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ASIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ISSN: 0976-3376

Asian Journal of Science and Technology
Vol. 12, Issue, 12, pp.11996-12002, December, 2021

RESEARCH ARTICLE

COUPLING OF REMOTE SENSING AND GEOPHYSICS FOR THE STUDY OF GROUNDWATER RESOURCES IN THE OUADDAÏ REGION EAST OF CHAD

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ARTICLE INFO

Article History:
Received 15th September, 2021
Received in revised form
18th October, 2021
Accepted 07th November, 2021
Published online 30th December, 2021

Key words:
Remote sensing, Geophysics, Lineaments, Water Resources, Fractures.

ABSTRACT

This study covers the town of Abéché and its surroundings, located in eastern Chad in the province of Ouaddaï. Sitting on a Precambrian basement, the fractures constitute the preferential flow zones for underground water reserves. In order to highlight these fractures, a linear study was carried out using a Landsat 8 image. The techniques used made it possible to enhance the discontinuities contained in the first main component, facilitating the mapping of the lineaments. The lineament map obtained was validated from existing geological maps, geophysical data and field knowledge. The map of potential points for the siting of boreholes is obtained by digitizing the points of intersection of hydraulic fractures. This study, based on remote sensing and geophysics, identified favorable points for the siting of future hydraulic boreholes for the supply of drinking water

Citation: ADOUM Issak, MASSING Oursingbé, ABDERAMANE Hamit and Issa ZAKARIA HASSAN, 2021. "Coupling of remote sensing and geophysics for the study of groundwater resources in the Ouaddaï region East of Chad", *Asian Journal of Science and Technology*, 12, (12), 11996-12002.

INTRODUCTION

Water is an essential resource for the basic needs of man and his environment. The socio-economic development of human populations is dependent on water resources for the supply of drinking water, the expansion of agriculture and animal husbandry. Crystalline basement regions are known for their structural complexities. The research and exploitation of groundwater has always been a challenge in these environments. Banks et al, 2002 point out that groundwater in crystalline media constitutes an unknown resource. Neumann (2005)describes the characterization of water resources in fractured environments as one of the greatest challenges for modern hydrogeologist. In Chad, discontinuous aquifers represent 340,000 km2, i.e. a quarter of Chadian territory. In the east and more precisely in the Ouaddaï region, the geological formations do not favour the presence of a generalized water table.Added to this is the pluviometric context which shows a significant drop in rainfall since the 1960s in a general and local context of increased temperature(Schneider. 2001). The repercussions of this rainfall deficit have obviously led to a drop in groundwater resources.

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The Ouaddaï region, the area of our study, is part of this difficult hydrogeological context, for which the problem of the rational choice of sites for the installation of structures arises. Despite prospecting techniques implemented in the province, borehole failure rates are high in discontinuous basement aquifers (Massing et al., 2010).In view of all these problems, in-depth studies are required to understand the aquifer system in the area. For this, remote sensing is an essential tool for lineament mapping. Geophysical methods then make it possible to validate these lineaments in order to identify sites favorable to the establishment of future water points.

Geographical context: Chad is located in the heart of Africa between 7° and 23° North latitude and 13° and 24° East longitude with an area of 1,284,000 km². The province of Ouaddai covers an area of 29,940 km^2 and has 731,679 inhabitants. The Ouaddaï region is built on a granite plateau and surrounded by two wadis flowing from the South-East to the North-West. A belt of fairly elevated mountains and hills can be found in the region. The mountain range rises to 890 m in the Northwest and West. The climate is characterized by low rainfall varying between 300 and 550 mm per year. The rainy season lasts from July to September, and heavy rainfall occurs in August. For almost three decades, precipitation has continued to decline. They start in May and end in October. Over a period of 28 years (1990-2017), the wettest months are the months of July and August when rainfall is highest with a monthly average of 134 mm. These rainfall deficits will lead to a drop in groundwater resources. Added to this is the sharp rise in temperatures: 35 - 45 ° C on average for the months of March, April, May and 21 - 25 ° C on average for the months of June and July. These large increases also promote evaporation.

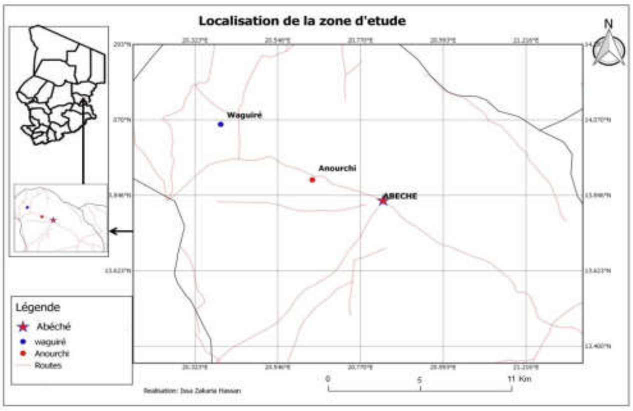


Fig. 1. Location of the study area

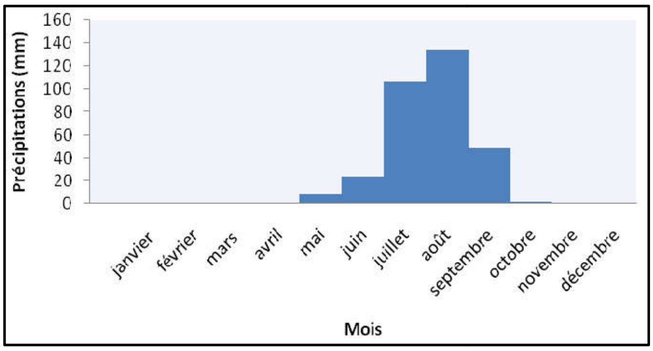


Figure 2. Monthly variation of precipitation in Abéché for the year 2017 (DGM)

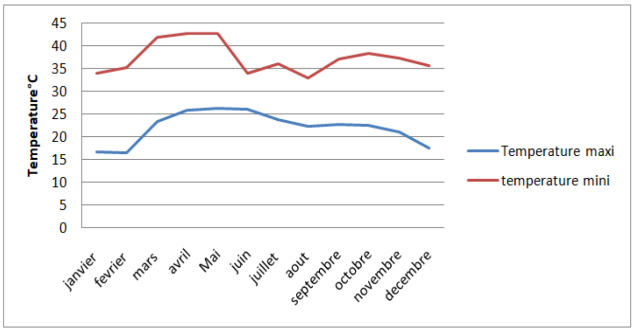


Figure 3. Minimum and maximum temperature variation for the year 2008 (DGM)

Geological and tectonic context: The study area belongs to a vast Precambrian calc-alkaline granite batholith, called “regional granite” (Plotte, 1970), traversed by numerous intrusions: acid granitoids (alkaline granites), basic (granodiorites), veins of aplite, pegmatite and quartz. The base is everywhere flush or sub-flush under a thin covering of quaternary sandy loam deposits from the surrounding reliefs.In places, a layer of grainy alterites develops, not very thick given the low efficiency of the current climate. Brittle tectonics are present but irregularly developed. The Ouaddaï massif, in the broadest sense of the term, forms the eastern limit of the Chadian basin. It is the largest crystalline massif in Chad, stretching over 500 kilometers from north to south to Sudan (Willud and Maurin, 1992; Kusnir, 1995). It is essentially made up of granite rocks. There are two large formations, namely the granite massifs of Ouaddaï and the sedimentary series within the massifs. The systematic map of the faults using radar images showed that the Ouaddai is at the intersection of two fault systems: an N45 ° -65 ° system linked to the Atlantic rifting and an N115 ° -135 ° system linked at the East African Rifting, (Gachet, 2005).The structural map of Ouaddaï revealed in the North, a granite terrain characterized by numerous dykes and large accidents, more or less rectilinear, separated from a southern metamorphic domain by a suture line. The intersection of these two areas is characterized by the presence of raised boulders, (Bunzli and Haeberlin, 2005).The region has developed around two large wadis: the Am Soudourieh and Am Kamil wadis and their tributaries which turn into devastating torrents after each rain. These wadis, which are temporary rivers, cross the city in several places. Completely dry in the dry season, they drain after the showers, in strong torrent, the waters of the city and all the villages located upstream.

MATERIAL AND METHODS

Two methods were used in this study: Remote sensing through the processing of satellite images and geophysics through electrical methods.

Remote sensing: Remote sensing is a method based on electromagnetic radiation. This radiation is composed of two electric and magnetic field vectors perpendicular and moving at the speed of light. Radiation can be passive(from the sun) or active (made by man through LAZERS). One of the main advantages of active remote sensing is the ability to take acquisitions anytime, in clear or cloudy skies, day or night. Radiation from a source, after passing through the atmosphere, can interact with a target at ground level through a process of absorption or reflection. It is the reflected radiation that is exploited in the process remote sensing. The reflected rays are picked up by a satellite which can then send them to a processing center to extract the useful information sought. The acquired data can be processed by appropriate image processing software. Several hydrogeological studies have been carried out in the context of the basement through the use of remote sensing (Savané*etal.,* 1997. Savané and Biémi, 1998, Kouamé *etal.,* 1999, Ta etal, 2008., Ngo *etal.* , 2010, Koita*etal.,* 2010). All of these studies are directed towards the identification and characterization of lineaments on satellite images. Lineament mapping can be done by analysis of topographic maps, hydrographic networks or by interpolation of aerial photos(Ousmane, 1988; Yameogo, 2008). In recent years, hydrogeologists increasingly use digital media such as DEM and satellite images for lineament extraction(Savadogo, 1984; Biemi, 1992; Koussoube, 1996). The raw data obtained by remote sensing is then filtered in order to always eliminate the noise. The most widely used filters for lineament identification are of the Sobel, Gradient and Laplacien types. They are also better suited for lithological discrimination.

Principal component data analysis (PCA) is a method of multidimensional data analysis based on the change of the repository of raw variables (remote sensing channels) into a new repository of synthetic variables (principal components).

The transformation process (translation-rotation of the original frame of reference) is based on maximizing the variance of the point cloud (here the pixels of the N channels) according to a hierarchy of components. The first component occupies the direction of space in which the variance is maximum (major axis of the pixel cloud). The second component is built according to the same rule, in the remaining space. And so on, the principal components have the advantage of being decorrelated (independent and orthogonal) unlike the raw data in the original frame of reference (channels). The prioritization of the components allows the eigenvalues of the covariance or correlation matrix. The sensors installed on board meteorological or earth observation satellites operating in the spectral range of solar emission are radiometers that measure the luminance reflected by the entire earth and atmosphere illuminated by the sun. In a non-cloudy atmosphere, the radiometric signal depends on the reflectance of the earth's surface but also on the atmosphere that occurs during the two paths (descent of the sun's rays to the surface and re-emission from the surface to the sensor). Atmospheric effects result from two processes, the absorption of diffusion exerted jointly by the two major constituents of the atmosphere, i.e. gases and liquid or solid particles suspended in the atmosphere.

Geophysics: Geophysics is used in the determination of basement zone fractures to confirm hydrogeologist guidelines. Our study focused on the electrical methods that are best suited, because of their lightness, their relatively low cost, their ease of implementation and especially their high reliability (Somboetal, 2011). Two types of electrical investigations were used namely: electric drag (horizontal investigation technique) and electrical sounding (vertical investigation technique).The principle of these methods is based on the measurement of the electrical resistivity by injection into the ground, of the electric current by means of emission electrodes, and the measurement of the potential difference at the surface by means of electrodes and reception.

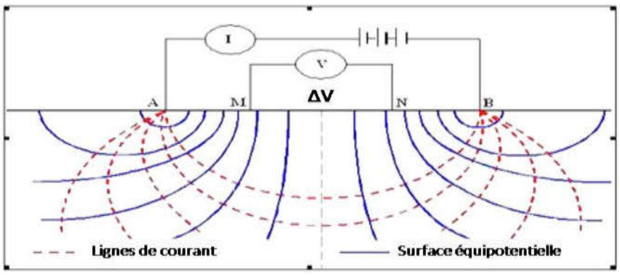
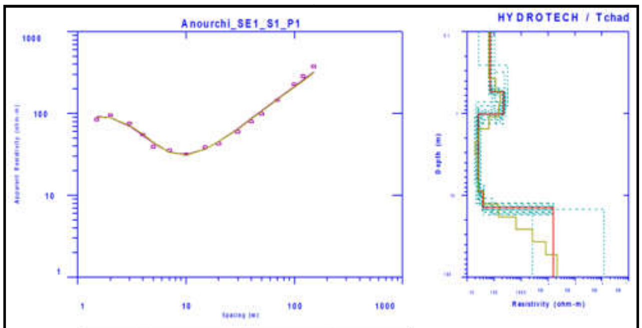


Figure 4. Soil resistivity measurement process

$$V_M - V_N = \frac{\rho I}{2\pi}\left(\frac{1}{MA} - \frac{1}{MB} - \frac{1}{NA} + \frac{1}{NB}\right)$$, Which give: $\rho = k.\frac{\Delta V}{I}$

$k = \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}$ k is the geometric factor of the device.

The measured resistivity value corresponds to an apparent value ρa defined as the resistivity of a homogeneous and isotropic soil. In general, the measured resistivities decrease as the water content and the degree of saturation increase. The water content and electrical resistivity ratio is a major advantage for electrical resistivity methods in the search for groundwater aquifers.



N°	Résistivité (ohm.m)	Epaisseur (m)	Profondeur (m)
1	72.165	0,54079	0.54079
2	231.37	0.47472	1.0155
3	25.433	7.8972	8.9127
4	38.699	5.2223	14.135
5	15887		

Figure 5. Electric Sounding Curve SE1 (Anourchi: Site 1)

RESULTS

Contribution of remote sensing: Remote sensing enabled the lineaments to be mapped in the areas studied. These lineaments represent linear geological objects or alignments of sufficiently close geological objects, topographic discontinuities or geomorphological structures inherited from old topographies. The preliminary phase for processing the Landsat 8 images consisted of radiometric and atmospheric correction. Some specific treatments were carried out, such as: contrast enhancement, principal component analysis, band combinations and the Sobel directional filter for the identification of lineaments. Principal component analysis allowed all of the information contained in the channels of the original images to be grouped into a relatively smaller number of channels or components. The first main component contains the maximum amount of information. Lineament extraction was performed on the initial and transformed bands (filtered or from PCR). The processing and filtering had the effect of accentuating and facilitating the detection of image discontinuities, thus allowing them to be detected by simple visual observation. Only lineaments of structural origin are of interest in this study. Also, by synthesizing information through a GIS, the linearities of anthropogenic origin previously vectorized (asphalt roads, tracks, high voltage line, forest delimitation radii and cultivated areas, etc.) have been identified in all the lineaments and eliminated. The geological and structural lineaments identified during previous mapping work, few in number but based on aerial photographs and field observations therefore considered to be true, were found in our lineament network. This ability of the method based on the interpretation of satellite images to find real fractures already known and not only among the largest, validates our method of extraction. This validation then leads us by extrapolation to grant a structural value to all of our lineaments and to switch from the use of the term lineament to that of potential hydraulic fractures.

Before extracting the lineaments, we vectorized structures such as the road network, streamlines and the hydrographic network and we superimposed them on the processed images to avoid considering them as lineaments. The pre-processing phase applied to the Landsat 8 scene 181-050 image improved the image quality by reducing atmospheric effects. The application of the Minimum Noise Fraction (MNF) reduced the minimum noise fraction after atmospheric correction. This operation thus made it possible to obtain a clear and sharp image, the results of which are illustrated in figures 6, 7 and 9.

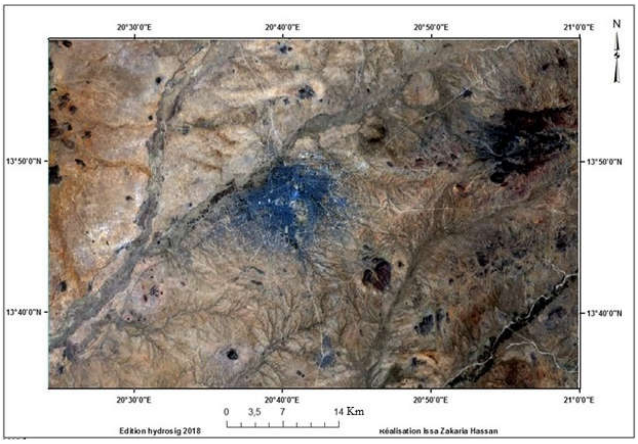


Figure 6. Initial image of the study area

Principal component analysis (PCA) made it possible to combine the volume of 7 bands into 7 components, the first two components of which contain the maximum amount of information. The Normalized Vegetation Index (NDVI) gives the overall abundant vegetation in the two bands. It tells us about an abundance of vegetation on the edge of the wadis and on the mountains. The filtering applied within the framework of this study is convolution type. In order to highlight the linear structures, the filter used is that of Sobel of matrix 7x7 applied to the first principal component (CP1) of North - South, East - West, North - East South - West and North - West South - East directions. According to Kouamé *et al.,* 1999, the application of this filter makes it possible to accentuate and better bring out the lineaments in order to map them. PCI Geomantic software enabled the lineaments to be automatically extracted. The Sobel East-West (E-W) filter applied to the image of the first principal component CP1 enhances the North-South (N-S) lineaments, and the North-South (N-S) filter enhances the East-West (E-W) lineaments. After a superposition of the lineaments with the topographic map, any element that does not correspond to the lineaments of geological origin is eliminated. At the end of this process, a map of the structural lineaments was produced (fig. 7). The directional rosette shows that the major directions of fractures in the area are N50E and N110E (fig. 8).

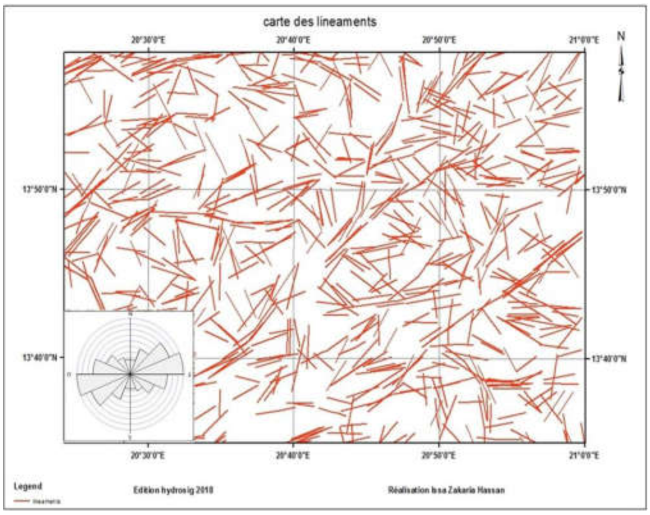


Figure 7. Lineament map

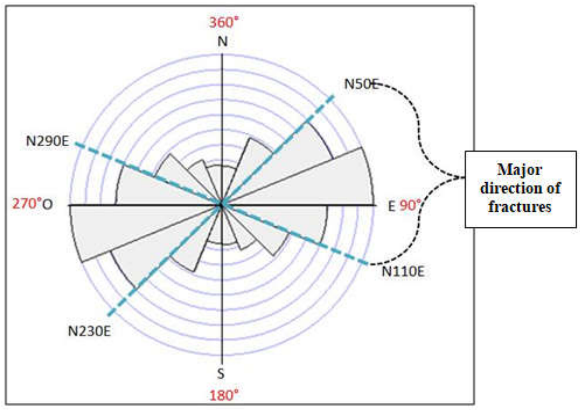


Figure 8. Directional rosette of the study area

Lineament map validations were performed before geophysical prospecting in the field. The first validation carried out consisted in projecting data from various existing boreholes that have a positive flow on the lineament map. This validation confirmed that all the boreholes that are placed on the lineaments or at the intersection of the two lineaments have a positive flow and some are still operational in the city of Abéché.

The map of future water points is obtained after analysing the different lineaments. These analyses have enabled us to understand that large lineaments are important from the point of view of water resource availability. The map of potential zones produced (fig. 9) shows the intersections of productive fractures near the localities, taking into account the productive directions N50 and N110. The points materialized at the intersection of the lineaments characterize areas potentially favorable to the siting of boreholes likely to produce good flows. Indeed, boreholes implanted on fracture nodes can have a very high productivity and success rate (Desquelles, 2009). Thus, several sites favorable to the installation of boreholes have been identified and mapped. These sites can serve as a database to guide future hydraulic campaigns.

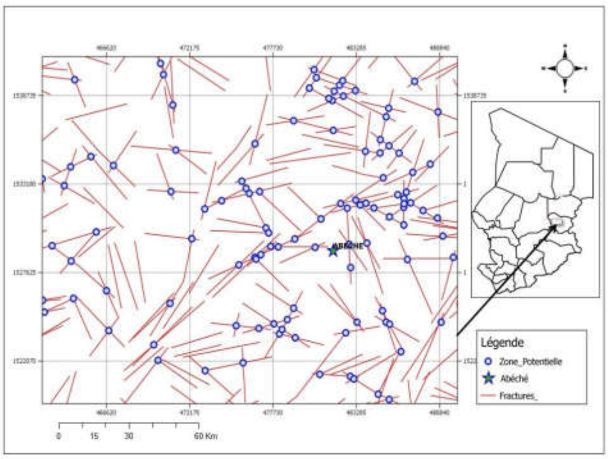


Figure 9. Map of potential areas for the siting of future boreholes

Contribution of geophysics: During the geophysical field campaign two villages were chosen, these are the villages of Anourchi and Waguiré located to the north-east of Abéché. Twelve electric trains were produced during the campaign on 6 different sites, therefore 3 sites in Anourchi and 3 sites in Waguiré.

Table 1. Volume of work carried out in the field

Région	Canton	Villages	Sites	Trainé électrique (m)		SEV	
				Profils	Azimut	Nombre	Azimut
Ouaddaï	Bourtail	Anourchi	1	P1 : 240 m	N150°	3	80°/260°
				P2 : 240 m			
				P3 : 240 m			
			2	P1 : 150 m	N60°		
				P2 : 130 m	N160°		
			3	P1 : 230 m	N150°	1	60°/240°
		Waguiré	1	P1 : 280 m	N150°	2	80°/260°
				P2 : 280 m			
				P3 : 280 m			
			2	P1 : 250 m	N175°	1	70°/250°
				P2 : 160 m			
			3	P1 : 180 m	N220°	1	20°/220°
Total				**2630 m**		**8**	

Table 2. Illustrating the different orientations

Angles	Longueurs	Nombres	
0-20	180540.044	58	6%
20-45	337457.026	106	11%
45-65	554879.741	160	18%
65-90	698981.083	204	22%
90-110	488241.563	155	17%
110-135	335206.743	101	11%
135-155	227848.671	77	8%
155-180	187004.597	63	7%

Only the trailed exhibiting considerable anomalies are taken into account for making vertical layouts (Electrical Soundings), namely: 4 trailed at Anourchi and 4 trailed at Waguiré (table 5). Those which do not present material anomalies are abandoned. The values of the resistivity measurements obtained are recorded on a data collection sheet and processed by the Excel software to obtain the various resistivity values.The volume of geophysical work carried out in the two villages (Anourchi and Waguiré) is established as follows: 6 sites investigated including 3 sites in Waguiré and 3 in Anourchi, 12 profiles carried out making 2630 m and 8 electrical holes carried out in accordance with the table below.

DISCUSSION

This study made it possible to show the good agreement between the various productive boreholes and the lineaments obtained after processing the satellite image. The different orientations and the density of lineaments have made it possible to define structural areas, the interest of which is of prime importance in the mapping of areas with high hydrogeological potential. Fracture nodes and kilometer-sized fractures are favorable areas for large flows. The directions of major lineaments extracted by the direction rosette highlight the different directions. The predominant directions N50E and N110E table 2 confirms the directions of work in the area carried out by (Bünzli and Haeberlin, 2005). The rosettes of directions taken from statistics compiled from the UNHCR mapping give the regional directions, associated with the opening of the Atlantic rift and the Red Sea more recently. This linear study highlights the different nodes of the fractures. These nodes formed by the intersections of the fractures would have significant water potential and make it possible to orient the reconnaissance campaigns by defining the potentially favorable zones and to select the specific sites for the installation of boreholes. Several studies carried out in different contexts have shown the interest and importance of the analysis of lineaments on satellite images for hydrogeological prospecting. Dutartre *et al.,*1990, in a study carried out in Burkina Faso, were able to define, from SPOT images, repetitive rules of interpretation in three complementary fields: The search for fractured zones, the delimitation of infiltration zones and identification of areas with agronomic potential. Bérard *et al.,* 1990, in a study for the water supply of an industrial complex (gold mine) in Sudan, showed the contribution of Landsat images combined with previous studies to establish boreholes and put evidence of the existence of new aquifers In a study of lineaments in the region of Marahoué (Ivory Coast) on Landsat images, Biémi *et al.,* 1999, established a diagram making it possible to define the boreholes in the middle of a fissured basement in order to control future boreholes and ensure their management. As part of this study, field data showed the existence of lineaments identified through images and confirmed by electrical prospecting. The average thicknesses of weathering in the villages of Anourchi and Waguiré are 10 m and 4.4 m, respectively. The roof of the plinth is located at an average depth of 13.7 m for the first and 11.7 m for the second. These two parameters are in favor of Anourchi where the basement is slightly deep and the alteration more developed which constitutes a storage zone (capacitive medium), fed by the surface, and forms a potential reservoir zone in contact with the saturated zones. in water from cracks and fractures of the basement (Detay*et al.,* 1989). If we take into account the criteria for siting the boreholes in the base, each borehole to be carried out must be positioned in relation to an accident belonging to a determined tectonic direction. If the boreholes are badly positioned on the fractures, there is a poor supply of water to the borehole, which causes the borehole to die back in the long term. Consequently, the study of the relationships between boreholes and fractures may prove to be interesting in explaining the hydraulic role of certain accident directions.

Conclusion

This study allowed us to understand the hydrogeological potential of our study area. Indeed, like much of eastern Chad, the province of Ouaddai sits on a Precambrian base composed of Precambrian metamorphic and magmatic rocks. In these formations, the water tables are discontinuous since the groundwater only circulates in the geological structures. The objectives here were to extract the lineaments, the validation of these structural lineaments which is carried out using auxiliary data (borehole data, NDVI map from our remote sensing processing and geophysical field campaign). The different treatment techniques applied as part of this study made it possible to extract a network of lineaments. The superimposition of the productive boreholes on that of the lineament layout made it possible to identify the different types of fractures likely to constitute significant reservoirs of water. The geophysical method used made it possible to determine the thicknesses of the laterites. The results of the geophysical campaign (trails and soundings) provide us with information on the formations of these areas investigated with a good thickness of alteration. The correlation between weathering and fracturing enhances the efficiency of detection methods for these reservoirs and characterizes hydrogeologically favorable areas of interest.

In order to improve and complete the results of this modest study, it is therefore essential for future studies to:

- Carry out fieldwork several times to collect information in order to complete the interpretation of satellite images;
- To calibrate the resistivity values of boreholes to lithological cross-sections of boreholes for better interpretations concerning the nature of the ground.
- In order to reduce the probabilities of drilling failures which could be due to multiple causes (bad interpretation for example), to compare the electrical method with new geophysical methods such as electric tomography or even Proton Magnetic Resonance (RMP)) whose exorbitant price hinders its use, especially in Africa. However, it can directly detect groundwater based on the resonance of hydrogen atoms.
- To determine the hydrodynamic parameters and to do piezometric monitoring to better understands the fluctuations of the water table.

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