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Research Article

Mapping and Assessment of Groundwater Recharge Zones in the Bongouanou Aquifer (Moronou Region)

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Abstract

Ensuring access to water and sanitation for all on the one hand, and ensuring sustainable and equitable management of water resources on the other hand, is one of the objectives for sustainable development. In the department of Bongouanou, most of the population's drinking water is supplied by groundwater contained in granite and schist basement aquifers This study delineates potential groundwater recharge zones in the Bongouanou department through an integrated geospatial and multi-criteria decision-making (MCDM) approach. The methodology combines remote sensing and GIS-based multi-criteria analysis with hydrochemical validation. Satellite imagery, base maps, and hydrochemical data were used to generate thematic layers representing the main factors controlling groundwater recharge, including slope, drainage density, lithology, fracture density, soil type, rainfall, and land use/land cover. These layers were weighted and overlaid to produce a groundwater recharge potential map. The results show that high recharge potential zones cover approximately 45% of the study area, while medium and low-to-moderate potential zones account for 33% and 21%, respectively. The reliability of the generated recharge potential map was validated using chloride concentration data. The development of a large-scale hydrogeological map of potential recharge zones for the fractured aquifers of Bongouanou, based on the integration of multiple datasets and methods, highlights the value of combining diverse sources of information.

Keywords

Map, Recharge Zones, Fracturing Density, Aquifer

1. Introduction

The effect of climate change on groundwater resources is being felt worldwide. Ensuring access to water and sanitation for all on the one hand, and ensuring sustainable and equitable management of water resources on the other hand, is one of the objectives for sustainable development [1] (Okoundé et al, 2022). Thus, the development of replaceable water resources has become an imminent task in the plan for efficient use of water resources, since surface water development is reaching

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its limits. Groundwater has therefore become the most prized resource in semi-arid regions [2]. Groundwater resources comprise 99% of global freshwater and are the slowest to renew [3]. Recent studies estimate total groundwater storage at about 22.6 million km^3, with residence times from a few months to thousands of years [4]. And potentials consumers include India (28%), the U.S. (13%), China (10%), Pakistan (7%), and Iran (6%) [5]. The real problem is that groundwater exploitation exceeded its recharge, leading to significant depletion in many places [6]. The depleting trend is expected to continue, as water and food requirements are expected to increase by 55% and 60%, respectively, by 2050 [7]. Some studies demonstrated that appropriate recharge can effectively elevate groundwater levels and improve groundwater quality to some extent [8] and [9]. Despite ongoing scientific efforts, estimating groundwater recharge remains a notoriously difficult task for hydrogeologists [10]. Basement aquifers (crystalline and metamorphic rocks) occupy a very large surface area both globally and in West Africa. Their groundwater resources play a significant role in the socio-economic development of the countries concerned as observed by [11] in semi-arid fractured karst systems. To assess the focused recharge (water infiltration), many methods including methods based on monitoring groundwater fluctuations, hydrological modeling can be found in the literature, on the use of environmental tracers [6, 12, 13].

In Côte d'Ivoire, particularly in the department of Bongouanou, most of the population's drinking water is supplied by groundwater contained in granite and schist basement aquifers [14]. Sustainable management of these water resources requires knowledge and assessment of fundamental processes such as recharge. Indeed, recharge refers to the volume of infiltrated water that reaches the water table and promotes its replenishment [7]. Knowledge of recharge is essential for the sustainable management of water resources, as it enables us to identify areas of an aquifer that are vulnerable to contamination, to determine its exploitation potential and to assess the sustainability of the resource [10].

The aim of this study is to map potential recharge zones for fractured aquifers using spatial techniques, in particular remote sensing and GIS. The methodology is essentially based on the description, classification and integration of the main factors influencing recharge, such as land use and type, geology, fractures, slopes and the hydrographic network.

2. Material and Methods

2.1. Study Area

Located in eastern Côte d'Ivoire, Bongouanou is part of the Moronou region. It lies between longitudes 3°44'W and 4°47'W, and latitudes 6°9'N and 6°59'N, and covers an area of 6,670 km^2. The department has four sub-prefectures: Bongouanou, Ande, N'guessankro and Assie Koumassi. The population is estimated at around 159,928 [14]. Bongouanou is bordered to the North by Bocanda and Daoukro, to the East by Abengourou, to the South by Tiassalé, Agboville and Adzopé, to the West by Dimbrokro and Toumodi [14]. Bongouanou is a significant administrative and economic center in the Comoe region of Côte d'Ivoire. The city plays a vital role in the agricultural sector, particularly in the production of cocoa and coffee, which are key export commodities for the nation. Historically, the region has been a hub for trade and cultural exchange, influenced by various ethnic groups and their traditions info@wisdomlib.org.

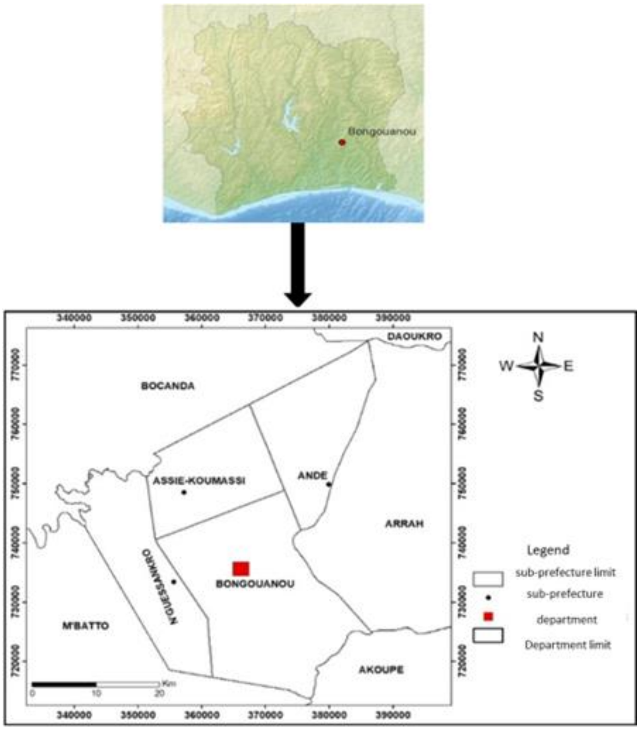

Figure 1. Geographical location of Bongouanou department.

2.2. Geological and Hydrogeological Context

According to [15] Bongouanou County is underlain by the basement of the old Precambrian shield. It is made up of Paleoproterozoic formations whose lithology consists of metasiltites, metaarenites, granitic intrusions and their alteration products (notably lateritic cuirasses) [10]. Small Quaternary formations are found along the banks of the N'Zi and Comoe rivers, consisting of leached sands. The bauxitic cuirasses extend over considerable topography, up to 600 m in altitude. The other formations are relatively flat, with an average altitude of around 120 m [16]. Volcano-sedimentary schists and granites are also found here. The shales generally have greater alteration thicknesses (loose alterites) than the granites, sometimes reaching 100 m [17].

Hydrogeologically, the basement aquifers in the Bongouanou region are not highly productive. Statistical results from [17] reveal that shales, which cover more than 80% of the area, are more productive than granites. Generally speaking, boreholes located on slopes and valley bottoms in this region have higher flow rates than those on plateaus [10, 17]. We also note that it is only the first 30 meters of the fissured horizon, just below the base of the loose alterites, that are the most permeable, and therefore the most productive ; beyond this limit, permeability decreases significantly with depth [15]. Thus, in this region, from the ground surface, the most productive optimal depths for groundwater are between 40 and 70 m for granites and 40 to 80 m for shales [16].

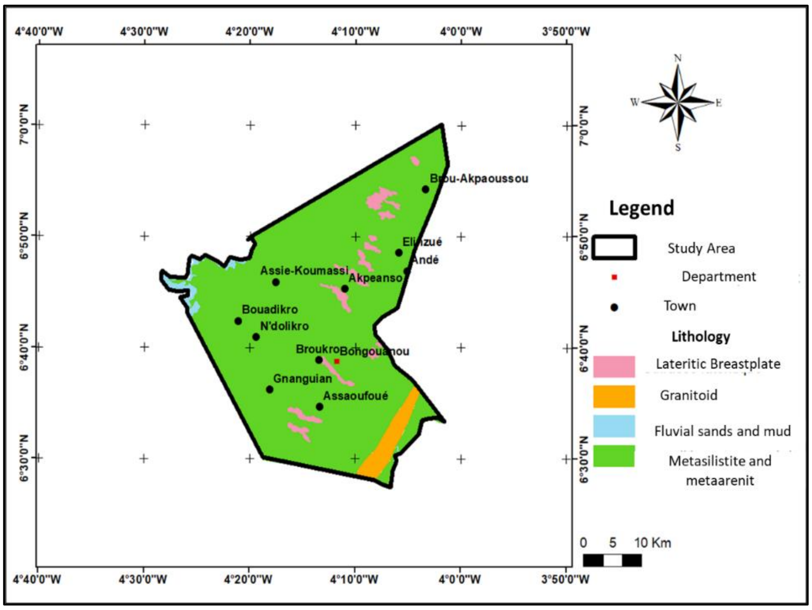

Figure 2. Geological map of Bongouanou department.

2.3. Study Data

Two main types of data were used for this study: satellite images and field data.

2.3.1. Image Data

The satellite images used to produce the various maps were downloaded from https://earthexplorer.usgs.gov. The images used come from the landsat landsat 8 satellite equipped with the OLI sensor. They were used to produce the fracturing map of the study area and the 2018 land use map. All these images correspond to the dry (February andMarch) and rainy (July) period and cover scene 196/055. They were chosen according to their availability.

2.3.2. Field Data

The campaign field was conducted from July 05 to July 07, 2019 in the department of Bongouanou to sample groundwater and measure certain physicochemical parameters. The parameters measured included cations (Na, K, Ca, and Mg) and anions (NO_3, SO_4, Cl), as well as physicochemical parameters such as pH, electrical conductivity, and temperature. These physicochemical parameters were measured in situ using a HANNA HI 991301 multiparameter with an accuracy of +/- 0.1, +/- 2%, and +/- 0.5 ℃, while the ions were analyzed in the laboratory. Water samples were collected from boreholes equipped with taps and from village pumps for sites without boreholes.

2.4. Study Material

To produce the various maps, ENVI 5.1 (Environment for visualising image) and ARCGIS 10.5 were used:

1) ENVI 5.1 software was used for image pre-processing and classification ;
2) ARCGIS software was used for mapping.

EXCEL from Microsoft Office 2013 was used for the statistical processing of field and laboratory data and for the construction of graphs.

2.5. Methods

2.5.1. Remote Sensing Technology

The land use maps were produced using supervised classification based on a maximum likelihood algorithm. This method consists in classifying pixels according to their similarity to geographical reference objects previously determined on the image (training plot or ROI).

Classification validation was carried out using the confusion matrix and Kappa index as statistical tools.

For a better interpretation of land cover features, three bands were selected: 5 (NIR), 6 (SWIR 1) and 7 (SWIR 2). The classifications were based on the composite RGB images.

Overall, the field missions and the composite image enabled us to retain 5 classes (type 1 degraded forest, type 2 graded forest, crop and fallow land, water reservoir, savannah and bare soil/habitats).

A series of post-classification treatments (generalization, homogenization and majority filtering) is applied beforehand to improve cartographic rendering.

2.5.2. Development of the Fracturing Map

Lineaments play a critical role in groundwater investigations within basement terrains, as they often reflect zones of enhanced secondary permeability. According to [18], a lineament is defined as any linear or curvilinear feature whose interpretation has geological significance. In this study, Landsat 8 OLI imagery acquired on 1 January 2018 was used for lineament mapping. The imagery was processed using ENVI Classic software to generate the lineament map. A spectral database was first constructed from the Landsat OLI bands, followed by the application of Principal Component Analysis (PCA) to identify the most informative spectral component(s). PCA reduces data dimensionality by compressing the information contained in the original bands into a limited number of uncorrelated principal components. The resulting components are independent and orthogonal, in contrast to the original raw data. Analysis of the PCA correlation matrix indicated that band 2 contains the highest information content. Consequently, band 2 was selected as the sole input for lineament extraction in the Bongouanou Department.

2.5.3. Application of Filters and Manual Extraction of Lineaments

Image filtering techniques were applied to enhance lineaments that are not readily visible on raw or neo-channel images. In Earth science applications, directional filters are commonly used to detect fractures characterized by high spatial frequencies [19]. In this study, 7 × 7 Sobel directional filters (Table 1) were applied. The Sobel filter, which is asymmetrical, was implemented on band 2 derived from the PCA of Landsat 8 OLI imagery. These filters enhance lithological and structural discontinuities oriented along the N–S, NE–SW, NW–SE, and E–W directions, thereby facilitating lineament extraction [20]. Structural discontinuities corresponding to lineaments were manually extracted through on-screen visual interpretation. Linearity detection involved identifying the two extremities of each linear segment; for curved features, only the rectilinear portions were digitized. The extracted lineaments represent linear geological features, including topographic breaks, drainage alignments, and lithological or structural trends observed in the field. Most lineaments were digitized directly on the PCA neo-channel (PC2) [18]. The resulting lineament map represents a synthesis of all identified structural discontinuities.

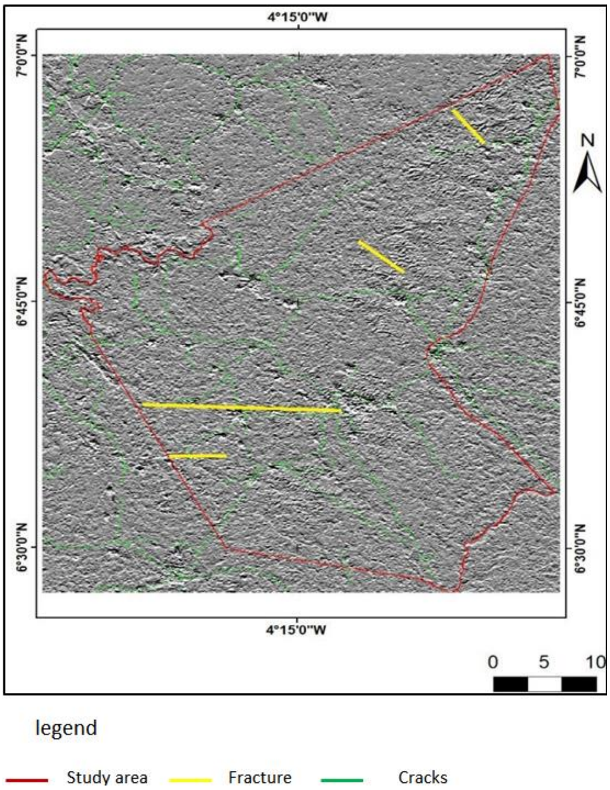

Figure 3. Filtered image with lineament extraction.

2.5.4. Lineament Validation and Lineament Map Reliability

The evaluation and validation of lineaments extracted from digital image processing constitute a critical step in assessing the reliability of the applied methodology [18]. In the present study, comprehensive field verification of all extracted lineaments was not feasible due to logistical and financial constraints. To address this limitation, the extracted lineament map was compared with the hydrographic network, whose spatial patterns and anomalies provide indirect evidence supporting the tectonic origin of the lineaments, despite potential masking by vegetation cover and weathered materials. The strong spatial correspondence between most lineaments and the hydrographic network, combined with their clear distinction from the road network, confirms the accuracy and authenticity of the extracted features. Consequently, the validated lineaments are interpreted as geological fractures, and the validation phase substantiates the robustness and credibility of the lineament extraction process.

2.5.5. Factors Controlling Aquifer Recharge

The hydrogeological interpretation of the recharge control factors in this study is recorded in Table 1:

Table 1. Description of the hydrogeological properties of the various factors.

Factors	Hydrogeological properties influencing recharge potential
Lithology	Involved in the recharge process of fractured aquifers, it determines the compactness and state of alteration of the rock, and provides important information on the infiltration capacity of geological formations.
Fractures	Gives an indication of the degree of fracturing in the rock. Fracture density mapping is therefore very useful in identifying potential recharge zones in fractured basement environments.
Drainage	In hydrogeology, it is well known that the denser the drainage network, the greater the runoff and therefore the lower the recharge.
Landcover	Vegetation cover improves recharge by confining water in the soil, preventing evaporation.
Floor type/ Floor thickness	Water infiltration through deep underground layers depends on soil type and thickness. When clay content is high, soils are better at retaining surface water than at infiltrating it. If these soils are rich in sandy elements, the percolation time is controlled by their thickness.
Slopes	Slopes are inversely proportional to aquifer recharge potential. Steep slopes accelerate water runoff.

2.5.6. Spatial Modeling of Recharge Zones Using Multi-criteria Analysis

The factors contributing to the delineation of groundwater recharge potential zones were analyzed through the generation of thematic maps. Initially, each factor was classified based on its hydrogeological significance and infiltration capacity, and a weight ranging from 1 to 10 was assigned to each class. Subsequently, a relative coefficient was attributed to each factor according to its level of influence on groundwater recharge, acknowledging that the contributing factors do not exert equal control on the recharge process. Figure 4 presents a conceptual diagram illustrating the interactions among factors within the hydrosystem [21, 22]. Two types of relationships are distinguished: major interactions, represented by solid lines, and minor interactions, indicated by dashed lines. When a major interaction exists between two factors, the dominant factor is assigned a coefficient of 1, whereas a coefficient of 0.5 is assigned in the case of a minor interaction. The cumulative coefficients derived from these interactions were then used to quantify the relative importance of each factor.

1) lithology: three (3) major relationships and one (1) minor relationship ($3\times1 + 1\times0.5$), giving 3.5;
2) lineament: two (2) major relationships (2×1), giving 2 ;
3) soil type: one major relationship (1×1) and three (3) minor relationships (3×0.5), giving 2.5 ;
4) landcover: one (1) major relationship (1×1) and three (3) minor relationships (3×0.5), giving 2.5;
5) Inclination: one (1) major relationship (1×1) and one (1) minor relationship (1×0.5), giving 1.5;
6) drainage: one (1) major relationship (1×1) and two (2) minor relationships (2×0.5), giving 2.

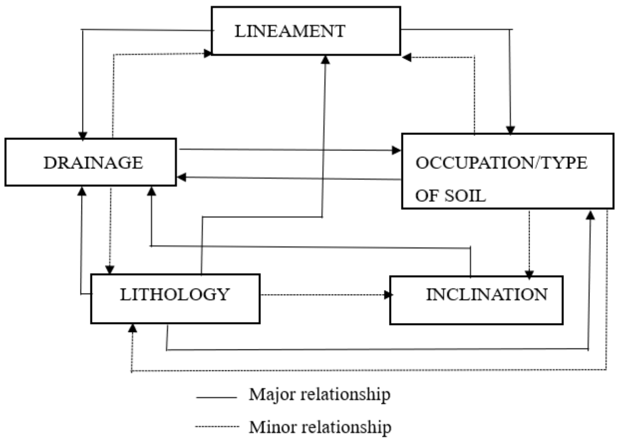

Figure 4. Diagram of interactions between factors [19].

3. Results

3.1. Drainage System

The drainage density map (Figure 5) delineates five classes ranging from very low to very high drainage density, reflecting the spatial variability of surface water drainage conditions in the Bongouanou Department. Areas characterized by high to very high drainage density occupy approximately 29.31% of the study area, whereas zones with low to very low drainage density account for 44.72%. Medium drainage density areas represent 25.96% of the total area. This classification provides insight into the hydrological behavior of the watershed and its potential influence on groundwater recharge processes.

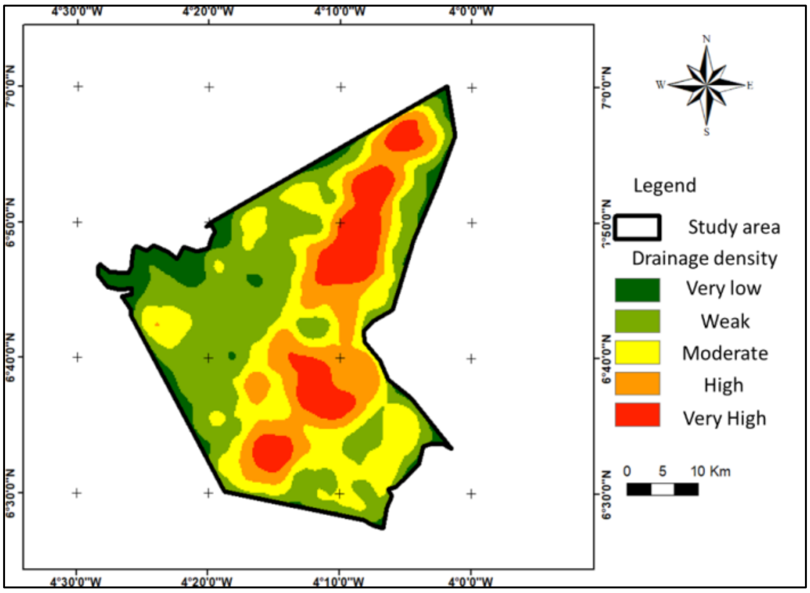

Figure 5. *Drainage density map.*

3.2. Fracturing Density

Analysis of the fracture map (Figure 6a) highlights the presence and spatial distribution of fractures across the study area. The corresponding fracture density map (Figure 6b) is classified into five density classes. Zones characterized by low fracture density cover approximately 32.5% of the study area, while medium-density zones account for 33.68%. Highly fractured zones represent 33.81% of the total surface area, indicating a relatively homogeneous distribution of fracture density across the region.

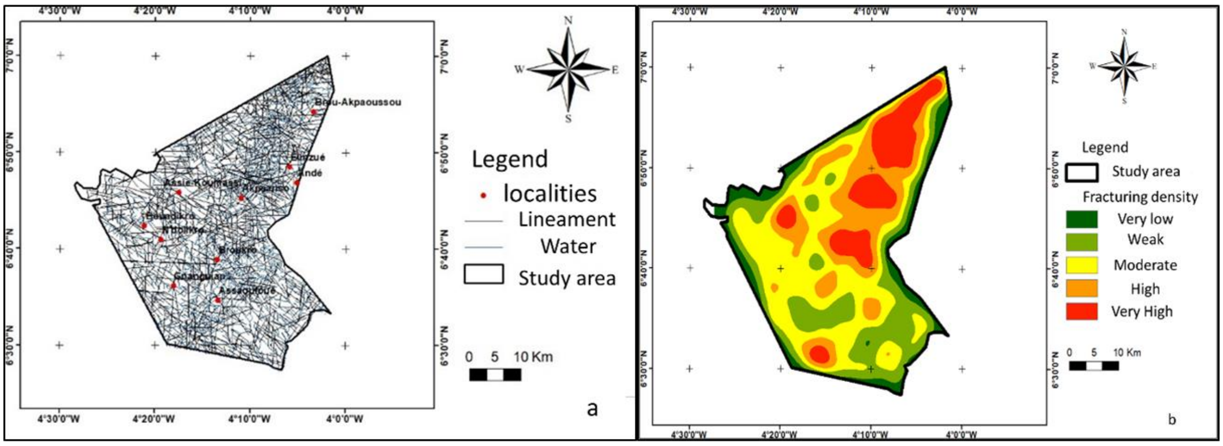

Figure 6. *Fracturing density map.*

3.3. Inclination Map

Figure 7 presents the slope (inclination) map of the Bongouanou department. The map is divided into five classes representing the topographic variability of the area. Observations indicate that low to very low slopes cover approximately 80.38% of the study area, medium slopes account for 55%, and steep slopes represent 7.07% of the territory. This classification provides a basis for assessing the influence of topography on surface runoff and groundwater recharge potential.

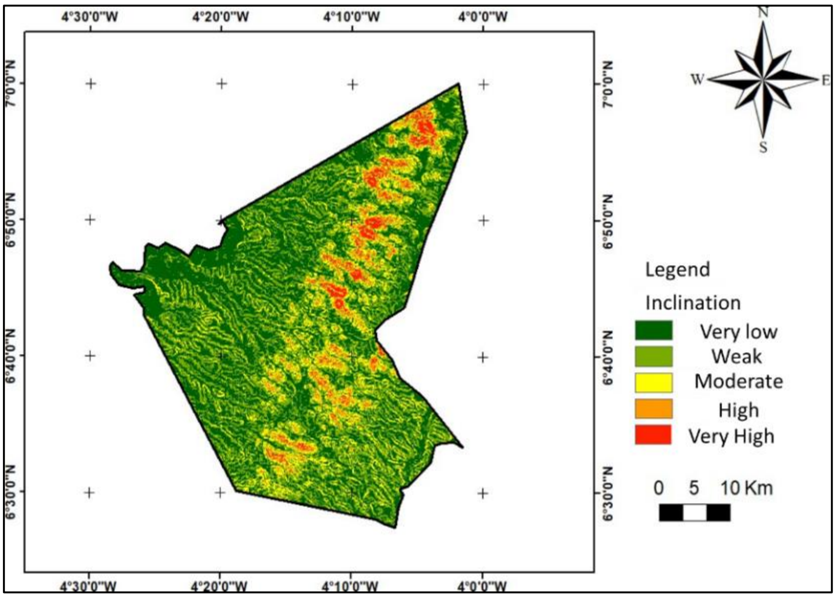

Figure 7. Inclinaion map.

3.4. Potential Recharge Zones

Table 2 summarizes the weights and interaction coefficients assigned to the various classes defined. Thus, factors with good infiltration capability are distinguished by high total weights; while those with poor infiltration capability will have low total weights. According to this table, lateritic and ferralitic breastworks, fluvial silt/sand, water reservoirs, high drainage and fracturing densities have the highest total weight values, and are therefore the areas of greatest water infiltration. Whereas granitoids, bare soils and habitats, with the lowest total weights, remain the areas with the lowest infiltration potential.

Table 2. Weighting of thematic maps according to their hydrogeological properties.

Factors	Hydrogeological properties				
Lithology	Lateritic Armor	Very good	10	3,5	35
	Fluvial vases and sands	Good	8		28
	Swampy Metasiltite and meta-arenite Medium	Moderate	6		21
	Granitoids	Bad	2		7
landcover	Water retention	Very good	10	2,5	25
	Degraded forest	Good	8		20
	Culture and Fallow Land	Good	8		20
	Savannah	Moderate	6		15
	Bare soil/habitat	Bad	2		5
Types of soils	Ferralitic cuirasses	Very good	10	2,5	25
	Hydromorphic soil	Good	8		20
	Reworked soils	Good	8		20
	Indian Suns	Bad	2		5
Drainage	Very strong	Very good	10	2	20
	High	Good	8		16
	Average	Moderate	5		10

Factors	Hydrogeological properties				
	Weak	Poor	3		6
	Very weak	Bad	1		2
	Very strong	Very good	10		20
	High	Good	8		16
Fracturing	Average	Moderate	5	2	10
	Weak	Poor	3		6
	Very weak	Bad	1		2
	Very strong	Very good	2		3
	High	Good	4		6
Inclination	Average	Moderate	6	1,5	9
	Weak	Poor	8		12
	Very weak	Bad	10		15

Figure 8 presents the integrated map of groundwater recharge potential obtained by combining the thematic layers. Recharge zones in the Bongouanou Department are classified according to their potential, ranging from very low to very high. Very high and high potential recharge zones are predominantly located in the northern part of the department, with a few scattered areas in the central and southern regions, collectively covering approximately 45.47% of the total area (Figure 9). In contrast, very low and low potential zones are mainly situated along the department's boundaries, representing 21.2% of the study area. Moderate potential zones, covering 33.34% of the territory, are primarily distributed in the western region and scattered throughout the department. This classification provides a comprehensive overview of the spatial variability of groundwater recharge potential across the study area.

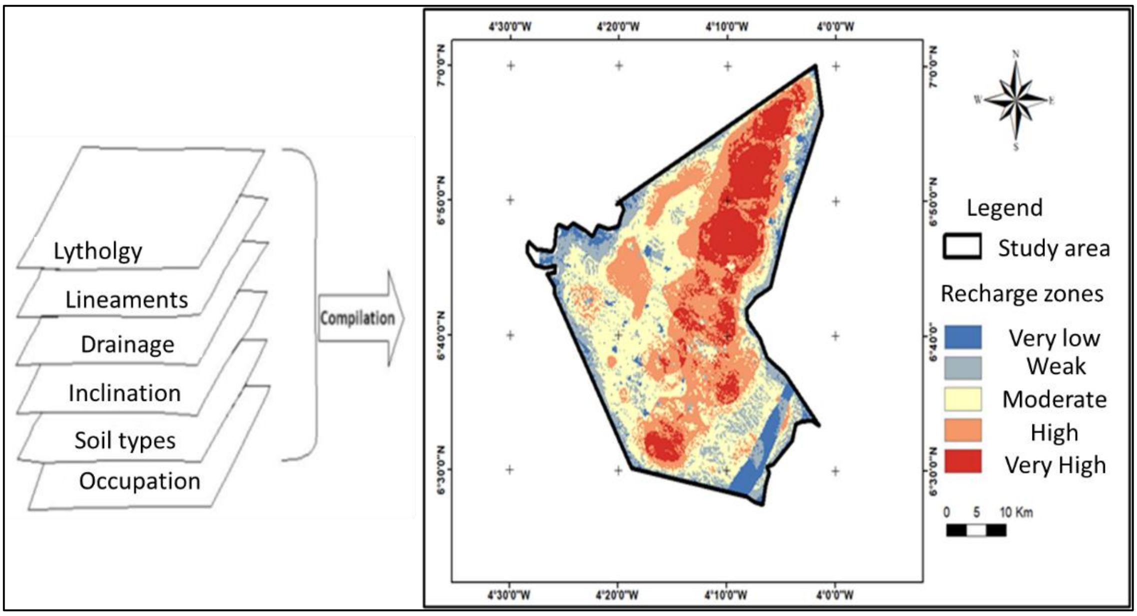

Figure 8. Summary map of potential recharge zones in Bongouanou department.

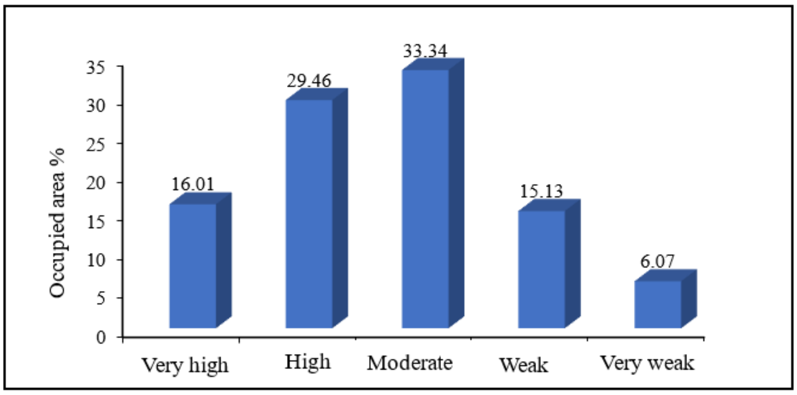

Figure 9. Percentage of potential recharge zone classes.

3.5. Validation of the Map of Potential Recharge Zones

The map in Figure 10, based on the map in Figure 8 and chloride data, is used to validate the potential recharge zones. Zones with high chloride levels (70 mg/L and 63 mg/L) represent high recharge zones. In contrast, the low chloride zone (6 mg/L) represents low recharge zones. The classes thus defined take account of analysis results. This is because water mineralization is governed by precipitation water (the main source of chlorides), which recharges aquifers.

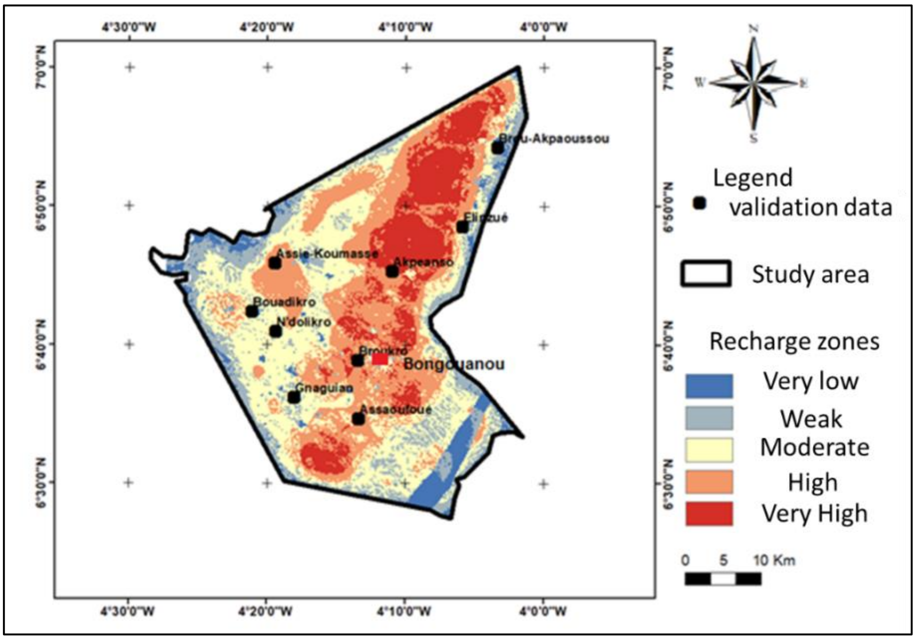

Figure 10. Validation map.

4. Discussion

Remote sensing provides diverse datasets in the form of thematic maps, which are essential for characterizing groundwater recharge zones at a regional scale. These datasets include landcover, slope, fracture, and drainage network maps. The heterogeneity of these data necessitates their integration within a GIS framework. Remote sensing and GIS have been widely recognized as effective tools for evaluating the recharge potential of fractured aquifers in regional-scale hydrological studies [23]. Furthermore, these methods have enabled researchers such as [24, 25] to identify suitable locations for high-yield boreholes. The parameters selected in this study, which control groundwater recharge, have also been employed by previous authors [26-28] for delineating potential recharge zones in their respective investigations. This method has been the subject of several studies, including those by [4], who used GIS, AHP, and remote sensing data to map recharge zones in a semi-arid basin. Their method integrated LULC, drainage density, and slope. They validated their results with hydrochemical data, particularly stable isotopes.

This study employed six criteria, a number comparable to that proposed by [29], who recommended limiting the number of parameters to seven per hierarchical level to reduce the risk of inconsistent judgments and facilitate the implementation of the Saaty method. According to [30], the boundaries between parametric classes should be considered as transitional zones rather than fixed thresholds. The resulting potential recharge map indicates that areas of high recharge potential cover 45.47% of the study area, compared with 33.34% for medium potential zones and 21.2% for low potential zones. These findings may explain the low failure rates observed in catchment works in the region, as reported by [31]. High-potential zones are therefore appropriate targets for defining protection perimeters, since surface-to-aquifer contaminant transfer is rapid in these areas [26], and they are often prioritized for artificial recharge to enhance aquifer hydraulic potential. While these results differ from those of [31], who reported that low-potential zones dominate (58%) with high-potential zones representing only 3%, they are consistent with studies in the western highlands of Cameroon [32, 33], where very high, high, and medium potential classes covered 18.06%, 26.54%, and 28.73% of the area, respectively, and low and very low potential zones accounted for only 17.66% and 9.02%.

Figure 9 shows the result of overlaying chloride concentration data on the synthesized map of potential recharge zones, providing a validation of the identified recharge areas in the region's aquifers. Chloride ions in groundwater primarily originate from precipitation and are minimally influenced by water–rock interactions in fractured aquifers [23]. In the absence of $A^{14}C$ data, chloride concentrations offer a suitable proxy for validating aquifer recharge zones. This method has been used by several authors, including [34], who show that Cl variability is analyzed to better understand atmospheric inputs and infiltration/recharge processes. Similarly, [35] reveal that Cl data allow for the quantification of water inputs (related to recharge via rainfall) and their spatio-temporal evolution.

The results obtained from the potential recharge zone map were validated using hydrochemistry. This method has been proposed in the work of [20] and by [30], as a method for validating maps of potential recharge zones. The determination of recharge zones from geochemical data such as isotopy, chloride and nitrate data has been the subject of several scientific works and confirmed by moment GIS results according to [24]. The results obtained in this study are therefore conclusive insofar as the different classes are in agreement with the chloride contents. These results are also in agreement with those of [36] who in a recent study on the annual and seasonal recharge of aquifers used the chloride mass balance (CMB) method and used the dilution of rain chlorides in groundwater to quantify infiltrated water.

Knowledge of these recharge zones is essential for protecting and preserving the resource, especially as it helps to prevent the risk of groundwater pollution and to define the protection perimeters of drinking water catchment areas, as shown by [20].

5. Conclusion

Mapping of potential recharge zones indicates that areas with high to very high recharge potential cover 45.45% of the study area, compared with 21.2% for low to very low potential zones. Zones with moderate recharge potential occupy 33.34% of the department. The development of a large-scale hydrogeological map of potential recharge zones for the fractured aquifers of Bongouanou, based on the integration of multiple datasets and methods, highlights the value of combining diverse sources of information. The resulting digital mapping model represents a valuable tool for groundwater resource exploration.

To further enhance understanding of groundwater geochemistry and ensure the quantitative and qualitative sustainability of the Bongouanou fractured aquifer, isotopic investigations of the department's waters are recommended. Future work could incorporate carbon-14 (^{14}C) activity, as well as oxygen-18 (^{18}O) and deuterium (^{2}H) analyses, to trace the origin of precipitation and, when combined with ^{14}C data, provide a more accurate assessment of aquifer recharge processes.

Abbreviations

ENVI	Environment for Visualizing Images
ROI	Region of Interest
NIR	Near-Infrared
SWIR	Shortwave Infrared
OLI	Operational Land Imager
MCDM	Multi-criteria Decision-making
PCA	Principal Component Analysis

Author Contributions

Bernard Adiaffi: Supervision
Brou Richmond Konan: Conceptualization, Data curation, Methodology, Writing – original draft
Prisca Kacou: Funding acquisition
Gbele Hermann Kouame Loukou: Visualization
Florent Koffi N'da Ayezou: Visualization
Christophe Kobenan Kra: Visualization

Conflicts of Interest

The authors declare no conflicts of interest.

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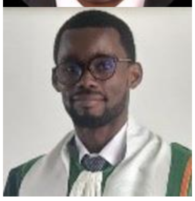

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