Study of hydrogeological potential in the basement areas in eastern Chad: a case study of Ouaddaï-Biltine

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Abstract: This study carries on the assessing of the productivity of fissured aquifers of the regions of *Ouaddaï* and *Biltine* from an approach which takes into account climate variability, water balance, the thickness of regolith, the total depth of boreholes and the exploitation flow rates. An analysis of the hydrogeological parameters of 659 boreholes drillings was carried out. The results highlight four unfavourable zones as well as principal regional fractures direction associated with the recently opening of the Atlantic rift and the Red Sea. From this analysis it shows up clearly that the preferential targets of positive boreholes in the area of Ouaddaï-Biltine are the fractures with wide lengths oriented N60°E and N90°E. The analysis of depths of water inflows made it possible to highlight the presence of a shallow aquifer whose productive levels are located at a depth of 20 to 40m and a second productive level at a depth of 50m and more. The granite formations which constitute the majority of the geological formations are in general most productive. The best results are located in the pink granites and rhyolites and gray granite. The average flow rates of positive boreholes are range between 1.4 and 1.6m^3/h in the north and move between 3 and 4.4m^3/h in the south. These results contribute to make known the groundwater potentialities. They direct the future hydrogeological prospection for an economic boreholes establishment in this region.
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Key words: Borehole drilling, success rates, rural water supply, basement, geophysical survey.

1. Introduction

Groundwater has been identified as the best source for rural water supply in most rural communities in the Ouaddaï and Biltine (OB) Eastern region of Chad because it eliminates the problems of water borne diseases which have affected communities in this region over the years. Adequate groundwater exploration and management appears to be the key to ensure that potable and safe water is available for the entire population of the region and that its availability on a sustainable basis is guaranteed. Groundwater facilities being provided in the area include engineered hand dug wells, boreholes fitted with hand pumps.

Unfortunately, groundwater in some parts of Chad occurs in fractured crystalline basement rocks (axes of fracturing affecting the bedrock) and in the interface between the overburden and bedrock (HCNE-MEE-PNUD-DAES, 2005). These discontinuous aquifers often of Precambrian age (Liégeois J.P, 1992 et 1993) are consisting of eruptive and/or metamorphic rocks occupy an area of 340 000Km^2, that is to say approximately the quarter of the surface of Chad (Mbaitoudji., Leclerc, 1978; Schneider et al, 1992; Mbaitoudji, 1982). Access to groundwater remains then uncertain for these regions where the aquifers have certain complexity. The District of OB, located at Chad eastern is fit into this complex geological setting of groundwater systems.

Given the difficulties related to the groundwater resources mobilization in the fractured crystalline basement aquifer of OB, Chad government under the assistance of French Development Agency (FDA) have been initiated the project of rural water supply in OB to facilitate accessibility to drinking water to this community. This project went out from 2001 to 2008 allowed the realization of 659 positive boreholes in this region close to the border with Darfur region of Sudan.

The concept of rural water supply is to provide drinking water to population isolated starting from borehole drillings generally equipped with hand pumps. The principal objectives of this hydrogeological study are to: (i) Synthesize the main data acquired via boreholes drilling and their hydrogeological and geophysical establishment; (ii) Define hydrogeological areas for which various parameters are known; (iii) Make recommendations for the knowledge and monitoring of the resource and for possible future projects.

2. Description of the study area

The study area is located at the East of Chad in the region of Ouaddaï, delimited in the East by the Sudanese frontier and West by the sedimentary plain of the Chad basin. The region includes three great geomorphological entities: Reliefs from 600 to 1200 m of altitude in the east; the glacis zone of piedmont plain in the west with more modest altitudes (from 400 to 600 m) and a sedimentary zone in the west of relief which behaves like a partially dry bevel. It is an area poorly fed and hydrogeologically unfavorable. The population is scattered in many villages and is estimated at about 600 000 people for which it is necessary to add about 200,000 refugees, displaced following the events of Darfur (Steenhoutdt, 1993).

The context of rainfall in the last century shows a significant decline in rainfall since the 1960s in a general context and local of increase temperature (Schneider, 2001) Thus, rainfall in this region is estimated between 250 and 650 mm/year on the whole area (Marc-André., Yves H, 2005). This context deficit of rainfall and warming is particularly visible on the surface by observing in comparison the shrinkage of Lake Chad in the 20th century (UNEP/Grip-Arendal, 2002; Marc-André., Yves H, 2005). The impact of this rainfall deficit has obviously involved the decline of the groundwater resource.

The Precambrian massif of Ouaddaï, on which this study focuses, is the largest crystalline massif of Chad, which stretches over 500 km from north to south while extending to Sudan (Guiraud and Maurin, 1992; Kusnir, 1995). The basement in the west under the sedimentary formations of the Chad basin appears locally only by granitic outcrops or inselbergs. The massif of Ouaddaï appears as a plateau at an altitude ranging between 800 and 1000 meters (Marc-André., Yves, 2005). It is essentially an old granitic massif in which the metamorphic formations of middle Proterozoic age (Panafrican) take a certain importance only in the south of the 13th parallel (Kusnir, 1995). It is a stable region since the Pan-African orogeny, and besides some marine invasions in the Paleozoic and Mesozoic, the main part of the recent deposits corresponds to the products of continental erosion, transported by water and winds, which one find as a powerful lake series, river and wind (Guiraud and Maurin, 1992; Marc-André., Yves, 2005).

On the tectonics level, the ground of Ouaddaï basement, dated mainly from the Precambrian, are particularly affected by two principal directions (Gachet, 2004 and 2005]: direction N45°-65° assigned to the Atlantic rift, in the continuation of the lineament of Cameroon, which is strewn with volcanic edifice such as Mount of Cameroon and the islands of the Gulf of Guinea (Malabo); the direction N115°-135° connected to the East-African rift, which extends from Tibesti to the Elgon Mount in the limit between Uganda and Kenya, and incorporates the Djebel Marra in Darfur.

From the hydrogeological point of view, the study area is characterized by the classical superposition of the superficial porous reservoir (alluvium and regolith) and by a discontinuous aquifer hosted by the basement fractures (Cefigre, 1990). These aquifers are located in areas of outcrops basement and where it is sub-outcrops, including under several meters of covering thickness (regolith, Quaternary and Tertiary deposits) (Steenhoutdt, 1993). This configuration is encountered throughout the study area. The geometry of the aquifers reservoir includes the covering formation likely, under certain conditions, to contain a resource of sub-surface circumscribed within the spatial limits of the store rock and the bedrock formations, under their various lithology, their evolution stages and alteration (Massing *et al*, 2010). The weakness and the irregularity of rainfall, coupled with the importance of evaporation and transpiration, allows only a low infiltration estimated at 40mm/year (Moussie, 1986). These conditions do not make it possible to maintain in saturation the superficial aquifer (Engalenc *et al*, 1981) and the static water level is established within the fractured bedrock. This discontinuous aquifer is a reflection of the fractal distribution of fractures in reservoir rock.

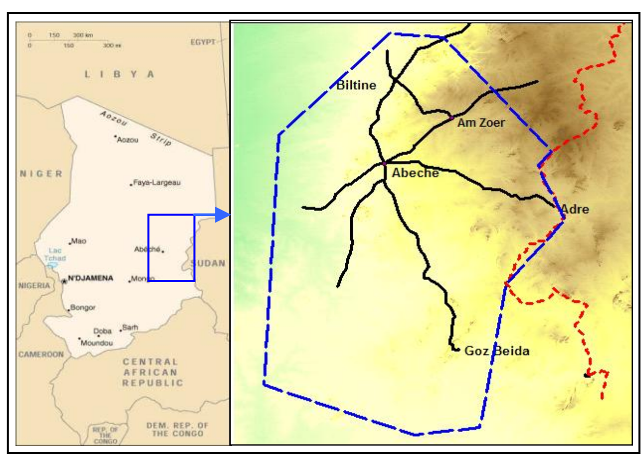


Figure 1. Map of Chad and the location of the study area

3. Materials and methods

This study was initially carried out through the collection of existing data at the Directorate of Hydraulics (DH) of the Ministry of water. These data consist of maps and field reports, enabled us to circumscribe our study area. To these bibliographical data, come to be added the data of 659 boreholes drillings of rural water supply in OB program. Data were extracted from the logs of drillings, geophysics prospecting and aerial photos (directions of lineaments on the sites drilled). All these data identified in the XY were then plotted on the UNHCR/RTF maps in order to assign to each drilling the parameters resulting from the processing satellite. Thus one allotted to each borehole: its rainfall, its geology, watersheds and its attributes, the distance from a dyke, a fault, a watex zone and their different attributes. All these data were then treated by graphs and by maps of distribution.

The methodology of establishment by village was characterized by: the identification of lineaments on satellite images. The main criteria were the presence of at least two lineaments of kilometric extension crossing on a node of fault; the proximity of a wadi to promote recharge, the presence of certain tectonic directions N40 to 60°E and N110 to 130°E considered as potentially more favorable; the possible presence of dyke to form waterproof barriers or drains. The interpretation of satellite images has allowed the location in a hierarchy from 2 to 4 geophysical points and to define two types of establishments. An establishment called "at risk" close to the village having a radius of 500m and another hydrogeologically more favorable of radius 2 km. The geophysical prospections are carried out by Vertical Electrical Sounding (VES) in order to validate and specify the anomalies on the ground. Then two Electrical Resistivity Imaging (ERI) are carrying out on the two best anomalies for an establishment of two hierarchical boreholes. After establishment it follows the realization of two boreholes drillings, often established primarily on the location called "at risk".

The geophysical campaign was carried out using the multimode Syscal Jr. R1-Switch-48 of IRIS Instrument (French leader of geophysical equipment, Orleans). It is a new all-in-one multinode resistivity imaging system which has an internal switching board for 48 electrodes spacing's of 5m and has two internal batteries, but can be also supplied by a 12V external battery (IRIS, 2001). Two strings of cable with 24 electrode take-out each are connected on the back of the resistivity meter. The system enabling fully automated measurements of the shallow subsurface apparent resistivity. According to the prospecting plan, the profiles of ERI were realized perpendicularly to the fractures directions. The center of each profile is located exactly at the site proposed by the interpretation of the radar image. All ERI profiles were carried out with 235m of total length and the measurement geometries used are Pole-Dipole (PD) and Pole-Pole (PP) configurations. The geoelectrical data collected were processed using Res2Dinv version 3.58 (Loke, 2009) modeling software in order to perform 2D geoelectrical data inversion. This software is based on an algorithm that uses measured apparent resistivity data as starting model (Barker, 1992). The inversion routine used by the program is based on the smoothness constrained least square method (Tsourlos and Ogilvy, 1999). The main objective of the inversion model is to find the resistivity of the cell that will minimize the difference between the calculated and measured resistivity values (Ramirez and Daily, 2000). The inverted data produce the 2D resistivity distribution pseudo section, which can then be used for borehole establishment. Based on these data interpretation, the precise locations of the potential boreholes are determined according to the resistivities anomaly. The best anomalies were then proposed for drilling where locations have been provided in real time with GPS coordinates, ground markings and visual involvement.

4. Results and Discussion

4.1. Results

The Table 1 shows the results of drilling according to rainfall making it possible to know the number of positive drillings. It includes all drilling of the project of rural water supply in Ouaddaï and Biltine and those of the updated database of the Ministry of Water.

The Table 2 summarizes the characteristics of different watersheds concerned by the study area. It indeed gathers the classification of the flows rate according to the watershed (in percentage). In particular on notes: the decrease in flow rate average (including negative drillings) from south to north (*Batha, Bitéa, Chaou and Khaba*); the watershed of *Saoué* provides the flow rates slightly higher in the north because it incorporates a part of the Am-Zoer zone; the watershed of *Kadja* which is potentially the most interesting in terms of average flows. However, it is the zone of *Adré*, where the sandstones have been very mixed (many dry drillings and many drillings with flow rates greater than 10 even 20m^3/h).

Table 1. Flow rate average distribution according to rainfall

Rain Fall (mm/year)	Flow rate (m^3/h) <0,5	0,5- 1,5	1,5 -3	3 -5	5 -10	>10	Nb	Flow rate mean
175	14	0	1	1	0	0	16	0.3
225	27	4	2	2	0	1	36	0.91
275	87	16	9	2	0	0	114	0.35
325	130	32	11	5	2	1	181	0.53
375	88	38	36	12	10	1	185	1.24
425	112	29	26	19	12	7	205	1.65
475	64	25	17	10	7	0	123	1.14
525	54	28	24	9	3	3	121	1.49
575	81	13	11	11	6	10	132	2.37
625	45	22	16	8	4	9	104	2.83
675	15	5	2	0	1	0	23	0.7
Total	**717**	**212**	**155**	**79**	**45**	**32**	**1240**	

Table 2. Flow rates average of drillings by watershed

Flow rate m^3/h - %	<0,5	0,5- 1,5	1,5- 3	3- 5	5- 10	>10
Batha Hamra	41.7	25.0	14.2	9.2	4.2	5.8
Bitea	35.6	22.1	17.8	14.7	6.1	3.7
Chaou	51.9	18.4	15.1	8.1	4.3	2.2
Kadja	60.2	2.3	11.4	4.5	8.0	13.6
Khaba	64.5	20.9	8.2	2.7	2.7	0.9
Saoue	59.7	19.4	11.9	4.5	4.5	0.0
others	68.8	14.1	9.9	4.0	2.7	0.4

The geology is mainly formed by granites for which the best results are located in the pink granites and rhyolites then gray granite (cuttings). It is possible that the pink granite merges with pegmatites in cuttings. It would seem that the rocks with coarse grains give a less clayey alteration and are therefore less prone to sealing of fissures. Conversely the fine rocks (dark rocks, white granite and gneiss) give lower values of flows. Figures 2 and 3 respectively illustrate the graphs of flow average of drilling based on the geology of the cuttings and the percentage of positive drillings according to the geology of the cuttings.

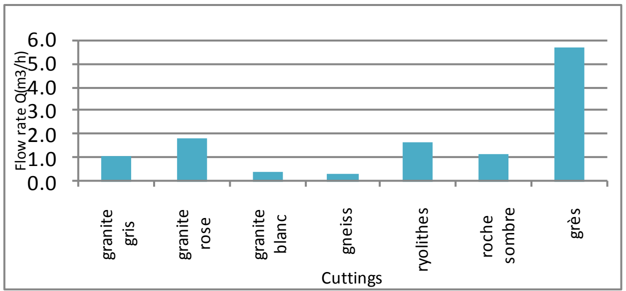


Figure 2. Flow average of drilling based on the geology of the cuttings

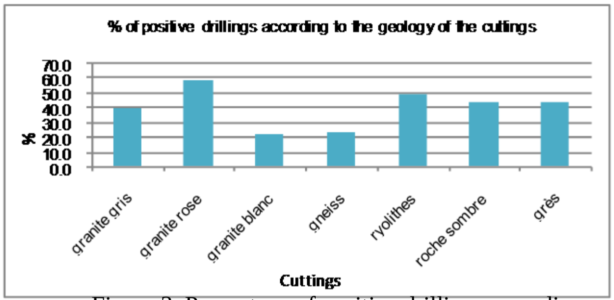


Figure 3. Percentage of positive drillings according to the geology of the cuttings

The tectonics aspect is a fundamental criterion for borehole establishment. However, the study of satellite images in comparison with those aerial photos makes it possible to know on which scale it is imperative to conduct a study for a project of rural water supply. The Table 3 shows the distribution of flow rates according to the faults and dykes mapped by UNHCR when they are located at distance less than 150 m from a borehole.

Table 3. Flow rates distribution according to the faults and dykes located at the distance less than 150 m from a borehole.

Flow rate Q(m^3/h)	<0.5	0.5 -1.5	1.5 - 3	3 - 5	5 - 10	>10	Nb
Faults <150 m	82	12	8	5	1	0	108
Dykes acids	2	0	0	1	0	0	3
Dykes basics	8	1	2	1	2	0	14
Quartz	9	1	0	0	0	0	10

The flows rates average (with or without dry boreholes) and the flow distribution according to the "hydrogeological" cantons are illustrated in Figure 4. The strong contrasts in rates are observed in the zone of Adré (dry or >15 m^3/h). On the other hand the flow averages of positive boreholes are range between 1.4 and 1.6m^3/h on the northern areas (Mimi, Gueri, Bourtail, Kodoye), except the Aboucharib area where the flows average are doubled. In the southern the flows average vary between 3 and 4.4 m^3/h with the exception of the Birguit area where the flows are low in view of the low number and an establishment into the bevel dry.

The figure 5 and 6 illustrate respectively the distributions graphs of the ratio S/Q according to the mean fractured length and the ratio S/Q as a function of the water conductivity of boreholes by cantons. The conductivity average is about 700 µS/m, except the Adré area where the values are low (<300 µS/m), on the other hand towards Mimi and Ouadi Chock the values are higher (about 1500 µS/m). It is in both cases the border of the dry bevel. One can consider that there are hydrothermal influences and/or the older waters.

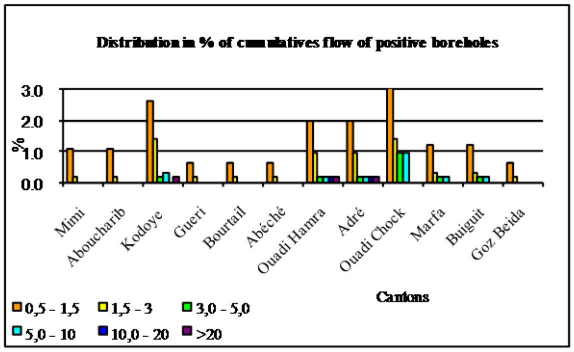


Figure 4. Distribution in % of cumulative flow of positive drillings

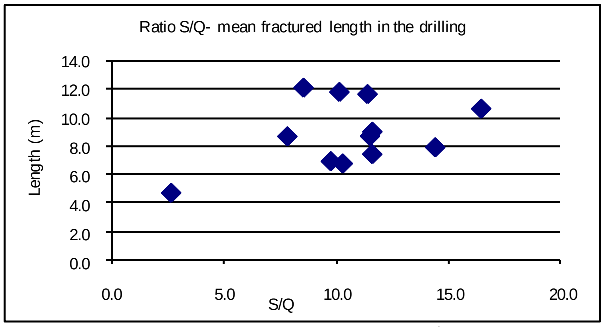


Figure 5. Ratio S/Q according to the mean fractured length

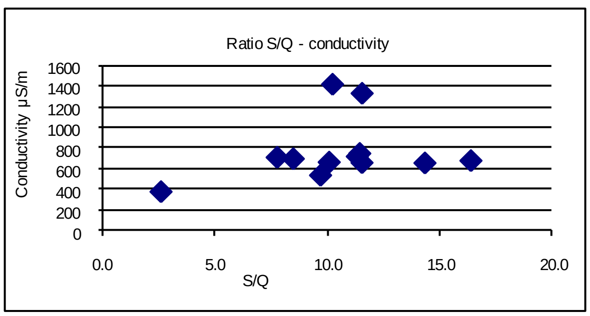


Figure 6. Ratio S/Q according to the conductivity

Table 4 summarizes concisely the main results of the drilling campaign highlighting the general success rate of this campaign and the percentage of satisfaction per village.It should be noted that each drilling carried out is positioned compared to at least one accident belonging to a specific tectonic direction. However, it maintains an excellent percentage of satisfaction per village which has been prospecting. It is noticed that these are the best results of the campaigns carried out in this study area, and, despite the prospection in the very unfavorable zones. Table 5 summarizes the mean values of different parameters which were integrated in this study.

Table 4. Summary of main results of the drilling campaign

	Number	Percentage (%)
Boreholes with water	422	64
Water inflow <0.5m^3/h	63	9.6
Satisfaction by village	282	72

Table 5. Summary of main parameters of the drilling campaign

Parameters	Mean values
Mean distance from borehole to village (m)	756
Population by borehole	510
Average depth of drilling (m)	61.3
Average depth of the basement roof (m)	48.7
Depth of the first water inflow (m)	34
Depth of the second water inflow (m)	45
Flow including dry boreholes (m^3/h)	1.5
Flow of positive boreholes (m^3/h)	3.3
Linear fractured by borehole (m)	8.8
Static water level (m)	19.80
Dynamic water level (m)	31.20
Drawdown (m)	11.40
Drawdown/ flow rate s/Q (specific flow rate) (m/m^3/h)	9.90
Temperature (Degree C)	31.63
PH	7.3
Water conductivity (µS/cm)	793

4.2. Discussion

In the zones of metamorphic or crystalline basement like those of this study area, the phreatic aquifer (closest to the ground surface) is a discontinuous aquifer. The groundwater flow is exclusively made at the fractures networks which affect these grounds. The productivity of a drilling will depend on the drainage capacity of the fractures that will overlap.

In general, waters which can be present in the fringe of alteration that covers these grounds only are with difficulty collected at this level. Its more or less clayey character does not make it possible to consider this alteration as an aquifer, its role in the functioning of the system is essentially capacitive. Finally, the productivity of drilling "strictly" to the basement depends only on the hydrodynamic properties of the fractures which they collect.

4.2.1. Climate variability in the region

Rainfall plays a fundamental role in the probability of finding a normal flow rate (0.5 to 1.5m^3/h). More one goes towards the south, more the rainfall increases and greater the chances of success. The damper to pose to this observation is that certain hydrogeological areas remain more or less favorable (*Adré*, *Guéri*, Mimi are not much favorable and the *Am-Zoer* zone is contrary very favorable). However there is no correlation between the range of flow rates higher to 1.5m^3/h and rainfall. Indeed, the high flows are directly related to the local characteristic of the aquifers traps and on their intrinsic supply.

4.2.2. Analysis according to the cuttings geology

A correlation was established between the different parameters of drilling and the geology of the cuttings. One note in particular: (i) higher thickness of alteration or soft ground in the sandstone and eolian or alluvial deposits. In the crystalline grounds, the average thicknesses range between 5 to 11m. These values are relatively low and show that there exists little or not water resources in this intermediary horizon which traditionally constitutes the reservoir of the regolith basement. (ii) The average thicknesses of fracturing in drilling are range between 6 and 13m. The higher thicknesses are located in the pink granites, migmatites and pegmatites (facies with pink coarse-grains). (iii) The average conductivity is highest in the rhyolites and eolian deposits. On the other hand, the sandstones give the values clearly lowest (about 200 µS/m). This lets supposed a high lateral supply by the lake and the Adré wadi.

In conclusion, these observations do not give really tracks on the establishment, because the village water supply is constrained to a small perimeter around the villages for the establishment of the works, and therefore with a low potential variability of the geological facies. For the facies of basement, the geology is not a very decisive criterion. Only the sandstone and the positioning of drilling can cause enormous contrasts results.

4.2.3. Analysis according to the tectonic

From the tectonic point of view, only 26 faults are nearby a positive drilling while more than 300 boreholes were given water. This proves that the scale of the interpretation of satellite image doesn't apply to village water supply. Indeed, the lineaments mapped in this interpretation are two to three by drilling on average. Similarly, the flows are not in correlation with the proximity of these regional accidents. The rosettes of directions showing the distribution and the orientation of dykes according to their petrography and of faults according to their geographical area, conducted by UNHCR (Marc-Andre., Yves, 2005) from the interpretation of satellite images made it possible to highlight the principal regional directions, associated with the recently opening of the Atlantic rift and the Red Sea. These directions are among others N50 to N70°E and N110 to N160°E in the northern and the directions N50 to N70°E and N110 to N120°E in the southern.

A comparative study of the dry and productive fractures made it possible to highlight that the main families of faults observed on a regional scale are found in boreholes. Figure 7 illustrates these remarks and shows that one well finds the regional namely N60 and N110-130°E. It adds the direction N40°E which is not emerged in the UNHCR study but which is present on the all types of drilling including on the main direction of drilling. The directions N60°E and 90°E give more positive boreholes. On the other hand the directions N20, 80, 110 and 130°E are often negative. The fact to find a lot of positive and negative drillings on the same directions enable us to hypothesize of the general decline of the resource, by considering that more than half of these accidents are any more or not fed.

Being given that the majority of drillings showed fracturing, one can consider that geophysics has filled its role of precision of the borehole establishment. However, as two electrical resistivity imaging (ERI) were carried out for two boreholes establishments, it is imperative to increase the number of ERI for the same number of boreholes, in order to really benefit from the results of geoelectric sections.

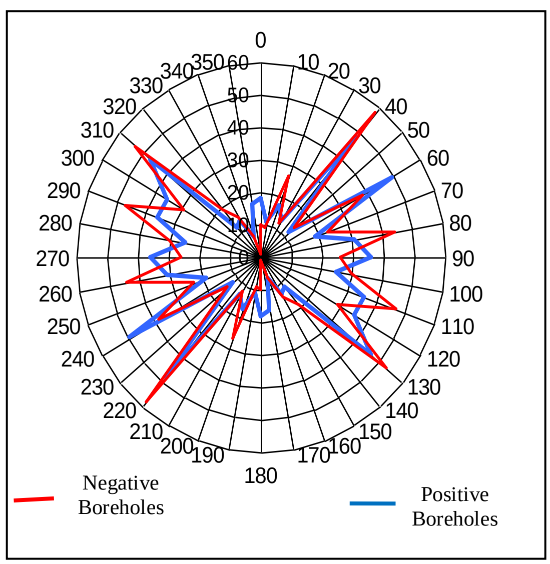
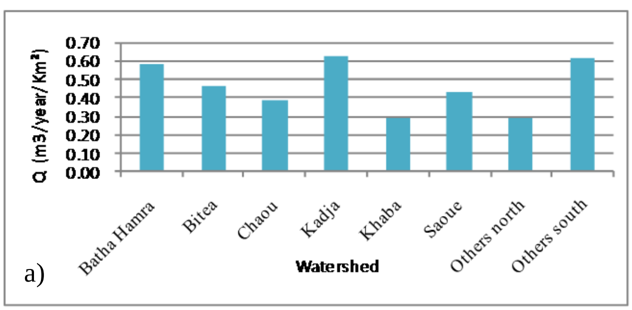


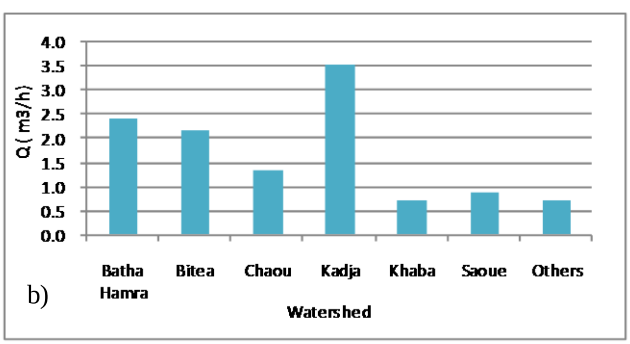
Figure 7. Rosettes of fracturing direction in boreholes modified by Ragot., 2005

4.2.4. Analysis of the results according to watershed

The graphs of Figure 8 group together the classification of flows according to the watershed (in a number and percentage). One notes in particular a decrease of the average flow rate (including negative drillings) from the south towards north (Batha, Bitéa, Chaou and Khaba). The watershed of Saoué provides a flow rates slightly higher in the north because it integrates a part of the Am-Zoer zone. The watershed ok Kadja is potentially the most interesting in terms of average flows. However, it is the area of Adré, where the sandstones gave very much contrasted results (many dry boreholes and many boreholes with flow rates higher than $10m^3/h$ even $2010m^3/h$).

Several correlations studies were established between the hydrogeological parameters S/Q and conductivity with the distance to the borders of watersheds. However, we do not find obvious correlation. The graphs established by watershed, according to the flow rates and of the distance of these basins do not show either obvious correlation, exceptions made to the zones of Kadja, Saoué and Chaou where one notices a slight tendency to the increases of flow rates while moving away from borders. In conclusion, and except the zone of Adré which is very much contrasted, the flow rates increase from north to south in correlation with the annual average flow per square kilometer watershed. The positioning of drilling within these perimeters does engender any more or not the probability of flow range.





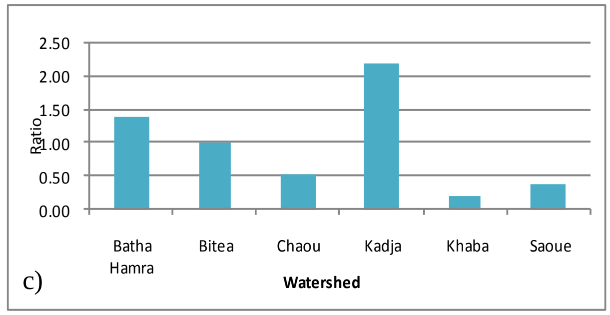


Figure.8. Flow rates classification according to the watersheds: **(a)** Annual average flow rates per km² per basin, **(b)** Average flow rates of drilling per watersheds **(c)** Ratio of the average flow rates of drilling by annual watershed per km²

4.2.5. *Depth of water inflows*

An analysis of the water inflows depths made it possible to affirm that there is a shallow aquifer [Ragot., 2005] whose productive levels are located at a depth ranging between 20 to 40m and a second productive level located at a depth of 50m and more. The figure 9 illustrates a comparative study of the productive levels of boreholes of the PHVOB project with those of the PNUD program in the 70s. This study shows that more than 70% of the drillings carried out by the PNUD had a lower depth of 40m, while 45% of drillings carried out in recent years have a depth greater than 40m. It result a significant decrease of the regional aquifer level resulting a decrease of the static water level of about 30m in thirty years [Ragot., 2005]. This fall of the regional level is to be put in relation to the climatic of these recent years.

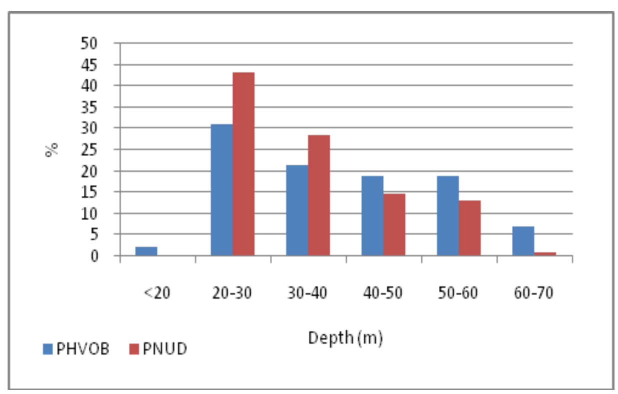


Figure.9. Depth of the water inflow of PHVOB and PNUD drillings

4.2.6. *Analysis of dry drilling*

Drillings which have not been reported as fractured are 121. However, the water was found in 19 of them. Among the 102 other boreholes, 21 was carried out in the sandstones of Adré, which do not present the visible fractures during drilling operation and 38 are located in the canton of dry bevels or close to this unfavourable geological zone (Mimi, Guéri, Bourtail and Birguit).

The number of dry boreholes without fracturing distributed according to their geophysical anomaly is very instructive. However, it is observed that the anomalies of type 2, 3 and 6 shows the driest boreholes not fractured. They are the large or very marked faults which may correspond to shearing. This type of anomaly should be the subject of a drilling on the geophysical gradients, and not in the center of the anomaly which could be systematically sealing. In addition, the anomalies probably corresponding to an area slightly fractured or cemented covering deeper faults give also very bad results (anomalies superimposed of type A). In this case, the ERI in pole dipole configuration direct and inverse could refine the establishment.

The failures of these boreholes are superimposed on the unfavourable zones previously defined and can thus be summarized by: a low rainfall and fracturing (Mimi zone), a low rainfall, low recharge in the dry bevel (Guéri zone), a low lateral recharge (Adré zone), a low fracturing, hydro-thermal, waterproof barrier, border of massif, and decline of the resource (Bitéa zone).

4.2.7. Definition of the hydrogeological perimeters

The establishment of the maps with the various results emerges intuitively several zones relatively superimposed to traditional administrative cantons. All drilling parameters were treated on the MapInfo program to visualize their distribution in plan on the supports of satellite maps (radar image, geology, topography, etc.). Some parameters seem to have a random distribution. It is particularly the temperature, the pH of water, the static and dynamic levels in the absence of altimetry dimensions. On the other hand, the negative villages (negative boreholes), the high flow rates, the rates success, the high conductivities and the fissures sealed with clay are parameters which make it possible to establish this classification.

According to the distributions of failure rates associated with limiting parameters (high conductivity, high ration S/Q, sealed fissures, presence of a dry bevel), four unfavorable zones were identified. They are Mimi zone, Guéri zone, Bitéa zone and Adré zone. The map of the Figure 10 makes it possible to locate them.

The sector of *Mimi* combines low precipitation, and especially a low fracturing in drilling. The success rate of drilling in this area is 35% with a satisfaction rate per village of about 20%. The low rainfall combined with low fracturing and with hardness of the rock makes it very weak the chance to improve the success rate. One can propose on the one hand the multiplication of the boreholes establishment and on the other hand to carry out a drilling on the edge of the large conductive geophysical anomalies. Indeed, it is possible that these anomalies correspond to the important shearing. So it is the hydraulic gradient upstream which can in this case being aquifer.

The sector *Guéri* is a zone of dry bevel which also shows low rainfall. In addition, the wadis located in distal zone are often sealed at the base. Thus, there exist only a little opportunity of recharge by these alluvium. They are the major accidents nonopen which can possibly recharge the aquifer. The drilling success rate is around 35% whose rate of satisfaction per village is estimated of about 17%. Given the complexity of this area, it would be judicious to carry out deep drilling (120 meters or more) in order to try to cross the tectonic faults in the basement and under the dry bevel formed by the sandstone. This implies deeper geophysical measurements with pole-pole configuration with direct and inverse measure on each ERI in order to free oneself to the maximum heterogeneity of the anisotropic areas.

The sector of *Adré* corresponds to a very paradoxical zone. Indeed, the flows are either very significant (> $15m^3/h$) or boreholes are systematically dry. It is likely that the zone of *Adré* and its extension along the wadi are directly recharged from the lake. This explains the very low conductivity and the alignment of the positive boreholes. As soon as one moves away from this zone, the sandstones do not seem to be fed. One can imagine in this case a kind of dry bevel where water is in the underlying basement along major accidents. It should be noted that there is no wadi on the sandstone plateau and its watershed is relatively small. To improve the success rate of drilling in this area, the strategies listed in the *Adré* zone are applicable.

In the sector of *Bitéa,* boreholes are well fed upstream. However one observed many dry boreholes at this place, a high sealing of fissures and a high conductivity of water. Several assumptions can illustrate these phenomena. It can probably be a question of the formation of a dry bevel at the edge of *Ouaddaï*. On the other hand, the sealing and higher mineralization of the water can be related to shearing zones and hydrothermal activity. The map of the Figure 11 illustrates well these shearing zones. Indeed, one clearly observes a corridor directed NE-SW delimiting the basic dykes in the region.

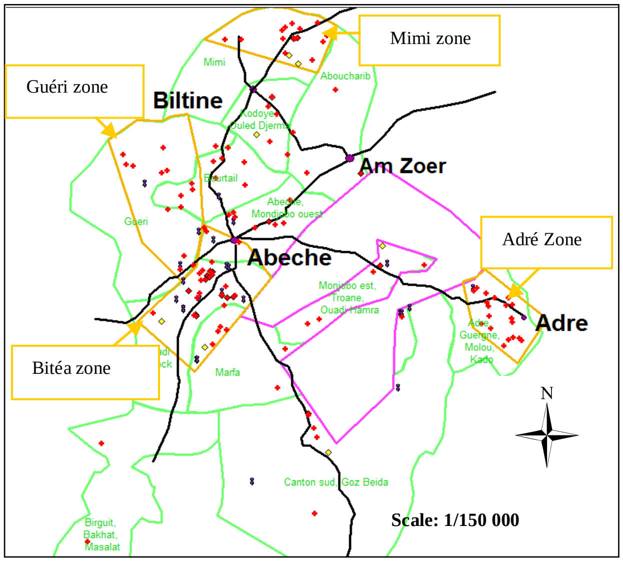


Figure 10. Map of the localization of unfavourable zones

This highly productive area upstream becomes unfavorable downstream. We can therefore consider the existence of a great accident or a structure behaving like a hydraulic barrier being located on the edge of the dry bevel.

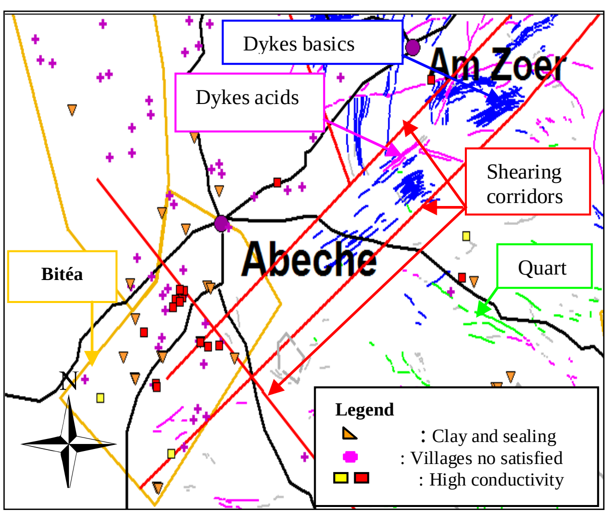


Figure 11. Map of the *Bitéa* zone localization highlighting the corridor limiting the basic dykes

5. Conclusion

From the analysis described in this study, it shows up clearly that the preferential targets of positive boreholes in the area of Ouaddaï-Biltine must be fractures with wide lengths oriented N60°E and 90°E. These fractures more productive than others are on the regional scale in extension. From general point of view, the studies of satellite images are very important for the general knowledge of the study area. The correlations with faults, dykes, geology, watersheds, etc. are interesting, even fundamental if there is a margin of establishment of several kilometers. In the case of urban centers, pastoral program or refugee camp water supply, the satellite option is very useful. On the other hand, in the case of village water supply (rural water supply), the perimeter of establishment is too limited to be interpreted without aerial photos. At the end of PHVOB many villages are satisfied of which come to be added of nearly 200,000 Sudanese refugees in the area. For that purpose, the strict monitoring of static water levels remains essential to assess daily the real impact of the water resources exploitation which tends to decrease as the actual climatic evolution. This is especially important in the actual climate context, which seems to correspond to a period of more unpredictable and probably reduced rainfall from the mid-twentieth (20th century) century.

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