Journal of Geographic Information System, 2022, 14, 527-545
https://www.scirp.org/journal/jgis
ISSN Online: 2151-1969
ISSN Print: 2151-1950

Mapping of Potential Recharge Areas of Fractured Aquifers in the Departments of Yamoussoukro and Toumodi (Central Côte d'Ivoire)

Kouassi Hervé Jacques Kokobou[1], Arthur Brice Konan-Waidhet[1]*, Tanina Drissa Soro[1], Jean Biemi[2]

[1]Laboratory of Science and Technology of Environment, Jean Lorougnon Guédé University, Daloa, Côte d'Ivoire
[2]UFR STRM/Felix Houphouet Boigny University, Abidjan, Côte d'Ivoire
Email: *konanwab@yahoo.fr, *konanwaidhet@ujlg.edu.ci

How to cite this paper: Kokobou, K.H.J., Konan-Waidhet, A.B., Soro, T.D. and Biemi, J. (2022) Mapping of Potential Recharge Areas of Fractured Aquifers in the Departments of Yamoussoukro and Toumodi (Central Côte d'Ivoire). *Journal of Geographic Information System*, **14**, 527-545.
https://doi.org/10.4236/jgis.2022.145030

Received: August 27, 2022
Accepted: October 21, 2022
Published: October 24, 2022

Abstract

Groundwater is an important natural resource for all human activity. Today, due to climate change and population growth, the demand has increased considerably, thus requiring their evaluation to ensure sustainability. However, one of the important but difficult to estimate parameters due to its variability is the recharge. This work aims to map the potential recharge of aquifers in the departments of Yamoussoukro and Toumodi. Saaty's AHP (Analytical Hierarchy Process) multi-criteria analysis technique was used by integrating different thematic layers. First, a reclassification then weighting of these parameters was made according to their influence in the recharge process. Finally, they were integrated into a GIS to produce the map of potential groundwater recharge zones. The results indicate that the potential high recharge areas represent approximately 43.11% of the area of the study area. These areas appear scattered in the sub-prefecture of Yamoussoukro, Kokoumbo Attiegouakro, Toumodi et Kpouèbo.

Keywords

Groundwater, Recharge, Multi-Criteria Analysis, GIS, Cote d'Ivoire

1. Introduction

Water is a very important resource at the center of sustainable development. It is essential for socio-economic development, ecosystem health, and human survival. However, this resource is becoming increasingly scarce [1]. Many countries in the world are faced with problems of drinking water supply and Côte d'Ivoire, a country located in West Africa, does not escape this situation. Indeed, while the needs are increasing, the supply is decreasing and therefore not very satisfactory. Thus, for several years, the exploitation of groundwater captured in the basement in Côte d'Ivoire has experienced a considerable boom, thousands of boreholes have been built and operated in almost all areas of the country, having difficulties in accessing drinking water [2]. Thus, for a sustainable management and perpetuation of this resource, it is necessary to know and evaluate the recharge, the flows and the discharge which constitute the fundamental elements of a hydrosystem [3]. Among these elements, recharge would be one of the current major concerns of the scientific community and decision makers in that it conditions the proper renewal and protection of groundwater resources [4].

Thus, in order to establish an optimal and rational management of groundwater resources, water managers need very precise information on the conditions of recharge and exploitation of groundwater. According to [5], the assessment of groundwater recharge is undoubtedly one of the most relevant parameters but also the most difficult to estimate. For this purpose, a wide range of techniques has been considered. These are the climatic method [6]; the physical method [7]; the geochemical method [8]. Despite all these approaches, the determination of recharge is still today unreliable [4] and expensive [9]. Therefore, it seems necessary to apply other techniques that could reduce uncertainties in order to increase confidence in recharge estimates.

The objective assigned to this work is therefore to map the potential recharge areas of the Yamoussoukro and Toumodi aquifer using remote sensing and geographic information systems (GIS). To provide assistance to decision makers and managers, GIS is considered one of the best tools to both gather all data, analyze them and visualize several layers of information on the same medium. The methodological approach of this study is based on the classification and combination of the different parameters that influence recharge.

2. Material and Methods

2.1. Study Area

The study was conducted in central Côte d'Ivoire, in the departments of Yamoussoukro and Toumodi, located between latitudes 6˚20'N and 7˚00'N and longitudes 4˚40'W and 5˚30'W (**Figure 1**). These departments include the sub-prefectures of Kossou, Lolobo, Attiegouakro, Kokoumbo, Djekanou, and Kpouebo. This area covers an area of 4.789.38 km^2.

The relief of the departments of Yamoussoukro and Toumodi is not very hilly and corresponds to the plateaus of the wooded savannah zone. The entire area is relatively uneven, marked by the presence of chains of hills with a granitic structure. The average altitude in these departments is 200 m [2]. The climate of the region is tropical humid and characterized by two seasons. Divided between a rainy season (March to November), and a dry season (December to February).

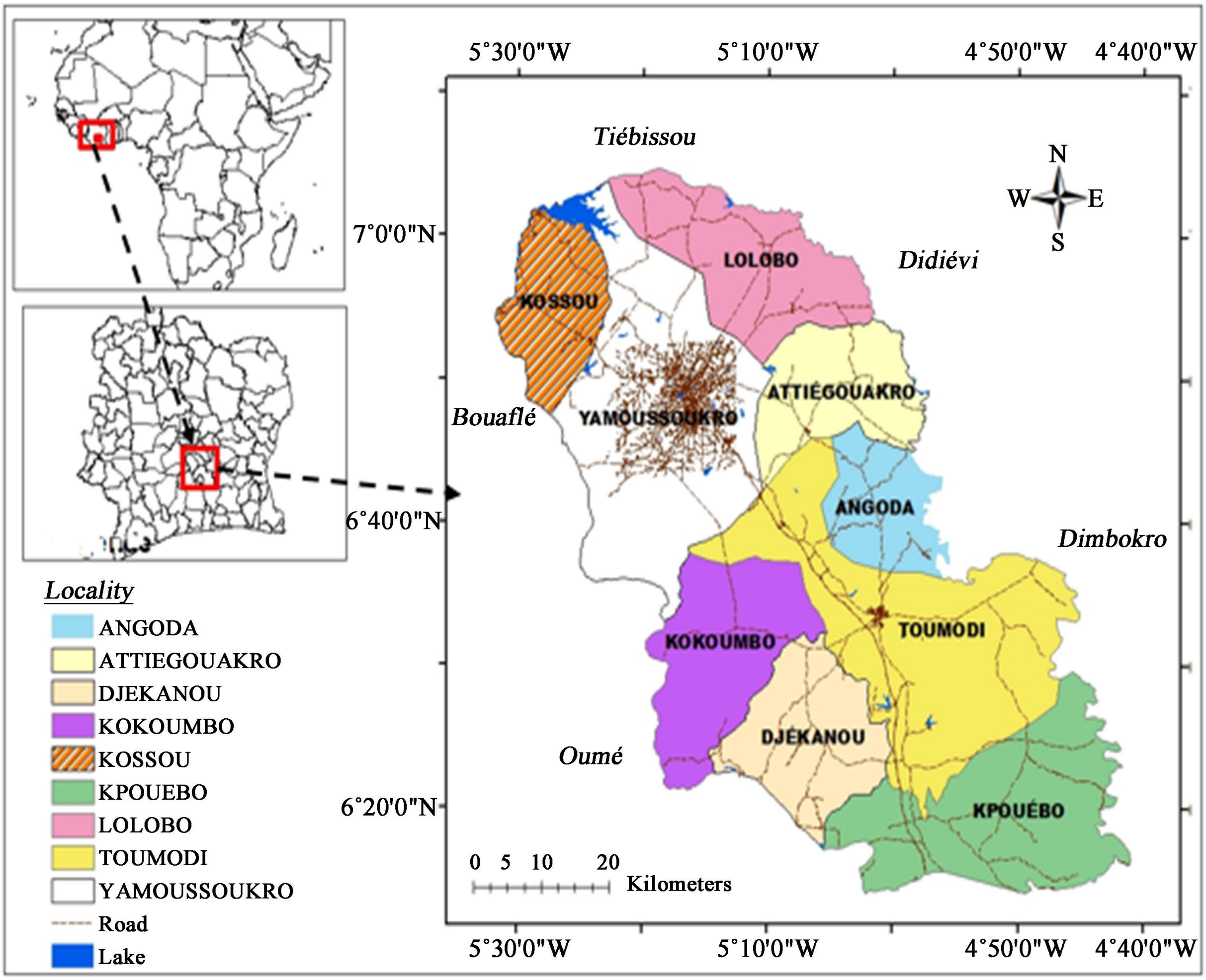

Figure 1. Location of the study area.

The average annual rainfall is 1148 mm/year while the average temperature is 30˚C. The hydrographic network in these departments is marked by the remarkable presence of the Bandama River, the N'zi and Kan rivers and their tributaries. They also have many artificial and natural lakes, including Lake Kossou, on which the Kossou hydroelectric dam was built. Their vegetation belongs to the Guinean domain and is dominated by the pre-forest savannah (transition zone between the southern forest and the northern savannah) dotted more or less densely with small trees and interspersed with copses and forest islands. Forest galleries occupy the lowlands along the watercourses. On the drained sandy soils, stands of rôniers and palm trees appear in tall grasslands [10]. Geologically, the rocks encountered in these departments are generally granitoids, green rocks, volcano-sedimentary rocks and shales [11]. These geological formations are characterized by the presence of schistosity, fractures, and large quartz veins [12], which would favor infiltration and therefore groundwater recharge. The aquifer system of Yamoussoukro and Toumodi is consistent with that generally encountered in the basement environment of tropical zones. There are both alterite and fractured reservoirs.

2.2. Materials

The working material consists of software (ArcGIS 10.4 and ENVI 4.5) and satellite data. The land cover and fracture network maps are produced with ENVI 4.5 software from Landsat 7 satellite scenes 197-053; 197-054 acquired on 02 February 2018 and available from http://earthexplorer.usgs.gov. ArcGIS 10.4 was also used to extract the slope and drainage density map from the 30 m resolution Digital Terrain Model (DTM) available at https://earthexplorer.usgs.gov and finally, to integrate all the thematic maps used for this study.

2.3. Methods

After having identified all the parameters considered representative in the recharge of the aquifers, it is necessary to determine which of them will have more impact in the recharge process. For this purpose, one of the usual statistical methods has been considered. It is based on the multi-criteria analysis AHP (Analytic Hierarchy Process) of [13]. The principle consisted in studying each parameter separately according to their role in infiltration, and then a thematic map was established for each of them. Then, a classification was defined for each factor and a rating was assigned to each class, followed by an attribution of weight to the parameters according to their degree of involvement in the infiltration phenomenon. Finally, all the spatial information related to the different factors was crossed in a GIS.

The approach is the one that was adopted by other authors including [3] [4] [14]. The process is organized in five steps which are, identification of parameters, mapping of parameters, reclassification of parameters, weighting by multi-criteria analysis and finally determination of potential recharge areas.

2.3.1. Identification of the Parameters Defining Infiltration

Many works ([3] [4] [15] [16] [17]) indicate that a number of factors would contribute to the definition of potential regional-scale aquifer recharge areas in the basement zone. These include: land use types, fracture density, aquifer permeability, slope, and drainage density.

2.3.2. Parameter Mapping and Reclassification

1) Fracture density mapping

The elaboration of the fracture density map started with the production of the lineament map. This is done by satellite image processing. In this work, the Landsat 7 satellite scene 197-053 and 197-054 images acquired on February 02, 2018 were used. As the image was already geometrically rectified and georeferenced at acquisition, the treatments performed were mainly summarized in two steps (enhancement and validation). The enhancement of the discontinuities was done by applying the directional filters of Sobel. Their use allowed to manually extract the lineaments and to elaborate the detailed lineament map. This map was validated using the borehole flow rates of the two departments. The validation consisted in assessing the proximity of large flow boreholes to major lineaments. The validated fracture map was processed to determine quantifiable parameters such as fracture density. The production of the fracture density map is done with ArcGIS 10.4 software. Different zones are then identified according to the cumulative length of fractures on $5 \times 5\ km^2$ grids.

2) Drainage density mapping

Drainage density is defined as the ratio of the total length of streams in a watershed to the area of the watershed [4]. The assessment of the hydrogeological properties of the drainage network was based on the characterization of density having a relationship with permeability. This map was developed by ArcGIS 10.4 software.

3) Land use map

The land cover map of the departments of Yamoussoukro and Toumodi was produced from a Landsat 7 satellite image acquired in 2018. The maximum likelihood algorithm was chosen for the supervised classification. This method is commonly used in the literature [18] [19]. This method was used to select five land use classes in the area. These are the class "forest"; "degraded forest"; "crop and fallow", "habitat and bare soil" and "water".

4) Slope mapping

The slopes are obtained from the DTM of Côte d'Ivoire from satellite images SRTM (Shuttle Radar Topography Mission) of 30 m resolution. The slopes calculated with ArcGIS 10.4 software are expressed in degrees. They were grouped into four classes.

5) Establishment of the permeability map or hydraulic conductivity of aquifers

The hydraulic conductivity was determined at the location of the boreholes that capture the fractures located in this area. This parameter expresses the capacity of a ground to let water pass through it. They were calculated considering the pumping tests. The deduction was made according to Equations (1) and (2).

$$T = Ke \tag{1}$$

$$K = T/e \tag{2}$$

with

K: hydraulic conductivity; T: transmissivity; e: thickness of the aquifer determined by the distance between the base and the top of the wells [20].

2.3.3. Reclassification of Parameters

The reclassification step consisted in assigning scores to the different classes of the selected parameters according to their degree of infiltration by defining intervals. This process makes it possible to standardize the parameters by defining the degree of membership of each criterion in a common interval of 1 to 10. Indeed, the strongly unfavorable class always has the lowest score contrary to the strongly favorable class which has the highest score. However, the choice of scores depends on the influence of the class on infiltration. The result of the reclassification of the identified criteria, whose combination favors the good recharge or not of the groundwater is recorded in Table 1.

2.3.4. Determination of the Weights of the Parameters by the Multicriteria Analysis Method (AHP)

The decision criteria are weighted using the linear combination method based on the pairwise comparison technique according to the Analytical Hierarchy Process (AHP) of Saaty [13] improved and used by [4] [16]. It produces standardized weights whose procedure consists of comparing the relative importance of all elements belonging to the same level of the hierarchy taken two by two,

Table 1. Ratings assigned to recharge parameters ([4] [21]).

Groundwater recharge parameters	Qualitative criteria	Degree of infiltration	Odds
Drain density (DD) (km/km^2)	<5	Very low	9
	5 - 10	low	7
	10 - 15	Medium	5
	15 - 20	High	3
	>20	Very high	1
Land use	Water	Very high	9
	Cultivation and fallow	High	7
	clear forest	Medium	5
	Dense forest	low	3
	Agglomerations and bare ground	Very low	1
Slope (Degree)	<4	Very low	9
	4 - 9	low	7
	9 - 16	Medium	5
	16 - 23	High	3
	>23	Very high	1
fracture density (Km/Km^2)	<1	Very low	1
	1 - 5	low	3
	10 - 15	Medium	5
	15 - 20	High	7
	>20	Very high	9
Aquifer permeability ($\times 10^{-8}$ m/s)	<3	Very low	1
	3 - 8	low	3
	10 - 15	Medium	5
	14 - 22	High	7
	>22	Very high	9

compared to the element of the level immediately above. This comparison was based on a numerical scale (**Table 2**).

Once all the combinations are made, it will be a question of deducing the eigenvector (Vp) (Equation (3)) and the weighting coefficient (Cp) (Equation (4)).

The principle of determination is as follows:

$$\mathrm{Vp} = \sqrt[K]{\mathrm{W1} \cdots \mathrm{Wk}} \tag{3}$$

With k = number of parameters compared; Wk = main values assigned to the variables;

$$\mathrm{Cp} = \frac{\mathrm{Vp}}{\mathrm{Vp1} + \cdots + \mathrm{Vpk}} \tag{4}$$

The sum of the Cp of all the parameters of a square matrix must be equal to 1 (one). A high Cp, will tend to accentuate the recharge while a low Cp will reduce it. **Table 3** summarizes the different binary combinations performed as well as the values of the corresponding eigenvectors and weighting coefficients.

In a study that relies on the subjectivity of values, it is imperative to determine the consistency of judgments [22]. Indeed, since the values assigned often present a certain degree of inconsistency, a synthesis of all the judgments proves wise. To verify the consistency of the judgments, [23] determined an assessment criterion which is the consistency ratio (CR). If this ratio is less than 10%, then the assessments are consistent; if it is more than 10%, they need to be revised. The verification principle is divided into several successive steps (Equations (5) to (11)):

- Normalization of the matrix [A]. It consists in dividing each element of a column by the sum of this column:

$$[\mathrm{A}] = \sum \frac{\mathrm{Wn}}{\sum \mathrm{Wn}} \tag{5}$$

Table 2. Scale of evaluation of different parameters towards infiltration ([4] [16]).

Class	Very high	High	High to Medium	Medium	Medium to low	low	Very low
Odds	10	8	6.5	5	3.5	2	1

Table 3. Matrix of weighting factors.

Parameters	Df	K	P	DD	OS	Vp	Cp
Df	1	3	3	5	7	3.160	0.459
K	1/3	1	3	4	5	1.817	0.264
P	1/3	1/3	1	3	4	1.055	0.153
OS	1/5	1/4	1/3	1	3	0.548	0.080
DD	1/7	1/5	1/4	1/3	1	0.297	0.043
Sum	2	4.78	7.58	13.33	20	6.877	1.000

K: alteration permeability, OS: land use, P: slope, DD: drainage density, Df: fracture density.

- Computation of the priority vector [C]. It consists in calculating the average of each line:

$$[C] = [A] \times \frac{1}{n} \tag{6}$$

- Multiplying each note of the matrix by the corresponding priority vector allows to deduce the global priority [D].

$$[D] = \sum Wn \times [C] \tag{7}$$

- Division of each global priority by its corresponding priority vector to find the rational priority [E].

$$[E] = \frac{[D]}{[C]} \tag{8}$$

- Calculation of the average of the rational priorities Ymax.

$$\text{Ymax} = \frac{[E]}{n} \tag{9}$$

- Calculation of the coherence index (IC).

$$IC = \frac{\text{Ymax} - n}{n - 1} \tag{10}$$

- Deduction of the consistency coefficient (RC).

$$Ia = \frac{Ic}{Ia} \tag{11}$$

where (Ia) is the random index. The values of (Ia) are recorded in **Table 4**.

2.3.5. Mapping of Potential Recharge Areas for the Yamoussoukro and Toumodi Aquifers

The computational method used in the GIS for overlaying the data is the operational approach of the single synthesis criterion of Roy in [22]. The principle is to sum the different layers according to their importance in groundwater recharge. The probability that the recharge in a zone is high is related to the values of the classes of parameters that intersect. In fact, it will depend on the index of the zones that favor recharge. Therefore, the calculation of the recharge index (Ir) is performed in GIS according to Equation (12).

$$Ir = 0.459[Df] + 0.264[K] + 0.153[P] + 0.080[OS] + 0.043[DD] \tag{12}$$

where Ir: is the sum of the weighted scores calculated for each pixel of the raster from the score of the five parameters.

The probability of recharge is related to the values of the classes of the crossed parameters. This depends on the index of recharge-promoting areas. Thus, [24] defined a method (Equation (13)) to help interpret the classes to which the

Table 4. Random index ([13]).

Number of variables	2	3	4	5	6	7	8	9	10	11
Ia	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

recharge class values relate.

$$\text{Irp} = \left(\text{P}\left(\text{Irmax} - \text{Irmin}\right)\right)/100 + \text{Irmin} \quad (13)$$

With Irp = recharge index in percentage; P = corresponds to a percentage class; Imax = maximum recharge index; Irmin = minimum recharge index.

Following this same logic, the Ir recharge index values were interpreted (Equation (14)).

Since the weighting coefficient is fixed, the minimum rating that a parameter can have is 1 and the maximum rating is 10. Substituting the different values of maximum and minimum rating, the equation becomes (Equation (14)):

$$\text{Ir} = \left(\text{P} \times 6.2\right)/100 + 1 \quad (14)$$

All the operations performed to arrive at the mapping of potential recharge areas are grouped in the conceptual data model (**Figure 2**).

3. Results and Discussion

3.1. Results

3.1.1. Fracture Map

The detailed lineament field includes all lineaments surveyed (in total, 1718)

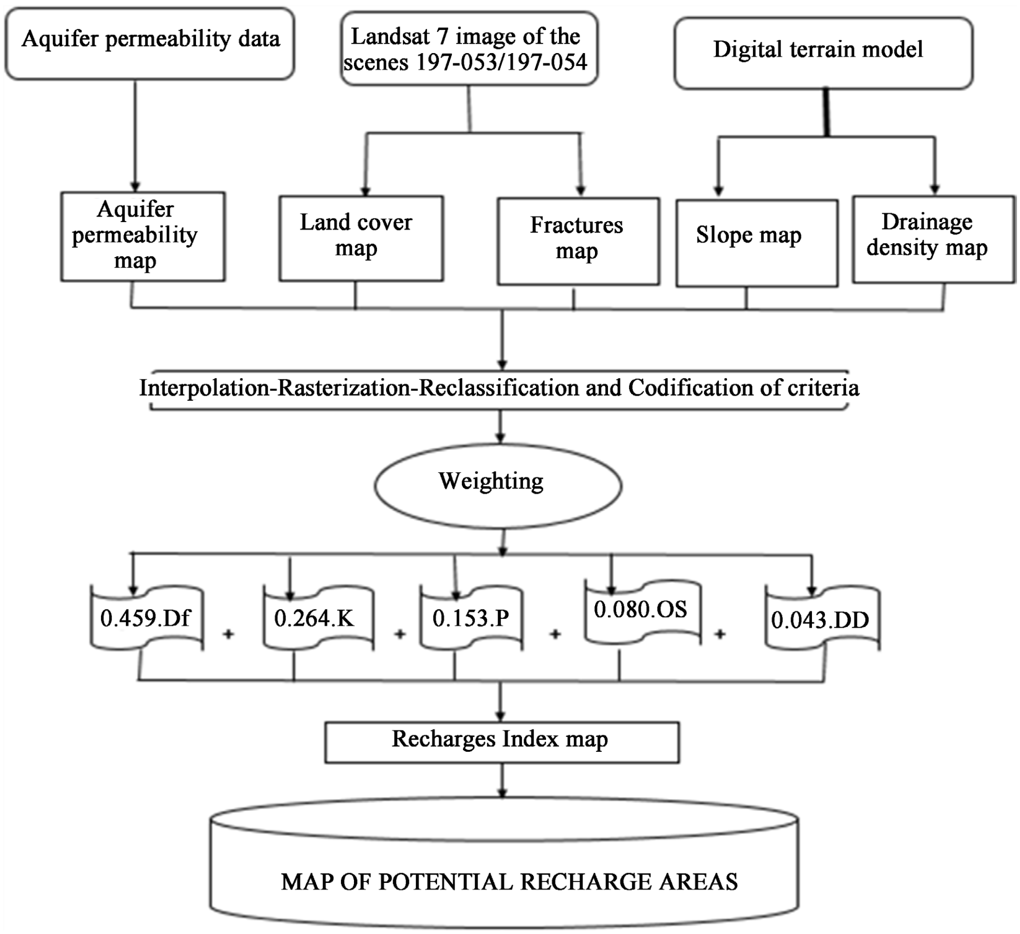

Figure 2. Conceptual data model.

during the manual extraction phase. The cumulative length of the lineaments is equal to 14.694 Km with an average of 2.6 Km over an area of 4.789 Km^2 (**Figure 3**).

L'exploitation de la carte détaillée des linéaments permet d'élaborer de nombreux fichiers thématiques à partir desquels sont définies et caractérisée la géométrie des aquifers souterrains (densité de fracturation, distribution des longueurs et des orientations des linéaments …).

3.1.2. Fracture Density Map

In order to better observe the spatial distribution of fracture density according to the number of fractures per unit area, the iso value map of distribution of this parameter was constructed (**Figure 4**).

The density is variable over the whole area. The fractures are therefore distributed differently over the entire study area. A global analysis of this map shows that the departments of Yamoussoukro and Toumodi are strongly fractured and therefore favourable to infiltration. Indeed, the medium, strong and very strong classes represent about 70.5% of the study area. On the other hand, areas of low fracture density occupy about 29.5% of the study area. Nevertheless, it should be noted that the zones of very high fracturing density occupy about 8.5% of this area and seem to be distributed over the whole area.

3.1.3. Hydraulic Conductivity Map

Data interpolation showed that almost the entire area is covered by hydraulic conductivities with values between 1.06×10^{-7} and 9.87×10^{-4} m/s (**Figure 5**).

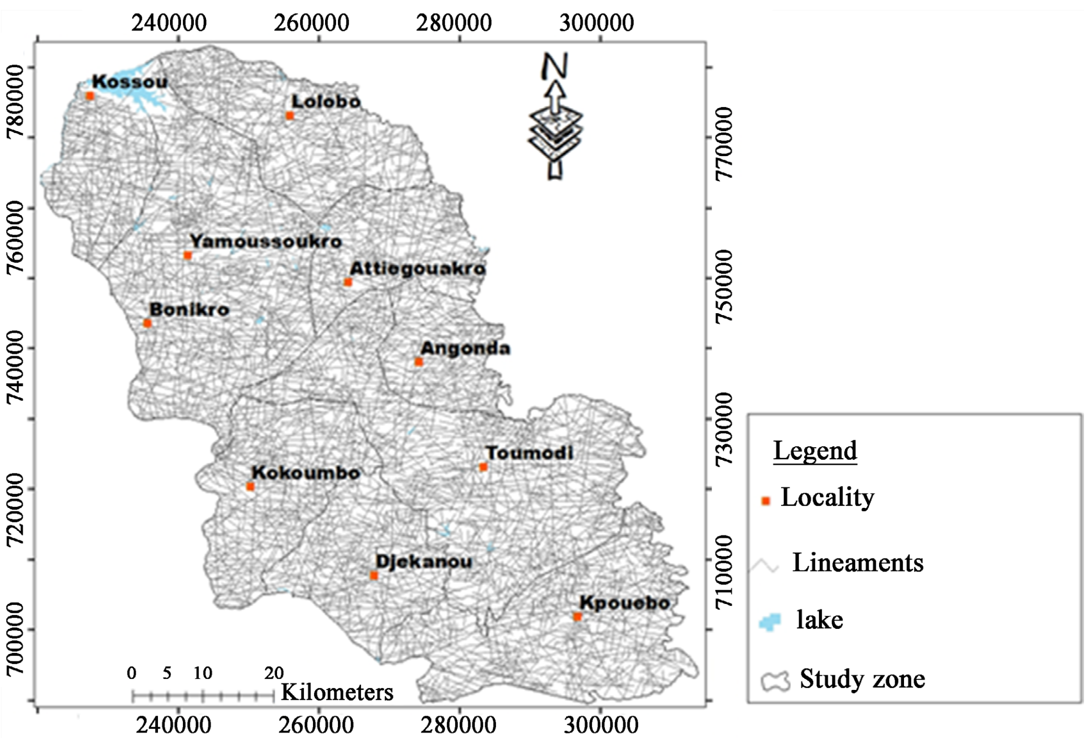

Figure 3. Map of the detailed lineament survey of the departments of Yamoussoukro and Toumodi.

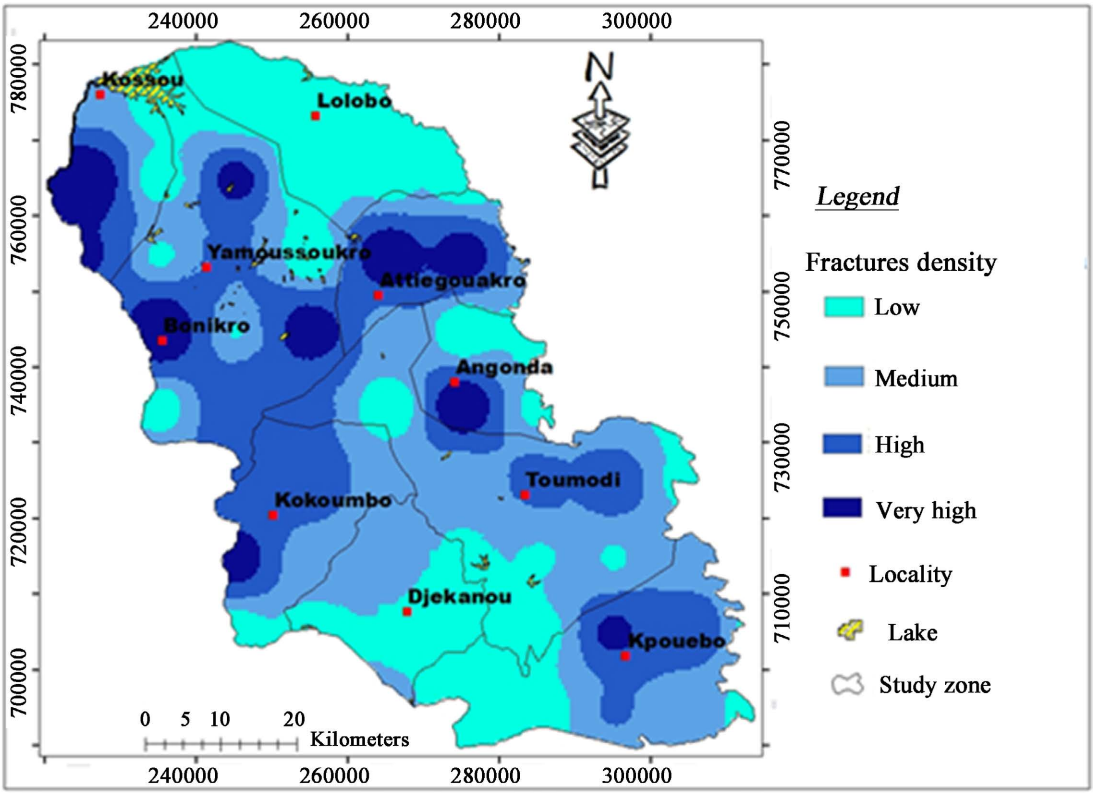

Figure 4. Fracture density map.

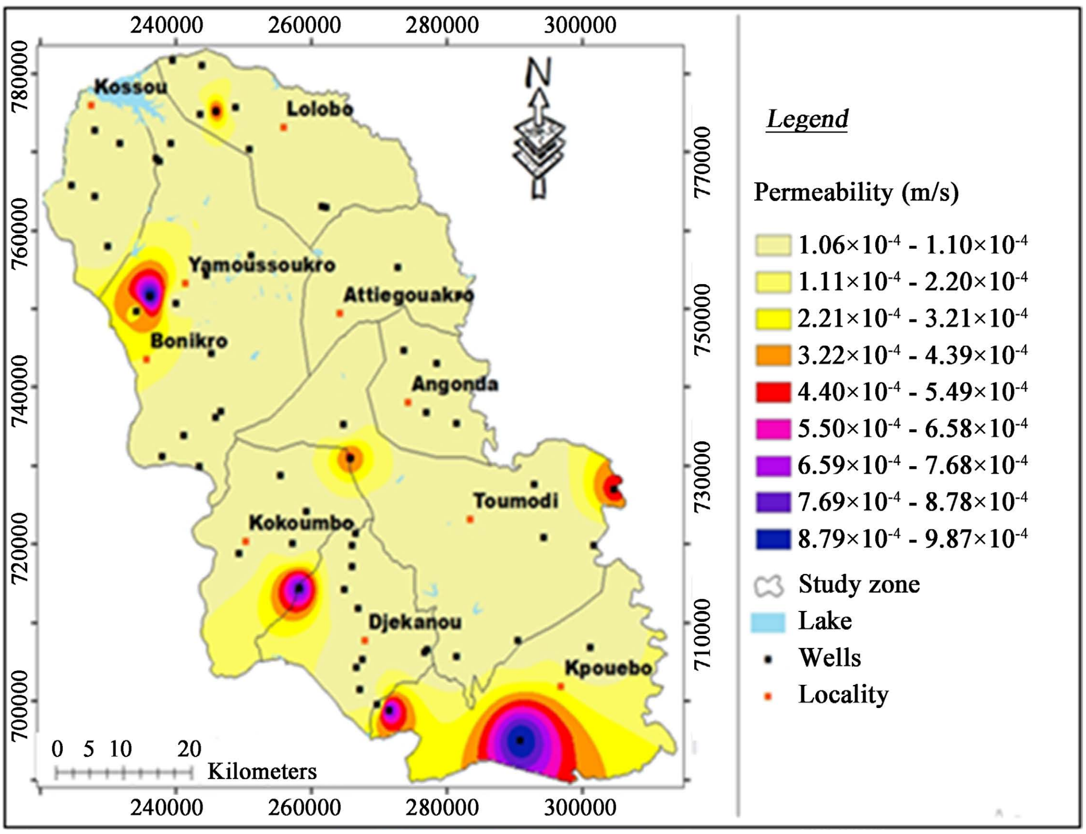

Figure 5. Map of hydraulic conductivity of the aquifer.

More than 80% of the area is covered by low conductivity. However, there are high values in the south in the Kpouebo sub-prefecture and a few sites scattered throughout the rest of the area.

3.1.4. Slope Map

The relief of the Yamoussoukro and Toumodi departments is relatively hilly. Structuring into four classes indicates that the spatial coverage is characterized by 33.5% low slope; 48.7% medium slope; 12.5% steep slope and 6.3% very steep slope (Figure 6). The steepest slopes are found in the sub-prefectures of Attiégouakro, Angonda and Kpouèbo due to the existence of mountain ranges.

3.1.5. Land Use Map

The spatial distribution map of land use shows six (6) classes (Figure 7). The class Habitats and Bare Soil represents 5.7% of the study area, the forest islands constitute 26.1%, the degraded forest represents 23.7%, in addition the crops and fallow land occupy 43.6% while water represents 0.9%.

3.1.6. Drainage Density Map

The drainage density map shows (4) four surface classes (Figure 8). The low density class is 22.1%, the medium density class is 35.3% of the study area, the high density class is 25.4% and the very high density class is 17.2% of the area.

Table 5 presents the results of the judgment audit.

With an RC equal to 5.8%, the prioritization matrix presented (Table 5) is

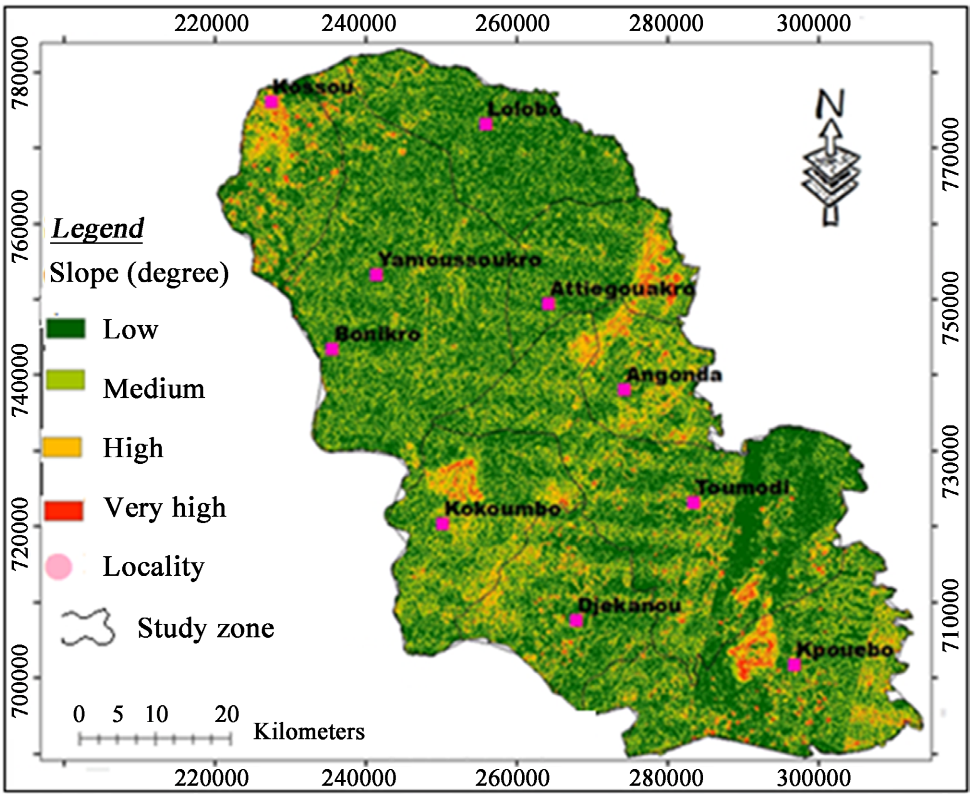

Figure 6. Slope map.

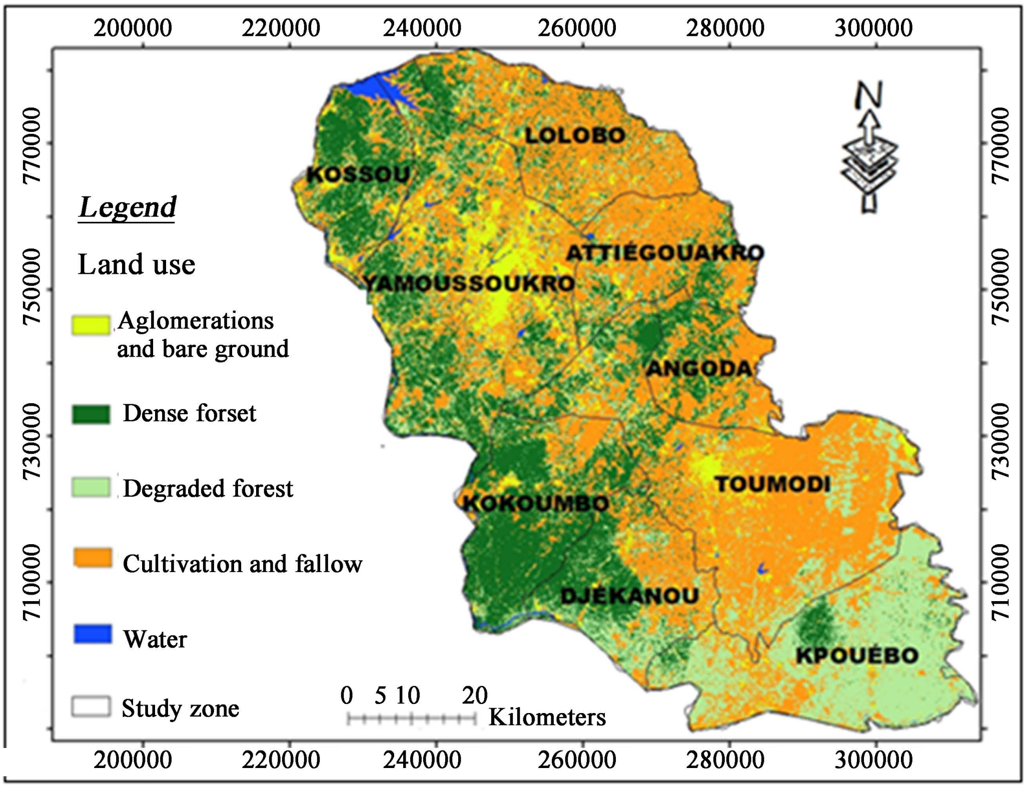

Figure 7. Land use map.

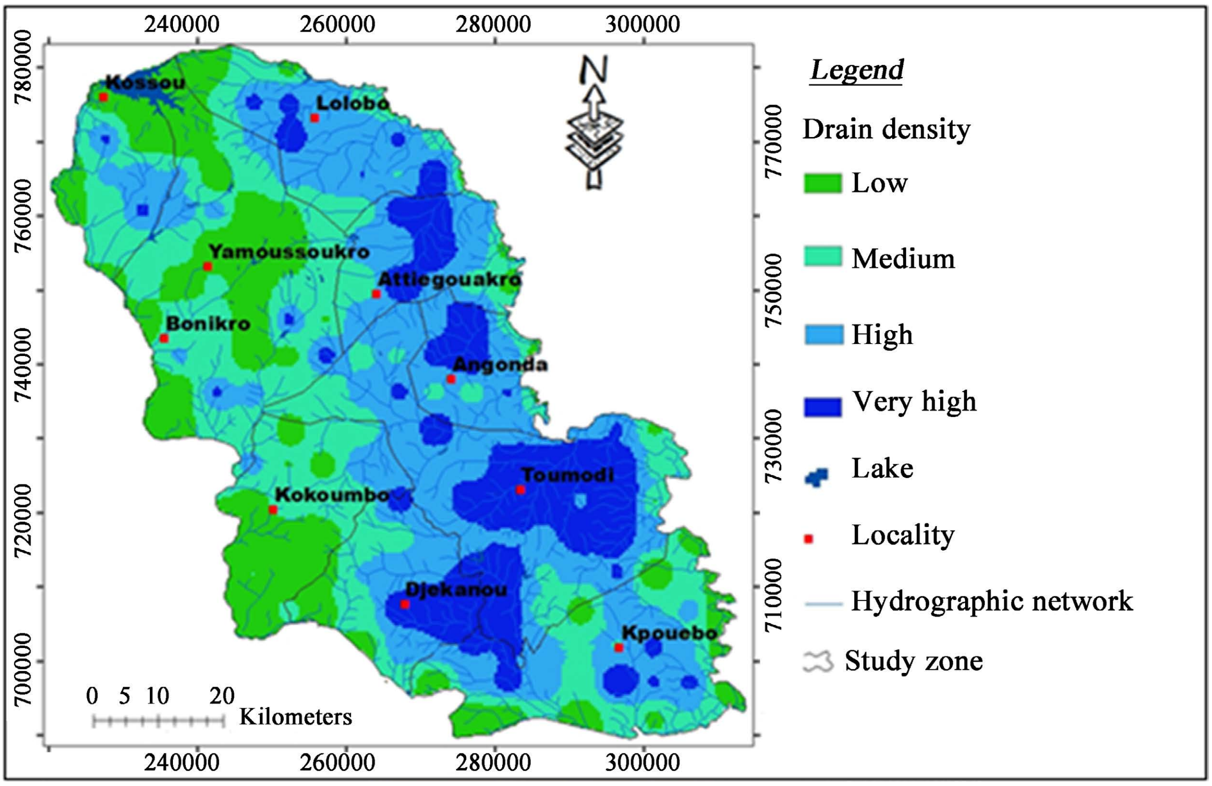

Figure 8. Drainage density map.

considered consistent. Therefore, the assigned judgments can be used for the determination of recharge areas in Yamoussoukro and Toumodi departments.

3.1.7. Recharge Index Map

Overlaying the different thematic maps obtained in a GIS made it possible to establish a map of groundwater recharge indices for the departments of Yamoussoukro and Toumodi (Figure 9), and from this map, the map of potential recharge areas.

The recharge index values range from 1 to 7.2. They highlight the areas where the degree of recharge is significant. Equation 17 yielded five recharge classes that range from "Poor" to "Excellent". The values of these indices are recorded in Table 6.

Table 5. Checking the consistency of judgments.

	Df	K	P	OS	DD	C	D	E	Ymax	IC	RC
Df	0.500	0.628	0.396	0.375	0.350	0.450	2.445	5.436			
K	0.165	0.209	0.396	0.300	0.250	0.264	1.443	5.467			
P	0.165	0.069	0.132	0.225	0.200	0.158	0.822	5.195	5.261	0.065	0.058
OS	0.100	0.052	0.044	0.075	0.150	0.084	0.424	5.038			
DD	0.070	0.042	0.033	0.025	0.050	0.044	0.227	5.169			

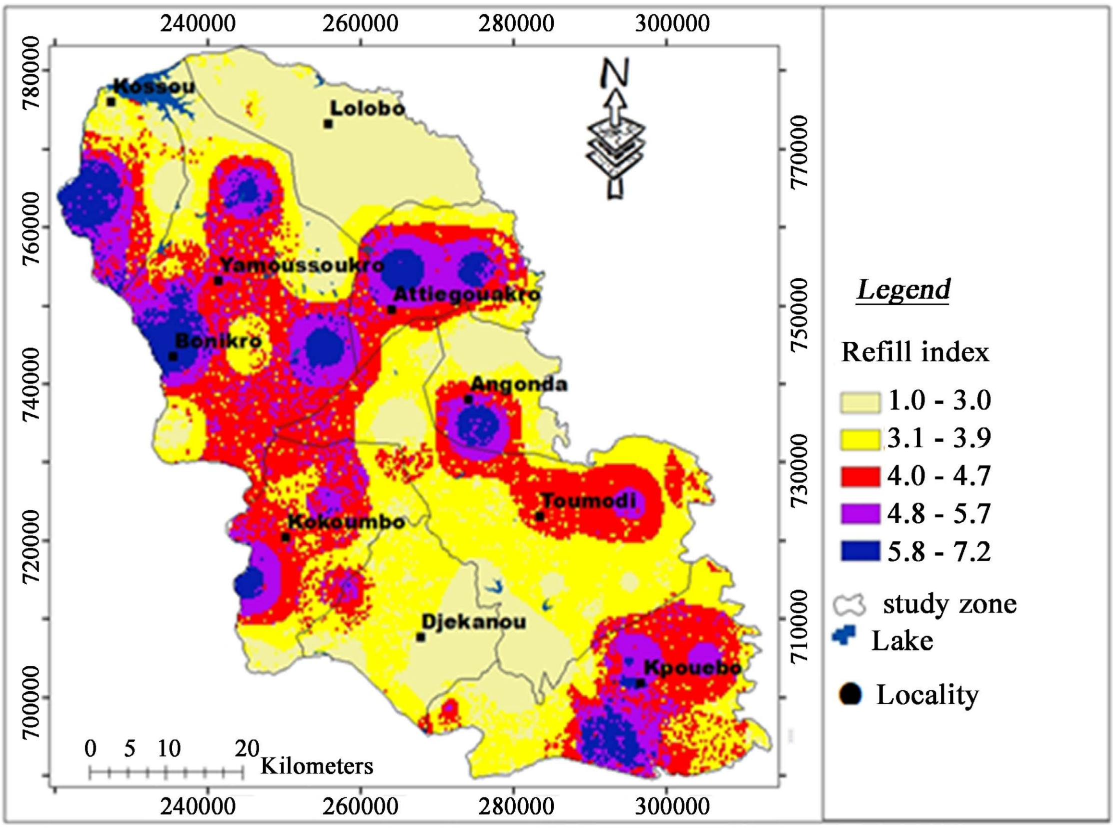

Figure 9. Recharge index map.

3.1.8. Map of Potential Recharge Areas for the Yamoussoukro and Toumodi Aquifers

The map of potential recharge areas is presented in Figure 10. Analysis of this map reveals five (5) classes (Bad, Poor, Good, Very good, Excellent) of potential groundwater recharge areas in the departments of Yamoussoukro and Toumodi. The "Poor" zones (26.2%) are concentrated in the sub-prefectures of Djékanou, Lolobo and Angonda. As for the "poor" class zones (30.69%), they are found throughout the zone. On the other hand, the "good", "very good" and "excellent" classes represent 43.11% of the entire study area. However, the "Excellent" class covers 5.46% and seems to be scattered throughout the area.

3.2. Discussion

Remote sensing and GIS offer the possibility of obtaining numerous data sources. These can be in the form of thematic maps that can help characterize potential

Table 6. Classes and indices of areas favorable to groundwater infiltration.

Classes of zone favorable to recharging	Normalized recharge indices (%)	Ir	Recharge degree
1.0 - 3.0	0 - 30	2.86	Bad
3.1 - 3.9	30 - 45	3.79	Poor
4.0 - 4.7	45 - 60	4.72	Good
4.8 - 5.7	60 - 75	5.65	Very good
5.8 - 7.2	75 - 100	7.2	Excellent

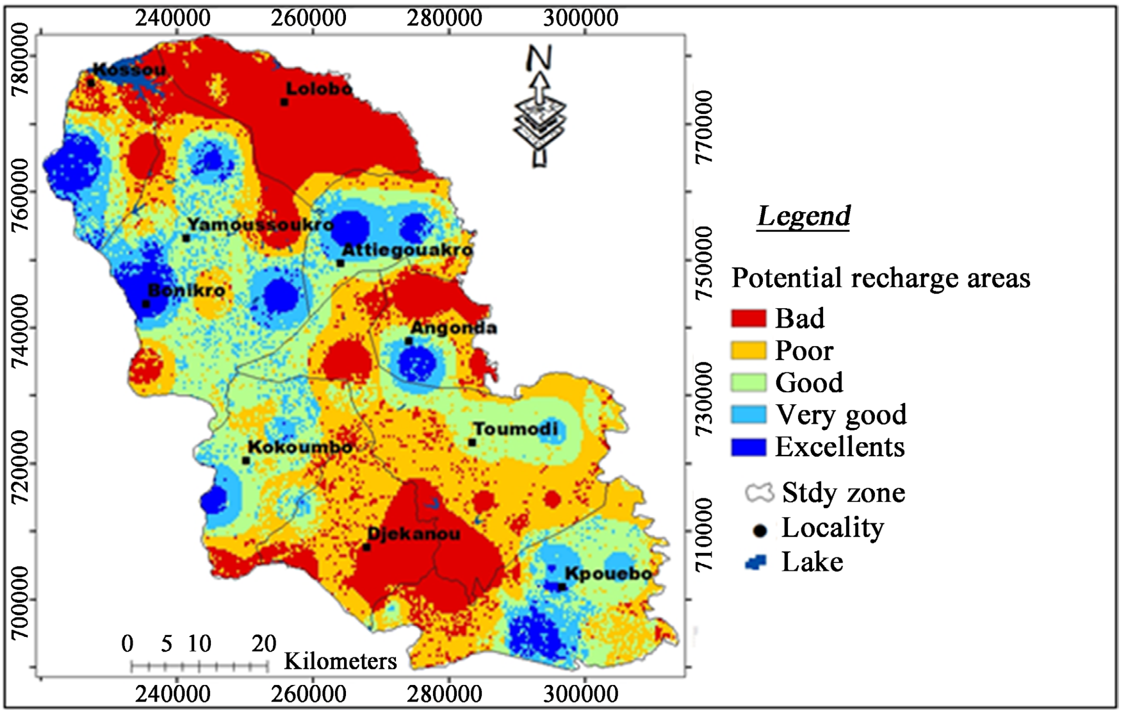

Figure 10. Map of potential recharge areas.

recharge areas over a large area. These include land use maps, slope maps, drainage network maps, lineament maps and alteration permeability maps. The multi-criteria analysis mapping approach was used in this study to determine the spatial variability of recharge from their integration into GIS. On the map of potential recharge areas, five classes of recharge degree (Bad, Poor, Good, Very Good and Excellent) were revealed. The high recharge areas are located in areas of strong fracturing. This result is in contradiction with the work of [25] who argue that highly fractured zones are the permeable places through which water percolates and whose fracture density mapping is very useful in identifying potential recharge zones in basement environments. However, despite the evolution that the use of lineaments in hydrogeology in the search for groundwater has undergone ([26] [27]), it remains much controversial in the literature [3]. Indeed, some hydrogeologists ([28] [29]) estimate that only 30% of the lineaments observed on an image are considered to be at the same location with the same orientation. Furthermore, in hydrogeology, it is well known that the denser the drainage network, the greater the runoff and therefore the less water available for aquifer recharge [30]. The degraded forest and the crops and fallow land that make up the bulk of the vegetation cover in the high recharge potential area have a high degree of weathering permeability with relatively low slopes. This can be explained by the fact that land use, which refers to a large number of parameters present on the ground surface, influences recharge. The most important hydrogeologically are vegetation cover and impervious surfaces. Impervious surfaces (buildings, roads, etc.) considerably delay the recharge process [31], while vegetation cover improves recharge, as it favors the confinement of water in the soil preventing direct evaporation.

The method adopted in this study seems reliable, as the application of it has shown good results with other authors, [16] in Algeria; [3] in Biankouma (Côte d'Ivoire) and [4] in Bonoua (Côte d'Ivoire). However, this method has limitations. Indeed, according to [26] cited by [4], the major difficulty lies in the definition of class boundaries and weights that are assigned to the different parameters entering the realization of the GIS. The choice of the class limits is most often made according to the operator's faculty of discernment and his sense of judgment.

4. Conclusion

The multi-criteria analysis method based on cartographic data provided by remote sensing and GIS allowed the delineation of potential recharge areas for the Yamoussoukro and Toumodi departments. The map of potential recharge areas provides important preliminary information on the spatial distribution of groundwater recharge. It is subdivided into five classes, with the cumulative high recharge classes covering 43.11% of the study area. The majority of the recharge areas are located in the sub-prefectures of Yamoussoukro, Kokoumbo Attiegouakro, Toumodi and Kpouèbo. The set of maps obtained from this study provides a general overview of the hydrogeological characteristics of the departments of

Yamoussoukro and Toumodi. It is therefore a decision-making tool for groundwater exploration. However, this method should be confirmed by in-situ measurements before it can be used in decision making. In addition to a more rigorous validation involving refined measurements at different points, the validation could also lead to the definition of new criteria or to the modification of the weightings assigned to them.

Acknowledgements

The authors would like to express their gratitude to the Directorate of Hydraulics of the Belier region, which agreed to provide us with some data related to the boreholes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Hounguevou, S.C.G., Tohozin, C.A.B., Soumah, M. and Mouhamadou, T.I. (2014) SIG et distribution spatiale des infrastructures hydrauliques dans la commune de Zè au Benin. *Afrique science*, **10**, 213-227.

[2] Kouassi, A.M., Coulibaly, D., Koffi, Y.B. and Biemi, J. (2013) Application de méthodes géophysiques à l'étude de la productivité des forages d'eau en milieu cristallin: Cas de la région de Toumodi (Centre de la Côte d'Ivoire). *International Journal of Innovation and Applied Studies*, **2**, 324-334.

[3] Sekouba, O., Fernand, K.K., Mahamane, B.S., Gabriel, E.A., Germain, M.A., Alexis, K.K. and René, T. (2014) Estimation et validation de la profondeur des nappes du bassin du N'zo, en Côte d'Ivoire, par le modèle WTR. *Physio-Géo*, **8**, 1-25. https://doi.org/10.4000/physio-geo.3752

[4] Ake, G.E., Kouame, K.J., Koffi, A.B. and Jourda, J.P. (2018) Cartographie des zones potentielles de recharge de la nappe de Bonoua (sud-est de la Côte d'Ivoire). *Journal of Water Science*, **31**, 129-144. https://doi.org/10.7202/1051696ar

[5] Ardana P.D.H., Sumarda, G., Sudika I.G.M. and Astariani, N.K. (2020) Comparison of Groundwater Recharge Quantification Method. *Solid State Technology*, **63**, 5088-5102.

[6] Rodier, J.A. and Ribstein, P. (1988) Estimation des caractéristiques de la crue décennale pour les petits bassins versants du Sahel couvrant de 1 à 10 km2. Orstom, Montpellier, 133 p.

[7] Milville, F. and Thierry, D. (1990) Evaluation de la recharge naturelle des aquifères en climat Soudano-Sahélien par modélisation hydrologique globale: Application a dix sites au Burkina Faso. *Journal des Sciences Hydrologiques*, **35**, 37. https://doi.org/10.1080/02626669009492403

[8] Abdelhamid, H., Boudoukha, A., Fatima, Z.H. and Rachid, N. (2010) Cartographie de la recharge potentielle des aquifères en zone aride: Cas de la plaine d'El Outaya, Biskra, Algérie. *EuroJournals*, **45**, 1-13.

[9] Sékouba, O., Adon G.C., Akpa, Y.L., Saley M.B., Koffi, K.K.F. and Therrien, R. (2017) Identification des zones potentielles de recharge des aquifères fracturés du bassin

versant du N'zo (Ouest de La Côte d'Ivoire): Contribution du SIG et de la Télédétection. *European Scientific Journal*, **13**, 1857-7881. https://doi.org/10.19044/esj.2017.v13n36p192

[10] Ehoussou, K.M., Kouassi, A.M. and Kamagaté, B. (2019) Caractérisation hydrogéochimique des aquifères fissurés de la région du bélier, centre de la Côte d'Ivoire. *Revue Ivoirienne des Sciences et Technologies*, **33**, 137-160.

[11] Yacé, I. (1976) Le volcanisme éburnéen dans les parties centrale et méridionale de la chaîne précambrienne de FETTEKRO en Côte d'Ivoire. Thèse de Doctorat ès Sciences Naturelles, Université de Cocody-Abidjan, Côte d'Ivoire, 373 p.

[12] Daouda, Y.B. (1998) Litho stratigraphie et pétrographie des formations birimiennes de Toumodi-Fêtêkro (Côte d'Ivoire). Implication pour l'évolution crustale du paléoprotérozoïque du craton ouest-africain. Thèse de Doctorat de l'Université d'Orléans, Orléans, 190 p.

[13] Saaty, T.L. (1980) The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York, 19 p.

[14] Edoukou, J.D., Kouame, J.K., Deh, K.S., Abinan, A.T. and Jourda, J.P. (2016) Contribution of the Sensitivity Analysis in Groundwater Vulnerability Assessing Using the Drastic Method: Application to Groundwater in Dabou Region (Southern of Côte d'Ivoire). *Journal of Environment Protection*, **7**, 129-143. https://doi.org/10.4236/jep.2016.71012

[15] Saley, M.B. (2003) Système d'informations hydrogéologiques à référence spatiale, discontinuités pseudo-images et cartographies thématiques des ressources en eau de la région semi-montagneuse de Man (Ouest de la Côte d'Ivoire). Thèse de doctorat, Univ. Cocody, Côte d'Ivoire, 195 p.

[16] Haouchine, A., Boudoukha, A., Fatima, Z.H. and Rachid, N. (2010) Cartographie de la recharge potentielle des aquifères en zone aride. *Euro Journals*, **45**, 1-13.

[17] Koudou, A., Adiaffi, B., Assoma, T.V., Sombo, A., Amani, E.M.E. and Biemi, J. (2013) Conception d'un outil d'aide à la décision pour la prospection des eaux souterraines en zone de socle du sud-est de la Côte d'Ivoire. *Geo Eco Trop Journal*, **37**, 211-226.

[18] McIver, D.K. and Friedl, M.A. (2002) Using Prior Probabilities in Decision-Tree Classification of Remotely Sensed Data. *Remote Sensing of Environment*, **81**, 253-261. https://doi.org/10.1016/S0034-4257(02)00003-2

[19] Gupta, R. and Sharma, L.K. (2020) Efficacy of Spatial Land Change Modeler as a Forecasting Indicator for Anthropogenic Change Dynamics over Five Decades: A Case Study of Shoolpaneshwar Wildlife Sanctuary, Gujarat, India. *Ecological Indicators*, **112**, 106-117. https://doi.org/10.1016/j.ecolind.2020.106171

[20] Mabillot, A. (1980) Le forage d'Eau; Guide pratique. Edition Offset à Saint Etienne (Loire). D.L., 3-1980, (France), 237 p.

[21] Youan Ta, M., Lasm, T., Jourda, J.P., Saley, M.B., Adja, M.G., Kouamé, K. and Biemi, J. (2011) Cartographie des eaux souterraines en milieu fissuré par analyse multicritère Cas de Bondoukou (Côte-d'Ivoire). *Revue Internationale de géomatique*, **21**, 34-38. https://doi.org/10.3166/rig.21.43-71

[22] Anoh, K.A. (2014) Apport d'un SIG Et du modèle agro-hydrologique SWAT Dans la gestion durable des ressources en eaux du bassin Versant du lac de Taabo (centre de la Cote d'Ivoire). Thèse de doctorat de l'Université de Cocody, Abidjan, 217 p.

[23] Saaty, T.L. (1984) Décider face à la complexité, une approche analytique multicritère d'aide à la decision. Entreprise moderne d'édition, Paris, 231 p.

[24] Aller, L., Bernett, T., Lehr, J.H., Petty, R.J. and Hackett, G. (1987) DRASTIC: A

Standardised System for Evaluation Groundwater Pollution Potential Using Hydrogeologic Settings. EPA, Ada, Oklahoma, 622 p.
https://doi.org/10.1021/bk-1986-0315.ch008

[25] Sener, E., Davraz, A. and Ozcelik, M. (2005) An Integration of GIS and Remote Sensing in Groundwater Investigations: A Case Study in Burdur, Turkey. *Hydrogeology Journal*, **13**, 826-834. https://doi.org/10.1007/s10040-004-0378-5

[26] Jourda, J.P.R., Saley, M.B., Djagoua, E.V., Kouamé, K.J., Biemi, J. and Razack, M. (2006) Utilisation des données ETM+ de Landsat et d'un SIG pour l'évaluation du potentiel en eau souterraine dans le milieu fissuré précambrien de la région de Korhogo (Nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Télédétection*, **4**, 339-357.

[27] Youan Ta, M. (2008) Contribution de la télédétection et des systèmes d'information géographiques à la prospection hydrogéologique du socle précambrien d'Afrique de l'Ouest: Cas de la région de Bondoukou Nord Est de la Côte d'Ivoire. Thèse Unique de Doctorat, Université de Cocody (Côte d'Ivoire), Cocody, 236 p.

[28] Podwysocki, M.H. (1979) An Analysis of Fracture Trace Patterns in Areas of Flat-Lying Sedimentary Rocks for the Detection of Buried Geologic Structure (abs). *Journal of Hydrology*, **366**, 35-45.

[29] Mabee, S.B., Hardcastle, K.C. and Wise, D.U. (1990) Correlation of Lineaments and Bedrock Fracture Fabric: Implications for Regional Fractured-Bedrock Aquifer Studies, Preliminary Results from Georgetown, Maine. *Ground Water Management*, **3**, 283-297.

[30] Hsin-Fu, Y., Cheng-Haw, L., Kuo-Chin, H. and Po-Sun C. (2009) GIS for Assessment of Groundwater Recharge Potential Zone. *Environmental Geology*, **58**, 185-195.
https://doi.org/10.1007/s00254-008-1504-9

[31] Bou Kheir, R., Shaban, A., Girard, M.-C., Khawlie, M. and Abdallah, C. (2003) Caractérisation morpho-pédologique des zones karstiques du Liban sensibilité des sols a l'érosion hydrique. *Science et changements planétaires/Sécheresse*, **14**, 247-255.