Open Journal of Modern Hydrology, 2025, 15(4), 308-322
https://www.scirp.org/journal/ojmh
ISSN Online: 2163-0496
ISSN Print: 2163-0461

Combined Use of Multi-Criteria Analysis and GIS to Map Favorable Areas for High-Yield Boreholes Installation in the Tonpki Region (Côte d'Ivoire)

Kouadio Assemien François Yao[1], Moussa Ouedraogo[1], Léréyaha Coulibaly[1], Arouna Silue[1], Sandotin Lassina Coulibaly[1], Kouassi Ernest Ahoussi[2]

[1]Unité de Formation et de Recherche Sciences Géologiques et Minières, Université de Man, Man, Côte d'Ivoire
[2]Unité de Formation et de Recherche Sciences de la Terre et des Ressources Minières, Université Félix Houphouët-Boigny, Abidjan, Côte d'Ivoire
Email: assemien.yao@univ-man.edu.ci

How to cite this paper: Yao, K.A.F., Ouedraogo, M., Coulibaly, L., Silue, A., Coulibaly, S.L. and Ahoussi, K.E. (2025) Combined Use of Multi-Criteria Analysis and GIS to Map Favorable Areas for High-Yield Boreholes Installation in the Tonpki Region (Côte d'Ivoire). *Open Journal of Modern Hydrology*, **15**, 308-322.
https://doi.org/10.4236/ojmh.2025.154019

Received: March 23, 2025
Accepted: August 25, 2025
Published: August 28, 2025

Abstract

Located in the west of the Ivory Coast, the Tonkpi region with its estimated population of around 884,700 inhabitants faces many drinking water problems, especially in the dry season. The objective of this study is to identify sites favorable to the establishment of high-yield boreholes in this region by using GIS methods and multicriteria analysis. The combination of the different decision criteria after their weighting allowed the development of thematic maps (availability, accessibility and usability). These thematic maps were then combined to generate the summary map expressing the groundwater potential of the region. This map showed that the Tonkpi region has high groundwater potential (55%). These groundwater resources are unfortunately not all accessible, let alone exploitable as a whole. Consequently, high-yield boreholes can be installed in more than half (55%) of the area studied, in particular in the western part.

Keywords

Groundwater Potential, Multi-Criteria Analysis, GIS, Tonkpi, Côte d'Ivoire

1. Introduction

In recent years, rapid population growth combined with urbanization led to a global water scarcity problem, hampering economic, social and environmental development, especially in developing countries [1]-[4]. Accessibility to drinking water is one of the major objectives of development projects worldwide [5]. This has been formally recognized by international instances, which have included it in the Millennium Development Goals (MDGs). The relevance of this issue for the United Nations lies in the fact that the proportion of people with sustainable access to drinking water remains low in the face of ever-increasing demand. In fact, some 2 billion people worldwide have no access to safe drinking water [6]. This represents nearly 26% of the world's population. Around 2 million people, most of them young children, die every year from diseases caused by drinking poor-quality water [7]. In some African countries, the situation is quite alarming due to poor management and the lack and/or dilapidation of infrastructure.

Like most countries south of the Sahara, Côte d'Ivoire faces these water-related problems. [8] argues that improving the living conditions of the Ivorian population is the responsibility of the State. It requires better access to basic services, including drinking water. The National Human Hydraulics Program (NHHP) was set up in 1973, followed by the creation of the National Drinking Water Office (known locally as ONEP for Office National de l'Eau Potable) in 2006. Several investment projects to supply drinking water have also been launched [9]. This program aims to provide access to drinking water for the entire population by 2030. Thus, in order to succeed in this ambitious program, decision-makers and water managers need very precise information from scientists on the existence and accessibility of groundwater resources, in order to guarantee optimal exploitation of these resources [10].

This information can come from a variety of techniques, including Gravity Method, Seismic Method, Drilling Test & Borehole Geophysical Logging techniques and other Geophysical Methods [9]. However, it is possible to combine several prospecting methods to increase success rates. Given the high cost of geophysical prospecting and the cumbersome nature of the equipment to be mobilized, the multi-criteria analysis approach, which is less costly and quicker, can provide water managers with reliable data for the siting of water wells.

The Tonkpi region, located in the west of Côte d'Ivoire in the crystalline basement, remains one of the regions most affected by water shortages. Demand for water is increasing and needs are becoming less and less satisfied. To provide assistance to decision-makers and improve living conditions of the population, the present study was initiated. It aims to identify favorable areas for the installation of high-yield boreholes in the Tonkpi region.

2. Material and Methods

2.1. Study Area

The study was conducted in extreme west part of Côte d'Ivoire, in the Tonkpi region, located between latitudes 7˚21' N and 7˚58' N and longitudes 7˚33' W and 8˚05' W (**Figure 1**). This region covers an area of 12.3 km^2 and includes the departments of Man, Biankouma, Danané, Zouan-Hounien, and Sipilou. It is bordered to the west by Republics of Guinea and Liberia.

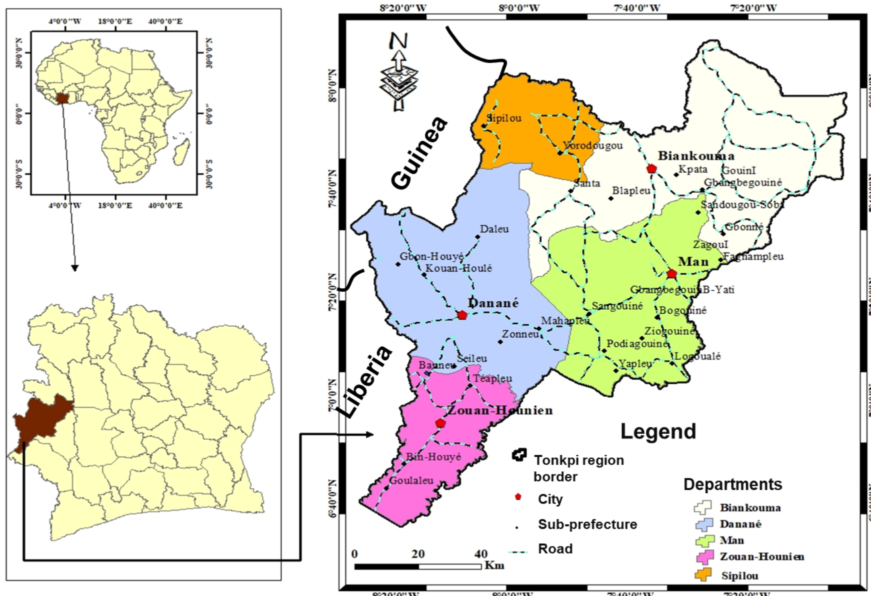

Figure 1. Location of study area.

The study area is characterized by a humid tropical climate, known locally as the mountain climate. It is a cold climate with 2 seasons: a rainy season beginning in March and ending in October, and a dry season from November to February, with average annual rainfall of around 1800 mm. With regard to temperature, the annual average is 21˚C [11]. The relief of the Tonkpi region is subdivided into two morphological complexes of unequal extent: a mountainous complex (Toura and Dan ranges) and a plateau zone [12]. The mountainous terrain features several high peaks exceeding 1000 m, the highest of which are Mont Nimba (1753 m) and Mont Tonkpi (1189 m). The valleys lie between 300 and 700 m. This original ensemble owes much to the local variety of rocky material in the hypersthene granite family, but also to tectonic variations [13]. The geological environment consists exclusively of hypersthene granites and granito-gneisses with varied facies, derived both from the remains of an ancient basement and from major granitic intrusions [14]. The area is fairly well drained by various rivers, including the Cavally, Koué, Bafing and N'zo, tributaries of the Sassandra river.

2.2. Materials

The material consisted of Shuttle Radar Topographic Mission (SRTM) images data representing the digital elevation model (DEM), cartographic data (Man-Danané square degree geological map) and borehole data from data sheets for boreholes drilled in the study area. The SRTM images were used to extract the slope map and the drainage density map using Linwin.2.2 software.

2.3. Methods

The methodology adopted is based on multi-criteria analysis methods for mapping favorable areas for the siting of high-yield boreholes [15]-[18] and for estimating groundwater recharge [6] [19] [20]. The main stages of multicriteria analysis can be summarized in three: i) identification and elaboration of decision criteria; ii) classification and standardization of these criteria; iii) weighting of the criteria and their aggregation following the multicriteria approach.

2.3.1. Identification and Elaboration of Decision Criteria

In the fractured environment of the crystalline and crystallophyllous basement, the search for favorable zones for the installation of high-yield boreholes is based on the hydrogeological characteristics of the aquifers as well as the geological, physiographical and hydroclimatic aspects of the region [21]. The decision criteria for mapping water resources can be grouped into three quantitative indicators [15] [18] [22]. These are: availability, accessibility and exploitability. These criteria are used to produce the thematic maps corresponding to the three indicators. The "availability" indicator refers to the existence of an aquifer and is the first condition to be known before any other activity [18]. The availability map is produced from the combination of slope, effective infiltration, weathering thickness, drainage density and fracture density.

The slope map of the study area was generated in raster format from SRTM images with a resolution of 30 m.

Effective infiltration was obtained by calculating the water balance using the Thornthwaite method. The calculation method is illustrated in Equation (1):

$$I_e = P - (AET) + R_s \quad (1)$$

With,

I_e: Effective Infiltration (mm);

P: Precipitation (mm);

AET: Actual Evapotranspiration (mm);

R_s: Surface Runoff (mm).

Alteration thicknesses were extracted directly from drilling data sheets. Drainage density was determined from the hydrographic network extracted from SRTM images. Once the hydrographic network had been extracted, the area covered by this network was meshed by 5 km^2. The total number of meshes obtained was 1200. The drainage density was then calculated for each elementary surface. This was done using Linwin 2.2 software. Fracture density was obtained from fractures extracted from the work of [13] in the Man-Danané region. Like drainage density, fracture density was calculated in Linwin 2.2 after discretizing the study area into a 5 km^2 square mesh.

The "exploitability" indicator refers to the quantity of the groundwater reserve. It integrates the criteria of operating flow rate and static groundwater level. The exploitation rate depends on the quantity of water in the groundwater reserve, but also on the rate of renewal of this reserve in the event of high demand [16]. The two parameters of the exploitability indicator come from drilling data provided by the Hydraulics Regional Office of Man.

The "accessibility" indicator provides information on the conditions of access to the groundwater resource. These conditions are considered to be economic and social factors, as they promote or hinder access to the resource [18]. The main accessibility criteria are total depth and success index. Total depth is the most important criterion in the accessibility indicator, as it indicates the depth to be drilled to obtain the optimum flow rate. The total depth was provided by drilling data and the success index was determined according to Equation (2) considering that an exploitation yield of at least 10 m^3/h is a large yield.

$$S = (100 * Q)/10 \quad (2)$$

With,

S: success index (%);

Q: operating yield (m^3/h).

2.3.2. Classification and Standardization of Criteria

Classification involves grouping the values of each criterion into a number of classes. The boundaries chosen for these classes are not necessarily equidistant, but depend on the objectives set and the general context of the study [23]. The choice of classes takes into account the variance of the available data and is inspired by the classification proposed by [15] [23] in the crystalline basement region. Thus, the classes Very Low, Low, Medium, High and Very High have been retained. In addition, as the criteria are measured on different scales, using different units, they need to be standardized for a good multi-criteria analysis. A common interval of 1 to 10 was selected for this operation, taking into account previous studies by [15] [23] in the Korhogo region and [24] in the Abidjan region, [17] in the Oumé region. The "very low" or "very heigh" classes are given a mark of 10, depending on whether they contribute to the excellent achievement of the indicator in question. If this is not the case, these classes are given a score of 1. Similarly, intermediate values are assigned to intermediate classes according to a linear distribution. The technique used to spatialize the criteria is interpolation, in particular the inverse distance weighting (IDW) interpolation method, and the areas obtained as a result of these operations have been categorized into five classes as shown in **Table 1**.

Table 1. Classification and standardization of criteria [16].

Indicators	Criteria	Criteria qualifiers	Classes	Odds
Availability	Slope (%)	Very Low	0 - 1	10
		Low	1 - 2	8
		Medium	2 - 3	5
		High	3 - 4	3
		Very High	>4	1
	Effective Infiltration (mm)	Very Low	10-25	1
		Low	25 - 50	3
		Medium	50 - 75	5
		High	75 - 100	8
		Very High	>100	10

Continued

Availability	Drainage Density (km/km²)	Very Low	<5	10
		Low	5 - 10	8
		Medium	10 - 15	5
		High	15 - 20	3
		Very High	>20	1
	Fractures Density (km/km²)	Very Low	1 - 5	1
		Low	5 - 10	3
		Medium	10 - 15	5
		High	15- 20	8
		Very High	>20	10
	Weathering thicknesses (m)	Very Low	11 - 25	1
		Low	25 - 52	3
		Medium	52 - 70	5
		High	70 - 85	8
		Very High	>85	10
Accessibility	Success index (%)	Very Low	0 - 1	1
		Low	1 - 3	3
		Medium	3 - 5	5
		High	5 - 8	8
		Very High	8 - 25	10
	Total Depth (m)	Very Low	0 - 20	10
		Low	20 - 40	8
		Medium	40 - 60	5
		High	60 - 80	3
		Very High	80 - 100	1
Exploitability	Operating yield (m³/h)	Very Low	1 - 5	1
		Low	5 - 15	3
		Medium	15 - 25	5
		High	25 - 40	8
		Very High	40 - 45	10
	Static Level (m)	Very Low	<10	10
		Low	10 - 20	8
		Medium	20 - 30	5
		High	30-40	3
		Very High	40 - 78	1

2.3.3. Weighting and Combination of Criteria

The criteria were weighted using the pairwise comparison method developed by

Saaty [25] [26] as part of the Analytical Hierarchy Process. It leads to standardized weighting coefficients whose sum is equal to 1. The weights used in this study are those obtained by [18] through the pairwise combination of criteria (**Table 2**). Their study was conducted in the Denguélé District, north of the Tonkpi region. These two areas therefore have similar geological and hydrogeological contexts.

Table 2. Assigning weights to different criteria [18].

Indicators	Criteria	Weights	Total
Availability	Slope	0.5	1
	Effective Infiltration	0.25	
	Drainage Density	0.13	
	Fractures Density	0.08	
	Weathering thicknesses	0.04	
Accessibility	Success index	0.25	1
	Total Depth	0.75	
Exploitability	Operating flow rate	0.25	1
	Static Level	0.75	

Once the weighting coefficients have been obtained, it becomes easier to combine the criteria. Thus, the thematic maps corresponding to slope, Effective Infiltration, drainage density, fracture density and weathering thickness were classified into four classes: Poor, Mediocre, Good and Excellent. These were then combined using layer addition (raster layer addition) to obtain the availability map. The process was repeated with total depth and success index to obtain the accessibility map, and with flow rate and static level to obtain the operability map. Finally, these three maps (availability, accessibility and exploitability) were combined to produce the map of potential areas for the siting of high-yield boreholes. All combinations were carried out in "Raster" mode, using the "raster calculator" tool.

2.3.4. Validation of Thematic Maps

The validation of the thematic maps consisted in calculating the uncertainties on the values of the parameters taken into account by each indicator. These uncertainties were determined on the averages of the various parameters as proposed by [18] and [27] translated by Equation (3).

$$\Delta\overline{X} = \sigma/\sqrt{n} \quad (3)$$

With,

$\Delta\overline{X}$: Uncertainty on the mean of data series,

σ : Standard deviation of the data series;

n: number of data sets.

In addition, an expansion factor K is calculated to determine the confidence interval. In fact, the K factor expressed by Equation (4), makes it possible to define an interval of sufficient scope having as its goal the certification of results [18].

$$K = \left| E - \Delta \bar{X} \right| / \sigma \quad (3)$$

With,

E: extreme value of the data series, which can be the maximum or minimum of the series.

$K = 1$, indicates a confidence level of 68%.

$K = 1$, expresses a confidence level of 68%.

$K = 2$, indicates a confidence level of 95%.

The confidence level is 99% when $K = 3$.

3. Results and Discussion

3.1. Results

3.1.1. Availability Map

Groundwater availability brings together the conditions required for the establishment of a probable aquifer. It is defined by the combination of slope, effective infiltration, drainage density, fracture density and alteration thickness. The purpose of the availability map is to guide the hydrogeologist in the design of water catchment structures, in order to obtain the best possible results. This map is made up of 4 classes distributed as follows (**Figure 2**): The poor availability class occupies 43.77% of the region and the mediocre class covers 16%. These classes characterize areas with low fracturing density and high drainage density. They are not recommended for drilling, as a dense hydrographic network is unfavorable for groundwater recharge. Good and excellent availability classes represent 14.60% and 25.63% respectively. They characterize suitable areas for drilling. They reflect good groundwater recharge. Fracturing is intense and contributes to the effective infiltration of meteoric water.

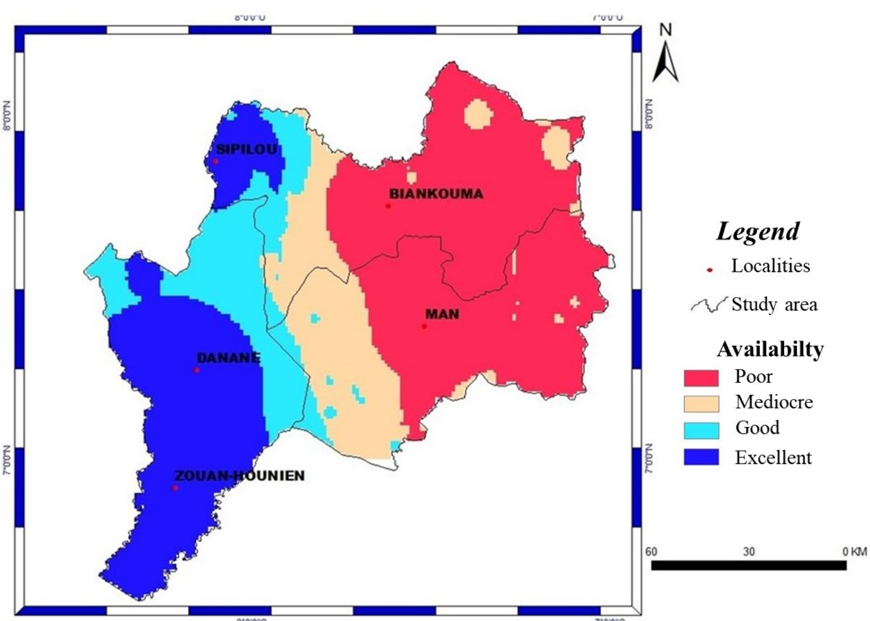

Figure 2. Groundwater availability map.

3.1.2. Accessibility Map

The groundwater resource accessibility map was produced after combining the total depth and success index criteria. **Figure 3** shows that poor and mediocre accessibility classes occupy more than half of the area (56.18%). They are located almost everywhere in the region (**Figure 3**). These are areas characterized by very low flows and very high depths, ranging from 45.2 to 84 m. The good accessibility class represents 31.82% of the total area of the region and is characterized by structures of generally shallow depths and with a high success index (>50%). The excellent accessibility class represents 12% of the study area. The areas characterized by the good and excellent classes are more or less scattered throughout the region, particularly in the center.

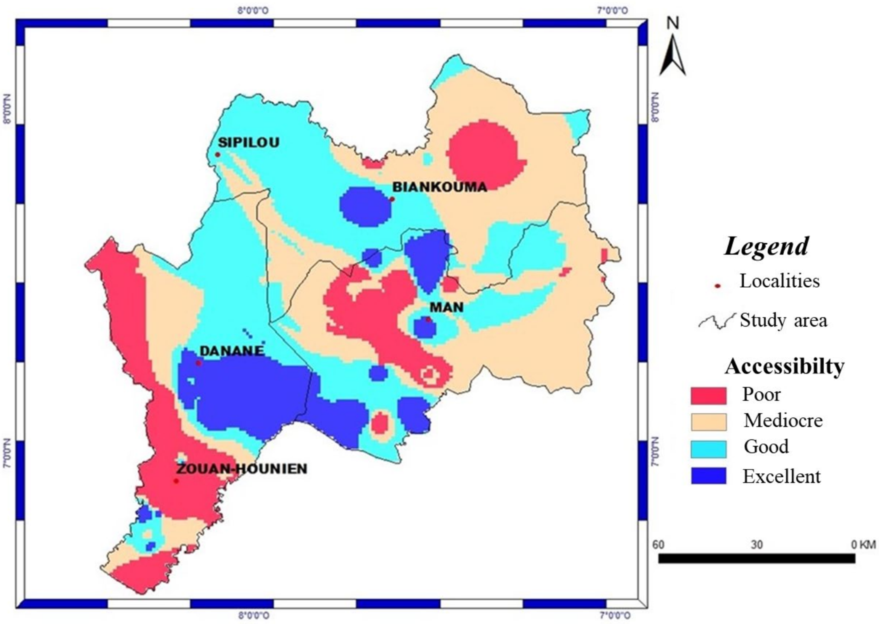

Figure 3. Groundwater accessibility map.

3.1.3. Exploitability Map

The cross-referencing of the exploitation rate and the static level led to the elaboration of the exploitability map (**Figure 4**). Analysis of the figure reveals four (4) exploitability classes, unevenly distributed across the study area. The poor class occupies 4.13% of the study area and is located in sectors where resources are generally not exploitable, although they are probably available. In fact, these areas are characterized by very low exploitation yields (<2 m^3/h) and a slightly deep static level (>10 m). They represent the survival threshold for wells, and the largest pocket is located in the northern part of the region. The mediocre exploitability class is estimated at 11.2%. It expresses a relative difficulty in exploiting underground resources and is mainly found in the northern part of the study area. This class includes areas that are favorable to village hydraulics. The good exploitation class is characterized by medium and high yields accompanied by lower static levels (8 - 11 m) and occupies 35.15% of the study area. These localities are ideal for supplying drinking water to secondary centers and for urban water supply. Finally, areas of excellent exploitability account for 49.52% of the region. They are characterized by medium to high flow rates (>10 m^3/h) and shallower static levels (<7 m). These zones are found to the west and east of the study area. They also constitute favorable areas for the supply of drinking water for urban hydraulics and secondary centers.

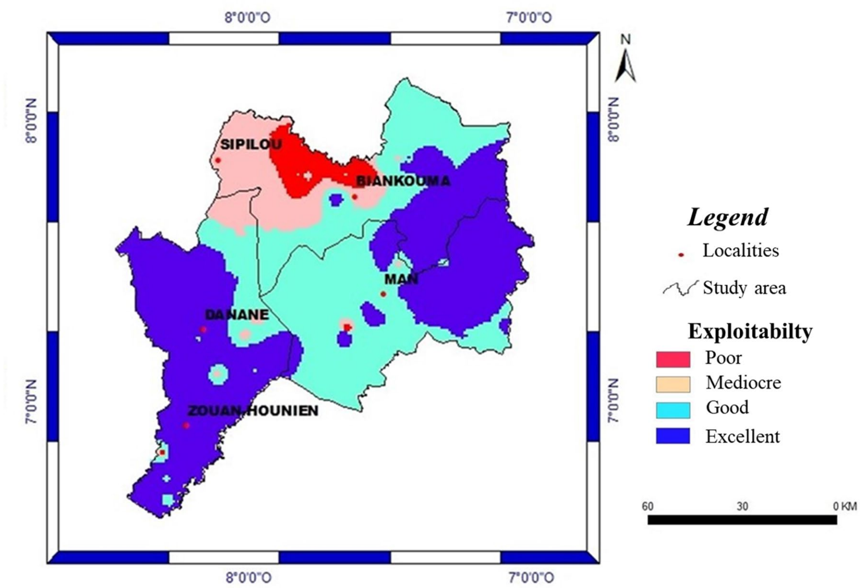

Figure 4. Groundwater exploitability map.

3.1.4. Groundwater Potential

The map of potential zones was produced by combining the thematic maps of availability, accessibility and exploitability. **Figure 5** shows four classes of zones suitable for borehole installation:

- The poor groundwater potential class covers 8.65% of the area studied. It is located mainly in the north and center of the region (Biankouma and Man). These areas are unsuitable for drilling as they are characterized by poor availability;
- The mediocre groundwater potential class covers 36.72% of the area, mainly in the eastern part of the region. These areas are suitable for the installation of boreholes with acceptable yields as part of village hydraulics. This class is characterized by mediocre to good availability, mediocre to good accessibility and mediocre to good exploitability;
- The good water potential class accounts for 29%. It is mainly found in the central and western parts of the region. These are acceptable zones for the installation of boreholes as part of Improved Village Hydraulics (IVH);
- The excellent potential class represents 25.63% of the study area. It is characterized by excellent groundwater availability and good to excellent exploitability. These zones are located in the west and north-west, notably in the depart-

ments of Sipilou, Danané and Zouan-Hounien. These zones are therefore the most sought-after for high-flow drilling campaigns.

In short, in the Tonkpi region, more than half of the land (54.63%) is suitable high-yields boreholes.

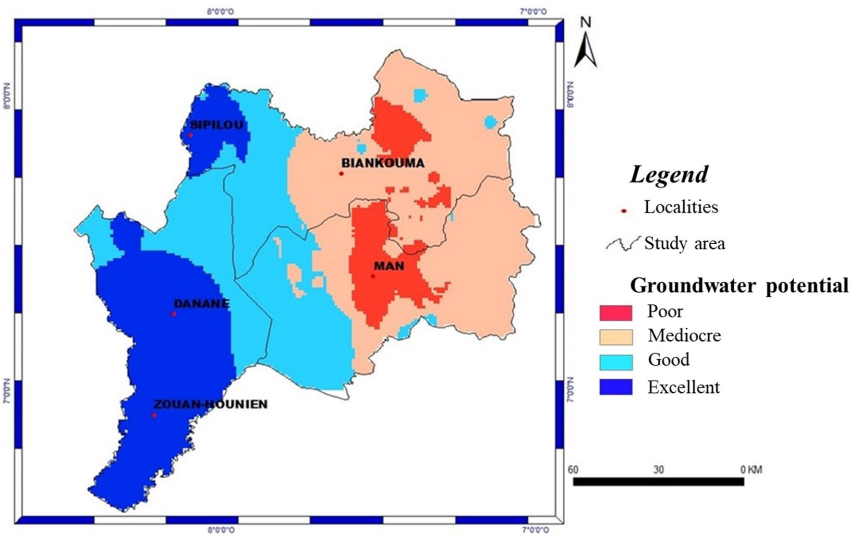

Figure 5. Groundwater exploitability map.

3.1.5. Validation of Thematic Maps

The validation of the thematic maps obtained consisted in calculating the uncertainties of the parameters used. Analysis of **Table 3** shows that the uncertainties of the parameters used to calculate groundwater availability are minimal (±0.06 to ±0.89), with the exception of groundwater recharge, which is ±54. This indicates a minimization of errors in the matrix calculations used to produce the availability map. However, the uncertainty on recharge is much higher, probably due to the low number of rainfall stations. On the other hand, the confidence levels are interesting, representing 95% for drainage density and 99% for groundwater recharge, weathering thickness and fracture density. In terms of accessibility parameters, the uncertainty is ±1.01 for the total depth and ±4.98 for the success index. Although these values are somewhat high, they are still acceptable, with respective confidence levels of 68% and 95%. With regard to the static level and yield used to assess groundwater operability, the errors are ±0.43 and ±0.95 for 99% confidence.

These uncertainty values and confidence levels show that errors were minimized in the creation of the various maps, thus demonstrating their validity.

Table 3. Uncertainties and confidence levels for thematic map evaluation criteria.

Criteria	Min	Max	Average	Standard deviation	Uncertainty	K	NC (%)
Slope	2.6	59.5	31.05	16.45	±0.69	1	68
Effective Infiltration	257.36	573.76	402.69	121.52	±54.34	3	99

Continued

Weathering thicknesses	3.65	52.65	18.48	9.23	±0.88	3	99
Drainage Density	1	4	1.29	0.55	±0.021	2	95
Fractures Density	0.013	8.82	1.99	1.58	±0.06	3	99
Success index	2	100	49.05	36.61	±4.98	1	95
Total Depth	16.13	88.4	59.48	10.64	±1.01	1	68
Operating high-yield	0.14	36	5.81	7.01	±0.95	3	99
Static Level	2.73	23.82	9.16	4.14	±0.43	3	99

3.2. Discussion

Multicriteria analysis is a valuable technique for characterizing geospatial hydrogeological phenomena involving several criteria. Coupled with GIS, multicriteria analysis makes an undeniable contribution to the management of groundwater resources and guides decision-making in land-use planning. In fact, they provide a pre-prospecting tool that avoids the need for cumbersome, time-consuming and costly research phases [28]. In the Tonkpi region, these techniques have led to the production of thematic maps: availability, accessibility and exploitability on the one hand, and the map of potential areas for the installation of high-yield boreholes on the other. They have been successfully applied in several regions of Côte d'Ivoire to identify favorable areas, [15] in Korhogo in the north of the country, [16] in Boundoukou in the east, [29] in the department of Oumé (Centre-west) and [18] in Odienné, in the northwest of Côte d'Ivoire. These techniques have also made it possible to select suitable sites for waste storage [26] and [24]. The potentiality map obtained shows that the Tonkpi region has good water potential, as do the regions of Korhogo [23], Bondoukou [16], M'bahiakro [30] and Oumé [29]. Thus, the water shortages observed in the region could be attributed to poorly conducted prospecting studies (often based solely on geomorphology) and drilling installation work [9].

Although multi-criteria analysis techniques are undeniable for their many advantages, they do have their limitations. In fact, parameter estimates often lack precision due to insufficient or totally missing data at certain points in the study area. In reality, the thematic maps produced only represent a relative assessment of the phenomena. However, these phenomena evolve over time and space. Multicriteria analysis is therefore error-prone, since it considers all the criteria involved in producing a thematic map to be perfectly comparable [21]. However, the technique of standardizing the criteria makes it easier to combine them. Several sources of error resulting from natural variations, numerical errors in the computer, the age of the data, etc. can somewhat alter the quality and reliability of the results. Despite all these shortcomings, it is interesting to note that GIS and multi-criteria analysis techniques offer results that are close enough to reality to facilitate decision-making in both groundwater research and exploitation.

4. Conclusion

The hydrogeological potential of the Tonkpi region was determined by assessing the three main factors involved in groundwater exploration, namely availability, accessibility, and exploitability. The groundwater potential map provides important preliminary information on spatial distribution of groundwater. It shows that more than half of the Tonkpi region (54.63%) is suitable for high-yield boreholes. The main areas with high groundwater potential (good and excellent classes) are located in the western part of the Tonpki region. These areas cover the entire department of Danané and some parts of Man and Biankouma departments. This groundwater potential map of the Tonkpi region can therefore be used as a reference document to guide hydrogeologists in hydrogeological prospecting campaigns. It will help to identify the areas to be investigated, thereby optimizing working time and financial resources and, above all, reducing failure rates. This map is therefore a decision-making tool for groundwater exploration. However, it could be improved or confirmed by in-situ measurements such as geophysics or exploratory drillings.

Acknowledgements

The authors would like to express the gratitude to the Hydraulics Regional Office of Man, in particular to Mr. YAO Franck Zokou, for providing the drilling data.

Conflicts of Interest

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

References

[1] Changwony, C., Sichangi, A.W. and Murimi Ngigi, M. (2017) Using GIS and Remote Sensing in Assessment of Water Scarcity in Nakuru County, Kenya. *Advances in Remote Sensing*, **6**, 88-102. https://doi.org/10.4236/ars.2017.61007

[2] Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., *et al.* (2017) Water Scarcity Assessments in the Past, Present, and Future. *Earth's Future*, **5**, 545-559. https://doi.org/10.1002/2016ef000518

[3] Lu, S., Bai, X., Zhang, J., Li, J., Li, W. and Lin, J. (2022) Impact of Virtual Water Export on Water Resource Security Associated with the Energy and Food Bases in Northeast China. *Technological Forecasting and Social Change*, **180**, Article ID: 121635. https://doi.org/10.1016/j.techfore.2022.121635

[4] Diawara, B.L., Jr, G.D.S.Q., Li, Z. and Loua, J.J. (2024) Water Scarcity in Conakry, Guinea: Challenges and Proposed Strategies for a Way Forward. *Journal of Water Resource and Protection*, **16**, 264-280. https://doi.org/10.4236/jwarp.2024.164015

[5] 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

[6] OMS-UNICEF (2021) Note d'orientation pour faciliter la consultation des pays sur les estimations sur l'eau de boisson, l'assainissement et l'hygiène dans les écoles. Rapport, Novembre 2021, 9 p.

[7] ONU (2015) Objectif du millénaire pour le développement. Rapport 2015, 78 p.

[8] Koukougnon, W. (2012) Milieu urbain et accès à l'eau potable: Cas de Daloa (centre-

ouest de la Côte d'Ivoire). Thèse unique de Doctorat en Géographie, Université Felix Houphouët Bobigny, 370 p.

[9] Kouassi, A.M., Coulibaly, D., Koffi, Y.B. and Biémi, 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.

[10] Juandi, M. (2018) The Interpretation of Underground Water Physical Parameters of Housing in the Region of Asahan Indah Palm Oil Factory Area Rokan Hulu District. *Open Journal of Modern Hydrology*, **8**, 119-125. https://doi.org/10.4236/ojmh.2018.84009

[11] Zahouli, B.G.D. (2023) Impacts de la dynamique paysagère et de la variabilité climatique sur les ressources en eau dans le bassin versant du Cavally à l'exutoire de Toulepleu (Ouest de la Côte d'Ivoire). Mémoire de Master, Université de Man, 61 p.

[12] Tiesse, C.B., Wandan, E.N. and N'da, H.D. (2017) Apport De La Teledetection Pour Le Suivi SpatioTemporel De L'occupation Du Sol Dans La Region Montagneuse Du Tonkpi (Cote D'ivoire). *European Scientific Journal*, *ESJ*, **13**, 310-329. https://doi.org/10.19044/esj.2017.v13n15p310

[13] Kouamé, K.F. (1999) Hydrogéologie des aquifères discontinus de la région semi-montagneuse de Man-Danané (Ouest de la Côte d'Ivoire). Apport des données des images satellitales et des méthodes statistique et fractale à l'élaboration d'un système d'information hydrogéologique à référence spatiale. Thèse 3ème cycle, Université de Cocody-Abidjan, 194 p.

[14] Avenard, J.-M., Eldin, M., Girard, G., Sircoulon, J., Touchebeuf, P., Guillaumet, J.-L. and Adjanohoun, E. (1971) Le milieu naturel de la Côte d'Ivoire. Mémoire ORSTOM, 50, 161-262.

[15] Jourda, J.P.R., Saley, M.B., Djagoua, E.M., Kouamé, K.J., Biémi, 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 fissure précambrien de la région de Korhogo (nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Revue Internationale de Télédétection*, **5**, 339-357.

[16] Youan Ta, M., Lasm, T., Jourda, J.P.J., Bachir Saley, M., Adja Miessan, G., Kouamé, K., *et al.* (2011) Cartographie des eaux souterraines en milieu fissuré par analyse multicritère. Cas de Bondoukou (Côte-d'Ivoire). *Revue Internationale de Géomatique*, **21**, 43-71. https://doi.org/10.3166/rig.21.43-71

[17] Youan, T.M., Yao, K.A.F., Bakar, D., De Lasm, Z.O., Lasm, T., Adja, M.G., Kouakou, S., Onétié, Z.O., Jourda, J.P.R. and Biémi, J. (2015) L'implantation des forages a gros débits en milieu fissure par analyse multicritère cas du département d'Oumé (Centre-Ouest de la Côte d'Ivoire). *Larhyss Journal*, No. 23, 155-181.

[18] Pinatibi, H., Coulibaly, N., Coulibaly, T.J.H. and Savane, I. (2015) Cartographie des potentialités en eaux souterraines par l'utilisation de l'analyse multicritère et les SIG: Cas du district du Denguelé (Nord-Ouest de la Côte d'Ivoire). *European Scientific Journal*, **11**, 106-122.

[19] Koudou, A., Kouamé, K.F., Youan Ta, M., Saley, M.B., Jourda, J.P. and BiemI, J. (2010) Contribution des données ETM+ de Landsat, de l'analyse multicritère et d'un SIG à l'identification de secteurs à potentialité aquifère en zone de socle du bassin versant du N'zi (Côte d'Ivoire), *Photo-Interpretation European Journal of Applied Remote Sensing*, **3-4**, 98-115.

[20] 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). *Revue*

des sciences de l'eau, **31**, 129-144. https://doi.org/10.7202/1051696ar

[21] Youan Ta, M. (2008) Contribution de la télédétection et des systèmes d'information géographiques a 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), 236 p.

[22] Mangoua, M.J., Dibi, B., Koblan, E.W., Douagui, G.A., Kouassi, K.A., Savané, I. and Biémi, J. (2014) Map of Potential Areas of Groundwater by the Multi-Criteria Analysis for the Needs for Water of the Baya's Catchment Basin (East of Côte d'Ivoire). *Academic Journals*, **9**, 3319-3329.

[23] Jourda, J.P. (2005) Méthodologie d'application des techniques de Télédétection et des systèmes d'information géographique à l'étude des aquifères fissures d'Afrique de l'Ouest. Concept de l'hydrotechnique spatiale: Cas des zones tests de la Côte d'Ivoire. Thèse de Doctorat d'Etat, Université de Cocody, 430 p.

[24] Kouamé, K.J. (2007) Contribution à la gestion intégrée des ressources en eaux (GIRE) du district d'Abidjan (Sud de la Côte d'Ivoire): Outils d'aide à la décision pour la prévention et la protection des eaux souterraines contre la pollution. Thèse unique de doctorat, Université de Cocody, 225 p.

[25] Saaty, T.L. (1977) A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology*, **15**, 234-281. https://doi.org/10.1016/0022-2496(77)90033-5

[26] El Moorjani, Z. (2003) Conception d'un système d'information à référence spatiale pour la gestion environnementale; application à la sélection de sites potentiels de stockage de déchets ménagers et industriels en région semiaride (Souss, Maroc). Thèse de doctorat, Université de Genève, Terre et Environnement, Vol. 42, 300 p.

[27] Doumouya, I., Dibi, B., Kouame, K.I., Saley, B., Jourda, J.P., Savane, I., *et al.* (2012) Modelling of Favourable Zones for the Establishment of Water Points by Geographical Information System (GIS) and Multicriteria Analysis (MCA) in the Aboisso Area (South-East of Côte D'ivoire). *Environmental Earth Sciences*, **67**, 1763-1780. https://doi.org/10.1007/s12665-012-1622-2

[28] Langevin, C., Pernel, F. and Pointet, T. (1991) Aide à la décision en matière de prospection hydrogéologique. L'analyse multicritère au service de l'évaluation du potentiel aquifère, en milieu fissuré (granite de Huelgoat, Finistère, France). *Hydrogéologie*, No. 1, 51-64.

[29] Akossi, O.S. (2009) Apport de la télédétection et d'un système d'informations géographiques dans la détermination des zones potentielles en eau souterraine du département de M'Bahiakro (Centre-Est de la Côte d'Ivoire). Mémoire de DEA des Sciences de la Terre, option Hydrogéologie, Université de Cocody, 93 p.

[30] Yao, K.A.F. (2014) Cartographie des ressources en eau souterraine de la région d'Oumé: Détermination des sites potentiels à l'implantation de forages gros débits par la méthode d'analyse multicritère. Mémoire de Master, Université Félix Houphouët-Boigny, 82 p.