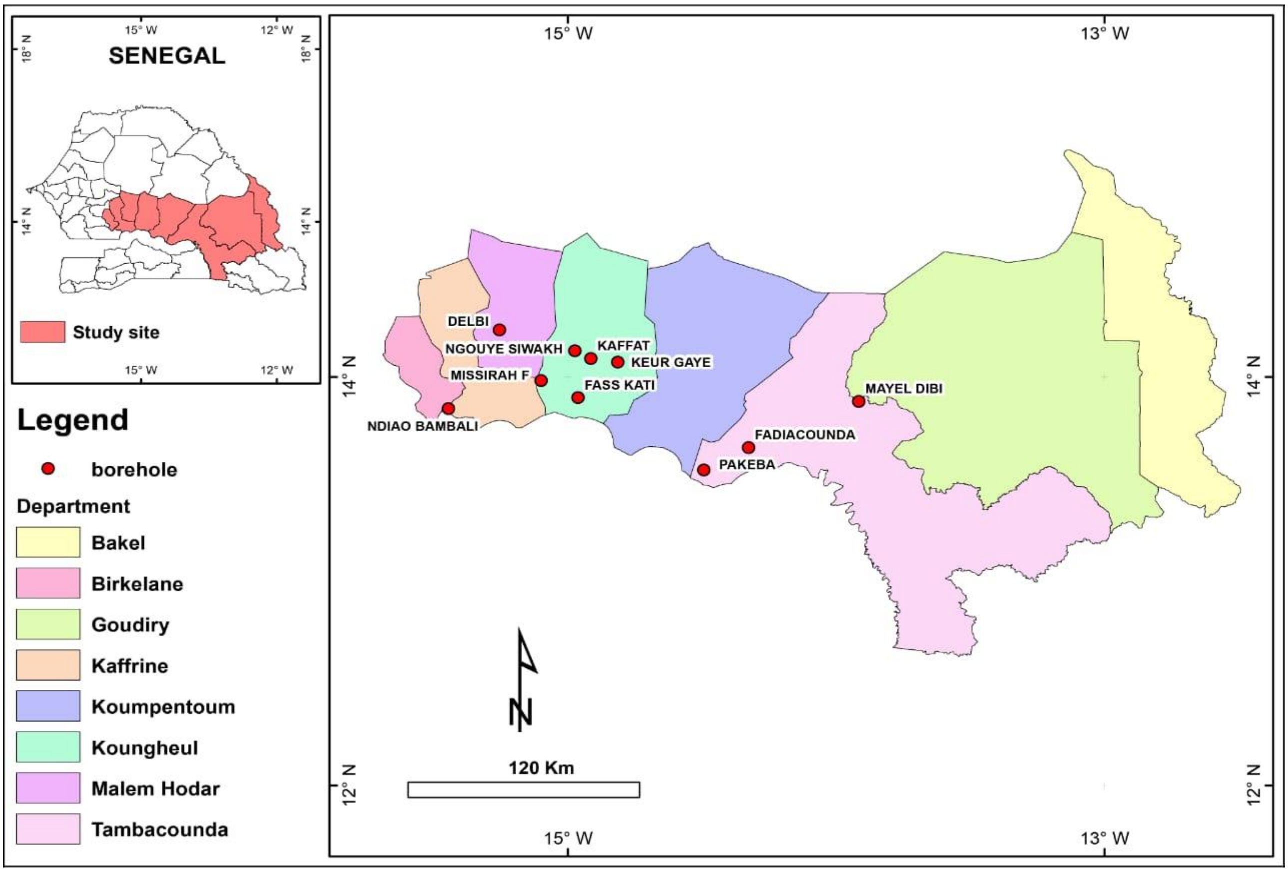


Fig. 3 Localization of boreholes on the study area Tambacounda-Kaffrine.

3.2.2 Method Used for Drawing the Piezometric Maps

Several trials of interpolation and mapping software were tested to produce the piezometric maps. ArcGIS software version 10.3.1 was chosen because the interpolation proved to be of better quality. The piezometric maps were realized on the latter by kriging method with a variogram model. Kriging is a geostatistical technique of spatial modeling allowing from some points to have a representation of values over the entire surface of the studied area [11]. This makes it possible to estimate the piezometric altitude outside the measurement points. This technique was chosen because it takes into account the distance between the measurement points [12]. Kriging is based on the assumption that two data that are close in space tend to have similar characteristics. It considers the presence of systematic drifts due to hydraulic gradients, the resulting map respects the spatial behaviour of the piezometry. For these reasons, it is the most accurate estimation method. The ArcGIS software draws the piezometric map by kriging with a variogram model independently.

4. Results and Discussion

4.1 Terminal Complex Aquifer Productivity

On the basis of data from 162 boreholes, a statistical study for the analysis of borehole parameters (total borehole depth, alteration thickness, static level) and hydrodynamic parameters (transmissivity, flow rate, specific flow rate) has been made. The results obtained are recorded in Table 4.

The total depth of the boreholes varies from 41.30 to 240 m with an average of 120.77 m. The deepest (240 m) is located in the Tambacounda region. It captures the sandy horizon of the Oligo-Miocene. The static levels vary from 5.55 to 72.35 m with an average of 41.16 m.

The transmissivity values vary from 0.010 to 0.090 m^2/s, with an average of 0.024 m^2/s which corresponds to the class of “high transmissivities” according to the CIEH classification. The high transmissivity values could be explained by the grain size of the captured aquifer. Indeed, the terminal complex (Continental Terminal and Oligo-Miocene) is composed of sands and sandy clay in varying proportions; 90% of the boreholes for which we have transmissivity data capture the sandy part of the aquifers of the terminal complex which, from a hydrogeological point of view, have good hydraulic properties. The study of Kouassi et al. [13], in the same context on the continental terminal in Abidjan, showed similar results with transmissivity values that vary from 0.028 m^2/s to 0.340 m^2/s.

The values of flow rates vary from 0.9 and 90 m^3/h with an average of 42.29 m^3/h. According to CIEH classification, the average value corresponds to “very high rate”.

The values of the specific flow rates vary from 0.03 to 88.83 $m^3/s/m$ with an average value of 8.93 $m^3/s/m$, corresponding to “urban hydraulics” according to CIEH classification.

Table 4 Elementary statistics of boreholes parameters and hydrodynamic parameters.

Statistics	Borehole depth (m)	Alteration thickness (m)	Static level (m)	Flow rate (m^3/h)	Specific flow rate ($m^3/h/m$)	Transmissivity (m^2/s)
Number of observations	162	34	161	160	134	23
Minimum	41.3	2.0	5.55	0.90	0.03	0.010
Maximum	240.0	91.0	72.35	90.00	88.83	0.090
Mean	120.77	40.27	41.15	42.29	5.96	0.024
Standard deviation	36.32	23.70	16.34	20.38	8.93	0.025
Coefficient of variation	3.33	1.70	2.52	2.08	0.67	0.96

It can then be noticed that aquifers of the Continental Terminal and Oligo Miocene have a very good productivity.

Fig. 4 shows the frequency of flow rates sorted by class. It shows that over all the observations, the very low (0 to 1 m^3/h) and low (1 to 2.5 m^3/h) flow rates each represent 0.62% of the total number of flow rates, high flow rates (Q varying from 5 to 10 m^3/h) represent 3.13% and very high flow rates ($Q > 10$ m^3/h) represent 95.66% of observations.

With regard to specific flow rates, it can be seen that the domain of rural hydraulics and small hydraulics each represents 0.75% of the observations, the domain of agricultural hydraulics represents 7.46%, the domain of urban hydraulics represents 91.04% of boreholes (Fig. 5). In view of these observations, the aquifers of the terminal complex show a relatively high productivity for all the lithologies highlighted in the study area.

The high values of the flow rates and specific flow rates are in adequacy with the values of the transmissivities. Indeed, Fig. 6 shows that 100% of transmissivity values belong to the class of high transmissivity. This confirms the high productivity of the aquifers of the Continental Terminal and Oligo-Miocene.

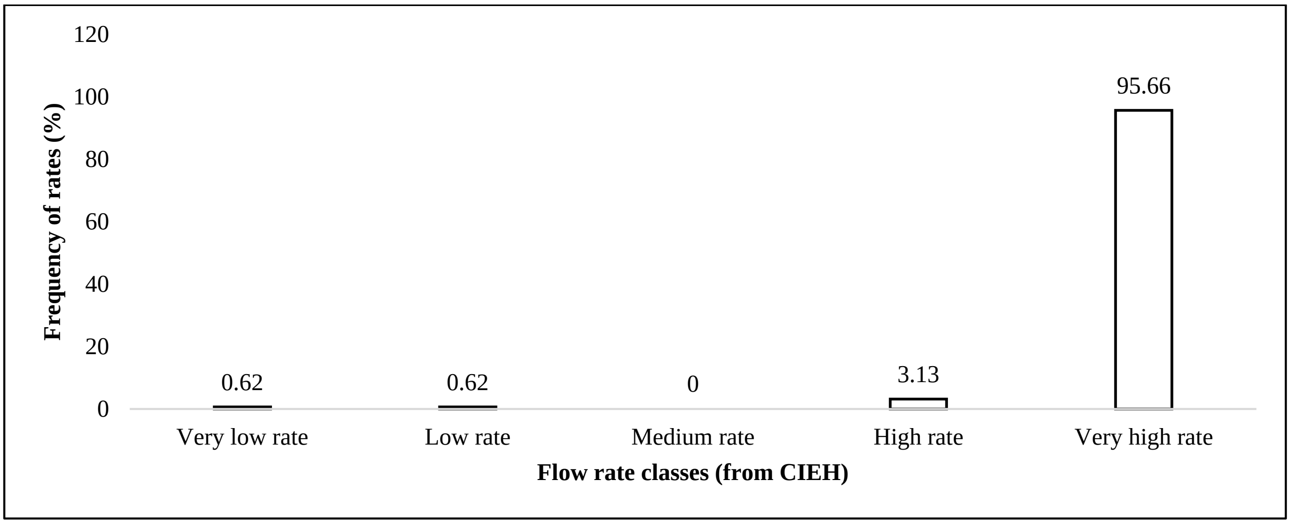


Fig. 4 Frequency of flow rates sorted by classes given by CIEH classification.

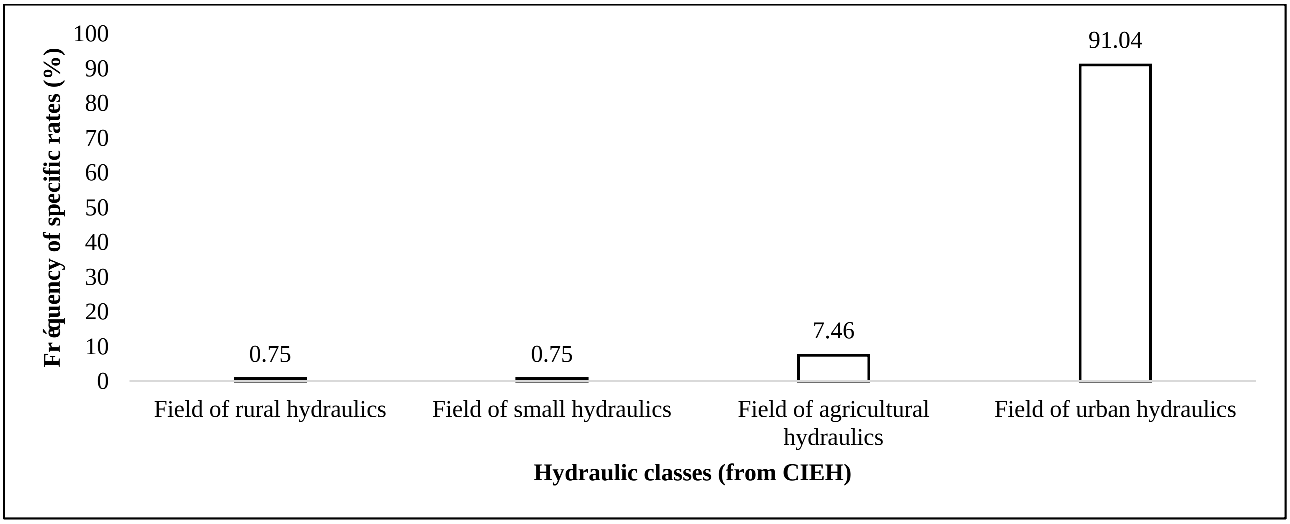
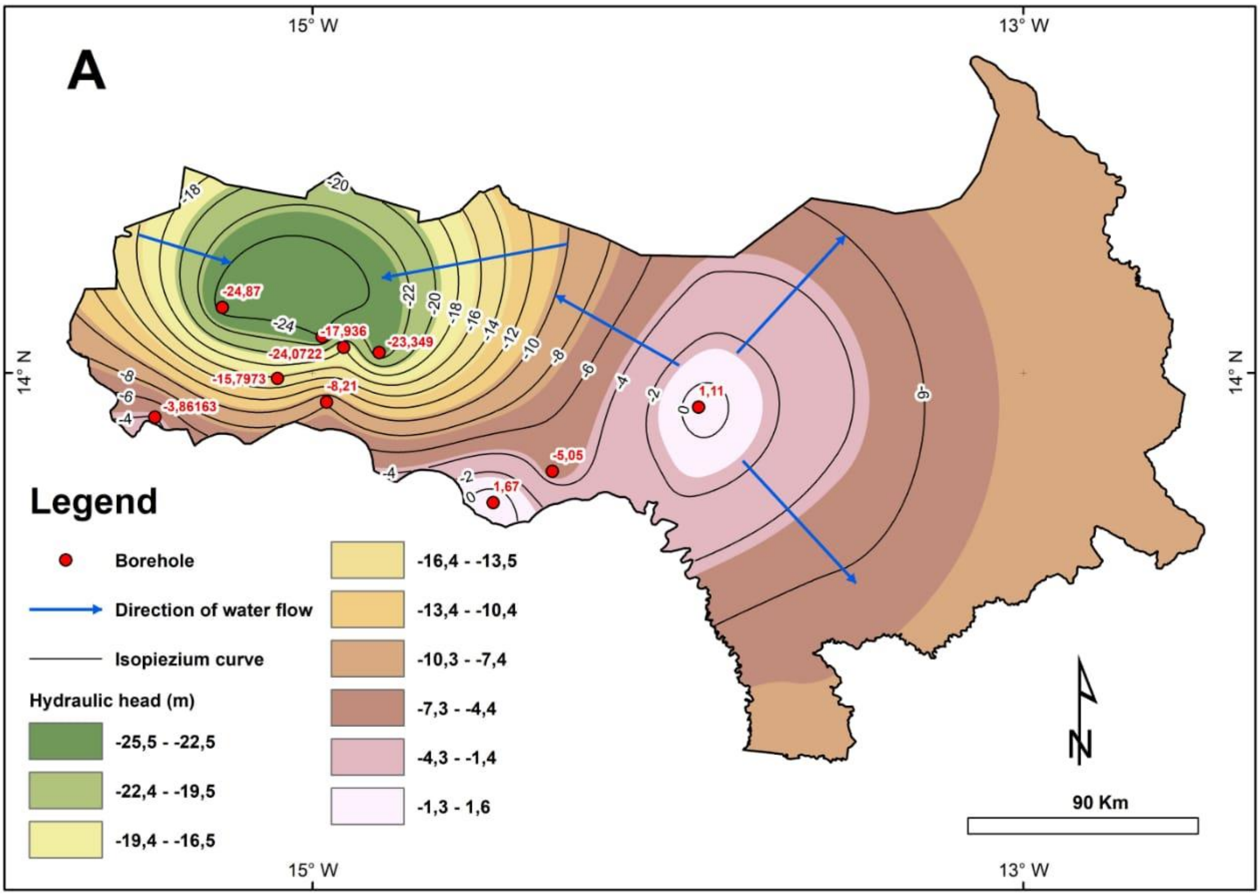


Fig. 5 Frequency of specific flow rates sorted by classes given by CIEH classification.

Fig. 6 Frequency of transmissivity values sorted by classes given by CIEH classification.



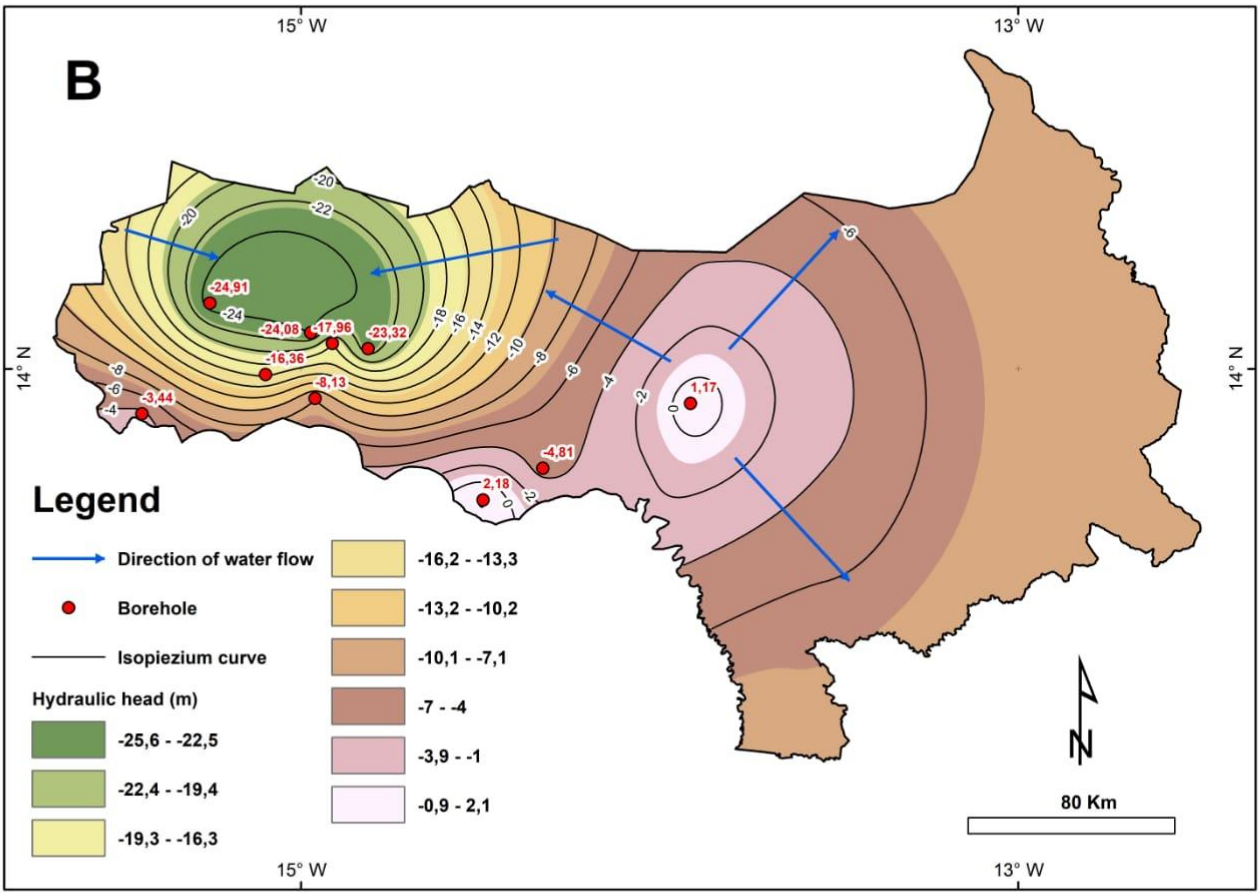


Fig. 7 Piezometric maps. (A) Low water level season; (B) High water level season.

4.2 Description of Piezometric Maps

The piezometric maps, established for the low water level season, present the same piezometric morphology as the map of the high water level season (Fig. 7A and 7B). These maps do not show a significant increase in the piezometric level with the exception of the piezometers on Pakéba and Fadiacounda (at the south center of the study site) where the piezometric surface fluctuates respectively by 51 cm and 24 cm, which remain low in absolute value. The central part of the study site where the piezometer of Mayel Dibi is located represents a recharge zone (piezometric dome) which controls the flow of this system towards the outlet. A depression (outlet) is located at the west part of the study area, close to the piezometer of Delbi. Both maps are similar, but we can notice a slight increase in hydraulic heads during the high water period. This situation is linked to rainfall, which leads to groundwater recharge.

5. Conclusion

It appears from this study that the aquifers of the Continental Terminal and the Oligo-Miocene are very productive. Indeed, the transmissivity values vary from 0.01 to 0.02 m^2/s, those of flow rates from 0.9 to 90 m^3/h and the specific flow rates vary from 0.03 to 88.83 $m^3/h/m$. The established piezometric maps show that the flows are from the center to the northwest of Tambacounda where the largest depression is located and could even be the outlet of the system. At the scale of the study site, there is an increase in the piezometric level during the high water season. This is explained by the fact that the high water season corresponds to the rainy season so there is a recharge of the water tables which takes place by infiltration then percolation.

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