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Landsat 8 Oli Satellite Imagery Mapping and Analysis of Bedrock Fracture Networks in the Departments of Yamoussoukro and Toumodi (Central Cote d'Ivoire)

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Abstract

This study focuses on the departments of Yamoussoukro and Toumodi located in central Côte d'Ivoire where the problem of drinking water supply is a growing reality. Its objective is to map and analyze the fracturing likely to develop underground aquifers from Landsat 8 OLI data. The set of techniques (color composition, directional and gradient filters) used resulted in the enhancement of linear structures present on satellite images, allowing a better mapping of geological features. The linear map obtained, after the different treatments, is very dense and includes 2063 lineaments. The validation of these different linear structures was made on the basis of the drillings already carried out, from the data of the geophysics. The analysis of the fracture networks has highlighted two dominant directions which are N0°-10° (N-S) and N90°-100° (E-W) highlighting the heterogeneity of the geological formations. These results constitute an essential contribution to the exploitation of groundwater resources in the departments of Yamoussoukro and Toumodi.

Keywords: Remote sensing, lineament, groundwater, the density of fracturation, Cote d'Ivoire

1. Introduction

Lineament mapping is one of the essential components in hydrogeological prospecting (Habib et al., 2013). It is an excellent way to access groundwater (Koudou et al. 2014). Indeed, fracture networks are the main pathways for groundwater flows, starting from the transport of solutes, pollutants, and heat in rocks. The fracture is thus considered a necessarily more conductive element than the affected rock volume (Yao et al., 2014). In Côte d'Ivoire, the main groundwater resources are located in fractured rocks of the Precambrian basement and in alterites. The complexity of fractured environments greatly increases the difficulty of their characterization (Koudou et al. 2014). This difficulty is related to the fact that underground water systems are invisible. Therefore, knowledge of underground fracture systems emerges as a major issue in the search for new groundwater sites. Indeed, drilling in basement environments is quite difficult and costly (Alfonsi et al., 2003). Moreover, according to Kouadio et al. (2020), groundwater resources in rock aquifers represent a major resource for rural populations south of the Sahara, as surface water is not perennial due to high evapotranspiration or poor quality. The study of aquifer fracture networks is important in hydrogeology and can be achieved by various approaches (Lasm et al., 2004). Thus, satellite imagery is the method that was used during this study, because remote sensing, thanks to its synoptic view, allows the study of large geographical fields and is a powerful tool for the study of underground fracturing. To this end, Landsat 8 Oli images have been used for lineament identification by several authors (Akokponhoué et al., 2017; Jie et al., 2018; Kouame et al., 2019; Miyouna et al., 2020) with satisfactory results. In addition, several works (Magesh et al., 2012; Ndatuwong and Yadav, 2014; Oikonomidis et al., 2015; Oussou et al., 2019) have shown that the study of groundwater potential takes into account geological, hydrological, and climatic factors. The objective of this study is to map and analyze fracture networks that may constitute groundwater aquifers from Landsat 8 OLI data in the departments of Yamoussoukro and Toumodi in central Côte d'Ivoire.

2. Material and methods

2.1. Study area

The departments of Yamoussoukro and Toumodi are located in central Côte d'Ivoire. They are located between longitudes 4°40' and 5°33' West and between latitudes 6°15' and 7°6' North and cover an area of 4789.4 km² (Figure 1).

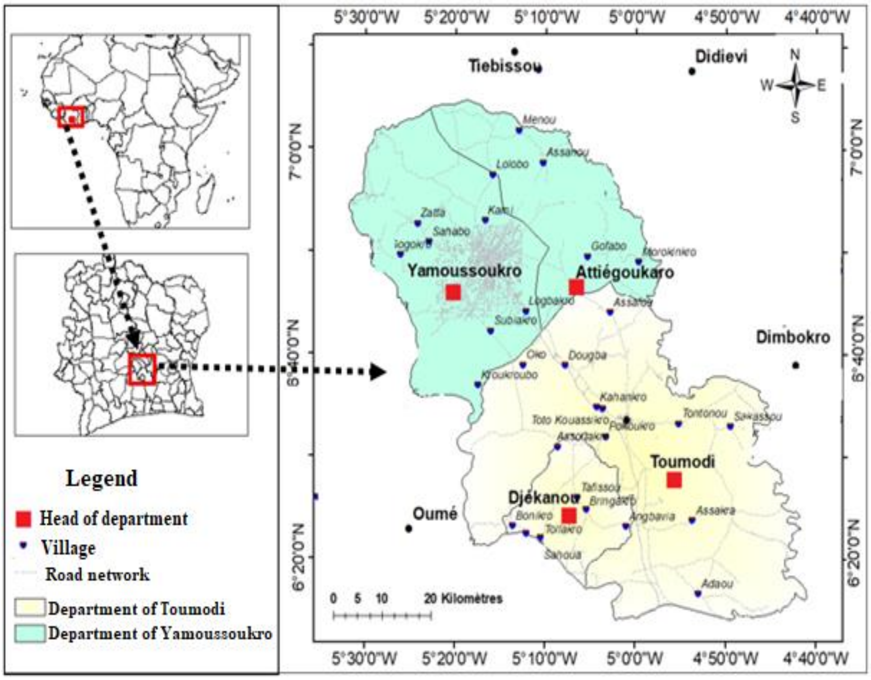

Figure 1 . Study area

The departments of Yamoussoukro and Toumodi are characterized by the plateaus of the tree savanna zone (Ehoussou et al, 2019). Indeed, the geomorphological landscape of the area is characterized by pediplains with quasi-rectilinear slopes, flat lowlands, and very flattened and low granite mountain ranges whose average altitude is around 200 m (Yao et al, 2010).

The climate of the basin is a mild transitional equatorial type characterized by a rainy season from March to October and a dry season from November to February (Figure 2). The average temperature of the region is about 26°C. The highest temperature is around 28°C and is observed in the months of February and March. Annual rainfall ranges from 900 mm to 1,600 mm per year, with a highly variable spatial distribution throughout the year (PRICI, 2016).

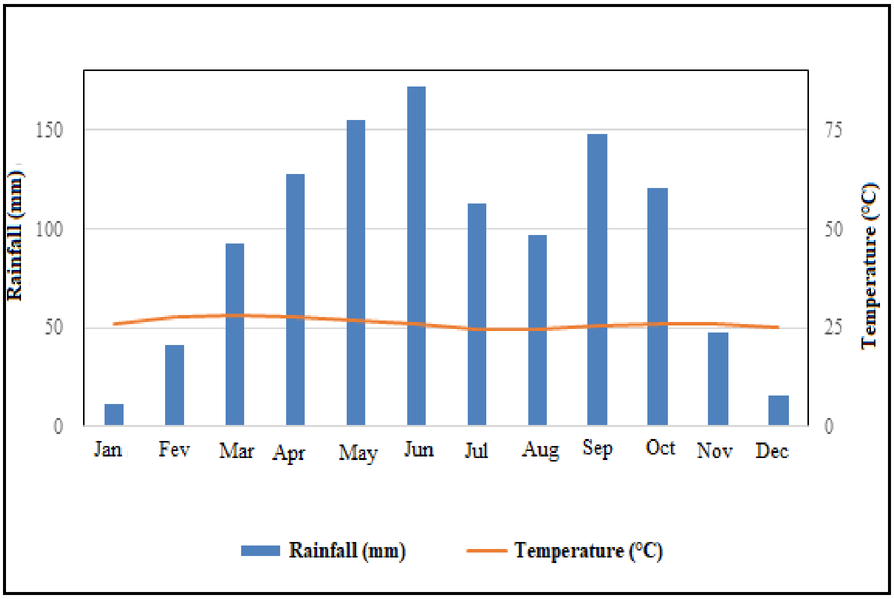

Figure 2. Umbrothermal diagram of the study area (1974-2019)

Ferralitic soils are the most abundant in these departments, where the vegetation consists of mesophilic forest, gallery forest, shrubby savannahs or savannahs with roasted trees. The Bandama River and its tributaries constitute the main hydrographic network.

2.2 Geological context

Côte d'Ivoire is located in the heart of the Man ridge and is made up of two major geological units: the Precambrian basement (97.5% of the territory) and the sedimentary domain (2.5% of the territory). The departments of Yamoussoukro and Toumodi belong to the granite-gneissic peneplain of the Precambrian basement. The main geological formations consist of magmatic rocks and metamorphic rocks (Yacé, 1976; Soro 2010; N'guessan et al., 2014). Metamorphic rocks are of sedimentary (sandstone, conglomerates, shale), volcanic (lava, acid or basic, predominant), and volcano-sedimentary (boulders, tuff, breccia, shale) origin. The magmatic rocks consist of recent granitoids, granites, migmatites and gneisses (Figure 3). These two main geological formations lead to the formation of a hydrogeological context characterized by a composite aquifer type (an alterite aquifer and a fissured or fractured aquifer).

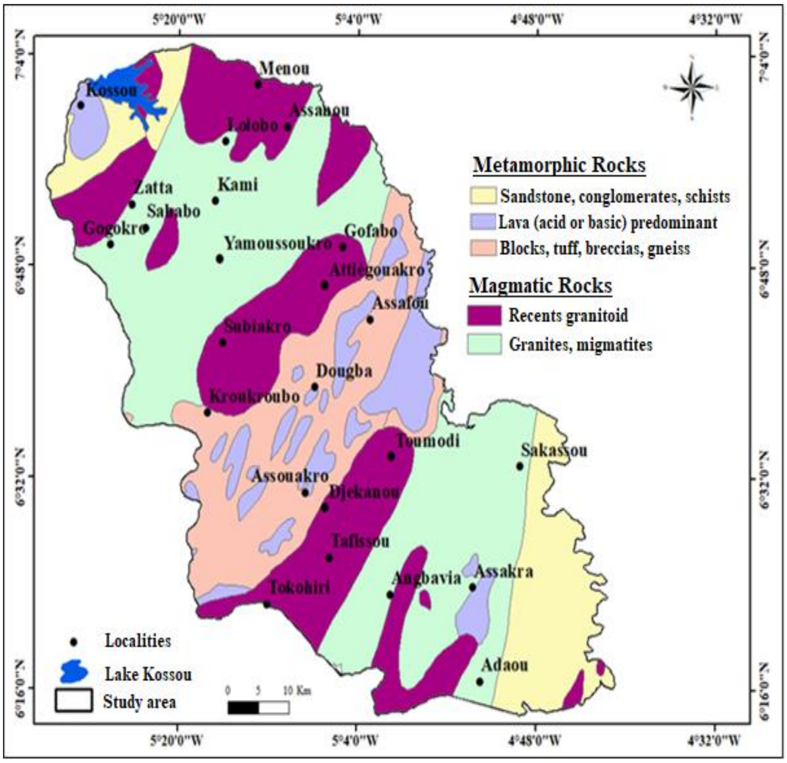

Figure 3 . Geological map of the study area

2.2. Materials

The study material consists of technical data from 100 boreholes collected at the Regional Directorate of Hydraulics of Yamoussoukro. Geological and topographical maps of the square degrees of Yamoussoukro and Toumodi at a scale of 1:200,000, produced respectively by the Geology Directorate and the Centre de Cartographie et de Télédétection de Côte d'Ivoire (CCT) were also collected. For the mapping of lineament maps, a Landsat 8 Oli satellite image consisting of scenes 197-55 and acquired on 12/02/2019 was used. The processing of these data required the use of several software packages: Envi 4.7 for the processing of satellite images, Linwin 2.1 for the processing and statistical analysis of lineaments, and ArcGIS 10.4.1 for the mapping of the fracture network.

2.3. Methods

The working methodology is based on mapping and lineament analysis. Several hydrogeological studies have been conducted in basement settings through the use of remote sensing (Koita, 2010; N'go et al., 2010; Mangoua, 2013; Yao, 2015). Their major objectives were to propose methodologies for characterizing tectonic faults and determining their role in subsurface flow. All these studies are oriented toward the identification and characterization of lineaments on satellite images. Lineaments are rectilinear objects identifiable on satellite images that reflect deep geological phenomena such as fractures, faults, or geological contacts. The identification of lineaments in satellite images depends on the ability of the sensor to detect the slight variations in reflectance associated with these geological phenomena (Dubois, 1999). According to El Hadani (1997), the study of lineaments can meet two objectives, namely: (i) the orientation of reconnaissance campaigns by defining potentially favorable areas; (ii) the selection of point sites for the implementation of drilling. The use of satellite images can therefore be one of the first means of studying aquifers before the implementation of other methods such as geophysical prospecting or pumping tests to confirm and/or complete the results. The mapping of lineaments will be done in four steps: pre-processing, image processing, validation, and statistical analysis of lineaments.

2.3.1. Preprocessing of Landsat 8 Oli images

The pre-processing applied to a satellite image is radiometric and geometric. They eliminate radiometric noise in the bands and correct geometric distortions, in order to make them perfectly superimposable on existing thematic maps (topographic, geological, and photogeological maps) (Jourda, 2005). Due to the fact that the images were taken during the dry season, these images appear without major radiometric noise and therefore do not require significant pre-processing.

2.3.2. Digital image processing for lineament extraction

Color compositions and directional spatial filtering were applied for image enhancement.

Colored composition techniques

This method is presented as an image enhancement technique for good visualization. This method is also called RGB (Red, Green, Blue) technique or RGB transformation, and allows one to obtain a multicolor image from three monochrome images. The colored compositions consisted in displaying simultaneously on the screen, three bands of images in the basic channels (Red/Green/Blue). The compositions that gave the most interesting results are made up of the bands Oli 2, Oli 3, and Oli 4. These compositions allow the distinction of bare soil, lithological discontinuities, water bodies, and regional and often local lineaments.

Spatial filtering techniques and lineament extraction

Spatial filtering is used to highlight the boundaries between two landscapes and certain features of the image such as lineament structures, roads, etc. In this study, the directional filters of Sobel and the gradient of dimension (7x7) were used. These processing techniques used by several authors have given very good results (Jourda, 2005; Mangoua, 2013; Yao, 2015). All of this processing on Landsat Oli 8 images provided complementary visual supports on which the lineament photo-interpretation work was based.

The survey of the structural lineaments itself was carried out manually with a visual analysis on the screen. The method consists in representing a line segment, the image discontinuities, and the abrupt changes of tonality observed on the processed images. Before the extraction of the lineaments, the road network and the high-voltage electrical wires are vectorized from several administrative maps set in the same coordinate system as the satellite images. Then, these different linear elements of anthropic origin (roads, tracks, electric and telephone wires) are superimposed on the different photo-interpreted images in order to avoid taking them into account during the manual extraction of the lineaments.

2.3.3. Statistical analysis of lineaments

Statistical analysis of lineaments has been the subject of several studies including Lasm (2000) and Kouassi et al., (2019). The lineaments made from Landsat 8 Oli images were subjected to frequency analysis to highlight the main directions through the directional rosette. Indeed, the orientation of the fractures is one of the essential parameters indicating the direction of groundwater flow in the basement. It allows for determining the water accumulation zones, potentially favorable to the implantation of drillings. Indeed, the geometric analysis of the lineament network is essential to describe the structure of a watershed. The geometric parameters studied in this work are the orientation and the length of the fractures. From these parameters, directional rosettes were drawn up that allow us to observe along the main directions the weight of fractures (percentages in cumulative lengths) and their number (Abdou Boko et al., 2017). Thus, the statistical analysis of the orientation of the lineaments forming the network makes it possible to identify the dominant directions. The conventional method is to produce a directional rosette whose petals are proportional to the cumulative length of the lineaments (Yao et al., 2012). This lineament map allows for highlighting, the spatial variability of lineament intensity at the small scale of investigation. To do this, the lineament map is georeferenced to be recognized by the Linwin software. The software program allows for establishing at the same time the directional rosette, the cumulative length, and the cumulative number of lineaments.

2.3.4. Validation of the lineament map

Once the lineament map is completed, its structural significance must be clarified (Razack, 1984). That is, it must be shown that the lineaments identified on the Landsat Oli 8 image are in agreement with the fracturing (measured in the outcrop and on the geological map) of the geological formations of the study site. This validation is based on the comparison of the directions of the major lineament families (from the Landsat 8 Oli image processing) with the fracturing directions found on the geological map and in the outcrop (Koita, 2010). Similarly, the superposition of the lineament map with the geophysical drilling map allows us to highlight the coincidences between the major tectonic features and the most productive drillings (Jourda, 2005). Indeed, according to Jourda (2005), the most productive boreholes are located on major faults and can therefore be an essential tool for lineament validation. In this study, the lineaments were validated using previous work done in the study area and the drill holes established by geophysics.

3. Results and Discussion

3.1. Lineament map

Image processing using different techniques revealed many discontinuities. The detailed lineament map (Figure 4) contains 2063 lineaments extracted manually from the image interpretation. The cumulative length of the lineaments is equal to 2410 km. The exploitation of the detailed lineament map allows the elaboration of numerous thematic files from which the geometry of the underground aquifers is defined and characterized (fracturing density, distribution of the lengths, and orientations of the lineaments). This lineament network map is not exhaustive, but it is representative of the studied area.

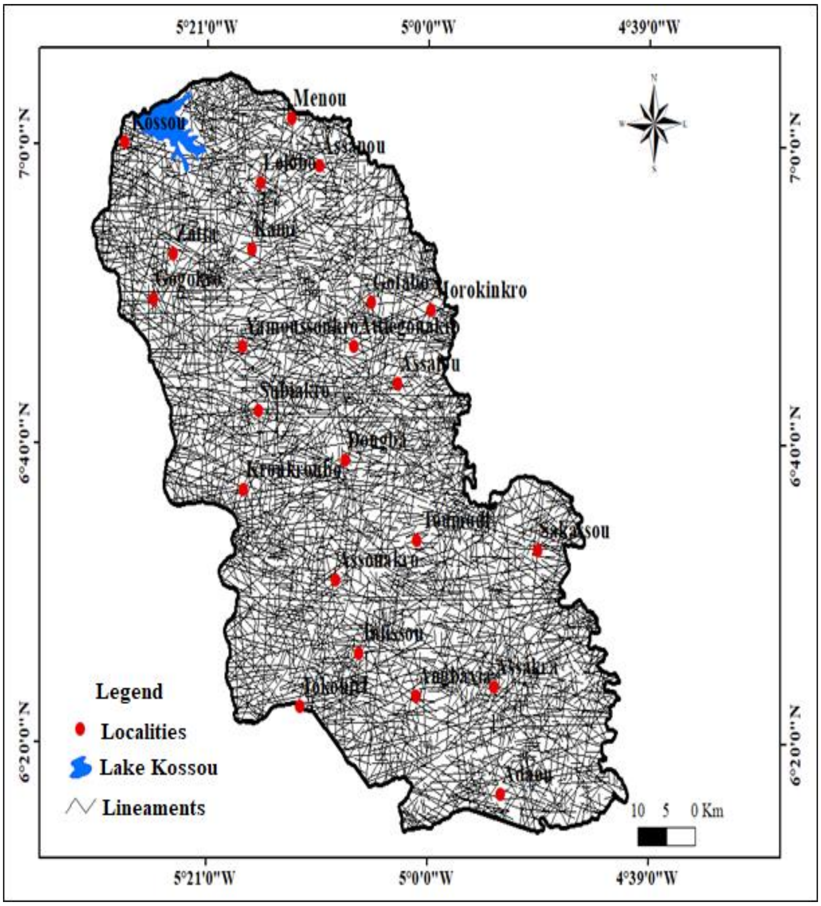

Figure 4. Detailed lineament map of Yamoussoukro and Toumodi departments

3.2. Statistical analysis of lineaments

Statistical analysis of the fractures allowed us to determine the percentages in number and cumulative lengths of lineaments. It also led to the realization of the directional rosette in cumulative number and length of lineaments (Figure 5). The distribution of lineaments expressed in number and cumulative length on the directional rosette is almost homogeneous. The fractures are grouped according to their orientation into 18 orientation classes by 10-degree angular crescents. The dominant directions are those with a percentage greater than or equal to 10%. The directions obtained (Figure 5) define three main orientations which are N0°-10° (N-S), N90°-100° (E-W), and N70°-80° (NW-SE). The most dominant directions are N 0°-10° (N-S) and N90°-100° (E-W).

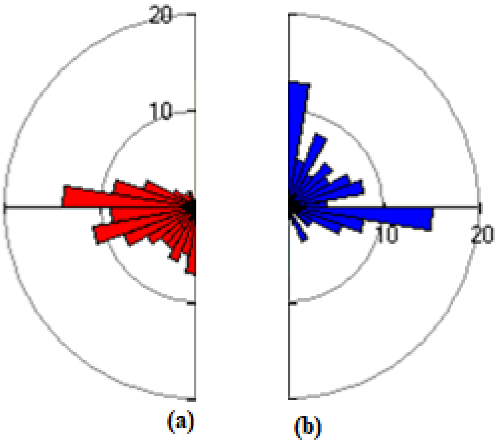

Figure 5. Directional rosette of lineaments: (a) in cumulative length and (b) in number

3.3. Validation of the lineament map

Boreholes drilled with geophysics were overlaid on the lineament map from Landsat 8 Oli images (Figure 6). Most of these boreholes are located on or near lineaments and have large flow rates. However, some of these boreholes have low flow rates. This result shows that the largest flow rates obtained in this region would be related to major fractures. The validation of the detailed lineament map allows us to assign to all the lineaments selected, the fracture value.

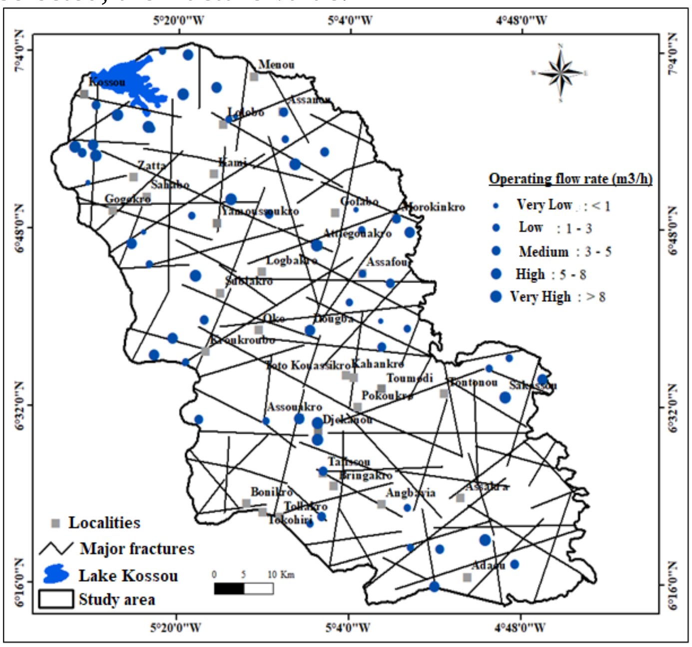

Figure 6. Validation map (Overlaying of boreholes drilled using geophysics on the lineaments)

3.4. Spatial distribution of fracture intensities

The overall analysis of fracture density distribution (Figure 7) shows a spatial variability of fracture intensity, which is divided into 5 classes. The class of very low fracture density occupies 2.3% of the study area. These areas are distributed mostly in the northwest, southwest, south, and east of the study area. The low fracture density zones occupy 19.1% of the study area. They are mostly distributed in the southern and eastern parts of the study area. These zones are also found in the form of pockets in the northwest, west, and southwest extremities of the study area. The medium and high fracture density classes represent 36% and 35.2% of the study area, respectively. These classes are present over almost the entire study area. The very high fracture density class occupies 7.4% of the study area. This class is mostly found in the form of pockets in the north central and south central parts of the study area.

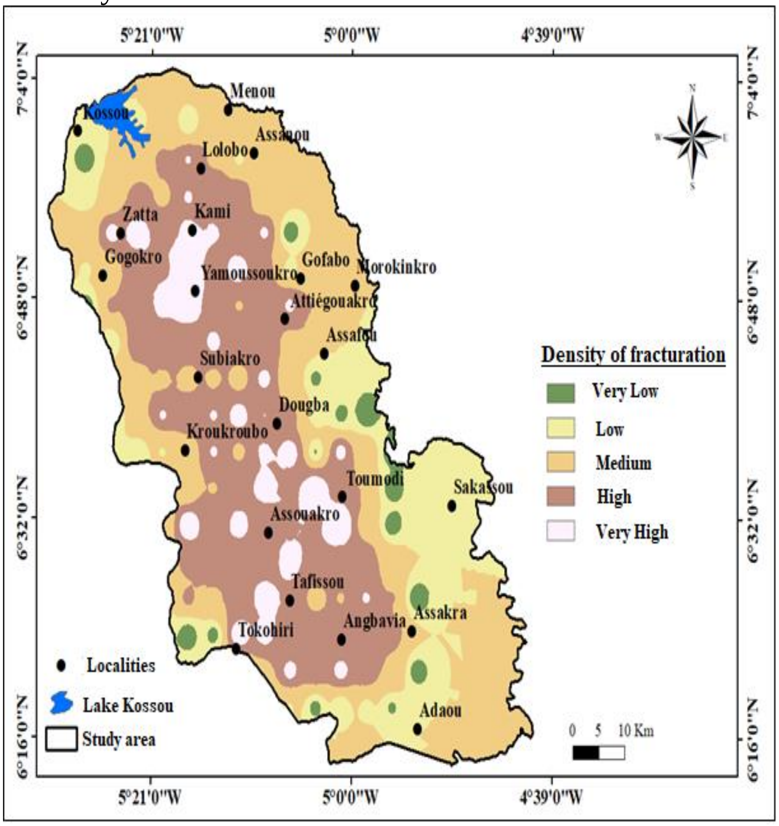

Figure 7. Fracture density map of Yamoussoukro and Toumodi departments

3.5. Discussion

Characterization of fracture geometry has been the subject of many studies (Biémi, 1992; Gillespie et al., 1993; Bodin and Razack, 1999; Darcel et al., 2003; Razack and Lasm, 2006; Youan Ta et al, 2008; Yao, 2009;

Sorokoby et al.,2010; De Lasme, 2013; Baka, 2012; Oulare et al., 2016; Akokponhoue et al., 2018; Onetié et al., 2020; Kouadio et al, 2020; Koffi et al., 2021). These studies have provided a better understanding of fractured environments. In several regions of Cote d'Ivoire, the preferential fracture directions recorded are N0-10° and N90-100°. Thus, the main fracture directions identified in Yamoussoukro and Toumodi are similar to those recorded by Soro et al., (2010) in the Aries region of which our study area is part, as well as in the Nzi-Comoé region (Kouassi et al., 2013). This suggests that these regions were affected by similar tectonics. These lineaments can be equated, therefore, to fractures (Onetie et al., 2020). Matching the overlay of geophysically-implanted borehole flows with the fracturing map confirms that the identified lineaments are most likely associated with fracturing. The results of the manual mapping of the lineamentary structures showed that the departments of Yamoussoukro and Toumodi are strongly fractured. This also allows us to validate the methodology of mapping these fractures. Indeed, this methodology has allowed highlighting the fracturing map of the Marahoué watershed (Biémi,1992), the Odienné region (Savané, 1997), the Korhogo region (Jourda, 2005), the Baya watershed (Mangoua, 2013), the Lobo watershed (Yao, 2015; Kouadio et al., 2020), etc.

Lineament density is an indicator of the degree of rock fracturing. Zones of relatively high lineament density are identified as zones of a high degree of rock fracturing that are essential for groundwater conduit development in a given area. However, for Yao et al. (2014), the influence of lineament on the productivity of a borehole remains controversial as the role played by lineaments in groundwater circulation becomes difficult to decide when considering only borehole flow or when looking only at a regional scale. For this reason, a comparison is made with boreholes already established by geophysics to understand the contribution of lineaments to groundwater circulation. This approach has also been used by Koffi et al, (2021) to search for productive aquifers in the northern region of Côte d'Ivoire and by Koné et al (2019) in Bamako (Mali), who claim to have associated a good part of the field observations to already existing structures with greater accuracy than those observed on the images.

Conclusion

At the end of the work, we can say that the OLI images allowed us to make the lineament map with quite satisfactory results. The fracture density map shows that the study area is highly fractured. Thus, the detailed lineament map contains 2063 manually extracted lineaments with a cumulative length of lineaments equal to 2410 km. Statistical analysis of the detailed lineament map showed that the Yamoussoukro department is strongly fractured, and highlighted two dominant directions, namely N0°-10°

(N-S) and N90°-100° (E-W). In addition, a comparison made with boreholes already established by geophysics allowed us to understand the contribution of the lineaments in the circulation of groundwater. Thus, the validation of the detailed lineaments map allowed us to attribute to all the lineaments retained, the fracture value searched during the implantation of the boreholes.

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