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Mapping of Favourable Areas for the Establishment of Hydraulic Boreholes by Multicriteria Analysis in the Department of Yamoussoukro (South Central Côte d'Ivoire)

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ABSTRACT

Water is essential to life and an indisputable socio-economic asset. It is probably the most important of all natural resources. The aim of this study is to identify areas suitable for hydraulic drilling in the Yamoussoukro department. The application of GIS, multi-criteria analysis and field surveys have produced convincing results. These results highlight the good and excellent availability of groundwater in 32.22% of the department's surface area. The excellent accessibility class covers 11% of the territory. The department of Yamoussoukro has modest groundwater resources, with a proportion of 45.6% and a maximum flow rate of 12.5m3h-1. Areas favourable for productive drilling occupy around 30% of the department, compared with 70% considered less favourable.

Keywords: Yamoussoukro, mapping, favourable groundwater zones, GIS and multicriteria analysis

INTRODUCTION

Groundwater is a major global reservoir of freshwater. It is much less vulnerable than surface water. This water, which comes from captive and surface aquifers, is exploited by mankind for a variety of uses. Groundwater is a vital resource for meeting the freshwater needs of communities. According to the work of Lachassagne et al. (2001) and Assemian (2014), basement aquifers worldwide have a modest water production capacity, with flows of up to 50 m3 h-1. Their recharge is generally dependent on rainfall, weathering and the porosity of cracks or tectonic fractures.

In Côte d'Ivoire, the advent of global warming and strong anthropogenic pressure on the primeval forest ecosystem have led to a significant reduction in aquifer recharge and the drying up of a large number of surface waters (Assemian, 2014). In some areas, the region is experiencing drinking water supply problems.

Following the example of the other districts of Côte d'Ivoire, an inventory of the various water catchment structures was carried out in the Yamoussoukro district in 2001 by the Direction Régionale d'Hydraulique. This identified 438 water points, 306 of which were in the Yamoussoukro district. However, of these 306 structures, 102 have been abandoned for various reasons (mechanical breakdown and drying up), 05 have been declared negative because they have not reached a minimum flow rate of 1 m3h-1 and 74 have been converted to AEP (DDH, 2001). This is also due to the poor choice of borehole location and ignorance of the hydraulic and hydrodynamic properties of aquifers. In addition, the hydrodynamic characteristics of the aquifers in the basement formations of the Yamoussoukro department are known only in summary form. The optimum depths and productive zones for groundwater are in part unknown, which more often than not results in negative drilling at exorbitant cost. In view of the above, it is important to dwell on the subject entitled: "Mapping of favourable areas for the installation of hydraulic boreholes to obtain good flow rates using GIS and multi-criteria analysis in the Yamoussoukro department in the Centre-South of the Ivory Coast". As a result, the problem of unsatisfied water needs has arisen due to the limited use of GIS to identify areas suitable for the installation of hydraulic boreholes. The aim of this study is to identify areas suitable for the installation of hydraulic boreholes in the Yamoussoukro department. Specifically, it involves a spatial analysis of groundwater indicators and the mapping of areas suitable for hydraulic drilling.

MATERIALS AND METHODS

Presentation of the Study Area

The department of Yamoussoukro is located in south-central Côte d'Ivoire, between longitudes 5°30'W and 5°10'W and latitudes 6°36'N and 6°70'N).

It benefits from a transitional equatorial climate that favours the growth of a wooded savannah with gallery forests. This area, which occupies the eastern part of the Bandama Blanc watershed, is dominated by low plateaux with altitudes ranging from 32 to 471 m. The soils in this landscape are ferralitic and hydromorphic (ANADER, 2004).

The geological formation (Figure 1) is essentially made up of Proterozoic formations dominated by the Baoulé and Abronian granitoid complexes and Birimian formations. The drilled subsoil belongs to the discontinuous aquifer domain, composed of schistose bedrock, generally with thick layers of alterites and granitic bedrock (Adiaffi, 2008). Discontinuous aquifers contain reservoirs that often function as composite aquifers made up of alterites and fissures. These hydrogeological formations are important resources for groundwater exploitation.

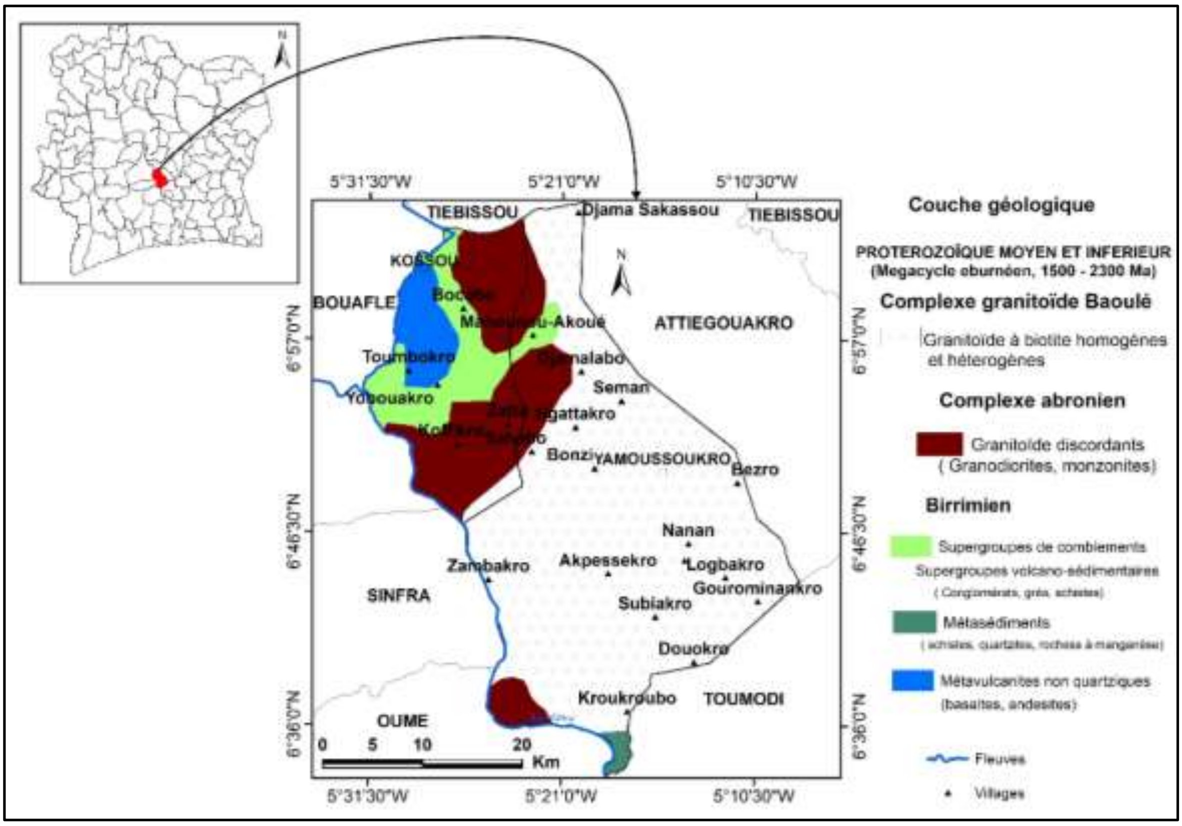


Figure 1: Location of Yamoussoukro department

Data and Software Used

The data used for this study were hydrogeological, climatological and satellite imagery. The hydrogeological data were obtained from the Direction Territoriale d'Hydraulique de Yamoussoukro. This consisted of technical data from 196 boreholes. Climatological data (rainfall and temperature for the period 1974-2020) were obtained from the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM). Satellite imagery is of the DTM (Digital Terrain Model) type for 2014 from the SRTM sensor, downloaded from the https://earthexplorer.usgs.gov/ website. To process the data, ENVI 5.3 and ArcGIS 2.2 were used to extract the lineaments and ArcGIS 2.2 was used to produce the various thematic maps.

Methods

Determination of effective aquifer recharge or infiltration

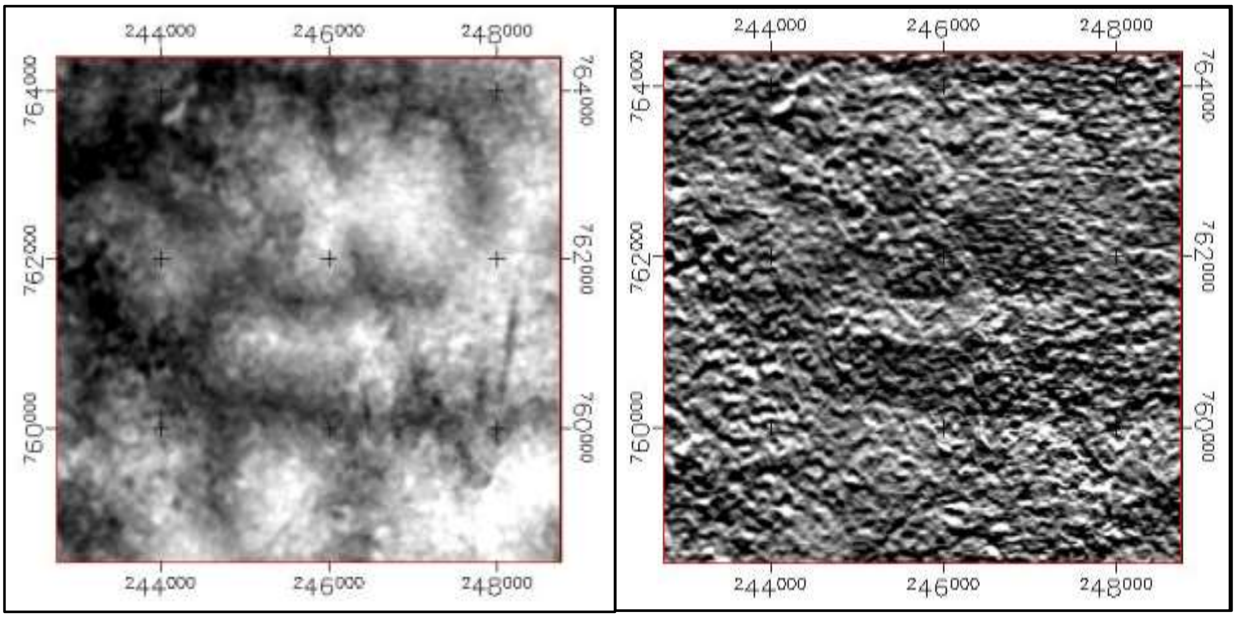
Infiltration is calculated by applying the hydrological balance. It is determined by the following formula:

$$Ie=P-(ETR+R)$$

Where P: rainfall (mm); R: runoff (mm); ETR: actual evapotranspiration (mm).
R and ETR are calculated using the methods of Tixeront-Berkaloff (1969) and Turc (1961) respectively.

Highlighting lineaments on the DTM

The DTM is processed by enhancing structural discontinuities to identify fractures (Figure 2).



A: Unprocessed DTM image of the study area and B: Processed DTM image of the study area

Figure 2: Applying Shaded Relief to the DTM

The Shaded Relief method under a size (Topographic Kemel Size 3) of Azumite 5 and elevation 6 of the ENVI 4.7 software is applied. This application has the particularity of enhancing structural lineaments (fractures). It accentuates the morpho-structural discontinuities on the DTM, in order to map most of the fractures in the Yamoussoukro department.

Lineament extraction

The choice of using DTM to extract lineaments is explained by the fact that SRTM sensor images are digital radar terrain models that explicitly represent physical features such as the hydrographic network, mountain ridges, slope breaks, structural accidents and their apparent or real discharges (Kanohin et al., 2012). Thus, in these images, lineaments are materialised by the boundaries formed by dark and light areas, which can sometimes extend over several kilometres (Youan et al., 2008). To extract structural lineaments, the methodological approach used consists of manually extracting lineaments using photo-interpretation. This method gives better results as it has been applied by many researchers (Youan et al., 2008; Kanohin et al., 2012; Assemian, 2014; Assoma et al., 2018). The fine structures, shapes and structural lineaments are clearly perceptible, and it is easy to record them by vector digitisation using ArcGIS software, simply by observing the images visually. Fracture density was obtained from fractures extracted from SRTM images. Figure 3 below highlights the extraction of lineaments.

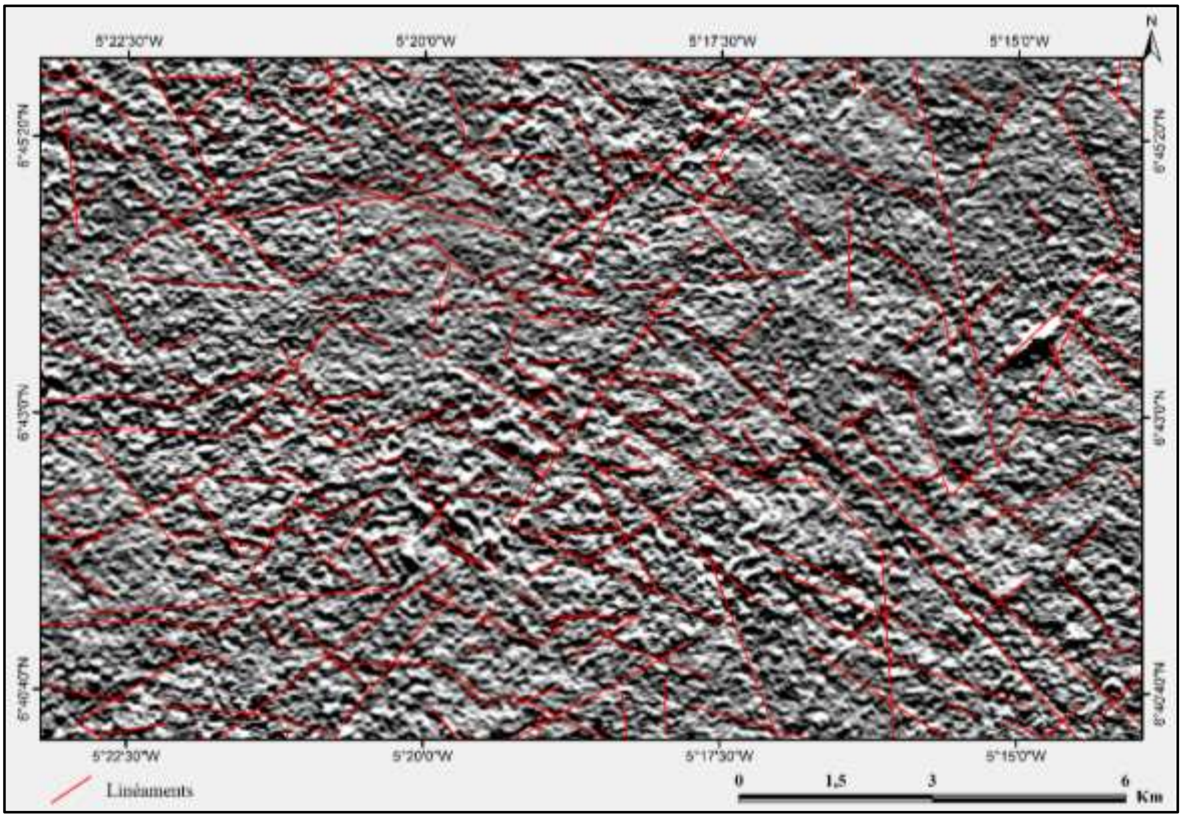


Figure 3: Lineament extraction

Lineament validation

The manually extracted lineaments were statistically analysed to construct the directional rosette using RockWorks 16 software to highlight the main (major) directions. Previous work by Assoma, et al. (2018) and Mangoua, et al. (2019) validated the lineaments obtained. Fracturing plays an important role in reservoir formation in crystalline and crystallophyllous terrains. Thus, knowledge of these phenomena through the study of lineaments using remote sensing tools is important for the characterisation of fractures and also for the mobilisation of groundwater resources.

The number of lineaments recorded on the map amounts to 1,210 structural elements, ranging in length from 0.26 km to 10.64 km, with an average length of 1.67 km in the field. The total length of the mapped lineaments is approximately 2027.67 km. The longest lineament (10.64 km) runs from the centre to the south-east of the study area in a NW-SE direction from Bonzi to Bozré via Yamoussoukro (Figure 4).

The fracture density was obtained from the fracture map. Fracture density is defined by the number of fractures or the cumulative length of fractures per mesh (1 km square in our case).

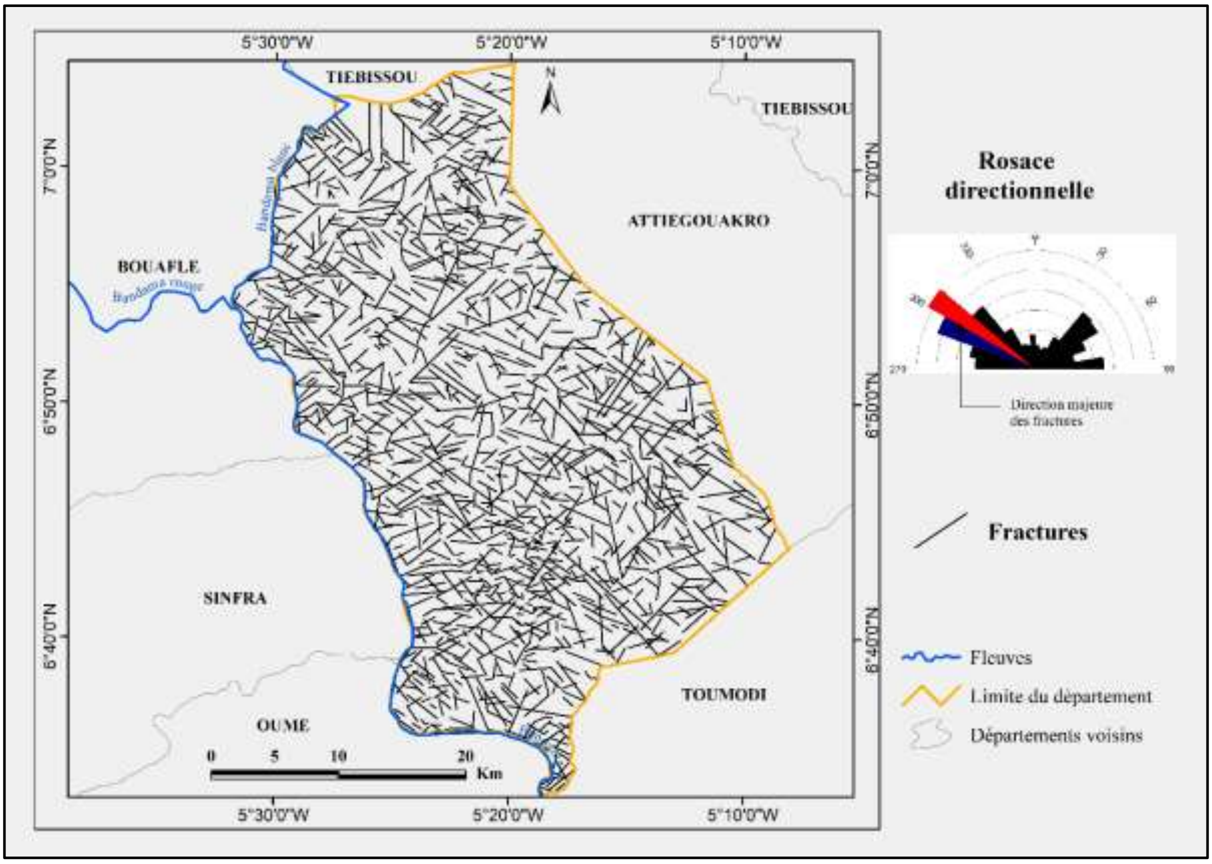


Figure 4: Detailed fracturing of the Yamoussoukro department

Multi-criteria analysis

The methods used to produce thematic maps of aquifer productivity are based on the use of GIS. The objective is to draw up thematic maps capable of describing the spatial groundwater productivity of the basement aquifers in the Yamoussoukro department. In order to model the indicators of groundwater availability, accessibility and usability, the approach adopted as part of this work followed the following stages: identification of decision criteria, classification and standardisation of the criteria.

Identification of decision criteria

With reference to the work of Kanohin et al. (2012), Assemian (2014) and Yao et al. (2016) and depending on the availability of data, a number of criteria were identified for drawing up the various thematic maps of water resources. These criteria are slope (%), drainage density (Km/Km²), alteration thickness (m), fracturing density (km/Km²), effective recharge (mm), success index (%), total depth (m), operating flow rate (m3h-1) and static level (m).

Classification and standardisation of criteria

The different criteria were classified taking into account previous studies carried out by Yaouan et al. (2008), Assemian (2014). Three types of techniques were used for spatialization depending on whether the criterion is represented by points, polylines or polygons. Thus, points such as the depth of structures and the success index were interpolated using the "interpolatation-IDW" command in ArcGIS10.2 software; polylines were converted to points in ArcGIS software using the "Feature To Point" command for their interpolation. The different surfaces obtained following these operations were divided into five classes as shown in Table 1.

When standardised, the very unfavourable class always has the lowest score and the very favourable class the highest. However, these scores also depend on the quality of the factor. That is, if the factor fulfils the most interesting conditions where a large proportion of the values are maximum (100%). The very favourable class takes the highest score (weight). In the opposite case, the very unfavourable class takes the small value.

Availability indicator. The availability indicator expresses the notion of the existence of an aquifer and is the first condition to know, before any other activity (Yao et al., 2016). It results from the combination of parameters such as slope, drainage density, fracture density, weathering thickness and infiltration.

Accessibility indicator. Groundwater reserves are only truly usable when certain parameters combine to make access possible. The most important of these are the total depth (Pt) of the structures and the success index (Is) (Yao et al., 2016).

The success index gives the probability of drilling success. It varies from 10 to 100%. According to the recommendations of the Office National de l'Eau Potable (ONEP), the success index makes it possible to distinguish between areas of good productivity characterised by positive boreholes ($a \geq 10\%$) and areas of low productivity with a high number of negative boreholes ($a < 10\%$). A borehole with a success index $a > 10\%$ is therefore accessible to the population for exploitation.

Exploitability indicator. The water resource is exploitable only if the exploitation rate is significant (at least 1m3h-1). The exploitation rate itself is conditioned by the quantity of water available in the underground reserve and the speed of renewal of this reserve in the event of heavy demand (Youan, 2008). The factors used to highlight the exploitability indicator are the exploitation flow rates and the static level, with great importance given to the exploitation flow rates in reference to the work of Kanohin et al. (2012).

Weighting of assessment factors

The assessment factors were weighted using the pairwise comparison method developed by Kanohin et al. (2012), Yao et al. (2016) as part of the Analytical Hierarchy Process. It produces standardised weighting coefficients whose sum is equal to 1 (Table 1). The combination obtained using this method is estimated by: $S = \Sigma WiXi$, with S the result of the combination, Wi the weight of factor i and Xi the value of the criterion of factor i.

After this weighting stage, the multi-criteria analysis is completed by combining the various criteria. The integration of the criteria and the analysis were carried out in a GIS environment. The procedure involved firstly rasterising all the criteria (interpolation by the inverse of the weighted distance (IDW)) and secondly combining all the raster layers resulting from the rasterisation. This combination of layers was made possible by using the 'raster calculator' function in the 'spatial analysis' sub-menu of the Arc Gis 10.2.2 software.

Table 1: Weighting of the various criteria according to the nature of the card

Indicators	Criteria	Weight	Total
Availability	Infiltration (mm)	0,3	1
	Fracturing density (Km/Km^2)	0,2	
	Drainage density (Km/Km^2)	0,2	
	Slope (%)	0,2	
	Alteration thickness (m)	0,1	
Accessibility	Total depth (m)	0,25	1
	Index of success	0,75	
Operability	Operating flow rate (m h)$^{3-1}$	0,7	1
	Static level (m)	0,3	

Data spatialization techniques

The inverse weighted distance (IDW) method was chosen to spatialise the groundwater potential indicators. The IDW technique makes it possible to predict the attribute value of a variable at positions where no sample is available on the basis of the spatial distance between this position and other positions where samples have been collected. Observations that are spatially closer to the observation to be predicted receive a greater weight in the prediction, while observations that are further away will have a relatively small influence on the prediction. The weight assigned to each sample is also controlled by a power parameter p. As p increases, the weight assigned to distant samples decreases.

RESULTS

Availability of Groundwater Resources

In Yamoussoukro department, areas with good and excellent availability cover only 32.22% of the department (Figure 5).

They provide favourable conditions for the accumulation of groundwater and, consequently, for the formation of significant reserves. In these areas, the large interconnected open fractures have a high probability of being productive. It appears further south, with intrusions in the north-west. These zones are the most sought-after in hydraulic campaigns, as they contain huge reserves of underground water.

The class with poor groundwater availability covers 33.74% of the territory. It is found in the central-eastern part. This class indicates poor groundwater recharge in these areas. Next, the average availability class is the most represented with 34.03%. This class is found almost everywhere in the county, but is more prevalent in the central band running north-south-east. This class does not favour the formation of large underground reservoirs.

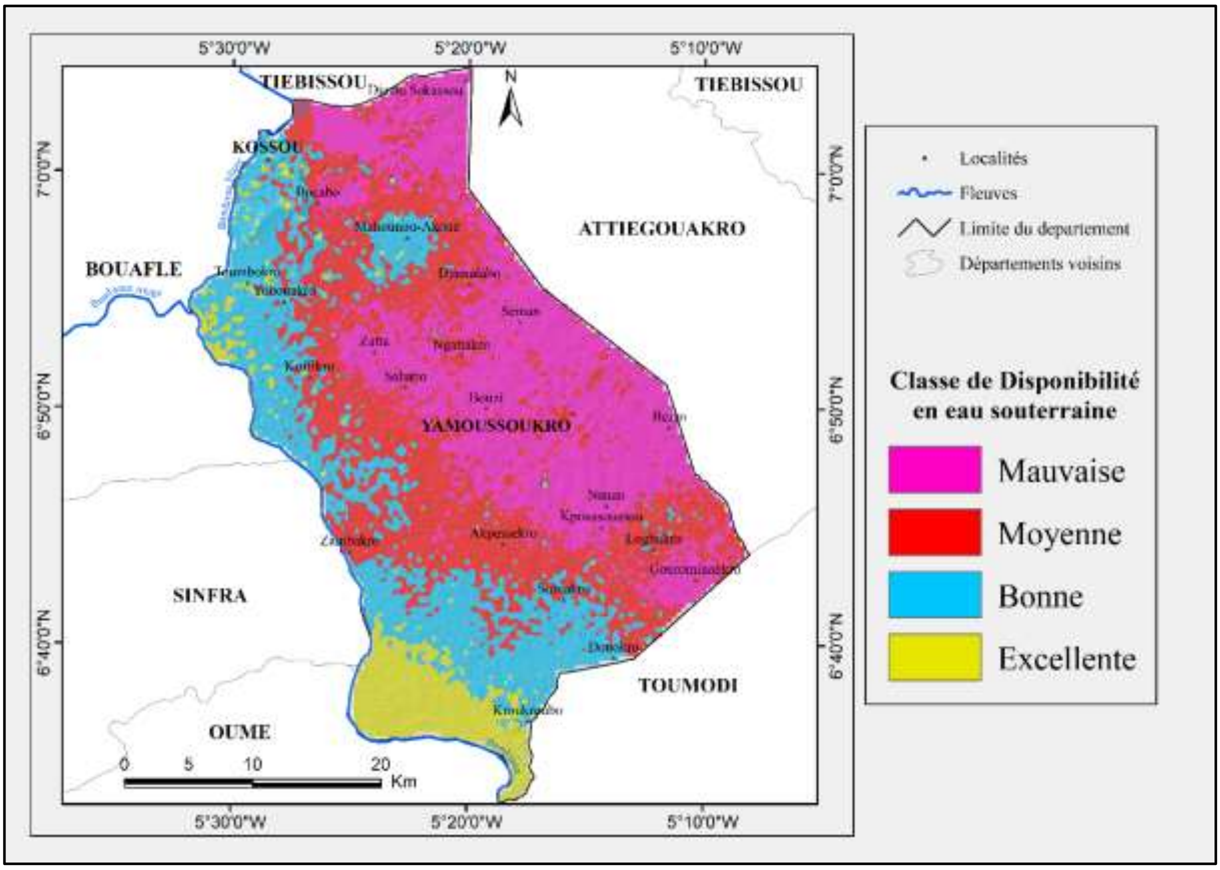


Figure 5: Spatial distribution of groundwater availability

Accessibility of Groundwater Resources

The study of the accessibility of groundwater resources depends on the parameters of the depth of the structure and the success index. A multi-criteria analysis of these two parameters was used to produce the groundwater accessibility map for the department (Figure 6).

The accessibility map of groundwater resources in Yamoussoukro department shows that the good and excellent accessibility classes cover 29% of the area. They are characterised by shallow depths to obtain positive flows. These classes are also determined by high fracturing densities and frequently high drilling flow rates. The depths at which strong flow rates are obtained are more or less shallow. They are identified in the centre-east, north and west. The average accessibility class covers 36% of the total surface area. It is more pronounced in the north, with smaller areas in the centre-south. These areas are sometimes characterised by thick weathering and often the depths at which significant flows are obtained are very high. The class of poor water accessibility covers 35% of the total surface area. It dominates the southern part. These areas have deep boreholes with very low flow rates.

Access to groundwater resources in the Yamoussoukro department is modest. This could be one of the characteristics of basement aquifers developed on volcano-sedimentary formations.

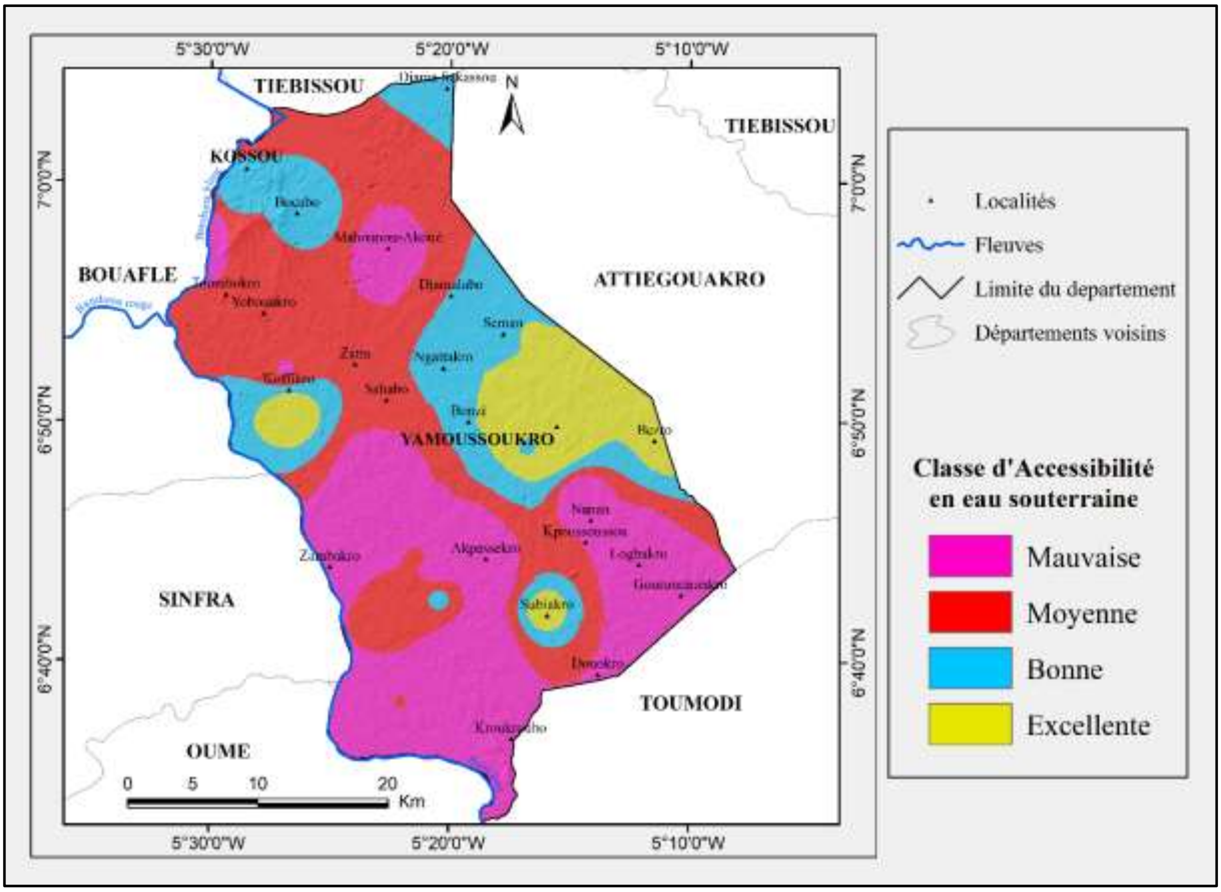


Figure 6: Spatial distribution of access to groundwater resources

Exploitability of Groundwater Resources

The exploitability of groundwater resources is guided by the flow that can be drawn from the water table. To produce the exploitable map (Figure 7), the criteria of exploitable flow and static level are used.

The poorly exploitable class is located in the central part of the department, with the exception of the east, with intrusions in the north-west and south-east. It covers 36% of the department's total surface area. It is characterised by areas with very low flows and very high static levels. The class with average operability is spread across the whole of the department, with a proportion of 42%. Borehole flow rates in this category are rarely high. The class with good operability is characterised by medium and high flow rates, with relatively low static levels. It accounts for around 20.2% and is concentrated mainly in the north, with intrusions in the centre and south. These areas are ideal for supplying drinking water to densely populated towns. The excellent exploitable class occupies only 2% of the territory. This sector is concentrated in the north-west, at the extreme end of the zone of good exploitability. Borehole flow rates are generally very high (> 5 m3h-1) in these localities.

The department of Yamoussoukro has modest exploitable groundwater resources, with a proportion of 45.6% and a maximum flow rate of 12.5m3h-1. These regions coincide with peneplain zones with high fracture densities and thick weathering.

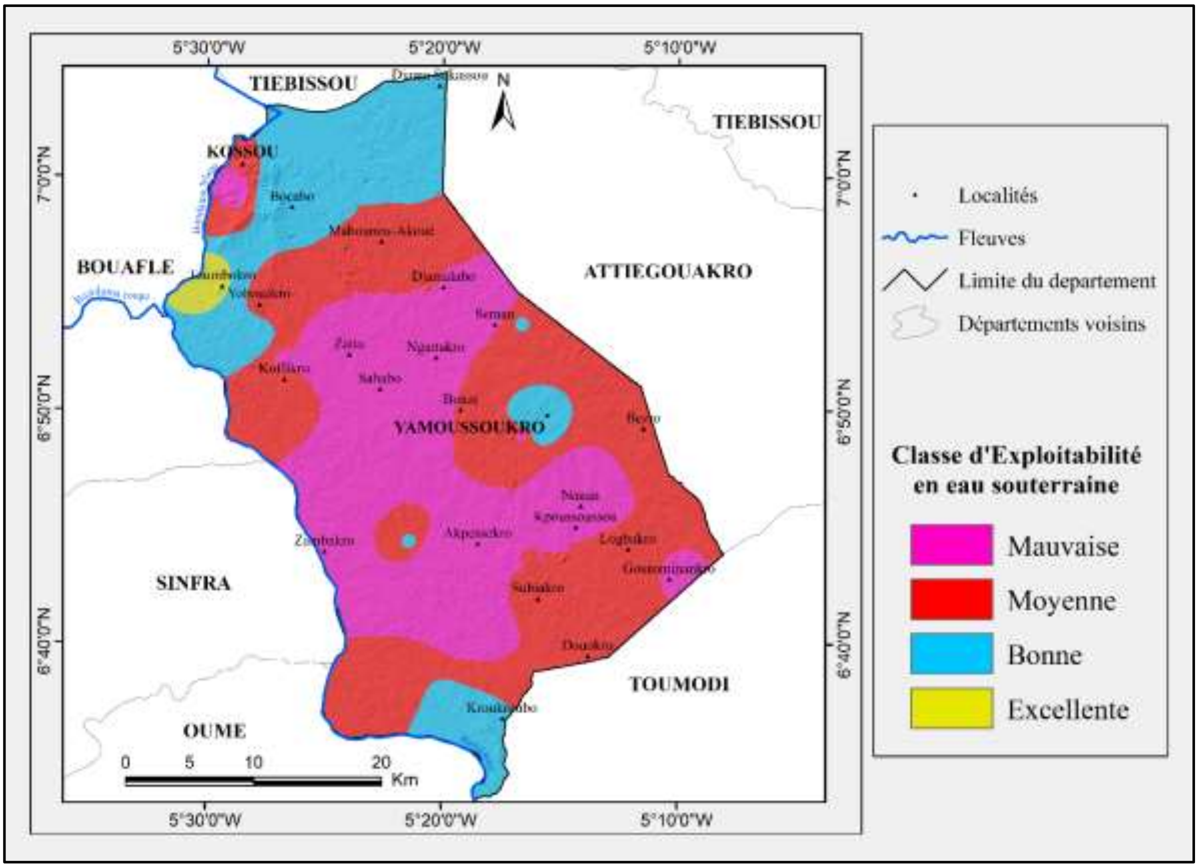


Figure 7: Spatial distribution of exploitable groundwater resources

Mapping of Areas Suitable for Hydraulic Drilling

By combining the three indicators of availability, accessibility and usability, it was possible to produce a thematic map of favourable areas for the installation of productive boreholes (Figure 8). Observation of the map shows that the classes of good and excellent favourable areas cover around 30% of the department, compared with 70% considered less favourable.

The different classes of areas favourable to drilling show that the class of poor areas is represented by a proportion of 25.30% of the department. These are areas of poor or mediocre availability and accessibility, to which poor operability may be added. Most of these areas are found in the centre-south of the county. This class is also marked in the north. These are areas where water availability is poor and accessibility is not obvious. These areas are characterised by less fractured geological structures made up of granitoids, making infiltration difficult. Next, the medium zone class covers 45.09% of the department and covers areas of average availability and accessibility, sometimes combined with good workability. It is found almost everywhere in the county. However, the north and south are predominant. In this area, the density of fracturing is low, with average recharge of the water table. Borehole flow rates fall over time. Under these conditions, boreholes can dry up. However, these areas are suitable for the installation of boreholes as part of village hydraulics. In addition, the class of areas suitable for drilling covers 23.62% of the county, in the east and north and in the south at Subiakro and Kroukroubo. These zones are characterised by a high fracturing density, with a relatively shallow gradient. This enables the aquifer to be well recharged. Boreholes can be drilled in these zones as part of improved village hydraulics (HVA). Finally, the class of zones that are excellent for the installation of high-flow boreholes covers only 5.98% of the county. It is identified within the class of areas that are good for drilling in the centre-east, west and south. These areas have an excellent availability of groundwater that is easily accessible and exploitable for drinking water supply. They are also highly fractured zones in places. This class is the most sought-after during campaigns to install high-flow boreholes. According to Assemian (2014), in highly fractured regions, basement aquifers offer high flow rates at shallow depths. Therefore, a borehole located near a fracture will certainly produce a good flow, as the interconnection between the favourable fractures.

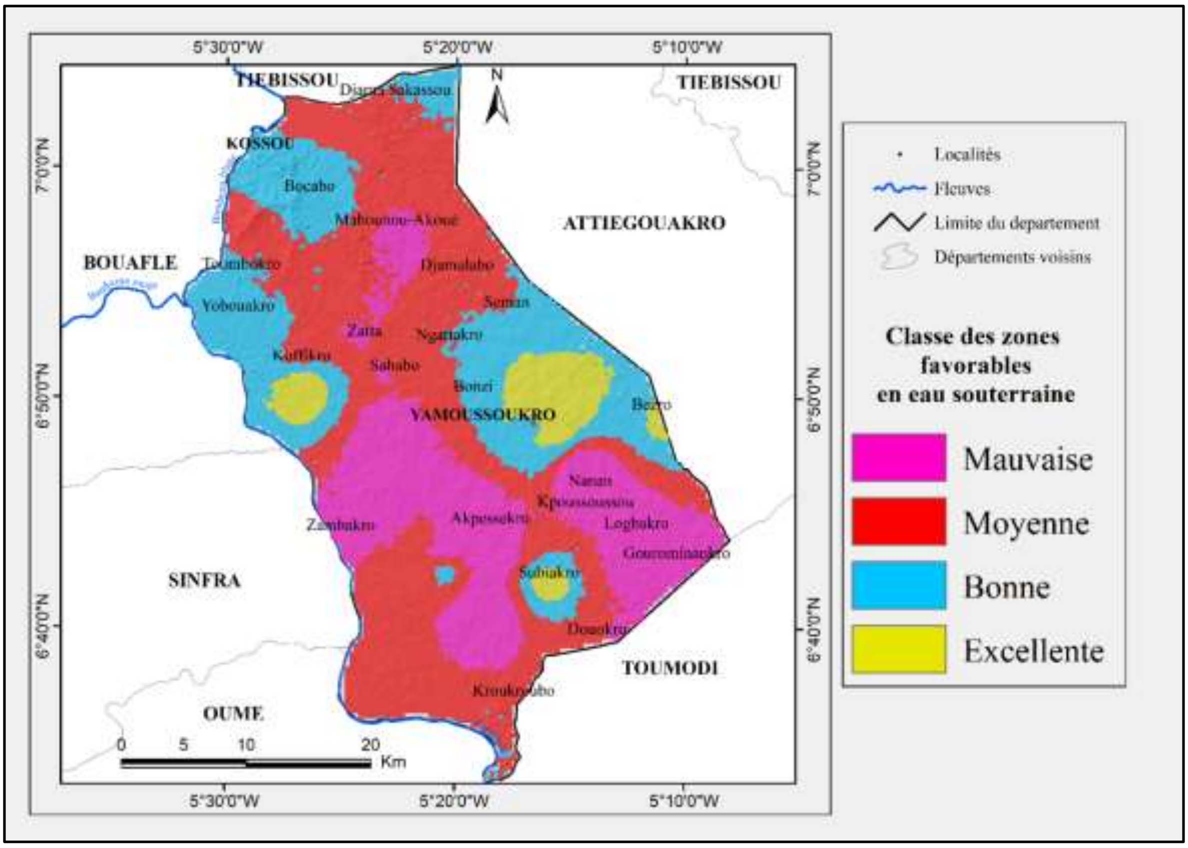


Figure 8: Spatial distribution of areas favourable to the installation of high-flow hydraulic boreholes

DISCUSSION

This study highlights the zones that are favourable for the installation of high-capacity boreholes in the Yamoussoukro department. By combining maps of availability, accessibility and usability, it was possible to produce a map of areas suitable for the installation of high-capacity hydraulic boreholes. Multi-criteria analysis methods have been used by many researchers. They have been used to map areas that are favourable for the installation of high-capacity boreholes (Youan et al., 2011; Assemian, 2014; Pinatibi et al., 2015). Studies carried out in the Bondoukou, Bongouanou and Denguele districts respectively by Youan et al. (2011), Assemian (2014) and Pinatibi et al. (2015) have shown that groundwater accessibility and usability are relatively modest. Their work was carried out using GIS and multi-criteria analysis. The results of these studies are consistent with the results obtained in this study. GIS and multi-criteria analysis have many advantages in the study of groundwater. They make an undeniable contribution to water resource management and rational decision-making. These results constitute pre-prospecting that avoids the need for heavy, slow and costly research phases (Pinatibi et al., 2015). Studies carried out at the scale of the Bandama catchment area by Mangoua et al. (2019), which includes the Yamoussoukro department, show that the Bandama basin has good groundwater reservoirs. This could conceal local disparities when considering this scale of analysis. However, in the department of Yamoussoukro, the classes of good and excellent areas for the installation of high-flow hydraulic boreholes occupy only 29.6% of the surface area, which is low compared with the poor and average classes (over 70%). The method of estimating recharge, which is one of the most important parameters in mapping water availability, could influence the results. Infiltration is a spatially discontinuous phenomenon and interpolation biases the result at the boundaries of recharge zones with different values. The thematic maps (accessibility, availability and usability) were therefore drawn up using interpolation. Although this method makes it possible to give values in sectors where no data are available, it leads to errors in the production of these indicators, as it is only reliable within the intervals delimited by the point data (Mangoua et al., 2019).

CONCLUSION

The study uses GIS and a multi-criteria analysis to highlight areas that are favourable for the installation of hydraulic boreholes. Favourable areas are identified in the centre-east, west and south of the department. These areas have an excellent supply of easily accessible groundwater that can be used to supply drinking water.

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