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)

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Received 18 April, 2014; Accepted 15 August, 2014

The watershed located Baya is facing difficulties of drinking water supply. The objective of this study is to develop a model for preferential zone mapping to the implementation of water points. To achieve this objective, a combined approach of Geographic Information System and Multicriteria Analysis has been adopted for the mapping of these preferential. Multi-criteria analysis methods including Boolean method and the linear combination of weights based on pairwise comparisons were used. Two types of indicators were used: The productivity indicator which combines the accessibility, exploitability and availability of groundwater and control indicator, which is represented by the vulnerability to pollution in groundwater. It appears that the preferential zone of future water points implantation covers 84% of the catchment area. When making water productivity map, the calculation of uncertainties parameters show that the most sensitive parameters are: The slope, recharge, induced permeability and total depth. However, the topography, vadose zone and hydraulic conductivity are the most sensitive to the development of the map of vulnerability to pollution. The errors determined on different maps are respectively 12, 20 and 12% for productive zone, vulnerability and preferential zone. Preferential areas cover almost all of the study area and are influenced by the topography, vadose zone and hydraulic conductivity; the margin of error is low.

Key words: Geographic information system, multi-criteria analysis, groundwater, vulnerability, catchment of Baya.

INTRODUCTION

Groundwater is one of the largest worldwide resources. In most countries, it provides drinking water to more than half of the population and is the only source of drinking water for many rural communities and some large cities (Hamza et al., 2007). Groundwater is also the source of much of the water used for irrigation and is a major...
contributor to flow in many streams and rivers, and has a strong influence on the river and wetland habitats for plants and animals (Solley et al., 1998). However, access to this valuable resource becomes very difficult precisely in hard rock where groundwater is in fissures. The term “hard rock” commonly applies to hard and dense rocks with the main part of the groundwater flowing in secondary structures, mainly fractures. Groundwater in hard rock aquifers is essentially confined to fractured and/or weathered horizons. Therefore, extensive hydrogeological investigations are required to thoroughly understand groundwater conditions. Modern technologies such as remote sensing and geographic information systems (GIS) have proved to be useful for studying geological, structural and geomorphological conditions together with conventional surveys. Integration of the two technologies has proven to be an efficient tool in groundwater studies (Solomon and Quiel, 2006; Elewa and Qaddah, 2011; Machiwal et al., 2011). In Côte d’Ivoire, crystalline rocks and cristallophyllienne represent 97.5% of geologic formations (Jourda et al., 2006; Doumouya et al., 2012).

In addition to the difficulties related to the availability, accessibility and exploitability of these resources, these groundwater could be exposed to pollution phenomena due to the existence of significant anthropogenic sources. Any pollution of these resources is only possible if the conditions for protection are threatened. To determine the degree of protection, vulnerability to pollution was assessed. Many methods have been proposed for mapping aquifer vulnerability: DRASTIC (Aller et al., 1987), GOD (Foster, 1987), AVI (Van Stempvoort, 1993), SINTACS (Civita, 1994), EPIK (Doerfliger and Zwahlen, 1998), PI (Goldscheider et al., 2000) and COP (Vias et al., 2006). DRASTIC is one of the most common methods used internationally to evaluate the intrinsic vulnerability. The application of this method has given interesting results in Côte d’Ivoire (Antonakos and Lambrakis, 2007; Gomezdelcampo and Dickerson, 2007; Panagopoulos and al., 2006). However, the combination of quantitative and qualitative aspects including different parameters to map preferential areas is virtually non-existent, especially in the eastern part of Côte d’Ivoire. Also, the diagnostic assessment of rural water supply programs for the period 1973 to 2000, show that the proportion of households having access to safe drinking water in the Baya’s catchment, site of this study, is only 37.6% (Mangoua, 2013). Besides, in some areas, the lack of water increases during dry periods. This increase conduct forcing people to make long distances to obtain water from permanent points of water (surface water) generally of dubious-looking quality and medium of many diseases such as dysentery, cholera, etc. Faced to this situation, the improvement of access to safe drinking water to people appears paramount. It is in this context that this study was conducted. This study aims to contribute to a better knowledge of groundwater resources of the basin by multi-criteria analysis to facilitate the supplying of people with drinking water.

Study area

The watershed of the Baya is located to the East of Côte d’Ivoire between longitudes 2° and 3° 50’50”W and latitude 6°90’ and 8°20”N on an area of 6,324.041 km² (Figure 1). The geomorphic landscape is monotonous penneplain occupied by cash crops and export (coffee, cocoa, cashew, rubber) and food crops. We meet in place hills and mountains rising to 700 m on average (Siméon et al., 1995). The climate is tropical and humid. The catchment is drained mainly by Baya River. Geology of this area, which is in the Baoule-Mossi, consists of Birimian and tarkwaiennes formations. These courses are a volcano sedimentary package in which appear intrusion volcanics and granitoids eburnean (Toure, 2007). Several phases of deformation affected the area and led to the establishment of a developed fracturing. In hydrogeological terms, are found in the basin aquifers weathering and cracking. The supply of drinking water to the people is through drilling capturing most often fractured aquifers. Alteration zones when they are thick, can contain significant water circulation which are sometimes exploited by wells.

MATERIALS AND METHODS

Several types of data were used in this study. It concerned technical data collected from 150 boreholes in the Territorial Directorate of Water at Bondoukou, geological and topographical maps of the square degrees of Abengourou of Agnibilékrou and Bondoukou scale 1/200000 respectively performed by the Department of Geology and the Centre of Cartography and Remote Sensing (CCRS) of Côte d’Ivoire. The hydro-climatic data (flows, rainfall and ETP for the period 1965 to 1983) were used for the estimation of infiltration from the hydrological model GR2M, which is a model of rural engineering with 2 parameters and Monthly step. For more details on this hydrological model, we refer the reader to the work of Ardoine (2004). Satellite images EMT Landsat 7 are used to produce lineament map. These images concerned the scenes 195-54 and 195-55 acquired in February 2000. The processing of these data required the use of Envi 4.5 software for satellite images exploitation, MapInfo 7.5 and ArcView 3.2 for the treatment of the fracture network and the implementation of GIS.

Identification of criteria

The map preferential zonations for borehole are obtained by combining criteria of power and vulnerability from the Boolean method. Several criteria characterizing the quality and quantity of groundwater will be used. According to Elewa and Qaddah (2011), the higher the number of GIS parameters used in groundwater potentiality mapping, the higher the accuracy gained.

Quantitative indicators

The parameters used for assessment the quantity of groundwater...
are composed of the aquifer characteristics and other external factors which are grouped into three quantitative indicators (accessibility, exploitability and availability) (Table 1).

Availability indicator

Availability provides information on the conditions of accumulation of groundwater resources. It regroups the most important parameters in the mapping of productive zone. These parameters are slope, recharge, drainage density, lineament density and the weathered zone.

Net recharge is one of the most important parameters in groundwater availability. This factor represents the amount of water per unit area that percolates to the groundwater (Sinan and Razack, 2008). The net recharge of groundwater was calculated using GR2M. The recharge as defined by the US EPA with the potential of an area to have recharge. In other words, the net recharge parameter changed to the ability of an area to act as a recharge zone relative to another area (Al-Hanbali and Kondoh, 2008). It varies from 25 to 100 mm per year.

Slope is one of the factors controlling the infiltration. Indeed, high slope will cause more run-offs and less infiltration, and thus have poor groundwater prospects compared with a low slope region. Slope plays a very significant role in determining infiltration vs. runoff. Infiltration is inversely proportional to slope, that is, the water infiltration decreases with the increase in slope steepness (Elewa and Qaddah, 2011). Slope calculation was carried out by topographic map of the study area that has been product by CCRS. It varies from 0.6 to 15%.

The drainage density characterizes the relative rainwater that could have infiltrated the subsurface. Hence, according to the common geomorphologic concept, the denser the drainage, the less recharge rate and vice versa. However, one of the major approaches to express drainage density involves the number of drainage segments per unit area, which is also called “drainage frequency” (Elewa and Qaddah, 2011). The study area was divided into grids of 5 km². In this study, a drainage density map of the watershed of the Baya was created manually from the topographic map. The total length of all drains in each grid evolves
Exploitability indicator

The exploitability of groundwater resources regroups the parameters that are exploitation flow and the depth to water table. They are based on boreholes data sheets. The exploitation flows represent the productivity of borehole. In the Baya’s watershed, the exploitation flow ranged from 0.36 to 21.6 m³/h. The depth to water table allows for following the water level fluctuation and plays an important role in the groundwater potential zone delineation (Shankar and Mohan, 2006). In the study area, it ranges from 4 to 82.68 m. These parameters have been used in Erytrea to delineate groundwater potential zone in the central highlands of Eritrea (Solomon and Quiel, 2006).

Accessibility indicator

Integrating accessibility parameters in the preferential zone of boreholes delineation could be explained by the important role played by this factor in drinking water. These parameters also are considered as economic and social factors because they favour access or denial to the resource. The main factors of the accessibility indicator are well total depth and the success index. The well total depth gives information on the cost of the water point depending on the number of linear meters drilled. Some authors have defined the best depth interval or the maximum depth that a water point must reach in order to obtain satisfactory productivity in crystalline rock (Youan Ta et al., 2011). Most of them have shown that, because of the closure of discontinuities by lithostatic pressure in depth, when the water point goes deeper, productivity decreases (Neves and Morales, 2007). In this study, the depths of the water points were obtained from published well data and ranged from 42 to 110 m. The success index gives the probability of having a productive water point.

Weighing the quantitative factors

The quantitative factors were weighted starting from the weights linear combination method. The linear combination allowed the production of standardized weighting coefficients whose sum is equal to 1. The procedure consisted in:

1. Comparing the relative importance of all the elements belonging to the same level of hierarchy taken two by two, compared to the element of the immediately higher level;
2. Configuring a reciprocal square matrix formed through the evaluation of the ratios of the weights \((K \times K)\), \(K\) being the number of compared elements. Thus, one obtains (Saaty, 1977): \(a = a_{ij}\) with \(a_{ij} = 1\) and \(a_{ji} = 1 / a_{ij}\) (reciprocal value) and \(a\), the value of each factor \(i\) (lines) and \(j\) (columns);

The Analytic Hierarchy Process (AHP) method has been used respectively by Tudes and Duygu (2009) in Turkey for land use planning in Adana–Turkey and Doumouya et al. (2012); in Côte d’Ivoire. These coefficients are given starting from a series of comparisons per pair by taking account of their importance in the productive zone determination. In order to produce weighting coefficients for each factor and each indicator (Table 2), the procedure needs the eigenvector \(\mathbf{V}_p\) of the comparison matrix. The values of these vectors were obtained by calculating their geometric mean by line (Dibi et al., 2010):

\[
V_{pi} = \sqrt[n]{ \frac{1}{n} \prod_{i=1}^{n} N_i }
\]

Where \(V_{pi}\) is the load vector of each factor, \(N_i\) is the value of each factor.

The weighting coefficient \((W_i)\) of each factor is given as follows:

\[
W_{ij} = \frac{V_{pi}}{\sum_{i=1}^{n} V_{pi}}
\]

The Weighted Linear Combination (WLC) is applied according to the following equation (Eastman, 1997), where \(F\) is the favourability, \(W_i\) is the weight of class \(j\) from map \(i\) and \(X_i\) is the criterion score of map \(i\).
Table 2. Parameters weighting coefficients from pairwise comparison matrix.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Eigen-Vector</th>
<th>Weighting coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (%)</td>
<td>2.24</td>
<td>0.26</td>
</tr>
<tr>
<td>R (mm)</td>
<td>3.70</td>
<td>0.43</td>
</tr>
<tr>
<td>DD (Km/grid)</td>
<td>0.42</td>
<td>0.04</td>
</tr>
<tr>
<td>LD (Km/grid)</td>
<td>1.10</td>
<td>0.13</td>
</tr>
<tr>
<td>WL (m)</td>
<td>0.30</td>
<td>0.04</td>
</tr>
<tr>
<td>Availability</td>
<td>3.87</td>
<td>0.75</td>
</tr>
<tr>
<td>TD (m)</td>
<td>2.24</td>
<td>0.83</td>
</tr>
<tr>
<td>SI (%)</td>
<td>0.45</td>
<td>0.17</td>
</tr>
<tr>
<td>Accessibility</td>
<td>0.26</td>
<td>0.05</td>
</tr>
<tr>
<td>EF (m³/h)</td>
<td>2.24</td>
<td>0.83</td>
</tr>
<tr>
<td>WT (m)</td>
<td>0.45</td>
<td>0.17</td>
</tr>
<tr>
<td>Exploitability</td>
<td>1</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Qualitative indicators

Groundwater vulnerability assessment is an important process for understanding the intrinsic fragility that a certain region opposes to a given threat, whether this hazard has a natural or anthropogenic origin. This indicator had proved to be an effective tool for the delineation of protection zones in areas affected by groundwater contamination due to intensive fertilizer applications (Antonakos and Lambrakis, 2007). The present evaluation of the risk is based on the DRASTIC method as described by Aller et al. (1987), which uses seven parameters to evaluate the vulnerability of groundwater: depth to water, net recharge, impact of vadose zone media, soil media, topography, aquifer media and permeability of the aquifer. After the parametric evaluation, the index of DRASTIC vulnerability (Id) is given. This index allows the characterization of the vulnerability degree of a given sector of aquifer.

\[ \text{Id} = D_n D_p + R_n R_p + A_n A_p + S_n S_p + T_n T_p + I_n I_p + C_n C_p \]

With D, R, A, S, T, I, C, parameters referred to above n is the notation granted to each parameter; p is the factor loading granted to each parameter.

Map of preferential implanting zone (MPIZ)

MPIZ involves delineation of preferential zones to allow distinguishing areas suitable for the establishment of boreholes. Quantitative and qualitative indicators were combined from the Boolean method. This method uses Boolean operators: Such as AND and OR. It has consisted in assigning a weight “0” to the threatened area represented by the strong vulnerabilities, and “1” to the non-threatened area represented by the average and weak vulnerabilities.

Uncertainty and error map

Uncertainty analysis

The first step of the analysis was to compute uncertainties on averages of various parameters of the main indicators of potentiality and vulnerability. The uncertainty is calculated using the following equation:

\[ \Delta \text{V} = \frac{\sigma}{\sqrt{m}} \]

With \( \Delta \text{V} \) uncertainty on average of the data series, \( \sigma \) standard deviation, m number of data.

To determine to determine the confidence interval, an expansion factor (K) is then calculated. The determination of this parameter is based on the statistical principle of computation of the expanded uncertainty. The factor k allows the definition of an interval of sufficient scope to have great confidence in the results. The expression of this factor is as follows:

\[ K = \frac{|E - \mu|}{\sigma} \]

Where k is the expansion factor, E is the extreme value of the statistical series, which can be the maximum or the minimum of this series.

Confidence levels of the different parameters have been deduced from different values of k. Thus, k = 1 for a confidence of 68%, k = 2 for a confidence of 95%, and k = 3 for a confidence of 99%.

Map errors

The errors of the productive zone index and the DRASTIC index on the maps were calculated by the following formula:

\[ E_r = \frac{\Delta \text{V}}{I} \times 100 \]

With \( E_r \), the error (%) committed on the map of the productive zone or DRASTIC index; \( \Delta \text{V} \) or Inc, the uncertainty on the map of the productive zone index (Inc\( \text{pz} \)) or the DRASTIC index (Inc\( \text{d} \)); I, Productive Zone Index (Ipz) or DRASTIC index (Id).

The error of the MPIZ, \( E_{\text{MPIZ}} \) was obtained by the following calculation:

\[ E_{\text{MPIZ}} = \left| \frac{\text{Inc}_{\text{pz}} - \text{Inc}_{\text{d}}}{\text{Ipz} - \text{Id}} \right| \times 100 \]

RESULTS

Quantitative map indicators

The application of the weights linear combination method allowed obtaining maps of indicators of accessibility, exploitability and availability methods. The results of the availability map (Figure 2) revealed 4 classes dominated by good availability conditions, which occupied 74.95% of the entire study area, except the northern part. The class of excellent availability (11.67%) was observed on the outlet of watershed. The medium class of availability represented 13.17% of the area and occupies the northern part with a few appearances in the departments of Assuefry and Tanda. The low class of availability that remains practically absent (0.21%) was observed on the granitic and sedimentary formations where water points are shallow.

Three unequal classes (Figure 3) characterized map of groundwater accessibility resources of the Baya’s
watershed, the medium class was non-existent. On this map, the excellent and good classes of accessibility held respectively 70 and 20% of the study area. The class of excellent accessibility was characterized by low and medium depths and indices of success very high (> 80%). The low class of accessibility represented 10% of the area and occupies the south part (Akoboissoue) with few appearances in the north.

The medium class (51.09%) and the good class (28.74%) dominated the exploitability of groundwater (Figure 4). These classes are located mostly on the shale. The excellent and good classes of exploitability (33.5%) were generally present in the granitoids with exploitation flows greater than or equal to 9.5 m³/h. These areas are the most sought for the supply of drinking water to urban centers as is the case of the city of Bondoukou.

The linear combination of all the indicators according to their respective weights has produced the map of productive zones (Figure 5). The result showed that productivity was dominated by good and excellent classes. These classes represented 84% of the watershed area and were found in almost all the study area except the north zone and departments of Tanda and Koun-Fao. For the low and medium classes, which covered the remainder of the study area (16%), they were observed in the North with a few pockets in the Central-west.
Qualitative map indicator

Qualitative indicator presented by vulnerability map (Figure 6) indicated two classes (very low and low). Very low vulnerability class covered 85% of the study area and was regarded as having low pollution potential. This class was usually found throughout the study area from north to south. Groundwater in this area probably does not risk contamination. The class of low vulnerability representing 15% of the watershed occupied small portions in the west and some pockets in the north.

Map of preferential implanting zone (MPIZ)

The MPIZ resulting from the combination between the quantitative indicator maps and that of the vulnerability to pollution shows the areas, which are most appropriate for implantation of well points (Figure 7). The watershed of the Baya is well protected and is not a threat to groundwater in the study area. Indeed, it does not show any influence on the map of productive zone. The MPIZ has the same features as the map of productive zone. The good classes and excellent location occupied 84% of the basin. For the low and medium classes, which covered the remainder of the study area (16 %), they were observed in the North with a few pockets.
Table 3. Statistical summary of the potentiality parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Uncertainty</th>
<th>k</th>
<th>Confidence level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>107</td>
<td>481</td>
<td>250</td>
<td>50</td>
<td>± 0.02</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>R</td>
<td>17</td>
<td>141</td>
<td>139</td>
<td>5</td>
<td>± 0.01</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>DD</td>
<td>0</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>± 0.04</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>LD</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>2</td>
<td>± 0.02</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>WL</td>
<td>0</td>
<td>92</td>
<td>40</td>
<td>12</td>
<td>± 0.12</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>Availability</td>
<td>5</td>
<td>9</td>
<td>7</td>
<td>1</td>
<td>± 0.01</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>TD</td>
<td>43</td>
<td>111</td>
<td>71</td>
<td>14</td>
<td>± 0.12</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>SI</td>
<td>9</td>
<td>100</td>
<td>61</td>
<td>5</td>
<td>± 0.13</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>Accessibility</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>± 0.01</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>EF</td>
<td>0</td>
<td>22</td>
<td>4</td>
<td>1</td>
<td>± 0.02</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>WT</td>
<td>0</td>
<td>83</td>
<td>28</td>
<td>11</td>
<td>± 0.10</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>Exploitability</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>± 0.02</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>Productive zone</td>
<td>202</td>
<td>526</td>
<td>380</td>
<td>55</td>
<td>± 0.46</td>
<td>3</td>
<td>99</td>
</tr>
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</table>

Table 4. Statistical summary of the vulnerability factors.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Uncertainty</th>
<th>k</th>
<th>Confidence level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>10</td>
<td>50</td>
<td>22</td>
<td>11</td>
<td>± 0.09</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>R</td>
<td>12</td>
<td>24</td>
<td>18</td>
<td>8</td>
<td>± 0.07</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>A</td>
<td>12</td>
<td>24</td>
<td>16</td>
<td>6</td>
<td>± 0.05</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>S</td>
<td>8</td>
<td>20</td>
<td>14</td>
<td>5</td>
<td>± 0.04</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>T</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>± 0.01</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>I</td>
<td>20</td>
<td>40</td>
<td>30</td>
<td>10</td>
<td>± 0.08</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>33</td>
<td>5</td>
<td>2</td>
<td>± 0.02</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>DRASTIC index</td>
<td>40</td>
<td>95</td>
<td>55</td>
<td>13</td>
<td>± 0.11</td>
<td>1</td>
<td>68</td>
</tr>
</tbody>
</table>

Uncertainty analysis

The uncertainty analysis computed by determining confidence levels is presented in Tables 3 which gives the statistical summary of the parameters or factors of the productive zone indicator. The map of productive zone was obtained by combining maps of availability, exploitability and accessibility. The uncertainties were high on the parameters WL (±0.10) and DD (±0.04) with confidence levels 99 and 95% respectively. However, errors on the three other parameters (slope (S), recharge (R) and lineament density (LD)) were low. Their uncertainties were ± 0.02 for the lineament density and the slope and ±0.01 for the recharge. The slope and the recharge had a high confidence level of (99%). The lineament density confidence level is 95%. For the exploitability indicator, uncertainly of water table was higher (±0.10) than that of the exploitation flow (±0.02). However, the confidence level of these two parameters was 95%. According to the indicator of accessibility, the uncertainties showed that there is statistically more risk of error on the two parameters (success index (SI) (±0.13) and the total depth (TD) (±0.12)). The confidence level was therefore higher at the success index (99%) than the total depth (95%).

Uncertainties and confidence levels were also determined for factors of vulnerability (Table 4). The vulnerability map was obtained by a combination of D, R, A, S, I, C factors. The confidence level is 68% for the parameters D, R, A, S, I and 95% for T, and C. Also, analysis of the uncertainties allowed a classification of levels of error committed on the factors. The highest risk of error which could be committed in the conception of the vulnerability map originated from the recharge (±0.07), depth (±0.09) and the impact of the vadose zone (±0.08). The second risk of error originated from the soil (±0.06) and the type of aquifer (±0.05). The lowest level of error on the vulnerability map could be attributed to the topography (±0.01) and the hydraulic conductivity (±0.02).

Map errors

The results of calculation errors on the map of productive zone and DRASTIC map determined from the indices are shown in the following Table 5. On the map of productive zone...
zone, the error was only ±12% whereas it was ±20% on the map of the DRASTIC that indicating the vulnerability to pollution of the groundwater. The final map (Map of Preferential implanting zone) representing the combination of the two previous maps gave an error percentage of ±12%. Therefore, the confidence levels of these three maps were respectively 99, 68 and 99%.

**DISCUSSION**

The use of GIS and multi-criteria analysis in the watershed Baya had resulted in the production of maps of availability, accessibility and exploitability of groundwater resources. The linear combination of these maps had achieved the map of productive zone. This map represented a pre-exploration phase, which avoided heavy, slow and costly research as indicated by the work of Langevin et al. (1991). The availability indicator is important for preferential zone delineation. This indicator was strongly influenced by the slope, recharge and lineament density in the area of Baya watershed. This catchment had a good availability of groundwater (87% of the watershed) that was due to a low slope and good lineament density which would lead to a good infiltration of water into the aquifer. This result is confirmed by Shankar and Mohan (2006) and Doumouya et al. (2012). According to these authors, the slope has direct control over groundwater recharging. The groundwater recharge by rivers was favored by the density of lineaments. Therefore, areas of very high lineament density corresponding to areas of high hydraulic conductivity were considered as areas of high recharge. According to Anbazhagan et al. (2005), this lineament density is closely linked to drainage density. The exploitability indicator was dominated by the class of medium (51.06%) and good (28.74%) exploitability which occurred on shales and granitoids respectively. The good exploitability of water from the granitoids could be explained by the fact that they were the most productive formations in the region according to Mangoua (2013). Indeed, this good exploitability of granitoids could be linked to their strong fracture density. The medium productivity of the shale was due to the lack of intercalations of carbonate in shale beds and pegmatite dykes and quartz in these formations (Touré, 2007).

As for accessibility, the results showed that they were still dominated by the class of good accessibility condition observed in almost all the study area. The presence of that class of good accessibility could be linked to the relatively shallow depth of water points. Besides depths, the exploitation flow which allowed determination of the success index was often superior or equal to 3.5 m³/h, corresponding to a success index higher or equal to 80% (Doumouya et al., 2012). In watershed of Baya, it was observed that the higher the water point is deeper, low the productivity is. This phenomenon could be linked to the closure of discontinuities due to lithostatic pressure in depth as noticed by Neves and Morales (2007) in Southeast Brazil or due to financial constraints which would restrict drilling not to exceed (Biémi, 1992).

The study of groundwater vulnerability to pollution showed that the study area was dominated by a class of the very low vulnerability (85%) with some pockets of low vulnerability (15%) observed in the South-west and the North. Indeed, steep sloping favours runoff accumulation in the valleys and thereafter its infiltration into underlying layers. Valley bottoms seen in the North and the outlet of the watershed are in general likely to favour contamination of groundwater by pollutant infiltration. This contamination is more likely in areas where water is shallow because the vadose zone is in general made up of a generally permeable sandy clay formation. Note that the watershed had a very low vulnerability generally with DRASTIC index of 55, so that the watershed is well protected.

The calculation of uncertainties and the confidence level allowed the organization of importance of errors made on preferential zone and vulnerability maps. The parameters which had high uncertainty were less important than those with low uncertainties. As for the preferential zone map, uncertainties were more important at the water table, the total depth, the success index and the weathered layer. The other parameters (slope, drainage density, recharge, exploitation flow and lineament density) presented relatively low uncertainty giving a high reliability to the map they allowed us to make. As for DRASTIC parameters, which determine vulnerability, the uncertainty mostly came from the topography and the hydraulic conductivity with confidence levels of 99%.

Overall, it was found that the parameters obtained from satellite images and geological maps (slope, drainage density, lineament density and recharge) had low uncertainties. These low uncertainties could be explained by the fact that these data came from sources already

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Error (%)</th>
<th>k</th>
<th>Confidence level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productive zone</td>
<td>202</td>
<td>526</td>
<td>380</td>
<td>55</td>
<td>12</td>
<td>3</td>
<td>99</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>40</td>
<td>95</td>
<td>55</td>
<td>13</td>
<td>20</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>Preferential zone</td>
<td>200</td>
<td>526</td>
<td>378</td>
<td>12</td>
<td>12</td>
<td>3</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 5. Statistical summary of productivity and vulnerability factors.
validated and therefore more reliable.

GIS and MCA have many advantages because they bring an undeniable contribution to the management of water resources and rational decision-making. However, they have limitations. The parameter estimation often lack of precision because of the inadequacy or total absence of data in some parts of the study area. In short, GIS shall be and remain an invaluable contribution in the management of water resources generally speaking (Putz, 2003).

**Conclusion**

In this research, an attempt was made to delineate the productive zone and the vulnerability of the aquifer to determine preferential zones for implantation of water points in the watershed of Baya. GIS and MCA are two complementary techniques used in the delineation of preferential areas. The results of this study indicate indicates that the preferential zones represented 84% of Baya area. This class was distributed throughout the region, with an exception in the North. The determination of confidence levels showed that groundwater reserves in the watershed of Baya were governed by the slope, recharge, Exploitation flow, depth and lineament density. However, the vulnerability of the aquifer was essentially the fact of the topography, the impact of vadose zone and the conductivity. Errors determined from the uncertainties are respectively were 12, 20 and 12% for maps of productive zone, vulnerability and preferential zones respectively. Preferential areas cover almost all of the study area and are influenced by the topography, vadose zone and hydraulic conductivity. The margin of error is low and showing the quality of the results.

**Conflict of Interests**

The authors have not declared any conflict of interests.

**REFERENCES**


REFERENCES


