Mapping of aquifer potential in the Northeast basement rock of Burkina Faso: Using remote sensing and geophysical methods

Abstract

The North-East of Burkina Faso is made up of formations of the Birimian basement rock. The region has a Sahelian climate where surface water resources are very limited. In order to assess the hydraulic potential of the existing aquifers, remote sensing and geophysical techniques (aeromagnetic and ground electric) were used. Satellite image processing and aeromagnetic survey data were used to generate a lineament map that was subsequently validated on the basis of existing geological, hydrogeological and topographical data, geomorphological field surveys and ground geophysical work. The resulting map displays a more or less dense network of 405 magnetic lineaments with a cumulative length of 1,787,676 meters as opposed to 94 lineaments from Landsat 8 images with a cumulative length of 970,054 meters. The average length of the magnetic lineaments is 4,414.01 meters while the average remote sensing length is 10,317.72 meters. The identified NE-SW and WNW-ESE fracture corridors are propitious for the presence of fracture aquifers. In addition to the lineament validation, the ground geophysics performed through electrical surveys allowed the characterization of the aquifers in the study area. Alteration thicknesses are generally less than 20 meters deep. The fractured horizon can reach 100 meters thickness under the alterites. The kernel density map highlights areas of good aquifer potential that could constitute significant groundwater reserves. Mapping aquifer potential is a crucial step in ensuring sustainable and efficient use of groundwater resources.

INTRODUCTION

The northeastern part of Burkina Faso is marked by a Sahelian climate where rainfall is scarce, with annual precipitation of less than 600 mm. Surface water resources are very limited in space and time (Mara, 2010). As groundwater is closely linked to rainfall, it is somewhat precarious. The growth of the population and the development of socio-economic activities considerably increase the need for water. Despite the continuous realization of hydraulic works, the satisfaction of the needs remains a challenge. Thus, it seems appropriate to characterize the aquifers of the area. The present study therefore aims to map the potential of the aquifers in order to ensure better management of the groundwater resource for the satisfaction of needs. In basement environments, groundwater resources are conditioned by fracture networks (Nakolendousse, 1991 ; Sombo, 2012). In such a context, the search for this resource will essentially rely on the identification of fractures in the subsurface. The complexity of the crystalline basement leads to the use of various investigation techniques to identify and characterize these tectonic structures (Boisvert et al., 2008). The identification, hydrogeological characterization and spatial analysis of regional geological features required a combined approach of remote sensing, geophysics (airborne and ground) and Geographic Information Systems (GIS). These methods are effective tools in this hydrogeological research study. Processing of airborne magnetic survey data allows for detailed structural analysis and identification of magnetic structures as well as fault and contact zones (Amar et al., 2012 ; Bouya et al., 2013). From the surface, the geophysics, by the method of electrical resistivity (electric trains, electric drillings) highlights, locally, the geological discontinuities and estimates their depths by the study of the physical properties related to the constitution of the basement. Prior to this last method, a hydrogeological exploratory trip was necessary to assess the geomorphology of the site. By means of GIS tools, it was now possible to obtain a map of the aquifer potentialities of the study area, which is the spatial expression of the fracturing density of the rocky compartments in presence, the image of the extent of the tectonic phenomena that have marked the said locality.

I. THE STUDY AREA

The study area is located in the northeastern part of Burkina Faso, a country located in the heart of West Africa (Figure 1). It has a total perimeter of 575,243 km and an area of 3,472,341 km2. It is inhabited by three communes whose overall population was estimated at 295948 in 2019 (INSD, RGPH 2019). It is made of the rural communities of Tougouri, Yalgo and Manni. It is located between the meridians 00°42'29,153" West longitude and 00°12'9,297" East longitude and the parallels 13°40'15,286" and 12°59'6,341" North latitude. With a relatively flat landscape, average altitudes vary between 250 and 300 meters. The climate is of the Sahelian type, marked by the alternation of two seasons: a rainy season of about four months (June to September) and a dry season of about eight months (October to May). It has recorded annual rainfall amounts of less than 600mm (ANAM, 2010). From a hydrological point of view, the study area belongs entirely to the watershed of the Faga River, one of the main right bank tributaries of the Niger River. Overall, the hydrographic network is dense with streams flowing eastward into the FagaThe vegetation is of the shrubby savanna type and the soils are mostly undeveloped. The lithologies of the study area are grouped into three formation groups. First, there are the granitoid rocks composed essentially of granites, quartz diorites, tonalites and leucogranites. Then, the volcano-sedimentary belts composed of schists, volcanites, acid volcanites, basic volcanites, gabbro and diorite gabbro. Finally, the metamorphic rocks that are: gneiss, amphibolites and leptynites (Castaing C, 2003b). We have moreover vein formations consisting essentially of quartz veins, dyke veins and dolerites. The latter are oriented NW-SE and cut the Birimian basement over several tens of kilometers. From a structural point of view, the study area is characterized by the presence of two distinct directions of ductile shear. On the one hand, we have the NNE-SSW and NW-SE directions, which correspond to the Y structure characteristic of the zone. On the other hand, we have the N-NE oriented shear that corresponds to the passage of the Tiébélé-Dori-Markoye shear zone. From a hydrogeological point of view and in the bedrock domain, two types of reservoirs can be distinguished. They are differentiated by their physical and hydrodynamic characteristics. These are the upper reservoirs of alterites, and those of fissures and faults (Ouedraogo, 2016). The typology of these reservoirs is intimately linked to the typical geomorphological profile which is essentially marked by two compartments: the altered fringe and the fissured or fractured part. Thus, we have upper reservoirs of alterites which are constituted by the formations composed of products of alteration of the crystalline base and lower reservoirs of cracks and/or fractures located under the alterites.

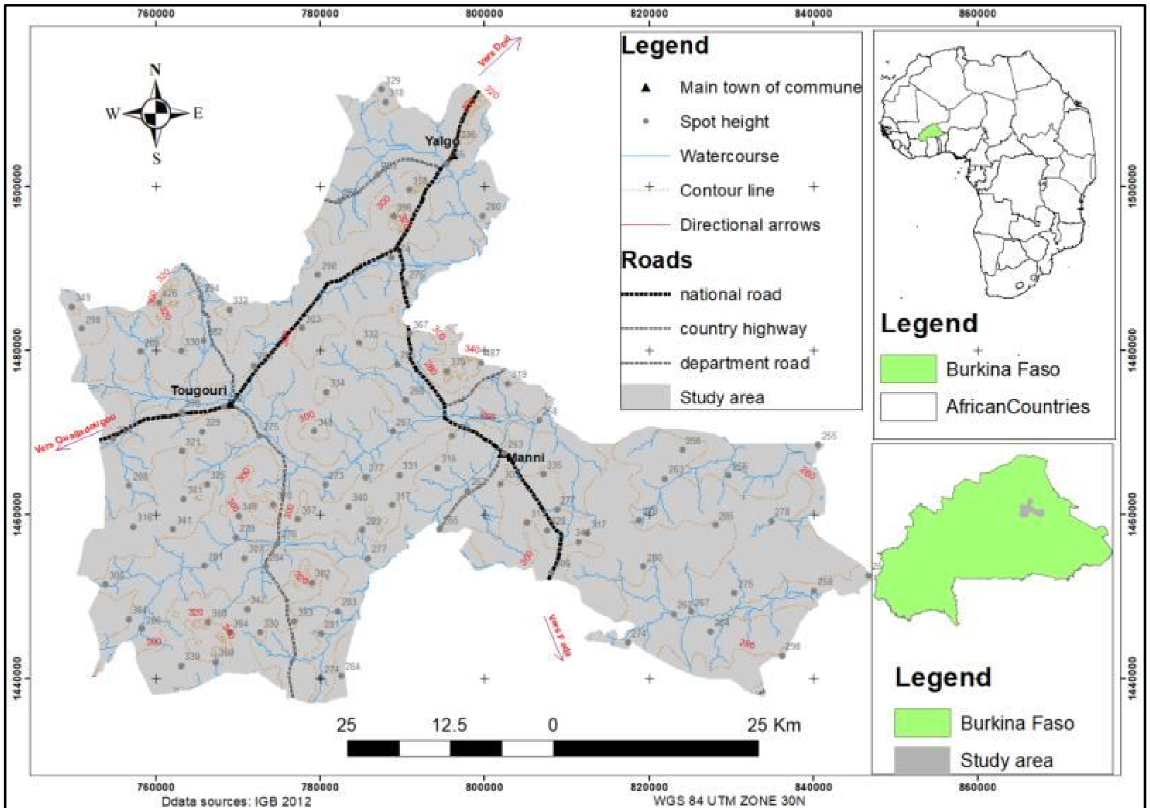

Figure 1: Location map of the study area

II. Material and methodology

II.1 Methodology

This section describes the method used to achieve the objectives of this study. It consists first of the mapping of lineaments from remote sensing and the use of airborne geophysical data. This was followed by the validation of the lineaments and their statistical and spatial analysis.

II.1.1 Lineament mapping

The lineament mapping consists of processing satellite images and aeromagnetic data and digitizing the highlighted structures.

II.1.1.1 Satellite Image Interpretation Process

The methodology for processing satellite images and extracting lineaments has been the subject of previous work (Jourda, 2005 ; Youan Ta, 2008). The first step in processing the ETM+ images consisted in creating a mosaic of four scenes covering the whole study area and previously corrected (calibration points found on the ETM+ strips).

To highlight the lineaments, these raw images have undergone some processing, in order to enhance the spectral information. These are: color composition, principal component analysis, band combinations and directional filtering. The false color composition in RGB of the ETM channels "6, 5 and 4" respectively was used.

Principal component analysis (PCA) was performed on the different bands and generated neo-channels. The 6/5 band ratio was also performed. The Sobel 0°, 45°, 90° and 135° directional filter on the principal components from the PCA was applied. In this study, the 7*7 matrix was chosen as it generated sufficiently detailed images for lineament detection.

II.1.1.2 Aeromagnetic data interpretation process

The use of classical and advanced filtering techniques through fast Fourier transforms provides a good understanding of the structural framework of the studied terrains. The processing of these data provides a detailed structural analysis and identification of magnetic structures and fault and contact zones (Amar et al., 2012 ; Bouya et al., 2013). The processing techniques applied are the residual magnetic field, the pole reduction, the derivatives of the magnetic field, the inclined derivative and the analytical signal.

II.1.1.3 Lineaments extraction

The processing and filtering had the effect of accentuating and simplifying the detection of structural discontinuities, thus allowing their survey by visual observation. The lineaments are manually plotted using ArcGIS software, considering all the supports resulting from the processing of Landsat 8 images, but particularly those resulting from the directional filtering used as the main support for satellite images. These lineaments obtained are said to be derived from remote sensing. As for the magnetic lineaments, they are obtained by digitizing the materials resulting from the processing of airborne geophysical data (1VD, 2VD, Tilt...). The linear patterns that are considered as anthropogenic activities (road, runway, power line) are eliminated by cross-referencing the lineament map with existing topographic maps.

II.1.2 Validation of lineaments

Various techniques were used to validate the lineaments. We have the pre-existing validation supports and the field work. the first one consists in the geological and structural map, the topographic and hydrographic map and the database of the drillings of the study area. As for the field work, they consisted in carrying out a geological and hydrogeological exploratory trip as well as carrying out geophysical investigations on the ground (geoelectric drag and geoelectric survey). This validation results in a structural value being assigned to all the lineaments. The structural map thus obtained will constitute the support for the production of the map of acquired potentialities.

- **Geoelectric drag (trail)**

This operation involves moving a generally symmetrical quadripole of constant dimensions over the site to be studied according to a predefined measurement step. At each station, the reading of ΔV and I is used to calculate the value of the apparent resistivity at the center of the dipole MN=10m. The depth of investigation being a function of the spacing between electrodes A and B, with AB=200m. This method makes it possible to highlight anomalies that can be assimilated to fracture zones, geological contacts, vein formations... which are, among others, structures of hydrogeological interest.

- **Vertical geoelectrical surveys**

Electrical survey is a method of vertical investigation at a fixed point. It allows the variation in resistivity of the different horizons located vertically to the sounded point to be studied. When applying this method, the potential electrodes remain fixed and the spacing between the current electrodes increases progressively. Thus, the depth of investigation becomes greater and greater, as the thickness of the ground where the significant part of the current flows depends on the spacing of the AB electrodes.

II.1.3 Statistical and spatial analysis of structures

The geometrical parameters studied in this study are the direction and the length of the lineaments. The attribute database of the layer of structures allowed us to extract the directions of the accidents by taking into account their angles of orientation. The conventional method is to produce a directional rosette whose petals are proportional to the cumulative length of the lineaments. Spatial density is the most important feature after orientation and thus requires analysis (Yao et al., 2012). Fracture density can be expressed on the average, in cumulative length of fracture traces related to the area of the observation window (Yao et al., 2012). Under the specific GIS tool used, the default observation window radius is calculated based on the spatial configuration and the number of data inputs (linear structures) (Sedrette et al., 2015). It was possible to perform a smoothing of the data ("cleaning" of the mosaic), by calculating the density by the kernel method (KDE = Kernel Density Estimation) on a grid. This was possible using the "Spatial Analyst" module of the "ArcGIS" tool which has a kernel density estimation function (Di Salvo et al., 2005). A Kernel density map was obtained for the entire study area. Figure 2 shows the general flow chart of the research methodology.

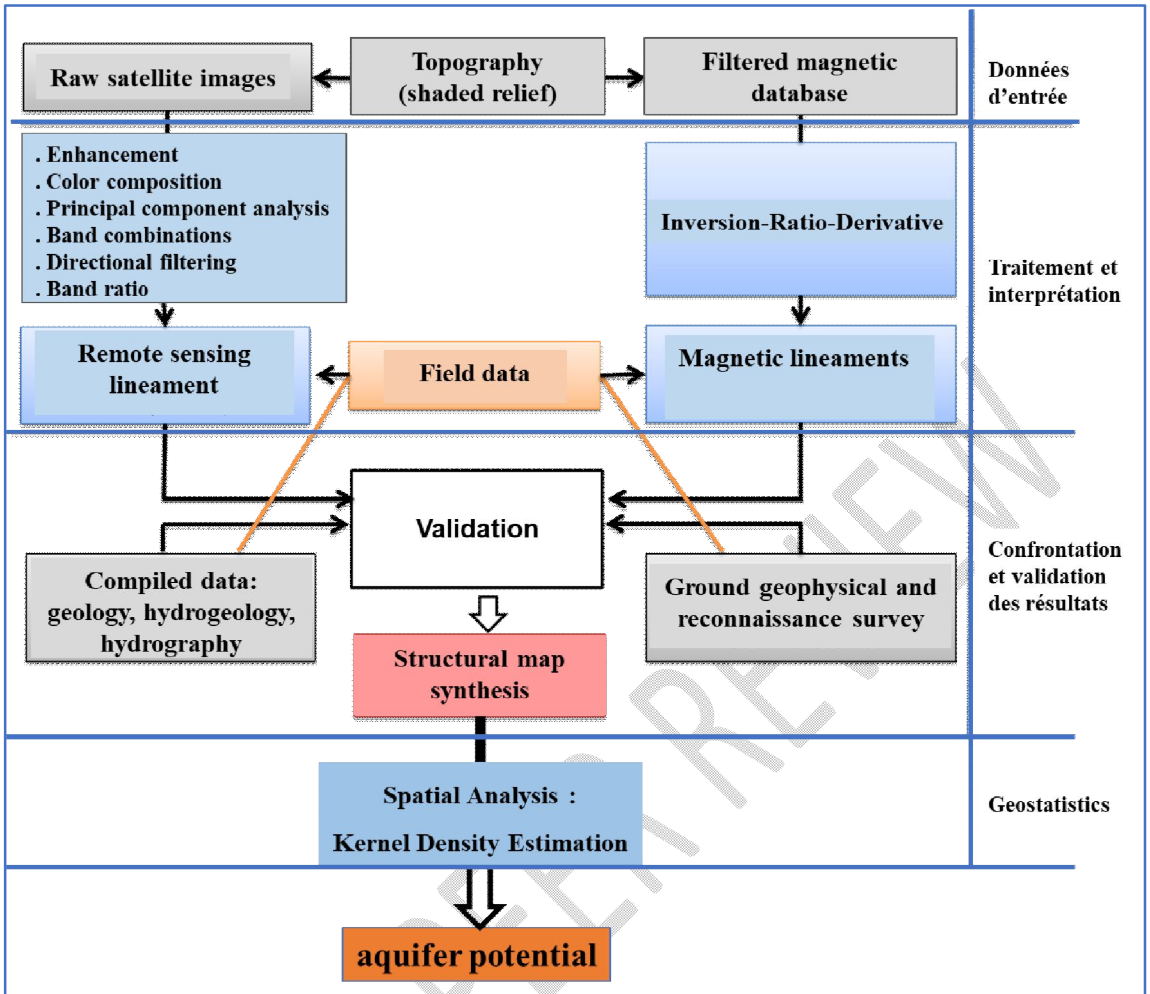

Figure 2 : Research methodology flowchart

II.2 Data and equipment used

The methodology used to achieve the objectives of this study involved the use of several types of data. These are the National Topographic Data Base (NTDB) acquired from the Burkina Geographic Institute (IGB, 2012); geology and airborne geophysics data from the Burkina Bureau of Mines and Geology (BUMIGEB, 2003); soil data from the National Soil Bureau (BUNASOL, 2012); climate data obtained from the National Meteorological Agency (ANAM, 2019); "Landsat 8" satellite images of the scenes: 194/50, 194/51, 195/50, 195/51 of March 2020 and "SRTM 30" (USGS, 2020, 2021, 2011); demographic data from the National Institute of Statistics and Demography (INSD, 2006, 2019); the drilling database of the General Directorate of Water Resources (DGRE, 2019 ; WI, 2021) and electrical resistivity data obtained from the geophysical work of this study. As for the equipment, there are two different types, the data processing equipment for obtaining the lineamentary structures and the equipment for acquiring and processing the ground geophysical data. The first type consists of a computer and ArcGis (version 10.3.1), Envi (version 5.1), Geosoft (version 9.5), RockWork (version 14), and the EXCEL spreadsheet (version 2016). The equipment for the acquisition and processing of ground geophysical data is composed of equipment for measuring the resistivity of the subsoil. First, the "SYSCAL R1 Plus" which is a compact and powerful device for the measurements of electrical resistivity and chargeability (PP).

It features a power source, a transmitter and a receiver in the same box. Secondly, the Winsev software which was used for the realization of the sounding curves and the Excel spreadsheet for the drag curves.

III. RESULTS

III.1 The lineament map

The interpretation of satellite images and aeromagnetic data followed by the verification campaign using ground geophysical methods allowed the structural map of the study area to be reinforced. The treatment results revealed linear features corresponding to structural lineaments (Figure 3).

The tilted derivative method is the one that allowed us to highlight the magnetic structures in the study area. The other techniques, the analytical signal, the first and second derivatives have not been of any great help. The lithological nature of the formations and the structural context of the terrain could be the reason for this.

As for remote sensing, the use of different techniques has enabled us to highlight several linear structures. Remote sensing provides longer but fewer lineaments than magnetism. The resulting map forms a more or less dense network of 405 magnetic lineaments with a cumulative length of 1,787,676 meters versus 94 remotely sensed lineaments with a cumulative length of 970,054 meters. The average length of the magnetic lineament is 4,414.01 meters while that of remote sensing is 10,317.72 meters (Table 1)

Table 1 : Statistical assessment of lineaments

Type of lineament	Number	Cumulative length (m)	Minimum Length (m)	Maximum length (m)	Average length of lineament (m)
Magnetic	405	1,787,676	110	394	4,414.01
Remote sensing	94	970,054	38,582	40,104	10,317.72

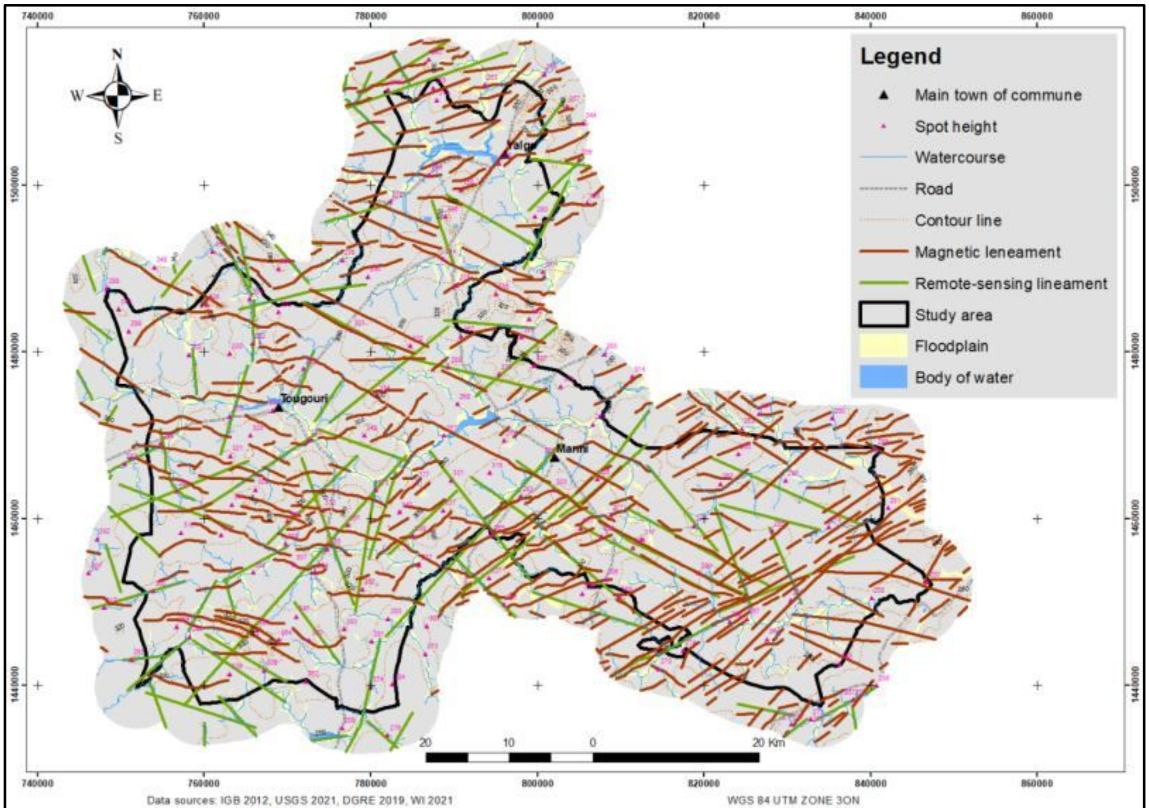

Figure 3: Magnetic and remote-sensing lineament map

III.2 The structural map

Geological (rock outcrop structures), geomorphological ("feeding window"), and biological (hydrophilic species) field observations at lineament sites are indicators of fractures and groundwater. For the geophysics, twelve (12) profiles of trainees, that is to say a total length of 3,760m of geoelectric trainees and four (04) drillings were realized. The electrical train profiles confirmed the lineaments identified for this purpose by highlighting conductive zones corresponding to fracturing corridors with resistivity values of the order of less than 100 Ohm.m.

The boreholes drilled on these fractures show a more developed alteration profile at Goundré (greater than 15m) in the village of Tougouri than at the other three sites (less than 15m) located in the villages of Yalgo and Manni (Figure 4).

At the level of all the drill holes, a more or less thick fissured horizon is observed, often marked by a dragging rise characterizing the presence of fractures in the substratum. Furthermore, at the Malyoma site, the bedrock is very shallow. The SE-Goundré and SE-Gori boreholes show boat bottoms that could be associated with the presence of an arena contact topped by armour. However, at the level of holes SE_Malyoma and SE_Taparko, this armour is not present.

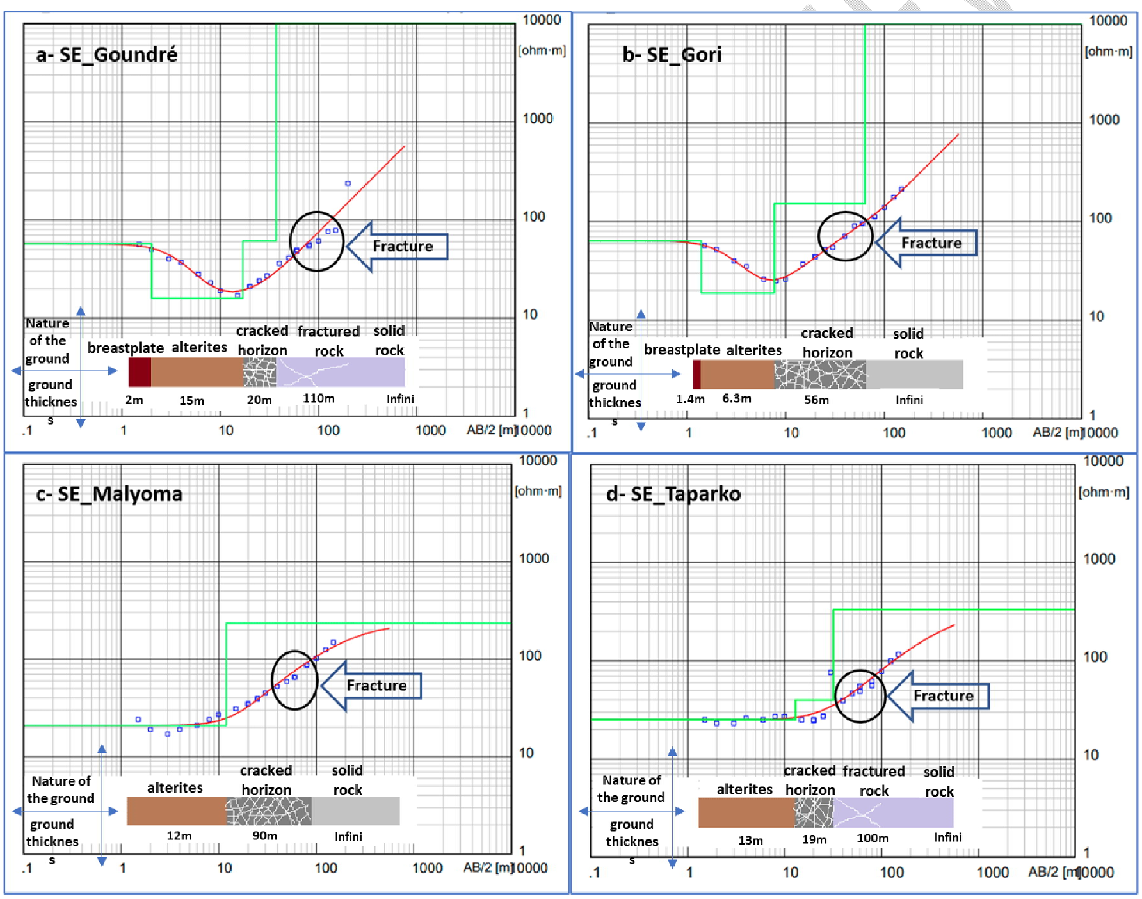

Figure 4 : Interpretation of electrical surveys

The synthetic structural map takes into account all the structures mapped by remote sensing and airborne geophysics (Figure 5). Structures of strong magnetism, assimilated to dykes are marked by the two main directions ENE-WSW, WNW-ESE. Structures mapped by remote sensing are preferentially marked in the NE-SW and

WNW-ESE direction (Figure 6). Secondary direction structures are noted as NNW-SSE and NNE-SSW. These structures are quite noticeable in the field. In the whole study area, the NE-SW and WNW-ESE geological structures are the most dominant.

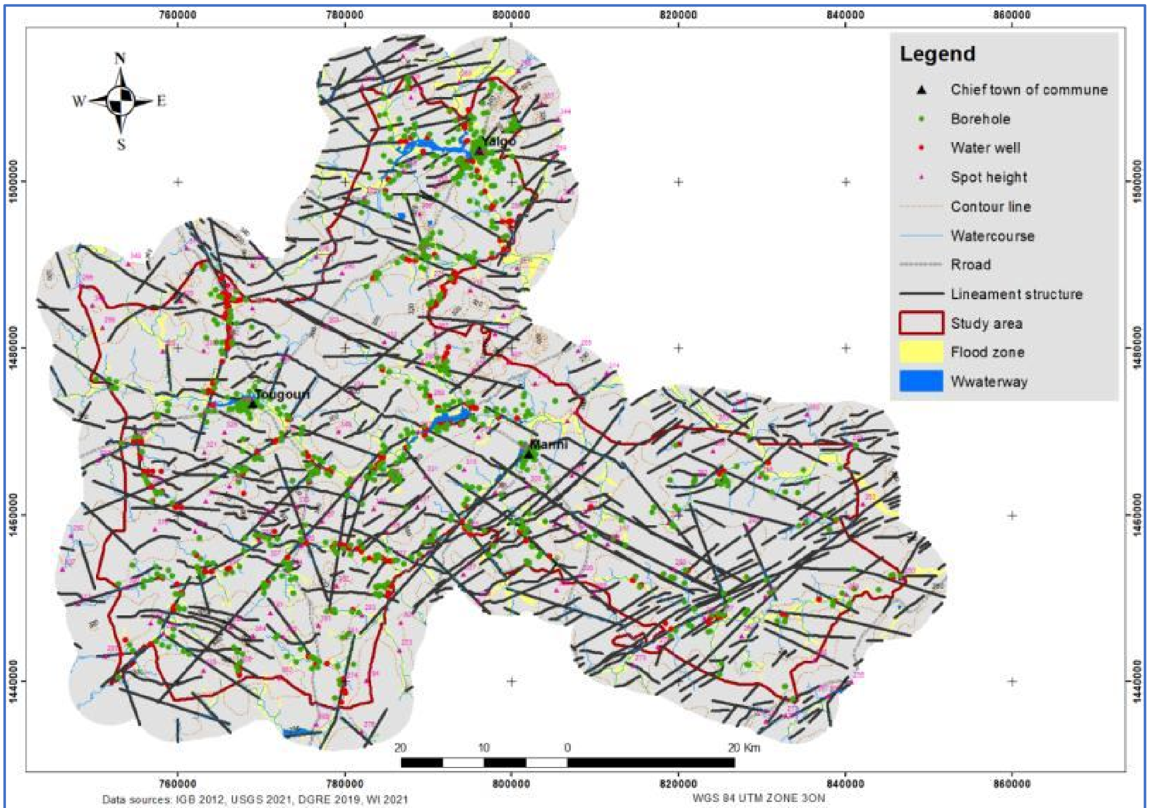

Figure 5: Lineament structural map

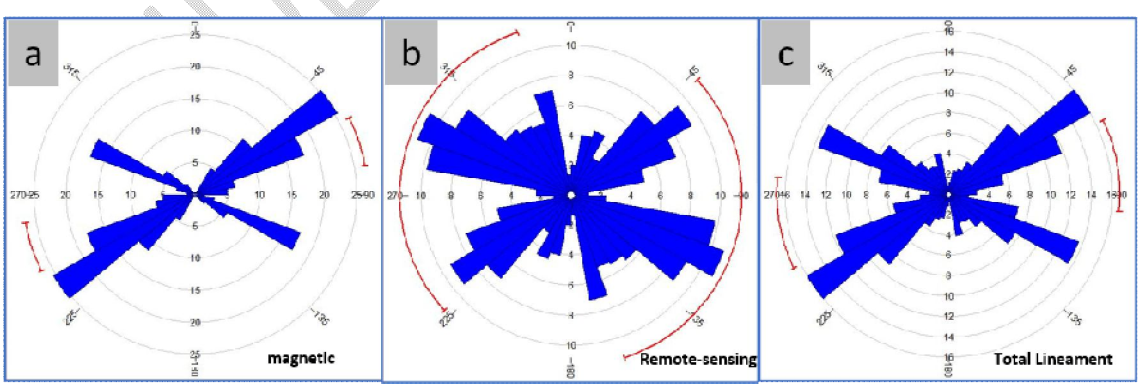

Figure 6: direction rosette

III.3 Aquifer potential

The assessment of groundwater potential was carried out on the basis of all linear structures recorded in the area. The overlapping of the drilling points with the fracture density map shows a very good correlation between the productivity (flow) of the drillings and the structural density. The areas of high structural density are the ones that record the large flow boreholes (Figure 7). The areas of highest density mapped generally correspond to terrains that have recorded at least two tectonic phases. These terrains are marked by a large number of nodes of linear structures: they are therefore the areas most affected by tectonics. Figure 6 shows a region of high and medium aquifer potential in the central and southeastern part of the study area, while its western, southern, eastern and northeastern extremities show low potential. This potentiality, which can be assimilated to the density of lineaments, is an indicator of the degree of fracturing of the rocks that are essential for the development of groundwater conduits in the study area. Mapping the hydraulic potential of aquifers is very important as it allows the identification of areas where groundwater is likely to be found and the assessment of its quantity. This is a function of the value of the density of the area. This value is expressed by an arbitrarily defined coefficient proportional to the cumulative length of the fractures in relation to the area of the observation window considered. In concrete terms, it is equivalent to the value of the pixel of the region considered on the potentiality map. Reading the map therefore allows the aquifer potential of the basement rocks to be assessed.

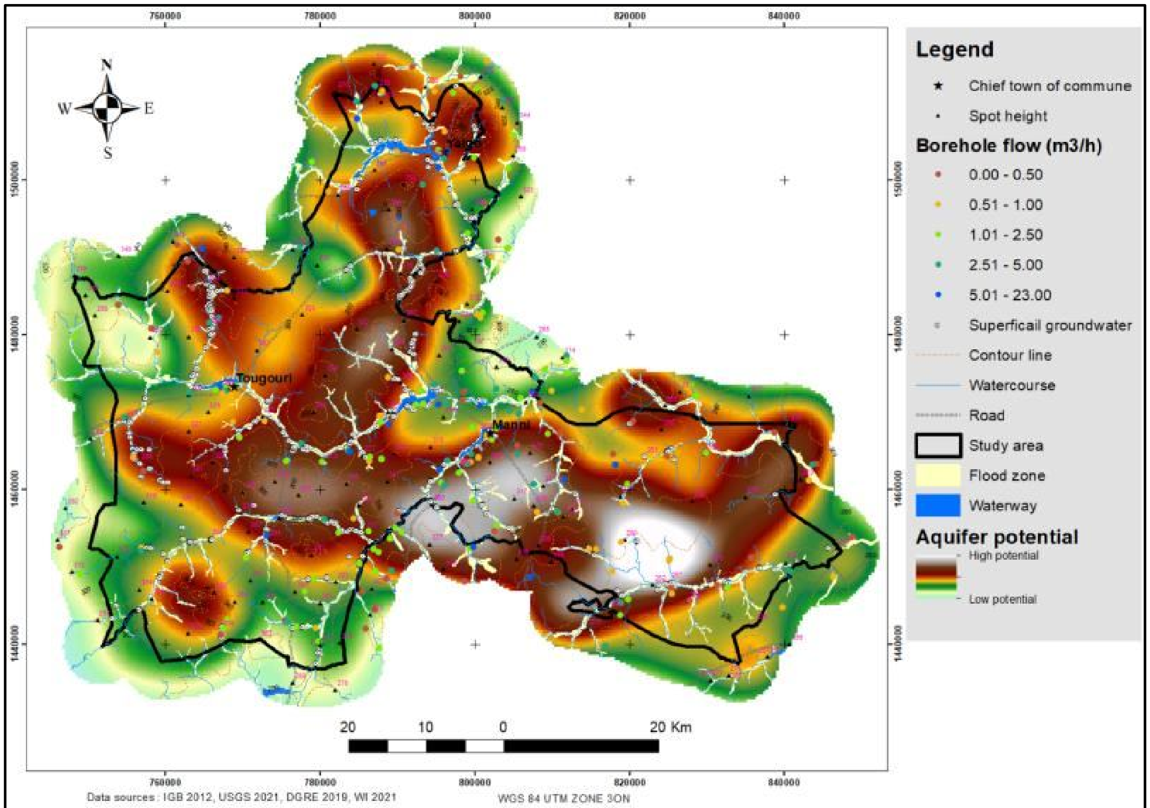

Figure 7 : Mapping of aquifer potential

IV. DISCUSSION

The use of remote sensing and geophysics is a fast and reliable way to survey and select fractures. In the study area, lineaments mapped from Landsat 8 satellite images and aeromagnetic data differ in number, length, and orientation. The lineaments obtained from remote sensing are longer but fewer in number than those obtained from aeromagnetic data. The overall pattern shows a predominance of NE-SW and WNW-ESE oriented structures. Indeed, the major phase of the Eburnian orogeny is marked around 2150 Ma by shearing along two predominant directions NE-SW and NNE-SSW. These last structures are the most detected by satellite images. After 1810 Ma, precisely in the Mesoproterozoic between 1300 and 1400 Ma, the structural evolution would have been marked by the successive setting up of dolerite dyke intrusions (Castaing C, 2003b). This phase corresponds to the Kibaran orogeny, structures marked by aeromagnetic lineaments (NW-SE). On the field, several indications of tectonic accidents can be observed on the identified fracturing axes. The structures detected by geophysics correspond to actual accidents that affect the bedrock. These cracks are found in the subsoil at different depths. The average minimum depth is 13m, but they can still be found at a depth of more than 100m. The overlying alterites are of variable thickness with or without a cuirass coating. Indeed, previous studies have shown that until now, two types of structure have been identified as potentially responsible for the groundwater resource in crystalline context, the fractured zone (Kouamé et al., 2010), and the altered zone (Lachassagne et al., 2011). In this study, the weathered zone resource is recognized by the presence of boreholes. Although these two types of structures may be related, they are very different in their hydraulic nature and geometry. Lineament density is an indicator of the degree of rock fracturing. Areas of high lineament density are zones of high degree of rock fracturing that are essential for the development of groundwater conduits in a given area (Habib et al., 2013). The high density areas are those that record high flow rate boreholes. There is thus a dependence between the density of the structural network and the productivity of the aquifers. Processing of satellite imagery and airborne geophysical data has provided further evidence of the structural network in the area. The Field Exploration mission was followed by the use of different geophysical processing techniques to certify the linear structures that could be mapped. The lineament map therefore becomes valid and is referred to as the "lineament structure map" (Figure 4).

CONCLUSION

The purpose of this work was to assess the aquifer potential of the study area. The methodology adopted was first based on the mapping of fracture zones by processing satellite images and aeromagnetic survey data. Secondly, it consisted of characterizing the identified structures by ground geophysical prospecting (trawls and electrical soundings) and finally, carrying out a spatial analysis of the density of these structures. The lineament structural map obtained shows that NE-SW and WNW-ESE oriented lineaments are the most dominant in the study area. Geophysics has made it possible to identify fracturing corridors. Boreholes drilled on these fractures show a cracked horizon from an average depth of 13m but reaching 17m in places (SE-Goundré) with thicknesses ranging from 20m (SE-Goundré) to 90m (SE-Malyoma). Deep fractures are often encountered in the bedrock below the fractured horizon. These are highlighted at the level of the borehole by dragging up the electric curve. The resulting potentiality map shows areas of high aquifer potential corresponding to lands marked by a large number of nodes of linear structures. Nevertheless, the areas of low density observed on the map naturally have a loose structural network. This aquifer potential mapping study contributes to the management of water resources such as the location of boreholes and wells and the development of irrigation systems. Additionally, mapping aquifer potential can help to identify areas where groundwater may be at risk of contamination or depletion, which can inform conservation and protection efforts.

References

- Amar, M., Manar, A., Boualoul, M., 2012. Contribution of aeromagnetic mapping to the structural identification of the aquifer system of the Figuig oasis springs (Morocco). Bull. Institute Sci. Rabat Sect. Sci. earth 34, 29-40.

- Boisvert, É., Bourque, E., Cloutier, V., Kirkwood, D., Lauziere, K., Lefebvre, R., Martel, R., Michaud, Y., Nastev, M., Ouellet, M., 2008. Methodological guide for the regional characterization of aquifers in fractured sedimentary rocks. Ministry of Sustainable Development and Environment Parks INRS-ETE Research report R-981.

- Bouya, N., El Ouardi, H., Habibou, E., Mercier, E., Ansan, V., 2013. Geological interpretation of aeromagnetic data and their use for structural mapping of the Agourai plateau (Tabular Middle Atlas, Morocco). Afr. Geosci. Rev. 20, 13-20.

- Castaing C, B.M., Milési J.P., Thiéblemont D., Le Métour J., Egal E., Donzeau M. (BRGM) (coordinators) and Geurrot C., Cocherie A., Chevremont P., Tegyey M., Itard Y. (BRGM), Zida B., Ouédraogo I, Koté S., Kaboré B.E., Ouédraogo C. (BUMIGEB), Ki J.C., Zunino C. (ANTEA), Castaing et, 2003b. Explanatory note of the Geological and Mining Map of Burkina Faso at 1:1 000 000.

- Di Salvo, M., Gadais, M., Roche-Woillez, G., 2005. Density estimation by the kernel method: Method and tools. Methodological and technical note.

- Habib, A., Labbassi, K., Akdim, N., Tajdi, A., 2013. Contribution of ALOS and LANDSAT data in lineament mapping and analysis in the Central Sahel (Western Morocco). Rev. Fr. Photogrammetry Remote Sensing N 203, 33.

- Jourda, J., 2005. Methodology for the application of remote sensing techniques and geographic information systems to the study of fissured aquifers in West Africa. Concept of Spatial Hydrotechnics: case of the test areas of Ivory Coast. Concept of Spatial Hydrotechnics: Case of Test Areas Ivory Coast Thesis Dr. D'Etat Univ. Cocody Abidjan.

- Kafando, 2020. Hydrogeological characterization and groundwater potentialities in crystalline basement environment: case of the Ouagadougou sheet. PhD thesis; Joseph KI-ZERBO University (Butkina Faso).

- Kouamé, K., Lasm, T., De Dreuzy, J., Akaffou, A., Bour, O., Davy, P., 2010. Contribution of a discreet fracture hydrogeological model to the study of fractured aquifers of the Archean basement of Touba (Northwest, Ivory Coast). Rev. Sci. Eau Journal Water Sci. 23, 41-56.

- Lachassagne, P., Wyns, R., Dewandel, B., 2011. The fracture permeability of hard rock aquifers is due neither to tectonics, nor to unloading, but to weathering processes. Terra Nova 23, 145–161.

- Mara, F., 2010. Development and analysis of vulnerability criteria of Sahelian populations in the face of climate variability: the case of water resources in the Sirba Valley in Burkina Faso/ thesis presented as a partial requirement for the PhD in Environmental Sciences by Fanta Mara ; [supervisors, Yves Baudouin, Philippe Gachon and Laurent Lepage].

- Nakolendousse, S., 1991. Method for evaluating the productivity of aquifer sites in Burkina Faso. Geology-Geophysics-Remote Sensing. Joseph-Fourier University Grenoble I.

- Ouedraogo, M., 2016. Characterization of bedrock aquifers for improving the productivity of village hydraulic boreholes in the upstream white Bandama watershed (Northern Côte d'Ivoire).

- Sedrette, S., Rebai, N., Turki, M., 2015. Development of a quantitative approach for semi-automatic extraction of tectonic faults from the Nefza 1:50,000 geological map in shp format. Arab. J. Earth Sci. 2, 53-6.

- Sombo, A., 2012. Application of electrical resistivity methods in the determination and characterization of bedrock aquifers in Côte d'Ivoire. Case of the departments of Sikensi and Tiassale (Southern Ivory Coast).

- Yao, T., Fouché-Grobla, O., Oga, M.-S., Assoma, V., 2012. Extraction of structural lineaments from satellite images, and estimation of induced biases, in a metamorphosed Precambrian basement environment. Remote Sensing 10, 161-178.

- Youan Ta, M., 2008. Contribution of remote sensing and geographic information systems to hydrogeological prospection of the Precambrian bedrock of West Africa : Case of the Bondoukou region, North East of Côte d'Ivoire. Case of the Bondoukou region North-East Côte D'Ivoire Thesis Dr.