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Research Paper

Groundwater exploration using extraction of lineaments from SRTM DEM and water flows in Béré region

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ABSTRACT

Lineaments analyses are widely included in the selection of groundwater exploration sites. It should also be noted that the junction zones of several fractures are often points of high water flow. The purpose is to suggest potential sites for setting water drillings in the Béré region based on drilling flows and fractures. The influence of lineaments and their intersections on groundwater yield was studied using SRTM satellite imagery and borehole flow data. We used the Line Detecting Segment algorithm to extract lineaments and fractures. Then we performed the ordinary kriging of the drilling flows and an Heatmap of the fracture intersection points using Kernel density estimation. The crossing between these two maps showed a good correlation between the flows and the fracture intersections. The SRTM DEM are efficient for fracture extraction. All this has allowed us to characterize the potential sites for setting drilling with good flow rates.

1. Introduction

According to (Soro, 1987) rainfall shortages recorded in Côte d'Ivoire since 1973 access to drinking water becomes extremely difficult. Thus the drying up of traditional supply points in the countryside since 1973 has led researches towards groundwater in fractured aquifers. basement aquifers, which are of particular interest for water supply, are located in altered and fissured/fractured layers of crystalline rocks. The weathered layers and fissured/fractured of crystalline rocks form aquifers that are of prime interest for water supply in hard rock areas (Dewandel et al., 2006). These fractures are represented on the soil surface by lineaments. Lineament analysis represents an important step in the geological mapping of cratonic domains and in the exploration of subsusrface resources. followed by field verification through geophysical exploration and/or drilling.

Various studies have shown that these linear structures play an important role in groundwater exploration (Magowe and Carr, 1999; Savané and Biémi, 1999; Saley, 2003; Jourda, 2005; Lattman and Parizek, 1964). Lineaments represent groundwater drainage systems in fractured aquifers (Koita, 2010; Brunner et al., 2007). Manual extraction of lineaments is subjective and difficult to extend to a wide area because smaller lineaments may be overlooked (Saepuloh et al., 2018). Previous work has focused mainly on mapping by conventional methods (field fault monitoring, analogue aerial photography), which does not always identify all existing lineaments. The identification of fractures from field missions is limited by the difficulty of access to several sectors of the studied regions. The main obstacles are generally of natural origin (rivers, mountains, vegetation, and more often the large surface area of the territories), they make this approach expensive and tedious (De Sève et al., 1994). The methods, which are mainly based on optical satellite imagery, allow the extraction of lineaments by photo-interpretation (Coulibaly, 1996; Youan et al., 2008; Sorokoby et al., 2010; Ibrahim and Mutua, 2014). Optical images allow a good extraction of the lineaments but in tropical environments elements such as vegetation cover and clouds often prevent a good observation of the lineaments. The results from manual image processing are sometimes very subjective as they depend on the skill, the experience of the analyst and the scale

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at which he is working. In order to overcome all these shortcomings, the automatic method of lineament extraction has been proposed (Moore and Waltz, 1983; Karnieli et al., 1996), This type of processing reduces the subjectivity and time required to analyze images by visual interpretation, these kind of results are rarely reproducible (Poncelet and Cornet, 2010).

We have chosen the segment detection algorithm for the automatic detection of lineaments. This method provides satisfactory results from radar interferometry images for geological studies (Koike et al., 1995; Koike et al., 1998; Masoud and Koike, 2011; Coulibaly et al., 2016). The influence of lineaments and their intersections on groundwater yield will be studied using SRTM satellite imagery and borehole flow data.

Therefore, the main objective of the present research is to suggest suitable areas for the installation of water drilling in the Béré region according to water flows and fractures. However the specific objectives included (i) to extract the structural lineaments using the LDS algorithm, (ii) to meet the extracted structural lineaments with cartographic, hydrographic, topographical and field data, (iii) to regionalize water flows and fracture junctions by geostatistics, and to propose suitable areas to the exploitation of groundwater.

2. Site description

The Béré region is five hundred kilometres from Abidjan (economic capital of Côte d'Ivoire). It is between longitudes 5° and 6° West and latitudes 7° and 9° North (Fig. 1). It covers an area of 19,122 km^2. This is about 6% of the total area of the Ivorian territory. The region is located in middle-north of Côte d'Ivoire. It is part of the Woroba District.

The Sudanese climate is the one that pervades in the Béré region. This climate is a tropical regime of transition between the sub-Saharan semi-arid zones and the tropical zones of the Gulf of Guinea. The topography of investigated area is very homogeneous set of plateaus falling moderately from north to south. It goes between 400 and 300 m of altitude.

The exposed rocks are mainly granites. several bands of Birrimian schistose formations join the granites near the boundaries; they constitute depressed gutters for rivers such as Bandama, Bou and Béré on some specific points of their streams (Trouchaud, 1968). The region lies at the core of the Leo rise and the geological formations of the Béré region belongs to the Birimian or Paleoproterozoic.

3. Materials and methods

3.1. Applying the LINE detection segment (L.D.S) algorithm

Lineaments are the places of significant variations in greyscale information. The notion of contour being related to that of variation, it is obvious that such a definition naturally leads to an evaluation of the variation in each pixel. We used LINE module of PCI Geomatica For lineament extraction. We applied the L.D.S algorithm, which is the algorithm of detection of lineaments on a satellite image. The algorithm consists of three steps: edge detection, thresholding, and extraction curve. In the first stage which is edge detection, Canny algorithm of edge detection was applied to make an edge strength image. The image is further threshold in the second stage to get a binary image. In the last step, linear features were extracted from the threshold binary edge image and saved as a vector data of polylines.

3.2. Validation of the obtained lineaments

To carry out this study, we used hydrography and radar satellite images through indirect methods of analysing structural geology. In fact, in the Craton regions, like in the case of our study area, rivers and the topography bear the sign of regional tectonics (Horton, 1945; Bessoles, 1977; Biémi, 1992).

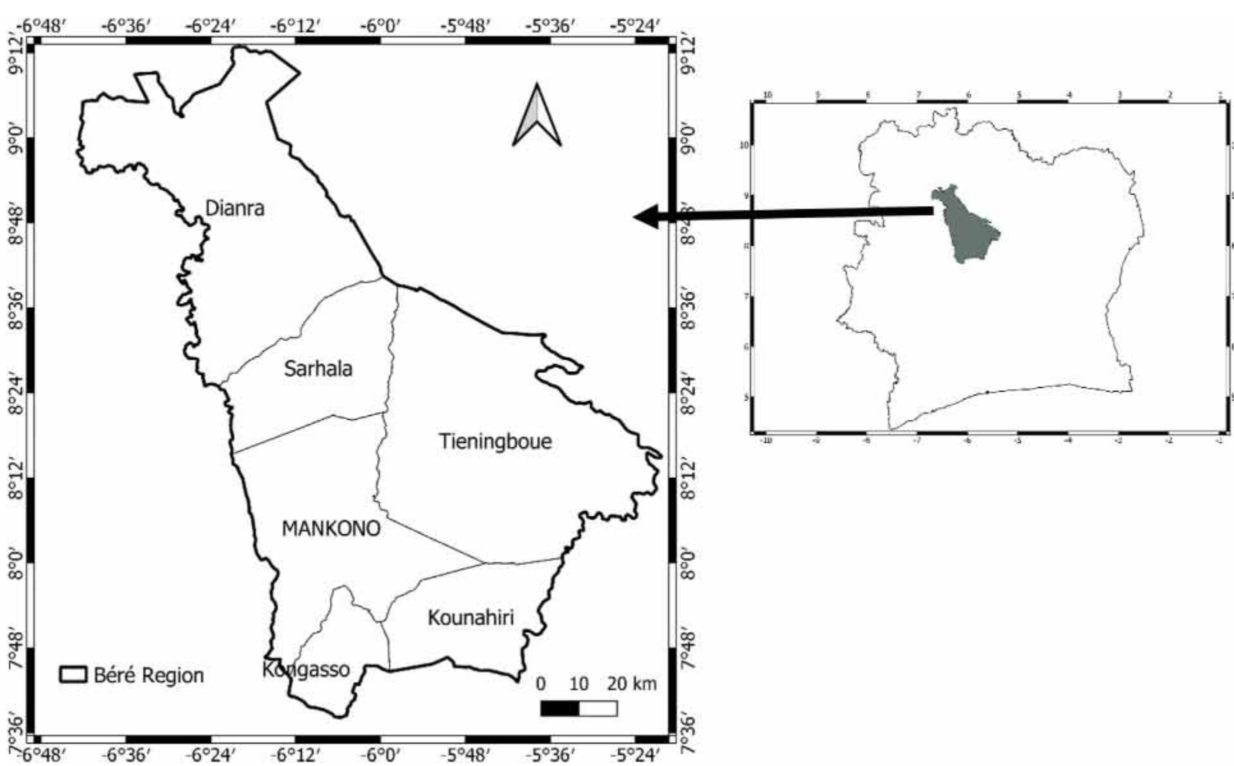

Fig. 1. Location map of the study area.

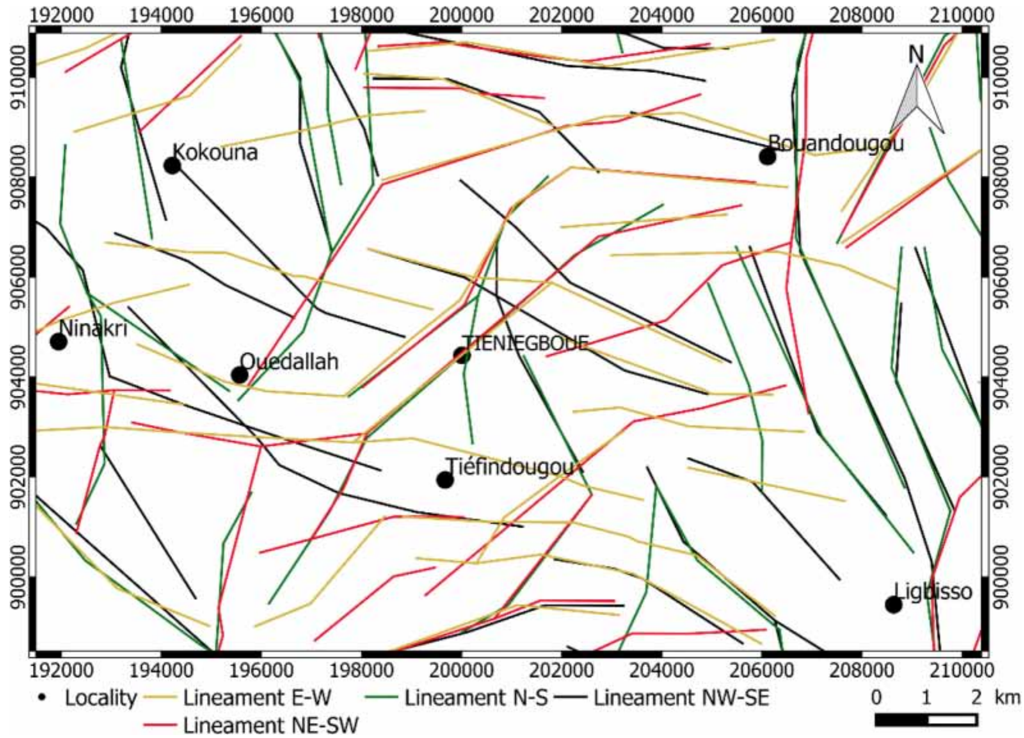

Fig. 2. Omnidirectional structural lineaments.

Table 1
Number and total length of lineament per direction.

Extraction direction	Number of lineaments	Percent (%)	Lengths in km
E-W	1139	25.76	12 150.503
N-S	1072	24.24	11,037,816
NW-SE	1071	24.22	10 839.831
NE-SW	1139	25.76	11,567,584
All directions	4421	100	45595.537

All essential information for mapping and structural geological analysis of the region are integrated into a Geographic Information Systems (GIS). This will allow, on one hand, to identify already known lineaments and on the other hand, to interpret new lineaments and make the link with the geology of the field.

The geological, hydrographic, traffic and topographic maps and the spatial data set have been integrated in QGIS, which allows a good extraction and validation of the lineaments. The process consisted in identifying and listing all the parallel faults to the straight stream segments. We also had to take into account the similar lineaments on the different maps, then combining them with the field data from a GIS software. This method allowed us to draw a structural map.

3.3. Density of the points of intersection of the lineaments: Smoothing by the kernel method

This method is a smoothing function that produces a continuous estimate of cumulative density around the points of the seedling (Rosenblatt, 1956; Parzen, 1962; Sheather and Jones, 1991).

Smoothing by the kernel method is especially suitable for interpolation from location seedlings not weighted by an enumeration variable (Zaninetti, 2005). It is necessary to choose the nature of the smoothing function (kernel function) and the radius of influence of the estimated area around each point of the seedling.

For choosing the smoothing function, we used the Gaussian function (normal) because we want to estimate the trend surface for a uniformly distributed phenomenon.

If $x_1, x_2, \ldots, x_N$ is a sample of a random variable, then the non-parametric estimator by the kernel density method is:

$$\hat{f}_h(x) = \frac{1}{Nh}\sum_{j=1}^{N} K\left(\frac{x - x_i}{h}\right) x \in \mathbb{R} \tag{1}$$

In this formula, K (x) refers to the kernel, h is a parameter labelled as window, and it governs the smoothing degree of the estimation. Often, we chose K as the density of a standard Gaussian function:

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1x^2}{2}} \tag{2}$$

For this Gaussian kernel the non-parametric estimator by the kernel density method is:

$$\hat{f}(x) = \frac{1}{n}\sum_{j=1}^{n} \frac{1}{\sqrt{2\pi h}} e^{\left(-\frac{(x-x_i)^2}{2h^2}\right)} x \in \mathbb{R} \tag{3}$$

3.4. Regionalization of pumped flows from different boreholes

3.4.1. Variogram

This exploratory phase allows making assumptions about the spatial structure of the surface to be studied. The variogram allows us to describe the spatial structure and see the deterioration of the correlation between the measured points when the distance increases (Zaninetti, 2005). It also helps specifying some qualitative characteristics of the environment (continuity, anisotropy, regionalization, etc.).

Z is the quantitative variable of interest. The measure of semi-variance is to consider pairs of points at a distance which is less than or equal to a critical distance h.

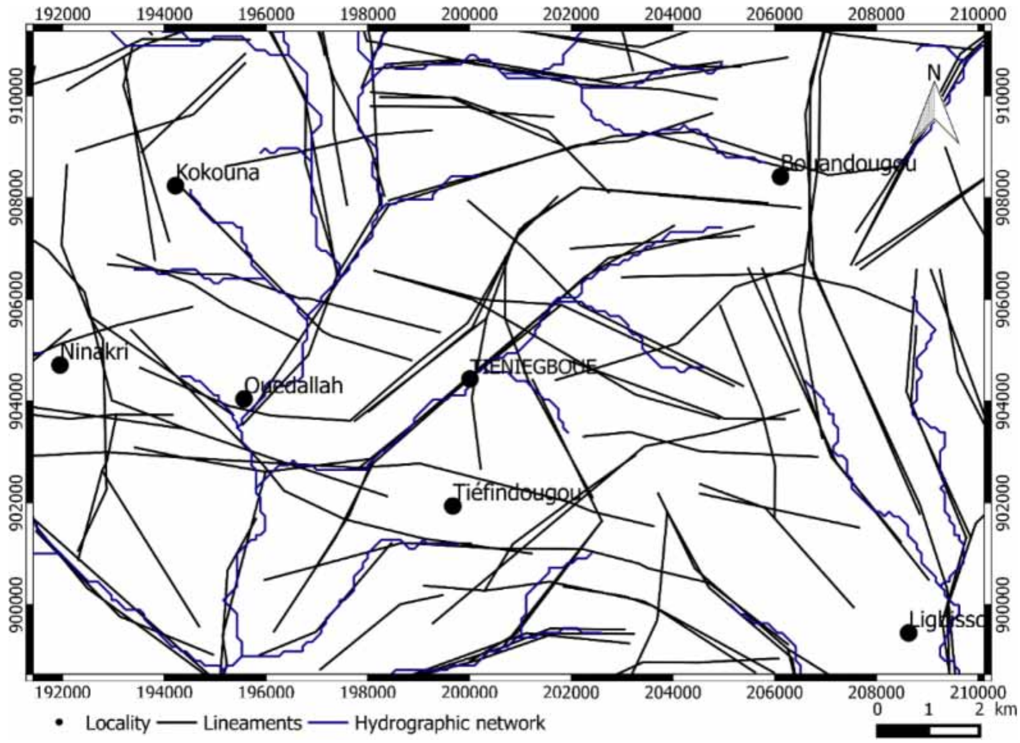

Fig. 3. Overlaying of the structural lineaments obtained with the hydrographic network.

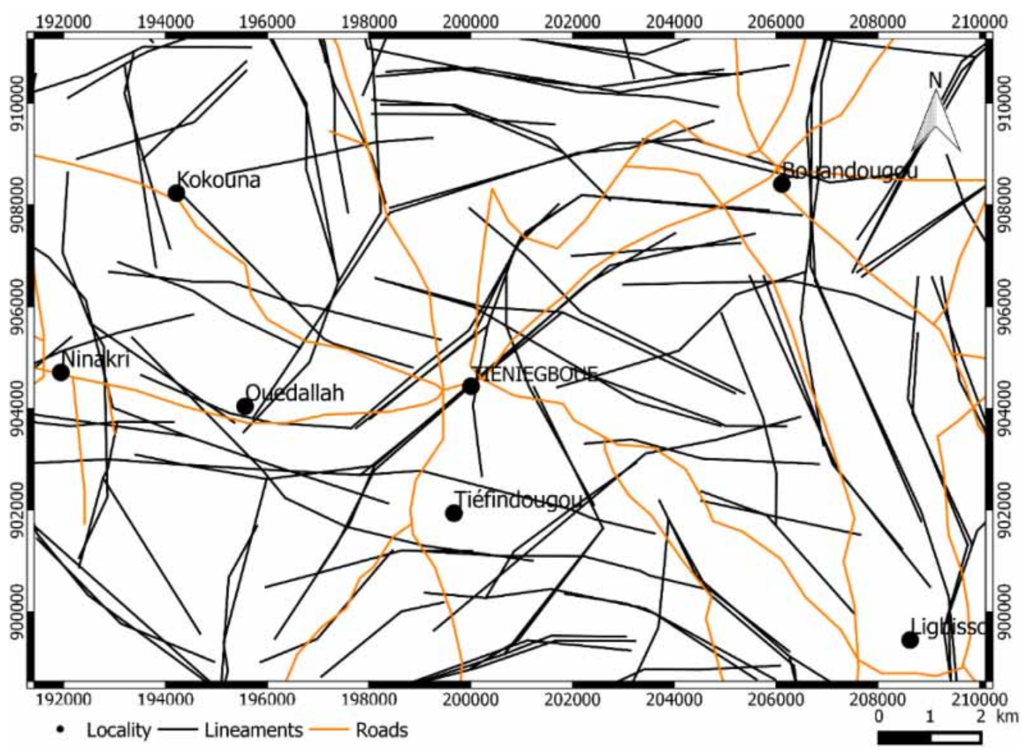

Fig. 4. Overlaying the structural lineaments obtained with the traffic system.

It is defined under intrinsic hypothesis, by the function γ (h) as follow:

$$\gamma(h) = \frac{1}{2} * Var\left[Z_{(x+h)} - Z_{(x)}\right] = \frac{1}{2} * E\left[\left(Z_{(x+h)} - Z_{(x)}\right)\right] \quad (4)$$

In this function, x represents the coordinates vector, h the distance vector, and Z (x) and Z (x + h) the values (pumped flow rate) at the coordinates x and x + h.

The semi-variogram is calculated using the following equation:

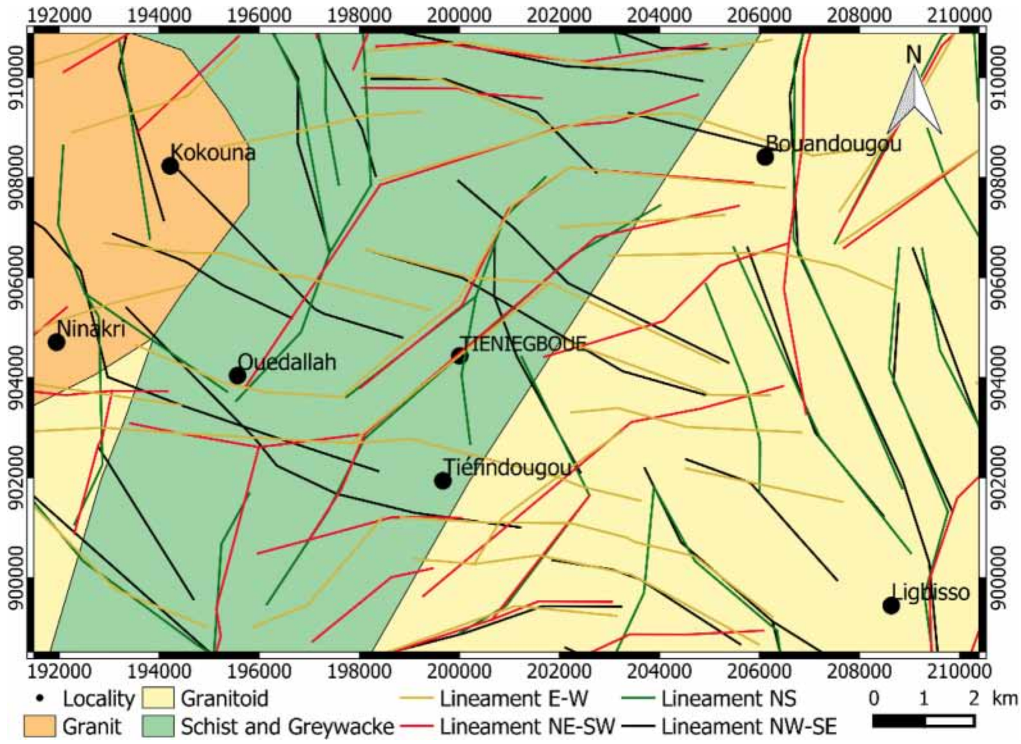

Fig. 5. Overlaying the boundary between the rock units with structural lineaments obtained.

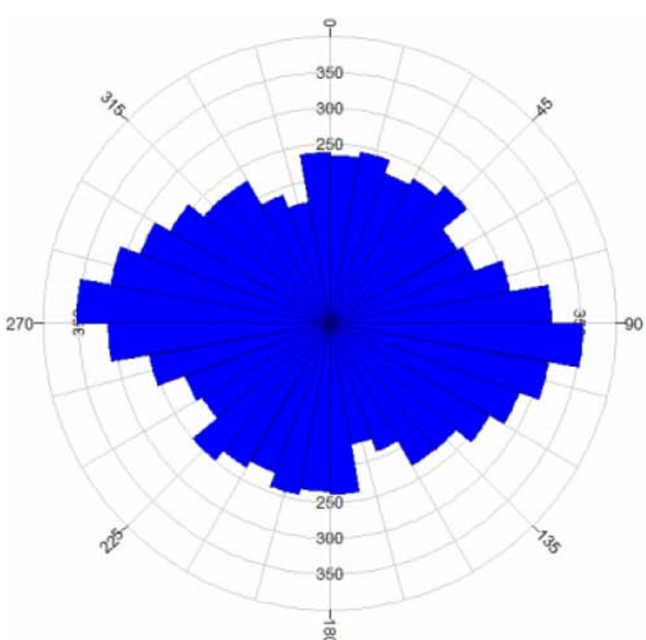

Fig. 6. Directional rosettes.

$$\gamma_e(x) = \frac{1}{2nh}\sum_{i=1}^{n(h)}\left[Z_{(x_i)} - Z_{(x_i+h)}\right]^2 \quad (5)$$

n(h): number of couple points separated by a distance h.

3.4.2. Ordinary kriging

Ordinary kriging, does not assume the knowledge of the mean and the covariance. It represents the most common kriging method in practice and its aim is to predict the value of the random variable Z(x) at an unsampled point x_0 of a geographical region as well (Webster and Oliver, 2007).

This is a modelling phase, which consists of interpolating a surface from the sample of known N values Z (flow rate). We want to estimate a block v centered at point x_0. Z_v is the true (unknown) value of this block, and $Z_v{}^*$ is the estimator that we obtain.

$$Z_v^* = \sum_{i=1}^{n}\lambda_i Z_i \quad (6)$$

It is necessary to estimate a linear coefficient vector λ_i. These estimates are unbiased. The sum of the coefficients is unitary:

$$\sum_{i=1}^{n}\lambda_i = 1 \quad (7)$$

They are estimated under constraint with the Lagrange method by minimizing the variance of forecast errors:

$$\sigma_{k_0}^2 = Var[Z_v] - \sum_{i=1}^{n}\lambda_i Cov[Z_v, Z_i] - \mu \quad (8)$$

In matrix form, we have:

$$K_o\lambda_o = k_o \quad (9)$$

$$\sigma_{k_0}^2 = \sigma_v^2 - \lambda_0' k_0 \quad (10)$$

$$\begin{bmatrix} \sigma^2 & Cov(Z_1,Z_2) & . & Cov(Z_1,Z_n) & 1 \\ Cov(Z_2,Z_1) & \sigma^2 & . & Cov(Z_2,Z_n) & 1 \\ . & . & . & . & . \\ Cov(Z_n,Z_1) & Cov(Z_n,Z_2) & . & \sigma^2 & 1 \\ 1 & 1 & . & 1 & 0 \end{bmatrix}\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ . \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} Cov(Z_1,Z_v) \\ Cov(Z_2,Z_v) \\ . \\ Cov(Z_n,Z_v) \\ 1 \end{bmatrix} \quad (11)$$

The kriging provides direct estimation of a block (Zv) or a point (Z_0). What makes the difference is the member of right, namely k_0. The kriging of a block is equal to the average of the occasional krigings in that block.

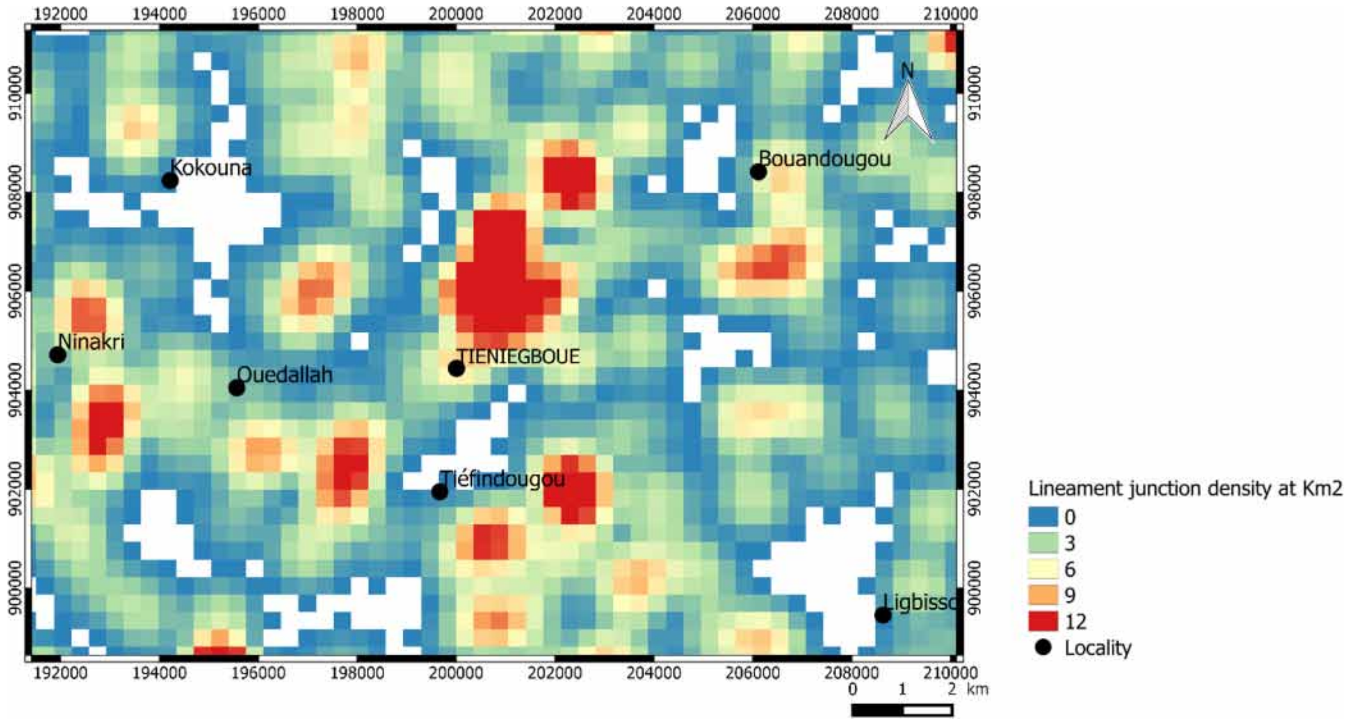

Fig. 7a. Heat map of fracture junction areas.

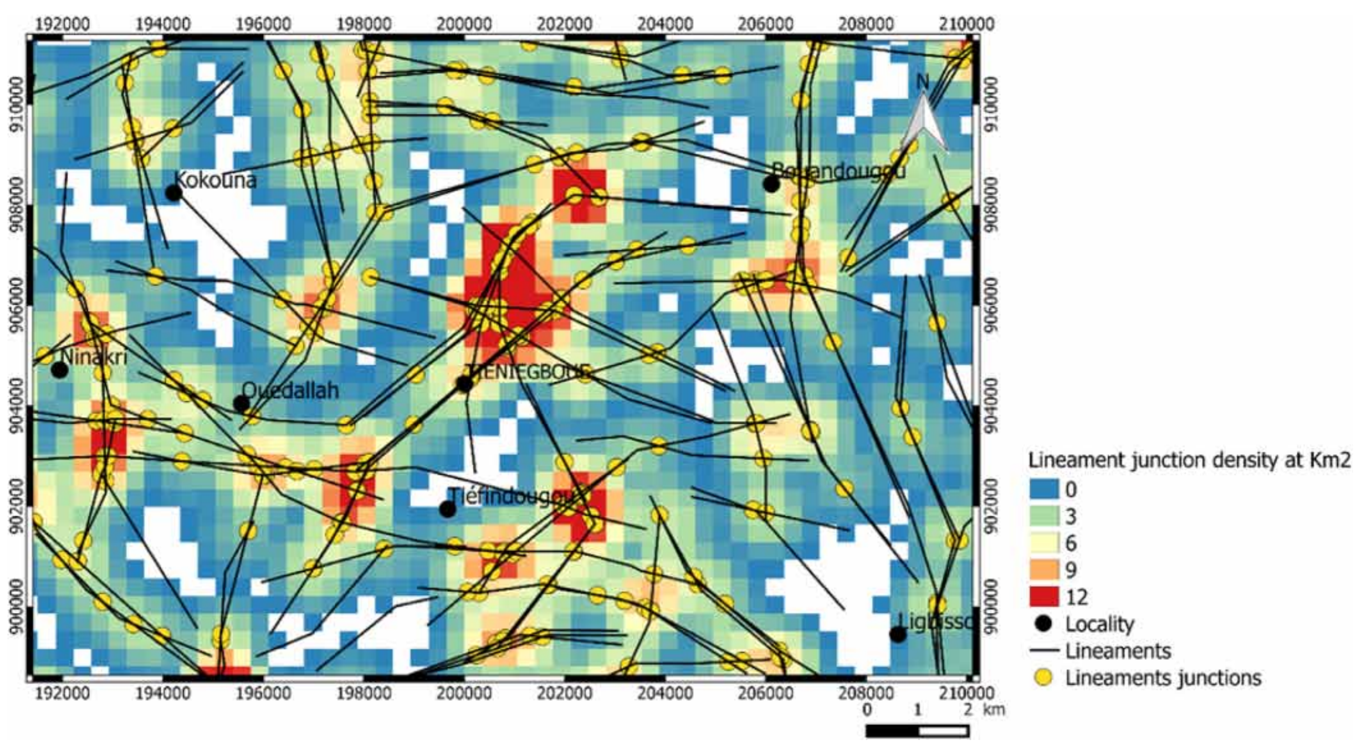

Fig. 7b. Overlaying fracturing and junction areas.

4. Results and discussion

4.1. Map of the lineaments network

Applying the LDS algorithm for the automatic extraction of lineaments gives the results as presented in Fig. 2. This concerns the Tiéniegboue area to better illustrate the automatically extracted lineaments. We overlaid the four maps of lineaments we obtained in the four directions (NS, NE-SW, EW and NW-SE), in order to create a synthesis map of the lineaments.

The table below summarizes the number of lineaments and the length in these directions Table 1. The lineament network is mainly oriented along the E-W and NE-SW directions with a rate of 26%, for each direction. Overall, these lineaments fit perfectly with the brittle tectonics of Côte d'Ivoire. 24% of the structural lineaments are oriented NW-SE and N-S.

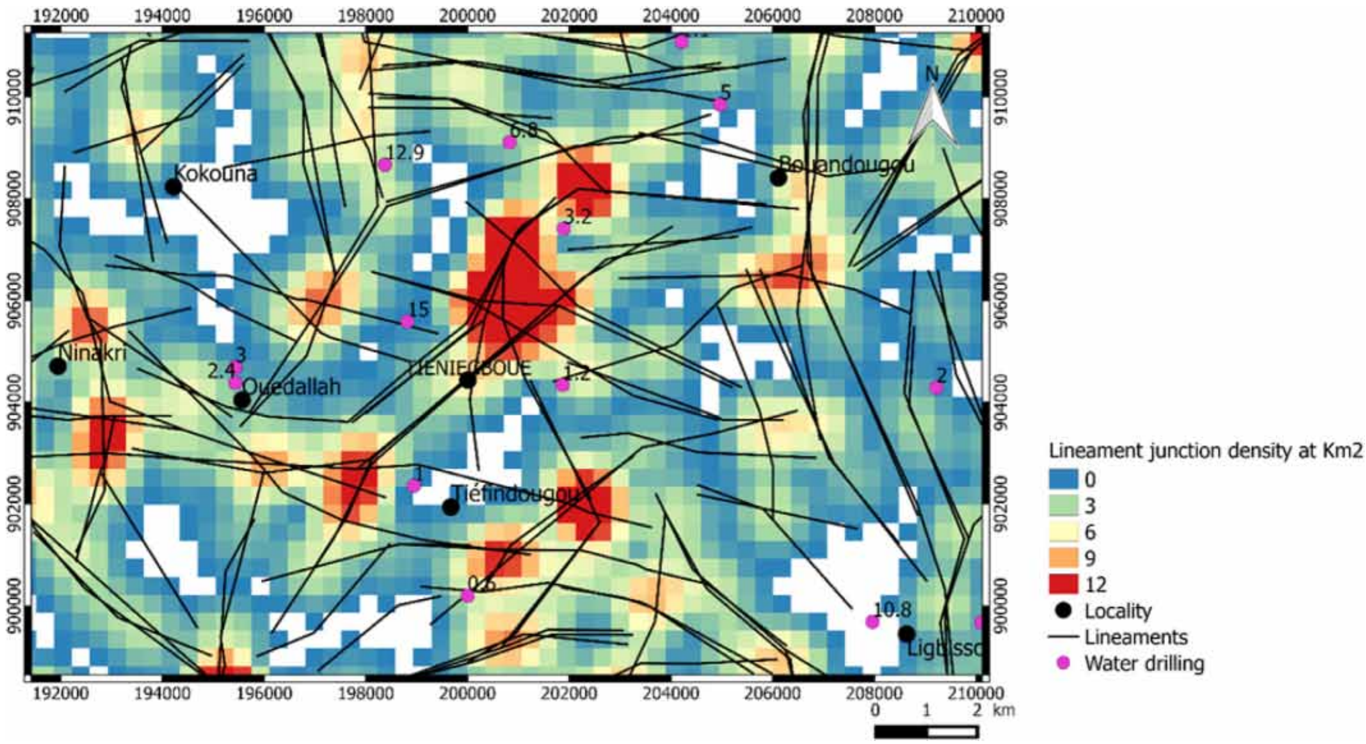

Fig. 8a. Overlaying drillings on the heat map.

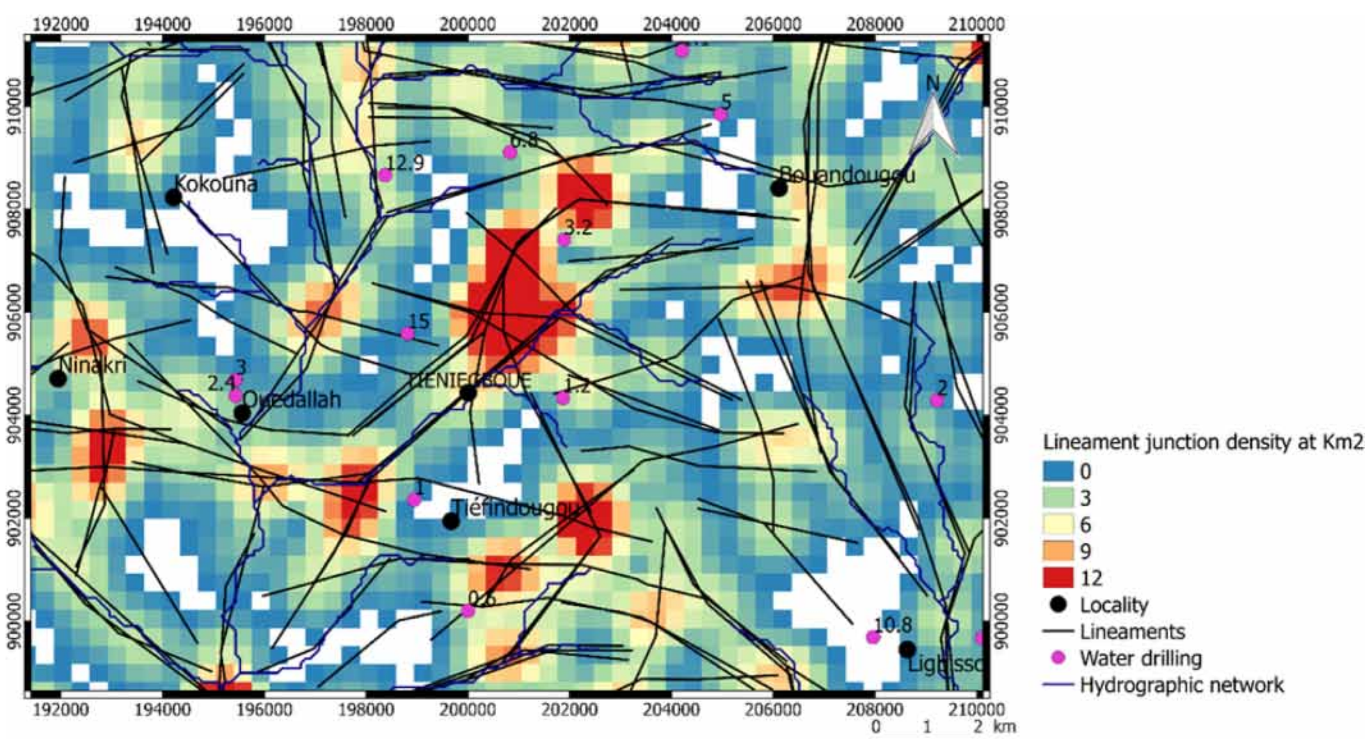

Fig. 8b. Overlaying drilling, stream and fracturing.

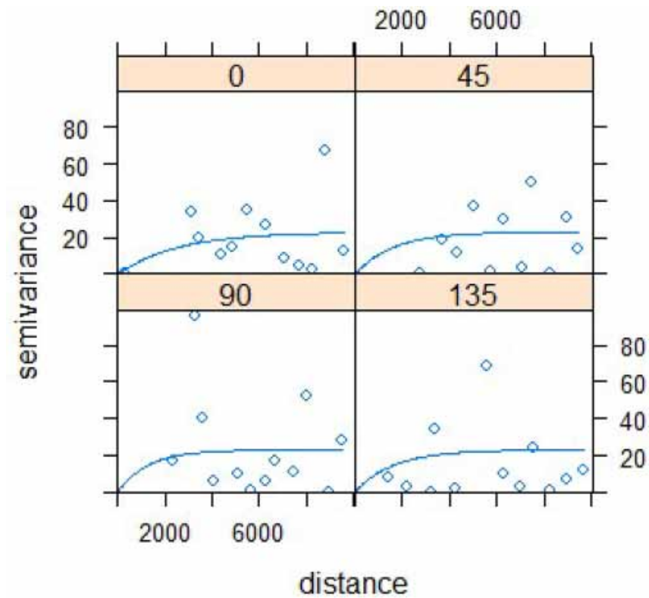

Fig. 9. Variogram in the N-S, NE-SW, NW-SE and E-West directions.

4.2. Results of lineaments comparing

4.2.1. Comparing the hydrographic network with the lineaments

Comparing the data of the hydrographic network with those of the lineaments made allowed to establish parallels between the orientations of the lineaments and the main directions of the surface waters streaming. The main rivers are often located most in the large fractures of the Precambrian base (Biemi et al., 1991) (Fig. 3).

4.2.2. Comparing of the structural lineaments extracted with the map of the traffic system.

We observe that there is no correlation between the traffic system and the automatically extracted lineaments. This shows that the lineaments extracted on SRTM images are related to local geology and not to human activities. These images can be used to extract structural lineaments (Fig. 4).

4.2.3. Comparing of the structural lineaments extracted with the map of the rock units.

There are correlations between the automatically extracted lineaments and boundary between the rock units (Fig. 5). The lineament network is predominantly oriented along the NE-SW direction. This direction is the Birimian tectonic direction. in general, the lineaments blend with the brittle tectonics of Côte d'Ivoire (Tagini, 1971).

4.3. Analysis of the direction

The analysis of the direction of the lineaments shows that the "E-W direction and the NE-SW" direction are dominant in number of lineaments (Fig. 6). We can say that the Béré region is part of the Birimian zone and that region has been affected mainly by the Eburnian orogenic cycle (Tagini, 1971).

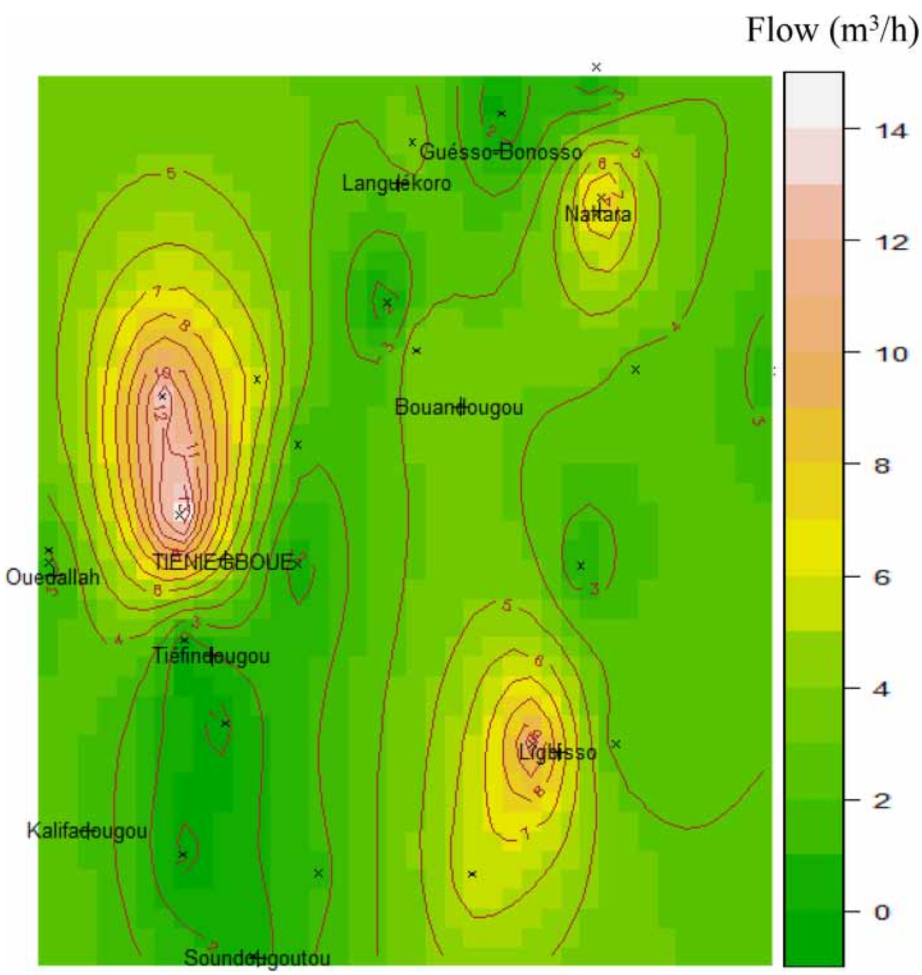

Fig. 10. Kriging of water drilling flow rates in the sub-prefecture of Tieniegboue.

4.4. Suggesting suitable areas for the implantation of water drillings in the Béré region (Côte d'Ivoire)

4.4.1. Smoothing results of fracture intersections by the kernel method

In plinth areas, we search for the junction areas of fractures. Below is the heat map of these areas (Fig. 7a and 7b). A capture was made at the sub-prefecture of Tiéniegboue to better illustrate this fact. The density of fracture intersections ranges from 0 to 12. Places with a high density of junction are in red and those with a low density are in blue.

Overlaying the drillings on the heat map allows us to notice that medium and high flow rate drillings are located in the high-density areas (Fig. 8a and 8b). This allows determining potential areas with high flow rate. These areas are in red and orange.

4.4.2. Prediction results for high flow rate areas

Spatial analysis of flow rates through the variogram and kriging allows us to predict favourable locations for drilling according to flow rates. Calibration of the variogram made it possible to retain the following parameters:

- Range: 23
- Sill: 2540 m
- The calculation of the experimental variogram for different directions has revealed an anisotropy of main direction NW-SE (Fig. 9). The variograms calculated in the different directions do not overlay, we will assume the anisotropic phenomenon.
- -The variogram is continuing with linear behaviour at the origin and absence of nugget effect.
- -We adjusted our experimental variogram with the combined exponential model with an absent nugget effect (Fig. 9).

High flow rates predictions are in the pink and yellow areas. These flows go from 6 to 14 m^3 for the Tieniegboue area. Fig. 10 shows the map of flow values we obtained by kriging.

5. Conclusion

The use of GIS and remote sensing in the research of productive aquifers in the Béré region allowed us to make some observations on the optimization of the positioning of water drillings in this region. These observations go like this:

The LDS algorithm allowed us to extract the structural lineaments that were confirmed in fracture after comparison and validation, using map and field data.

The results show that this area has been affected by intense tectonic activity.

The structural lineaments of the region are mostly ''North-east South-west'' direction. This means that the region has been affected largely by the Birimian orogeny.

Geostatistical tools such as the variogram, the kriging and the kernel smoothing method have allowed us to predict the flow rates and to determine the high-density areas of the intersection of the fractures.

Many additional details can be extracted from radar interferometry images such as SRTM. We mean the topography, lineaments and watersheds that will play an important role in the choice of the high flow water-drilling site.

We got good results that can serve as a guide or decision-making tools for future field investigations in the Béré region. The results obtained after satellite image processing are reliable and are close to the reality of the field. That is why satellite images are therefore a privileged tool for acquiring information capable of assisting decision-makers.

This study could be extended to the whole country. It could also concern several types of underground resources such as diamonds, aquifers, iron, etc. In addition, these works can serve as a first step before any conventional prospection of geological resources in the Béré region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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