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The Contribution of Remote Sensing to Groundwater Exploration: A Case Study in the Far North Region of Cameroon

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Abstract:- Faced with an arid and semi-arid climate and limited surface water resources, the Far North Region of Cameroon prioritizes groundwater exploration. Indeed, these waters, being more potable than surface water, represent a crucial issue for the region. It is in this context that our study focused on mapping the groundwater potential of this area. To do this, we combined multi-criteria analysis with remote sensing. Multi-criteria analysis allowed us to consider various key factors such as climate, slope, lineament density, drainage network, geology, soil types, land use, and soil moisture. Each of these factors was weighted according to its relative importance for the presence of groundwater. Remote sensing provided us with powerful tools to collect spatial data. Satellites and other image capture technologies enabled us to acquire valuable information about the Earth's surface, such as surface temperature, vegetation density, and much more. These images then underwent extensive processing, including resampling, composite channel creation, and mosaicking. Texture analysis was also performed to identify fine lineaments in the landscape, potentially indicative of tectonic fractures or faults, which are important clues to the presence of groundwater. The study results revealed a heterogeneous distribution of groundwater potential in the region. 32.93% of the area (10,905.661 Km²) has low water content, 37.5% (12,416.402 Km²) moderate water content, 29.54% (9,781.646 Km²) good water content, and only 0.01% (9.04 Km²) excellent water content. The use of remote sensing for groundwater exploration in the Far North Region of Cameroon is a promising approach that should continue to develop. Technological advancements and access to more sophisticated data will enable even more precise and detailed information about the region's water resources. This will undoubtedly contribute to better management of this precious resource and increased water security for local populations.

Keywords:- *Multi-Criteria Analysis, Groundwater, Remote Sensing, Texture Analysis, Resampling.*

I. INTRODUCTION

Water, the source of life and an essential element for development, is at the heart of the world's concerns. Sustainable management of this precious resource and access to drinking water for all are two major challenges. Many international organizations, including the United Nations, recognize water as an essential pillar of socio-economic development. And yet, in 2019, WHO and UNICEF deplored the fact that 2.2 billion people worldwide still lack access to safe, continuous drinking water. Cameroon, a Sahelian country, is one of the hardest hits by this crisis: 34% of its population has no access to drinking water. The situation has deteriorated considerably over the years, depriving a large part of the population of easy access to water fit for consumption. Inequalities between rural and urban areas are glaring, as access to water is highly discriminatory. This disparity is exacerbated by the unequal distribution of water resources and infrastructure, leaving rural populations without access to this vital resource. Given the urgency of the situation, the water issue has become a priority for major international institutions. The countries of the Sahel, faced with the continuing deterioration of their water resources due to the scarcity and poor distribution of rainfall, are particularly vulnerable. The drying-up of watercourses is exacerbating the difficulties of access to drinking water, threatening food security and development in the region. Meeting this major challenge requires urgent, concerted action. The implementation of sustainable water resource management strategies, coupled with efforts to guarantee universal access to drinking water, is essential to ensure a sustainable future for people and the environment.

All over the world, water resources, particularly surface water, are under increasing pressure from rising demand and deteriorating quality. In this context, groundwater stands out as a vitally important source of drinking water supply (Guergazi and Achour, 2005; Ehoussou et al., 2018). Their high storage capacity and low exposure to pollutants make them valuable allies. Located deep beneath a protective layer of weathering, underground aquifers are generally sheltered from seasonal fluctuations and pollutants (Biémi, 1992). This natural protection guarantees water quality that generally meets World Health Organization (WHO) standards (Biémi, 1992). Faced with the degradation of surface water, the

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exploitation of deep groundwater is becoming an increasingly preferred solution for the supply of drinking water.

In the arid and semi-arid Far North of Cameroon, water is becoming scarce, threatening the daily life of the population and their development. It is in this context that the search for groundwater becomes a matter of survival, an absolute priority for the inhabitants and local authorities. For the people of this region, groundwater is an asset of the utmost importance. It is the main source of water for domestic, agricultural and pastoral needs, which are essential to their existence. Faced with increasing pressure on these precious resources, it is vital to optimize their management and guarantee their sustainability. This is where remote sensing comes into its own, offering a revolutionary tool for prospecting and managing groundwater in this arid zone. Unlike traditional prospecting methods, such as drilling and geophysical surveys, which are often costly and time-consuming, remote sensing offers a promising alternative. By analyzing satellite images and other spatial data, remote sensing enables groundwater resources to be identified and mapped more efficiently and cost-effectively. This technology opens the way to a better understanding of groundwater distribution and quality, facilitating sustainable management of this resource vital to the future of the populations of Cameroon's Far North.

So, we ask ourselves, how can we use remote sensing for groundwater research to alleviate water problems in the Far North region of Cameroon?

The main objective of this study is to produce a map of areas likely to contain groundwater, using geospatial data.

➢ *To Achieve this Objective, we will have as Specific Objectives:*

- Study the various hazards (pedology, climate, precipitation, slope, building density, soil moisture) conducive to water retention;
- Determining, in accordance with requirements, the areas with the best characteristics by making a weighted combination of our different hazards;
- Drawing up the maps.

It should be noted that this work has not yet been carried out throughout Cameroon using geospatial techniques.

➢ *Presentation of the Study Area*

The Far North region is the most populous of Cameroon's ten regions. It is located in the north of the country and borders on Chad and Nigeria. It lies in the north of the country between latitudes 10° and 13° north and longitudes 14° and 16° east. Its capital is the town of Maroua. The region comprises six departments and 47 arrondissements, covering an area of 34,246 km2 (Wikipedia).

The region includes the Mandara Mountains to the west, the Logone floodplains to the east (yaéré), the Mayo Kebbi peneplain to the south and Lake Chad to the north. The vast majority of the Far North region belongs to the endoreic Lake Chad basin. Only the Chari and its tributary the Logone are permanent. Moving ever more narrowly northwards between the borders of Chad and Nigeria, its boundaries naturally form the Logone and Chari rivers.

The Region's hydrological overview shows that it is dependent on two major basins: the Lake Chad basin (the largest endoreic unit on the African continent) and the Benoué basin. With the exception of the Logone and Chari rivers to the north, which delimit Cameroon's eastern border with the Republic of Chad and originate from regions with higher rainfall, all the region's watercourses are characterized by non-permanent flows. Their regime is more closely linked to the length of the dry season than to the low level of annual rainfall, generally between 600 and 1,000 mm.

Given the limited potential of surface water resources, hydrological studies have tended to focus on development issues (water supply reservoirs, flood risk studies, etc.). Such research is generally limited to a few years of observation, and long hydrological records are only available in the region for the Logone, Chari and Lake Chad (Logone-Chad mission, hydrometric networks in Cameroon and Chad).

Much of the project area has been anthropized, and natural vegetation has all but disappeared. Originally, it was a floristically diverse Sudanian wooded savannah. Existing wildlife resources consist mainly of avian fauna (granivorous birds, piscivorous birds, partridges, pigeons, guinea fowl, scavengers). The Benoué River is home to a diverse aquatic fauna. The main species are Chrysichthys, Citharinus, Heterotis, Hydrocynus, Lates and Tilapia, as well as reptiles and a few mammals, the star of which is the hippopotamus.

The climate in the Far North of Cameroon is of the Sudano-Sahelian type, characterized by a seven-month dry season and a five-month rainy season. Cold from November to February, followed by increasingly hot months until the arrival of the rains. The climate is largely Sahelian, with high temperatures and rainfall ranging from 900 to 350 mm, decreasing with latitude from south to north. The heights (up to 1,400 meters) of the Mandara Mountains are cooler and much rainier. July and August alone account for 2/3 of the region's total annual rainfall.

It's summer in the northern hemisphere, but due to the relatively lower temperatures and intensity of rainfall in July and August, this rainy season is often referred to as wintering. Rivers overflow their banks, making traffic difficult off the main roads.

Savannahs, more or less wooded depending on latitude, cover the region, while flood plains are the domain of grasslands. Inter-annual irregularities characterize the climate and punctuate the work of the people, essentially farmers, farmer-breeders and a few Peul Bororo nomads on the shores of Lake Chad.

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Its population (and therefore its density) has grown considerably, rising from 2,721,500 in 2001 to 3,111,792 at the 2005 census. Its density rose from 40.7 to 90.8 inhabitants per km2 between the 1974 and 2005 censuses. Urban growth is exponential.

This population is very unevenly distributed between the overpopulated mountainous regions, with densities exceeding 300 inhabitants per km2 in the Monts Mandara, and the yaérés, the vast floodplain of the Logone, where densities are less than 10 inhabitants per km2, which enabled the creation of the vast Waza National Park and, away from the floods, the smaller Kalamaloué National Park. Numerous ethnic groups occupy clearly identified areas, whether in the mountains and plateaus of the Mandara (Mafa (people), Mofu (people), Podoko, Kapsiki (people), Mouktélé (people), Vamé (people), Brémé...) or in the plains (Kotoko (people), Toupouri (people), Massa, Moundang (people), Guisseye, Moussey (people)...). Formerly Islamized ethnic groups, the Fulani (in English: Fulas or Fulani; in Fulani: Fulbé) in the center and the Choua Arabs (in the north) are more devoted to livestock farming, some of them sedentary, others transhumant. Bororo Peul nomads frequent the shores of Lake Chad. Other groups, such as the Haoussas and Bornouans, are more urban. Agriculture and livestock farming account for 90% of the population. Supervised by SODECOTON, cotton is the main cash crop, exported for its fiber or for local oil consumption. Food crops are grown for self-consumption or to feed the fast-growing towns. Rice cultivation has expanded considerably with the various rice-growing perimeters created by SEMRY. Fishing, developed along the Logone and Chari rivers and in Lake Chad, has benefited from the creation of the Maga reservoir.

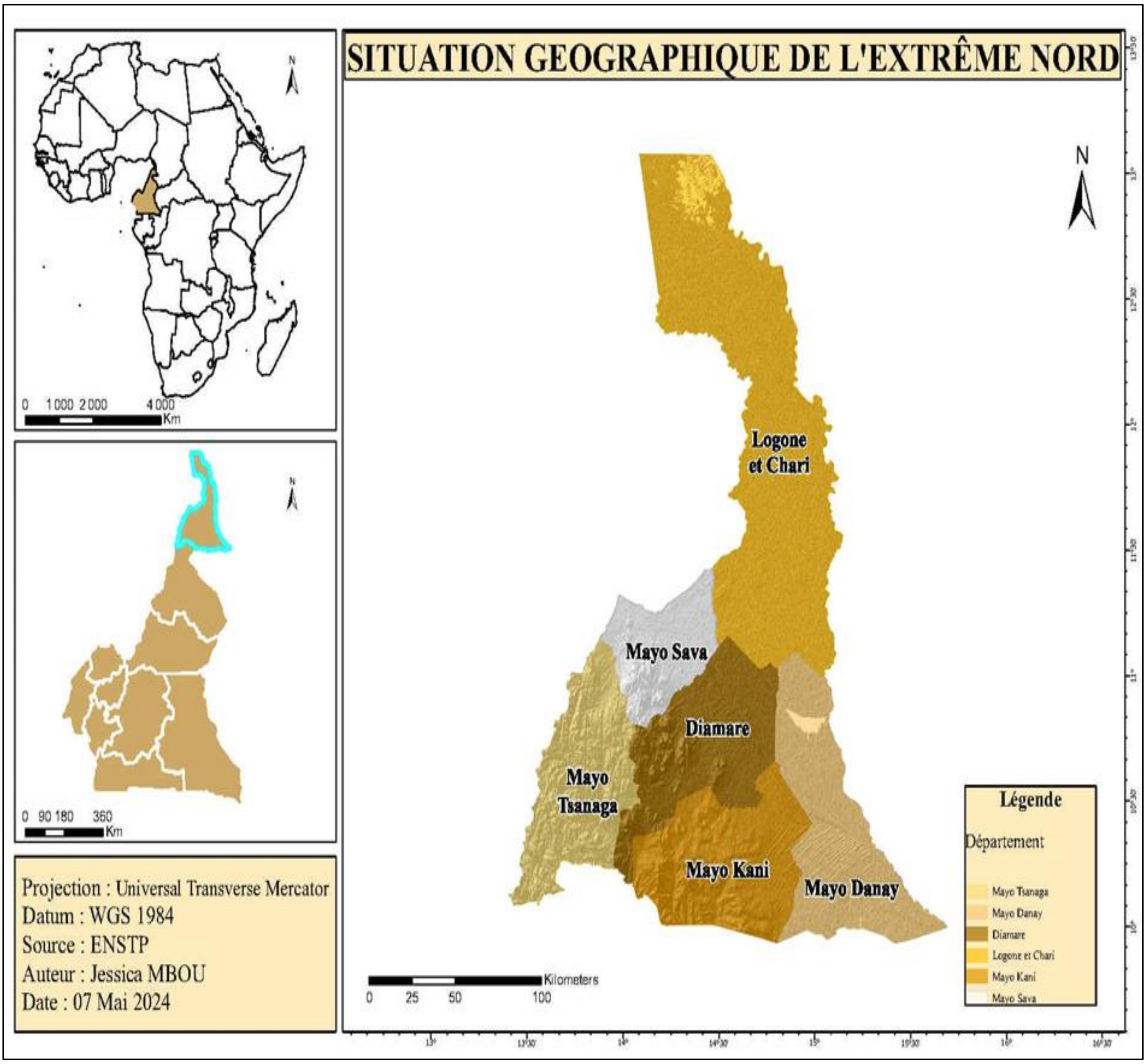

Fig 1 Location of Far North Cameroon

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II. METHODOLOGY

A. Data

This study required the use of several types of data, including geological and pedological maps at scales of 1:1,000,000 and 1:2,000,000 respectively, produced by MMIDT and IRD respectively; sentinel-2 satellite images (January 2024 scenes) were used to map the lineament network; STRM data from the USGS were used to extract the hydrographic network; the Land Use Map from the ESRI website and climatic data from the https://fr.climate-data.org website.

B. Methodology

➢ *Linear Mapping*

- *Texture Analysis: Haralick's Method*

Texture analysis is the study of spatial variations in textural properties in an image. Geological formations often have specific textures, such as linear patterns, granulations or "chevron" patterns. Using texture analysis methods, it is possible to detect and map these patterns, which can be useful for the identification and classification of geological formations.

Haralick's method is a widely used technique in the field of imaging and texture analysis, including in the context of geological mapping. It can be used to quantify and characterize the textural properties of images, which can provide valuable information for the discrimination and mapping of geological formations.

- *Linear Mapping*

Lineament mapping is a method used in geology to identify, locate and map lineaments, also known as linear fractures, in the landscape. Lineaments can be fractures, faults, joints or other types of linear discontinuities present in rocks or geological structure.

Lineament mapping is based on the analysis and interpretation of satellite images, aerial images or topographic data. These data are often processed and analyzed using specialized software to extract and identify lineaments present in the study area.

Lineaments can be identified by looking for variations in color, texture or shape in the images. For example, linear breaks in a vegetation pattern or color variations along a line can indicate the presence of lineaments. Radar images, particularly SAR images, are commonly used as they can detect differences in roughness and reflectivity that may be associated with lineaments.

Once lineaments have been identified, they are usually mapped using digitizing and georeferencing techniques. This involves plotting the lineaments on a map or geographic information system (GIS) with their precise geographic coordinates.

Lineaments can provide information on tectonic stresses, preferential fracture directions, fault systems and zones of weakness in the Earth's crust.

➢ *Groundwater Mapping*

The approach adopted is based on a spatial approach incorporating multi-criteria analysis. In order to draw up the map of areas containing groundwater, the hierarchical multicriteria analysis (HMA) method developed by Saaty (1980) was used to assign weights to the various criteria according to their importance. This method is based on a two-by-two comparison of the various hazards, using a square matrix to evaluate the importance of one criterion in relation to another, using a scale developed by Saaty. Once the comparison matrix has been filled in, we calculate the eigenvalue of each and the corresponding eigenvector. The eigenvector indicates the order of priority, while the eigenvalue is used to assess the consistency or quality of the solution obtained.

- *Hierarchical Multi-Criteria Formulation and Elaboration of the Various Criteria*

The AHP method is based on breaking down a problem into a hierarchical structure, with each level made up of specific indicators. This hierarchical structure highlights the indicators that will have the greatest impact on the final decision.

Establishing criteria is the first fundamental step in identifying areas containing groundwater. The choice of criteria stems from observations made by countries such as France and Morocco on the conditions required to retain water in the ground. The criteria will be evaluated using the spatial analysis functions of GIS, and each evaluation will result in a map representing the suitability of all surfaces for the criterion in question.

Table 1 The Different Criteria

Criteria	Input
The slope	Water management
Soils	Infiltration rate
Geology	For controlling infiltration, movement and water retention
The drainage system	For water distribution and infiltration
Land use	For areas that affect water recharge
Precipitation	Major water source
Lineament density	For hydraulic conduction
Soil moisture	For soil moisture measurement

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- *Categorization and Standardization of Criteria*

Setting up the criterion cards requires prior standardization of the various factors, a step based on continuous reclassification that enables the different factors to be quantified according to their suitability.

- *Weighting of Criteria*

A multi-criteria analysis often leads the decision-maker to consider that the factors are not of equal importance, so a weighting must be assigned to each of them. This phase involves comparing the various criteria to determine the importance of their contribution to solving the problem. The weighting of criteria forms the basis of any multi-criteria operation, as it has a direct influence on the results. Saaty (1980) developed a comparison scale for each level.

Once the degrees of importance have been assigned, the weight of the criterion is determined by applying formula (1).

$$Criteria\ weight = (Line\ sum)/(Number\ of\ criteria) \quad (1)$$

- *Consistency Check*

The consistency index measures the reliability of the comparison expressed in consistent judgments. The larger the index becomes, the more inconsistent the judgments expressed in the comparison matrix would be, and vice versa. In order to test the consistency of the response, which indicates whether the data are logically related, Saaty (1980) proposes a verification procedure based on the formulas in the following equations:

$$\alpha_{moy} = \sum\left(\sum ci.wi\right) \quad (2)$$

$$IC = \frac{\alpha_{moy} - n}{n-1} \quad (3)$$

$$RC = \frac{IC}{CA} \quad (4)$$

With :

Moy: average coherence

ci: column

Wi: weight

n: number of elements

IC: coherence index

RC: coherence ration

And CA: Random Coherence

Saaty's experiment defines a consistency ratio (CR) as the ratio of the consistency index to the random index of a matrix of the same dimension. The coherence ratio measures the logical consistency of experts' judgments, and can be used to assess the coherence of judgments using the pairwise comparison method. It provides information on the consistency in terms of ordinal and cardinal importance of the criteria to be compared. In general, for criteria of less than nine, a tolerance threshold of 10% is set for the consistency index. This implies that if the consistency ratio is greater than 0.1, then there is inconsistency in the pairwise comparisons, and the matrix resulting from the comparisons will have to be re-evaluated. To judge consistency acceptable, the consistency ratio should therefore be less than 10%.

- *Criteria Aggregation*

Once the criteria have been established and weighted, they will be aggregated by weighted linear combination based on the formula in the equation below:

$$\sum_i wi.xi \times \prod_j cj \quad (5)$$

III. RESULTS

A. Structural Mapping

- *Texture Analysis*

The application of GLCM to the satellite image generated 08 textural parameters: mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment and correlation. Only the mean (Figure 3.) enabled the morpho-structural discontinuities in the study area to be preserved and further enhanced.

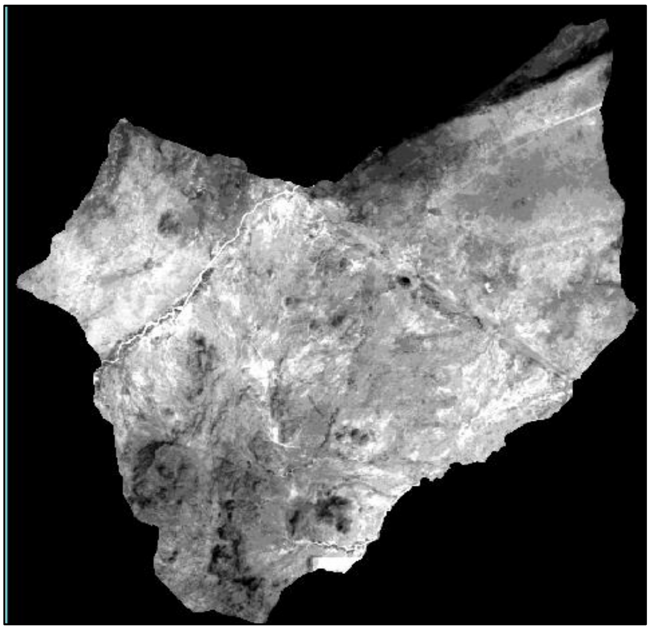

Fig 2 Texture Analysis of Mayo Sava (One of the Departments in the Study Area)

- *Linear Mapping*

Once the texture analysis had been carried out, the image obtained from the average parameter was transferred to Geomatica software, which, with its PC-LINE algorithm, automatically extracted the lineaments present in the study area, after which these were imported into ArcGIS pro to produce the lineament map (Figure 4).

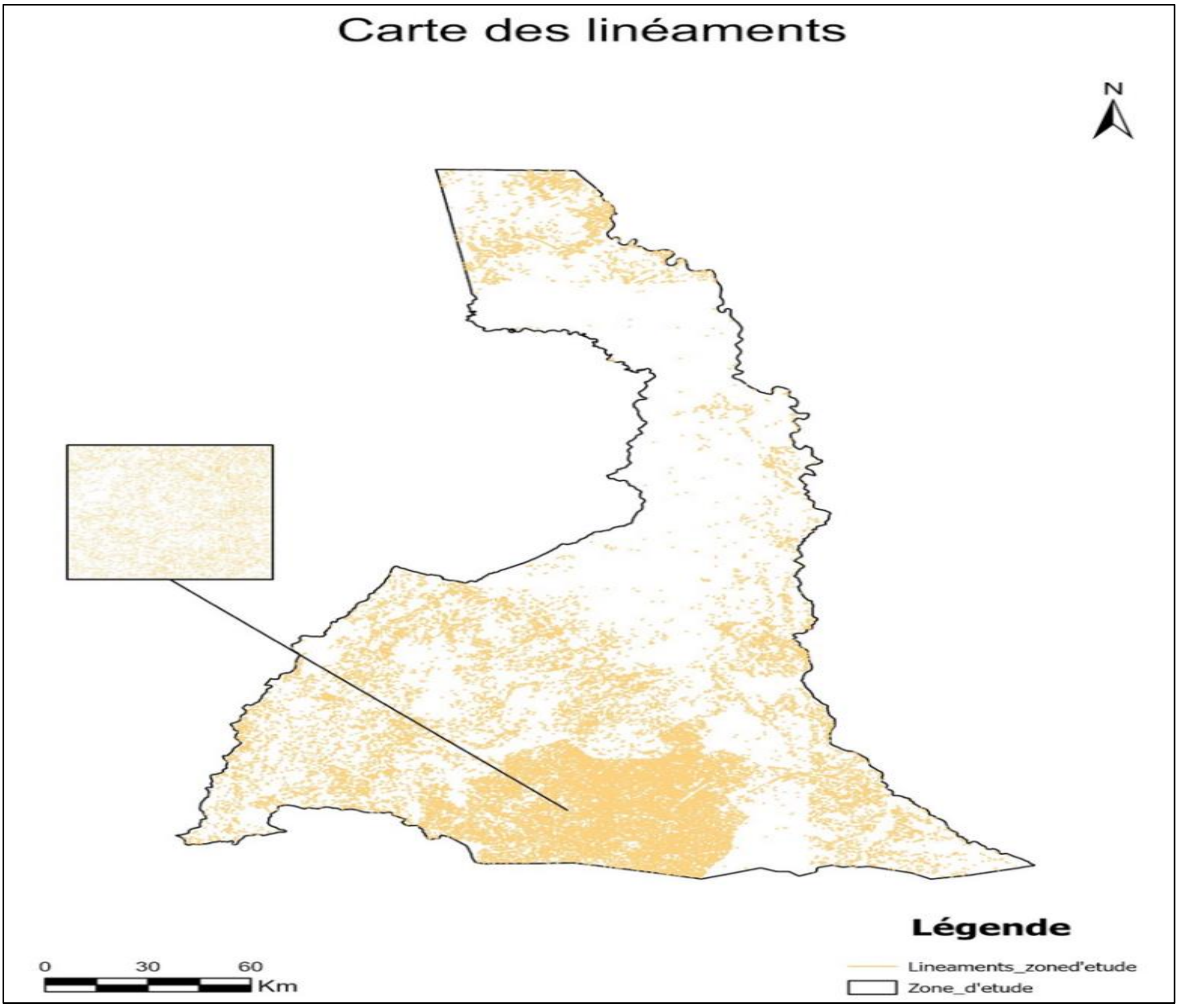

Fig 3 Linear Mapping

B. Groundwater Mapping

➢ *Weighting Of Criteria*

- *Weighting of Criteria*
  Based on the above considerations, we obtain the matrix shown in table 4.

Table 4 Comparison Matrix

Criteria	Climate	Geology	Slope	Drainage density	Land use	Lineament density	Pedology	MNDWI
Climate	1	3	3	5	5	5	7	3
Geology	1/3	1	3	3	5	5	5	3
Slope	1/3	1/3	1	1	3	3	5	3
Drainage density	1/5	1/3	1	1	1	2	3	3
Land use	1/5	1/5	1/3	1	1	1	3	3
Lineament density	1/5	1/5	1/3	1/2	1	1	1	1
Pedology	1/7	1/5	1/5	1/3	1/3	1	1	3
MNDWI	1/3	1/3	1/3	1/3	1/3	1	1/3	1

- *The Normalized Matrix is given in Table 5.*

Table 5 Normalized Comparison Matrix

Criteria	Climate	Geology	Slope	Drainage density	Land use	Lineament density	Pedology	MNDWI
Climate	0,36	0,54	0,33	0,41	0,30	0,26	0,28	0,15
Geology	0,12	0,18	0,33	0,25	0,30	0,26	0,20	0,15
Slope	0,12	0,06	0,11	0,08	0,18	0,16	0,20	0,15
Drainage density	0,07	0,06	0,11	0,08	0,06	0,11	0,12	0,15
Land use	0,07	0,04	0,04	0,08	0,06	0,05	0,12	0,15
Lineament density	0,07	0,04	0,04	0,04	0,06	0,05	0,04	0,05
Pedology	0,05	0,04	0,02	0,03	0,02	0,05	0,04	0,15
MNDWI	0,12	0,06	0,04	0,03	0,02	0,05	0,01	0,05

- *Weight of Criteria*

Formula (1) gives us the results shown in Table 6.

Table 6 Weight of Criteria

Criteria	Weight
Climate	0.33
Geology	0.23
Slope	0.13
Drainage density	0.09
Land use	0.07
Lineament density	0.05
Pedology	0.05
MNDWI	0.05

➢ *Assessing the Consistency of Judgements*

Consistency is assessed by first multiplying each column of the unnormalized comparison matrix by the weight of the associated criterion. The results of this operation are shown in Table 7.

Table 7 Coherence Assessment

	Climate	Geology	Slope	Drainage density	Land use	Lineament density	Pedology	MNDWI
Climate	0,33	0,69	0,39	0,45	0,35	0,25	0,35	0,15
Geology	0,11	0,23	0,39	0,27	0,35	0,25	0,25	0,15
Slope	0,11	0,07666	0,13	0,09	0,21	0,15	0,25	0,15
Drainage density	0,066	0,07666	0,13	0,09	0,07	0,1	0,15	0,15
Land use	0,066	0,046	0,04333	0,09	0,07	0,05	0,15	0,15
Lineament density	0,066	0,046	0,04333	0,045	0,07	0,05	0,05	0,05
Pedology	0,04714	0,046	0,026	0,03	0,02333	0,05	0,05	0,15
MNDWI	0,11	0,07666	0,04333	0,03	0,02333	0,05	0,01666	0,05

Secondly, the sum of the lines obtained is divided by the weight of the line criterion. The results are shown in Table 8.

Table 8 Weight of Criteria

Criteria	Weight
Climate	8,96969697
Geology	8,695652174
Slope	8,974358974
Drainage density	9,251851852
Land use	9,504761905
Lineament density	8,406666667
Pedology	8,44952381
MNDWI	8
Medium consistency	8,781564044

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Applying formulas (2.3) and (2.4), we obtain:
Consistency index: CI= 0.37
Consistency ratio: RC=0.075
RC<0.1;

The arbitrarily chosen comparison matrix is deemed acceptable.

➢ *Groundwater Potential Map of Maroua*

To obtain the groundwater potential map, we begin by cross-referencing the various criteria maps with their respective weights. Criteria maps are crossed using the raster calculator. The result is shown in figure 4.

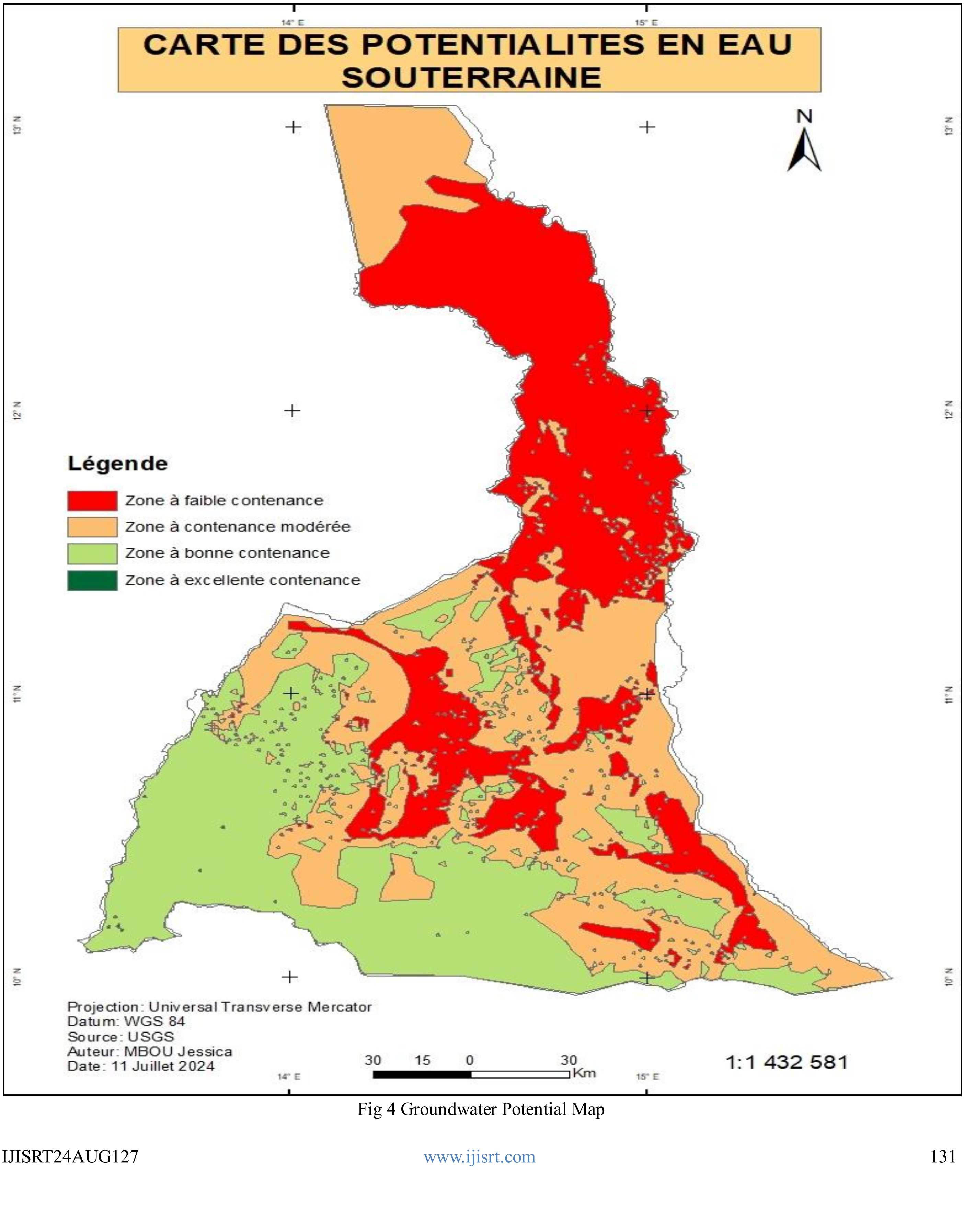

Fig 4 Groundwater Potential Map

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- *Extraction of Zone Classes by Category*

From our reclassification tab, we'll bring out the zone classes by maintaining the value of the class to be extracted and assigning the value No data to the other classes. The result is shown in figure 5.

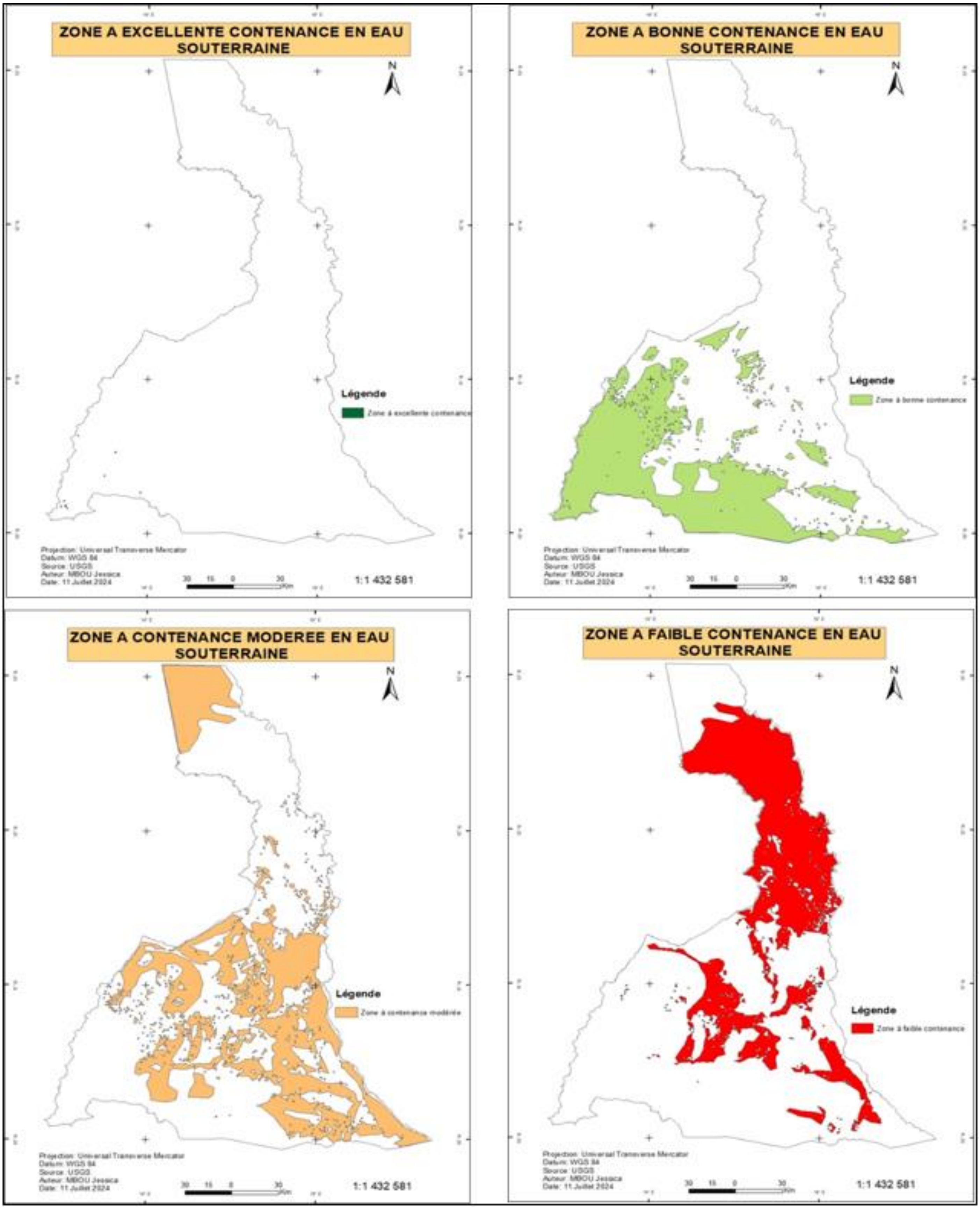

Fig 5 Classification of Zones by Category

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The properties of these maps indicate that a pixel has a side length of 1002.238506 m; a pixel being square in shape, we obtain its area, which is 1004482.023 m². By multiplying the area of the pixel by the number of pixels in each class, we obtain the area of the different classes. This procedure yields the values shown in Table 9.

Table 9 Area of Different Zones

Class	Area in km^2
Low-capacity zone	10 905 ,66132
Moderate-content zone	12 416,40229
Good capacity zone	9 781,64594
High-capacity zone	9,04034
Total	33 112,74989

The percentage of each zone can be calculated from formula (6).

$$Percentage\ of\ an\ area = (Area\ of\ area)/(Total\ area) \times 100 \qquad (6)$$

The results are shown in Table 10.

Table 10 Percentage of Surface Area of Different Zones

Class	Percentage (%)
Low-capacity zone	32.93
Moderate-content zone	37.50
Good capacity zone	29.54
High-capacity zone	0.01

IV. DISCUSSION

When mapping Maroua's groundwater potential, an analysis based on a combination of multi-criteria analysis and remote sensing was carried out on several factors influencing the presence of groundwater. The results obtained enabled us to identify the most favorable areas for groundwater retention, as well as areas where it might be more difficult to find groundwater. As a first step, various layers of data were collected from sources such as satellite images, climate data and soil data. These data were pre-processed and converted into relevant indicators for assessing the region's potential. A multi-criteria analysis was then carried out, assigning weights to each indicator according to its relative importance; this weighting was determined on the basis of knowledge established by experts from countries such as Canada, France and Morocco. Once the indicators had been weighted, a map combining the identified factors in the best possible way was drawn up to delimit areas with high potential from those with low potential.

As the results were divided into four classes (low-capacity zone, moderate-capacity zone, good-capacity zone, excellent-capacity zone), we can recommend that wells and boreholes be drilled in good-capacity zones without too much difficulty. In moderate-capacity zones, a geotechnical survey should be carried out beforehand to assess the depth of the water. No recommendation is made for low-capacity zones, as they do not meet any of the criteria for groundwater retention.

➢ *The Model Produced here is Questionable for Several Reasons:*

- *Uncertainty in input Data*

The input data used in this study are mostly obtained free of charge and of average resolution, which may have an impact on the final result.

- *Multiple Climate Changes*

The whole world is subject to significant climate change, which can render the present map derisory after a number of years. To remedy this problem, we therefore recommend updating climate data after a certain number of years.

V. CONCLUSION

The aim of this project was to produce a map of groundwater potential in the Far North of Cameroon, using remote sensing and multi-criteria analysis. To achieve this, the methodological approach employed consisted firstly in carrying out a general reconnaissance of the site, followed by a meticulous selection of the data and software required for such a study. Then came the processing phase, preceded by pre-processing to produce the criteria maps, which were then superimposed to create the final cartographic document. We succeeded in determining the groundwater potential of the city of Maroua. By combining criteria such as climate, geology, pedology, land use, lineament density, drainage network density, slope and soil moisture, we identified areas of low, moderate, good and excellent groundwater potential. Multi-criteria analysis and remote sensing are therefore proving to be powerful tools for selecting sites suitable for groundwater retention. Remote sensing is revolutionizing groundwater research and management by providing

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powerful, cost-effective tools for mapping, monitoring and assessing these critical resources. By tackling current challenges and pursuing innovation, remote sensing will continue to play a crucial role in sustainable groundwater management for the benefit of present and future generations. Remote sensing does not replace traditional field methods, but rather complements and reinforces them. The effectiveness of remote sensing depends on the selection of appropriate sensors, weather conditions and the expertise of analysts.

Looking ahead, this work could be complemented by collaboration between hydrogeologists, remote sensing specialists and political decision-makers is essential for the optimal use of remote sensing in groundwater management to remedy the problems of water scarcity in this region.

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