Mapping of groundwater vulnerability zones to pollution in various hydrogeological environments of Côte d'Ivoire by DRASTIC method

Kan Jean Kouamé, Jean Patrice Jourda , Mahaman Bachir Saley, Serges Kouakou Deh, Abenan Tawa Anani and Jean Biémi

Abstract- This study is a synthesis of the work realized by the Remote Sensing and Spatial Analysis Applied to Hydrogeology Laboratory (LATASAH) of the Félix Houphouët-Boigny University of Cocody-Abidjan, concerning the degree of groundwater vulnerability in Côte d'Ivoire. The aimed objective is to elaborate protection tools of groundwater against pollution in various hydrogeological environments. This study uses DRASTIC method. It was realized in Abidjan District (sedimentary environment) and in Korhogo department (crystalline environment). The integration and the overlay of the hydrogeological factors, by running the functionalities of the GIS ArcView, allowed calculating DRASTIC index. A classification of these vulnerabilities index leads to the maps of groundwater vulnerability to pollution. It emerges from the map of Abidjan vulnerability that the degrees of vulnerability are concentrated between moderate and high (88.37%) with 47.33% for the moderate class and 41.04% for the highest. In Korhogo department, the vulnerability map is also dominated by moderate and high vulnerability classes (88%) with 64% for the moderate class and 24% for the highest. These two vulnerability maps were validated by an overlapping of the highest vulnerabilities zones to the zones of high values of nitrate.

Index Terms- Côte d'Ivoire, GIS, vulnerability, pollution, DRASTIC, protection, groundwater

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1. INTRODUCTION

The access to the drinking water is an incompressible right of every citizen. The drinking water, this resource, is an essential and vital element for human and leads to the economical and social development of a nation. It also constitutes one of the strategic domains of a country [1]. Indeed, groundwaters constitute the main source of drinking water supply systems of big cities in Africa generally and in Côte d'Ivoire particularly.

Abidjan District, where the drinking water supply of populations depends on groundwater [2] is the first study zone (Fig. 1a). Abidjan is located in the South of Côte d'Ivoire. The groundwater quality of this city is threatened by diverse potential sources of pollution ([3], [4]).

The insufficiency or the absence of water treatment plants in domestic and industrial business allows dreading the degree of the disaster which threatens groundwater ([4], [5]). These deficiencies make that, mostly, waters pollution is noticed after its misdeeds, i.e. after its migration from its initial zone and affects groundwater by recharge.

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The department of Korhogo, located in the North of Côte d'Ivoire, is the second study zone. It's situated between the longitudes 5°15 and 6°20 West and the latitudes 8°30 and 10°25 North (Fig. 1b). It is a region which can have an important development in consideration for its position of crossroads zone crossed by the traders coming from Mali and Burkina Faso. Agricultural activities strongly bound to the export crop of the cotton take up a big party of the areas of this territory.

This agricultural region is considered as the capital of "white gold" of Côte d'Ivoire. This extensive farming uses many of agricultural intrants as artificial fertilizers. Thus, the development of this region cannot be made without raising problems connected to the quality of groundwater resources. Although the situation is not still alarming, the fact remains that the quality of groundwater resource is always threatened because of the growth of the pollution sources which can be diffuse or punctual [6].

So one of the assistant approaches to the protection and the prevention against all possible pollution of groundwater, is the mapping of vulnerable zones to pollution [7]. This study was undertaken with the aim to identify zones with high risk of groundwater contamination independently of pollutant type with a view to adopt rigorous measures of groundwater protection.
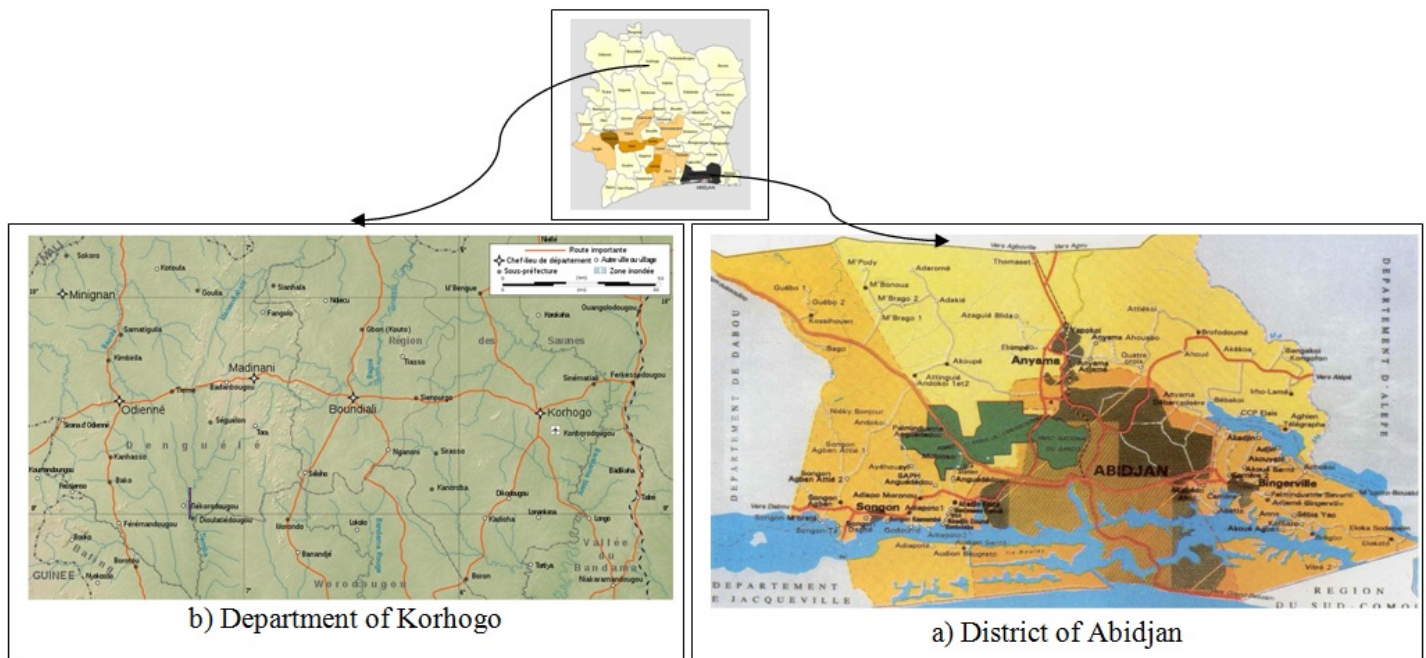
Fig. 1. Localization of study areas: a) Abidjan district; b) Korhogo department

2. PRESENTATION OF STUDY AREAS

2.1. Abidjan district

On the geological plan, Abidjan district belongs to the sedimentary basin of Cretaceous to Quaternary age representing only 2.5% of the country's surface ([8], [9]). It stretches on a length of 400 Km and a width of 40 Km from Fresco (Côte d'Ivoire) to the boundary of Ghana. This basin contains three levels of aquifer with an unequal importance which Continental Terminal aquifer is exploited for supply people in Abidjan with drinking-water (Fig. 2). Abidjan district has a good rainfall with an annual average height estimated at 1 600 mm.
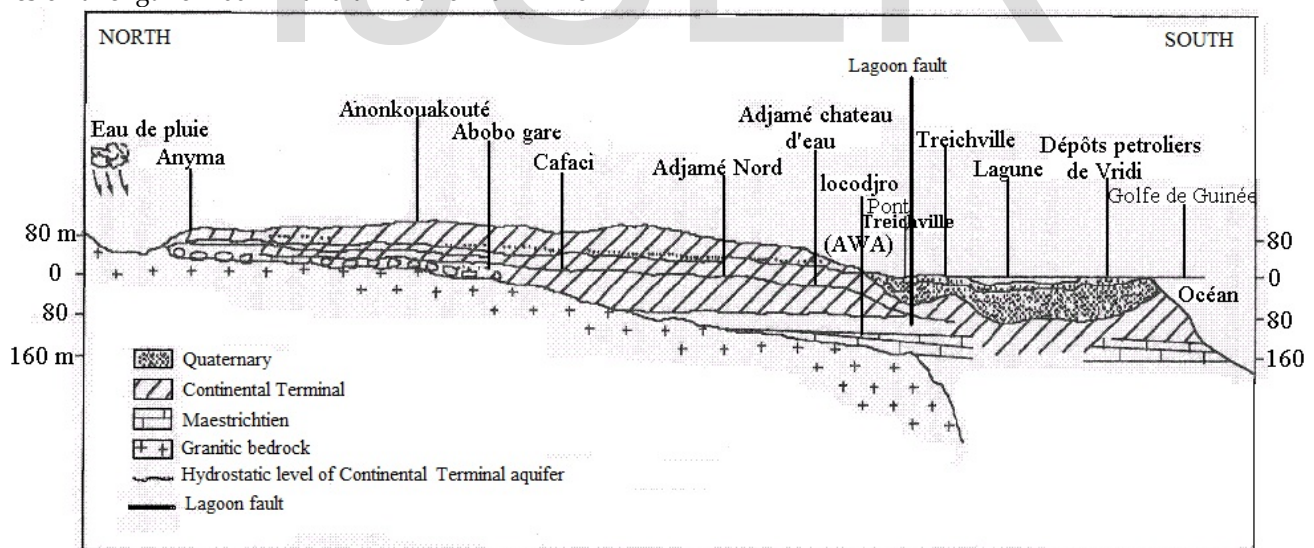

Fig.2. Cut north-south of the Ivorian coastal sedimentary basin [10]

2.2. Region of Korhogo

The relief of Korhogo region is monotonous with the altitudes which vary between 300 and 400 m. It is constituted by lateritic plateau with heights varying from 0 to 3 m, evidence of old peneplain. These plateaus are affected by a very weak and regular slope towards the river Bandama. The wet tropical climate of the region is translated by an annual average of rain fluctuating around 1200 mm [11].

On geological and tectonic plan, this region becomes integrated into the West African craton history. From the works of [12], [13] and [14], it emerges that the tectonic of

this region is polyphased and ended in the implementation of a fracturing very developed in these formations. From a lithological point of view, we can distinguish two big formations (Fig. 3):

-the birimienne formations are volcanic, volcano-sedimentary and sedimentary, metamorphosed formations deposited into intracratonic furrows;

-the eburnean granitoïd are granitic massifs within which we distinguish several generations of granites.
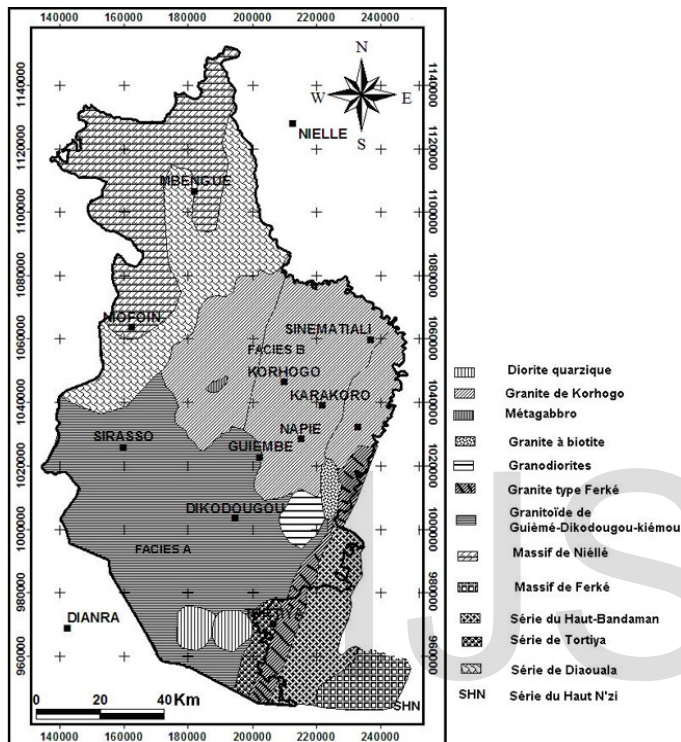

Fig. 3. Geological map of Korhogo department [11]

By taking into account the nature of rocks constituted essentially by granitic and crystalophyllien formations, we distinguish two aquifers: reservoir of alterite and fracture reservoir. Among these two aquifers, only fracture reservoirs offers long-lasting water resources and are the most reliable. Its productivity is connected to the underground network of fractures put in evidence by the works of [15], [16], [17] and [18] realized in the same geologic context.

It emerges from this presentation of the study zones, a difference at the geologic and hydrogeologic level. Groundwaters of Korhogo are contained in the fractured formations whereas those of Abidjan in the sedimentary formations are essentially constituted of sands.

3. MATERIAL AND METHOD
3.1. Data and material

For the elaboration of the physical parameters of Abidjan and Korhogo aquifers, the following data were used:
- geological maps;
- geotechnical map of Abidjan region;
- topographic maps;
- data of rain, temperature, piezometry, boreholes and wells;
- cups of boreholes;
- Landsat ETM+ images: 197-54 and 197-55 scenes of February 2000.

For the processing and layers elaboration, the software of MapInfo 5.0, ArcView 3.2, ENVI 4.0 and the EVC program were used.

All maps of Abidjan district are in 1/50 000e whereas those of Korhogo department are in 1/200 000e.

3.2. Methodology

The notion of "groundwater vulnerability" includes two approaches:
- the intrinsic vulnerability considers the natural physical conditions of the environment;
- the specific vulnerability brings only the natural parameters but the contaminant properties (its nature, its implementation), human activities, or people risk also [19].

This study is about an evaluation of the intrinsic vulnerability. The evaluation of the intrinsic vulnerability is defined by [20] as being an intrinsic property of the aquifers systems which depends on the sensibility of these systems before the human or natural impacts. This vulnerability is different from the risk of pollution, which depends not only on the vulnerability but also on the significant existence of pollution [21].

3.2.1. Method used description: DRASTIC method

DRASTIC method developed by the American Agency of the Environmental protection, [22] is a standardized method for evaluation and mapping of groundwater vulnerability independently of pollutant type. It bases on the following three basic hypotheses:
- The potential sources of contamination are on the ground;
- From the ground, the potential contaminants reach the aquifer by the mechanism of effective infiltration;
- The nature of the potential contaminants is not taken into account in the calculation of the index.

This method takes into account the major party of the hydrogeological factors which affect and control the groundwater flow [23]. It allows visualizing the relative degree of groundwater vulnerability of the study zone because based on seven parameters of vulnerability [24]. These are:
- D: Depth to water;
- R: Recharge;
- A: Aquifer media;
- S: Soil media;
- T: Topography;
- I: Impact of vadose;
- C: Conductivity.

The evaluation of the vulnerability by DRASTIC method is made by the calculation of the DRASTIC Index (DI)

according to the equation (1) where the indications r and w indicate respectively the "Rate" and the "Weight" of the parameter:

$$DI = Dr \times Dw + Rr \times Rw + Ar \times Aw + Sr \times Sw + Tr \times Tw + Ir \times Iw + Cr \times Cw \quad \text{(eq. 1)}$$

The importance of every parameter is estimated by its "Weight" varying between 1 and 5 (Table I). For every parameter, the "Rate" is multiplied by the corresponding "Weight".

We get the sum of the numbers from every parameter and we obtain the DRASTIC Index. The minimum value of the index is "23" and the maximum is "226". Such extreme values are rarely obtained in the studies of mapping of the aquifers vulnerability to pollution. Some studies showed that the DRASTIC Index possesses "50" as minimum value and "200" as maximum value [25]. An example of calculation is illustrated into the table II.

Table I. DRASTIC Hydrogeological parameters with their respective weights [20]

Hydrogeological parameters	Weights
Depth to water (D)	5
Recharge (R)	4
Aquifer media (A)	3
Soil media (S)	2
Topography (T)	1
Impact of vadose zone (I)	5
Conductivity (C)	3

Table II. Example of DRASTIC Index calculation

Parameters	Rate	Weights	Number (Rate × Weight)
D	7	5	35
R	1	4	4
A	8	3	24
S	5	2	10
T	9	1	9
I	8	5	40
C	2	3	6
DRASTIC Index			128

The vulnerability increases with the DRASTIC Index and this Index represents a relative measure of groundwater vulnerability. A site with a weak DRASTIC Index is not shelter from a contamination, but it may be less in the contamination compared to a site having a high DRASTIC Index [21].

After the calculation of the index (DI), we make correspondence classes of vulnerability with the various ranges of calculated index (Table III).

The classification of index map according to ranges defined by the method, allows elaborating the maps of groundwater vulnerability to pollution of Abidjan district and the department Korhogo.

These limits being relative values, another classification allows to fix other limits and to make correspondence classes of vulnerability to this index.

Table III. Intervals of DI values and corresponding classes [9]

Intervals	DRASTIC classes
23 – 80	Very weak vulnerability
80 – 100	Weak vulnerability
100 – 140	Moderate vulnerability
140 – 180	High vulnerability
180 – 226	Very high vulnerability

It was the case of the works realized by [26], [19], [27], [22], [28], [6] and [29]. From the works of these authors, classes of vulnerability according to the obtained values of the index were fixed in this study.

3.2.2. Validation method of vulnerability to pollution maps

The quality of the groundwater is appreciated by the measures of physico-chemical and bacteriological parameters. Several authors, who are [30], [7], [23], [2], [31], [11], [6], [4] and [29], verified the validity of the mapping of the vulnerability to pollution methods by basing itself on chemical data of groundwater. The contaminated zones must correspond to those where the vulnerability index are high. A vulnerable zone can have a weak vulnerability index due to the fact that the vulnerability notion is not synonymic of a current pollution, but rather of a predisposition for these zones to a possible contamination, if nothing is undertaken to protect them [29].

The validation of groundwater vulnerability to pollution maps of Korhogo and Abidjan is about the analysis of nitrates values contained in the boreholes and the wells of these regions. The data of nitrate in Abidjan are from the year 2001 whereas those of Korhogo are from the year 2002.

4. RESULTS AND DISCUSSION

The establishment of the various parameters and their crossing allowed realizing the maps of groundwater vulnerability to pollution of the study zones from the DRASTIC method. The obtained values of the DRASTIC index oscillate between 77 and 158 for the department of Korhogo and between 113 and 192 for Abidjan district. The Aquifers vulnerability to pollution increases with the obtained index. Allowing that the limit values of the DRASTIC index intervals are relatives, another classification adapted to the study was thus made

4.1. Abidjan's groundwater vulnerability map to pollution

The ranges of vulnerability degree elaborated from the DI vary from the "weak" to "very high". The adopted classification is recorded on the table IV. The map of the figure 4 stemming from this classification reveals that the

weak degree of vulnerability occupies a small space of the District (0.21% of the mapped zone) (Table V).

Table IV. Classification of vulnerability degrees according to the calculated IDRASTIC

Intervals of IDRASTIC	vulnerability classes
IDRASTIC < 129	Weak vulnerability
130 < IDRASTIC < 149	Moderate vulnerability
150 < IDRASTIC < 169	High vulnerability
IDRASTIC > 170	Very high vulnerability

This weak degree can be understandable by the fact that the aquifer possesses in this party the clay-sandy as vadose zone. So, a contamination of the aquifer due to a superficial pollution is insignificant, because the pollutant will have difficulty to cross the clay-sandy. The west, Southwest, South sectors and one part of the East of Abidjan district possess a moderate degree. This class guarantees a less severe pollution and represents 47.33% of the district. The moderate degree of vulnerability can be understandable by the fact that the vadose zone is constituted in major part by sand-clayey formation and this formation is associated with an average conductivity (29 – 41 m/day) with an average annual recharge oscillating between 110 and 480 mm/year.
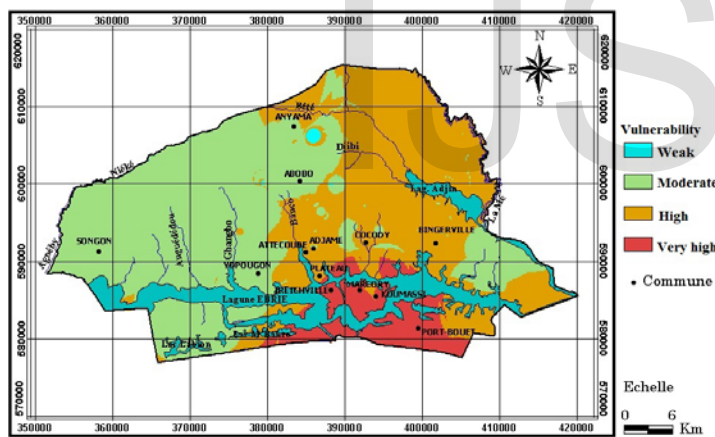

Fig. 4. Groundwater vulnerability map to pollution of Abidjan district [5]

Table V. Distribution of the DRASTIC Index values

DRASTIC Index	Number of pixels	Vulnerability	Percent (%)
113 – 119	151	weak	0.21
120 – 139	34283	Moderate	47.33
140 – 159	29733	High	41.04
> 159	8273	Very high	11.42
Total	72440		100

The East, Northeast and the Center of Abidjan district have a high degree of vulnerability. This class represents a proportion less important than the previous class with 41.04% of Abidjan. The high degree of vulnerability can be understandable by the fact that the conductivity is

important (41-81 m/day) and the annual recharge is also significant (from 480 to 760 mm/year).

Abidjan South municipalities (Treichville, Marcory, Koumassi and Port-Bouët) cover a very high degree of vulnerability. The very high index of vulnerability is perhaps due to the aquifer type (coarse sand) associated with an important infiltration (760–850 mm/year), an important conductivity (49–56 m/day) and a weak depth to water (1-11 m). All these parameters make groundwater very vulnerable in this party of Abidjan district. The progress of this class towards the Center of Abidjan is also remarkable in the case of a contamination.

4.2. Korhogo's groundwater vulnerability map to pollution

A statistical summary of the obtained DRASTIC index is recorded in the table VI. From this statistics, a classification of the index allowed to obtain the map of the figure 5.

Table VI. Statistical summary of the DRASTIC index

Min	Max	Mean	Median	Mode	Standard deviation
77	158	99.5	98	92	10.4

The analysis of the vulnerability to pollution map of Korhogo (Fig. 5) reveals that the class of high vulnerability is more present in the North of M'bengué. This zone is particularly remarkable because it is a zone with very high permeability, very important density of lineaments, very high effective recharge and a very weak surface flow. It is a flood zone of Badénou river. This area is thus sensitive and must be supervised because it is an agricultural zone. There is another zone with high vulnerability situated in the Southeast along Bandama. The Center and the South of the department are covered in majority by the class of moderate vulnerability. The class with weak vulnerability is essentially situated in the west sector following Sirasso-Niofoin road with some parties around the cities of Korhogo and Sinématiali. The Northeast and Southeast sectors of the department, situated along Bandama river are particularly marked by the class of high vulnerability. These zones are densely occupied (Fig. 6) by very developed agricultural activities (culture of cotton and rice). In addition to these agricultural activities, we observe the practice of the itinerant breeding which is also important in the region.

The Northeast sector around the cities of Korhogo, Sinématiali and Komborodougou must be supervised because the density of population is important and this zone is vulnerable. It is thus a zone where the risk of groundwater pollution is high.

The distribution in percent of surfaces covered with the degrees of vulnerability to pollution of this region is presented in the figure 7. The analysis of this figure reveals that the region is largely covered by the class of moderate vulnerability (63.5%) followed by the class of high

vulnerability (23.4%) and finally the class of weak vulnerability (13.09%).
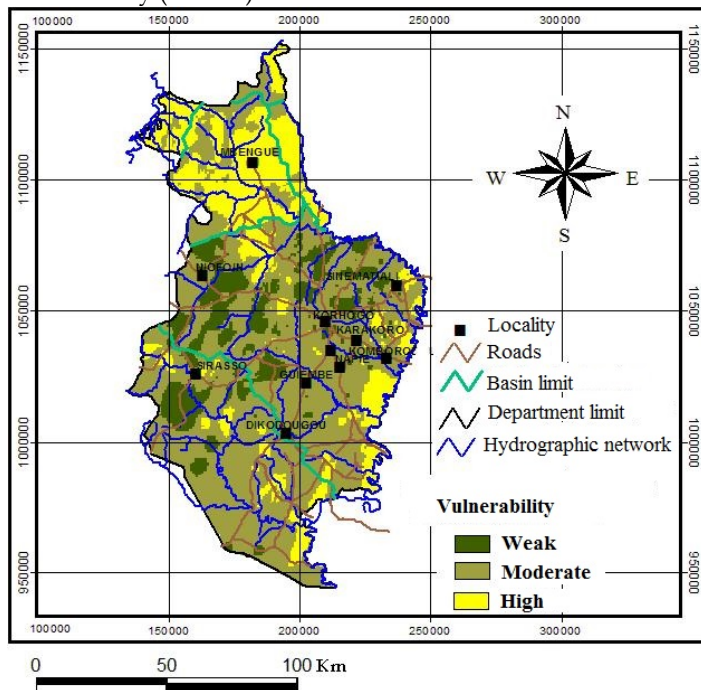

Fig. 5. Groundwater vulnerability map to pollution of Korhogo [11]

According to [6] DRASTIC method highlights bitterly the zones with moderate and high vulnerability. This result has already been noticed in a comparison study of the methods made in Switzerland [32].
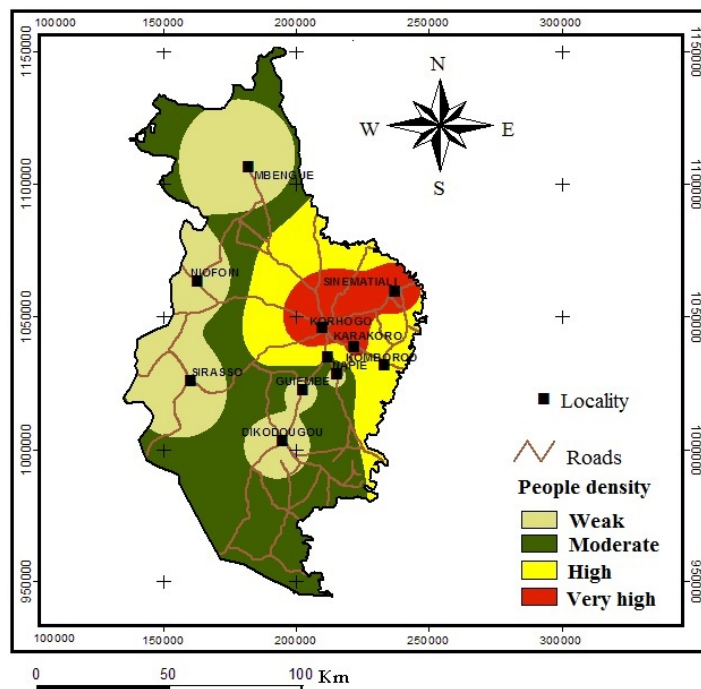

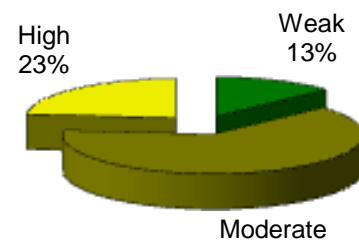Fig. 6. Population density map of Korhogo department [33]

Fig. 7. Space distribution of the degrees of vulnerability to pollution of Korhogo [11]

4.3. Validation of the vulnerability maps

This validation of maps was made from the data of nitrates contained into groundwaters. Concerning Abidjan these values of nitrate are included between 3 and 100 mg/L. A spatial distribution of the nitrate concentration for Abidjan is illustrated in the figure 8. It reveals that in the south part of Abidjan, in the municipalities of Plateau, Attécoubé, Adjamé and one part of Yopougon, Abobo and Cocody has a rate of nitrates superior to 50 mg/L. We can deduct from this observation that the pollution progresses from the south to the north direction with a new pole of pollution on the West. The produced vulnerability map has also showed a progress of the vulnerability from the south to the north of Abidjan. The zones with high rate of nitrates (> 50 mg/L), progressing also from the South to the north, overlap themselves to the zones of very high and high vulnerability to pollution. The overlapping of these two types of zones (high vulnerability and high values of nitrate) allows saying that the map established by DRASTIC method reflects the reality of the ground.
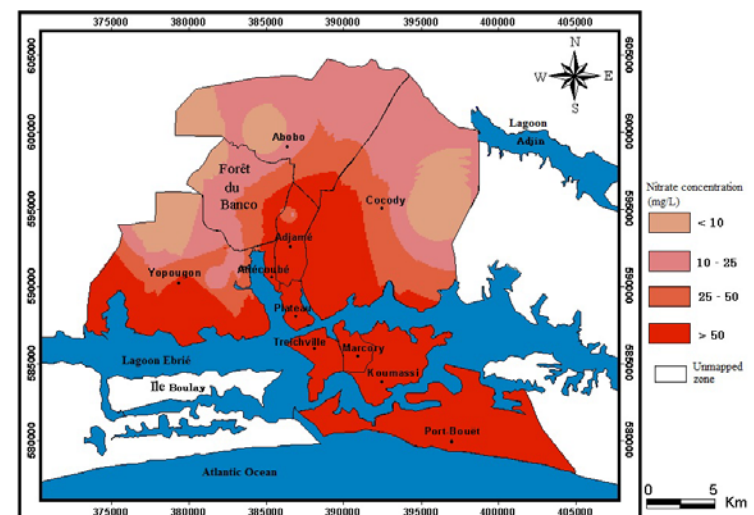

Fig. 8. Spatial distribution map of nitrate value of Abidjan [5]

In the Korhogo department, the values of nitrates contained into groundwater are generally weak and are included

between 0 and 10 mg/L for 83% of samples. However, there are some points where the values are relatively high such as Pédérékaha (51 mg/L), Ladjolakaha (58 mg/L), Diégon (69 mg/L), Galangbo (45 mg/L) and Pangarikaha (46 mg/L). These values exceed or are much closed to the standard of WHO (50 mg/L) of the drinking waters quality. We can also say that there is pollution from nitrates in these zones. The southeast of the region, which the vulnerability varies from moderate to high, presents also high and very high nitrate values (Fig. 9). This result confirms and validates the map of intrinsic vulnerability to pollution of that region. The North sector has a high vulnerability, although the value of nitrate is weak at the moment, deserves a particular attention for the arrangement of its areas to prevent all pollution in this zone.
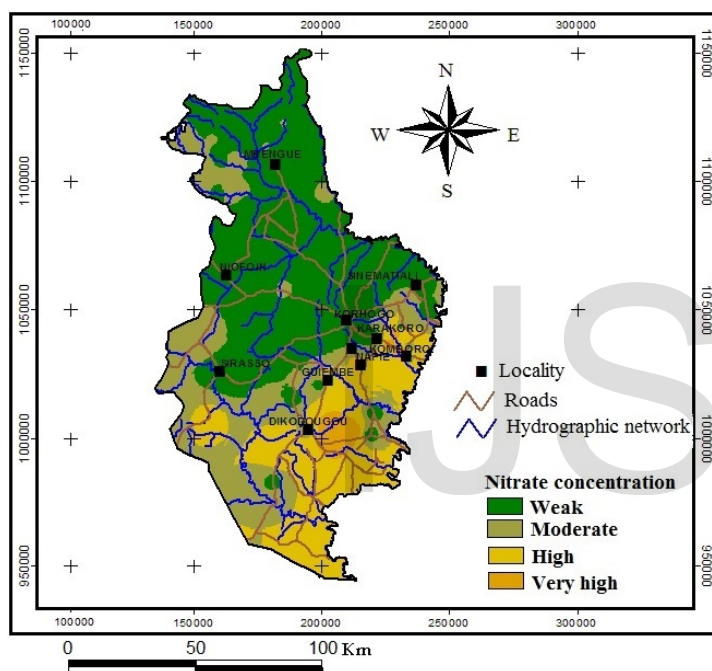

Fig. 9. Spatial distribution map of nitrate value of Korhogo department [11]

The validation of the maps of groundwater vulnerability to pollution of Abidjan and korhogo developed from DRASTIC method allows saying that this method is applicable in Côte d'Ivoire whatever the hydrogeological environment is (sedimentary or crystalline).

4.4. Discussion

The difficulty in the realization of a groundwater vulnerability map to pollution from DRASTIC method lies in the account of number of hydrogeological parameters (7). The values of certain parameters like recharge, conductivity, depth to water, impact of vadose zone, were obtained by interpolation. The interpolation used for groundwater of Abidjan can induce errors in the realization of these parameters. The interpolation is only reliable inside the intervals bounded by the punctual data although we are in a continuous environment [4]. Due to the lack of data

covering the entire study zone, all the punctual data for Abidjan (recharge, piezometry, conductivity) were interpolated, assigning thus values of some sectors where no data is known. It is an advantage for the interpolation method [29].

In the department of Korhogo, in fractured environment, the values of certain parameters, such as the recharge, was determined by extrapolating many data like the values flow of streams. In addition, it is necessary to notice a limitation connected to the precised measure of the water's depth. This precision is function to the isobaths interval of the aquifer. When the intervals are wider, less is the precision of water's depth estimation and this poses the problem of data continuity [6].

Are the values of permeability found those of the alterite or fractured aquifers?

One of the difficulties in the application of this method is also the classes' limits and the rate assigned to the various parameters [34]. Indeed, the limits of the standard classes do not often reflect the reality of the study zone due to the fact that these classes can include different entities [25]. So, the assignment of the rate is not always identical to that defined by the method as well as the index of vulnerability. It shows that these limits of the various classes are not absolutes, but are relative values [4]. These maps of vulnerability describe consequently a relative aquifers vulnerability based on the available data of various precision and resolution. The resolution itself depends on the number and the proximity of test points [6]. However, the combination of resolution is acceptable for the estimation of the relative aquifers vulnerability but not adequate to determine the specific vulnerability of one site [21]. In spite of the various limits underlined in the establishment of the vulnerability to pollution map by DRASTIC method, the fact remains that the maps of intrinsic vulnerability are reliable. These maps of vulnerability to pollution were confirmed by the values of nitrates contained into groundwater of Abidjan and Korhogo. These spatial distribution maps of nitrate values allow validating these maps of groundwater vulnerability to pollution of Abidjan. A particular attention must also be concerned these maps in the future development of Abidjan. The works of [35], [36], [28] and [34] have also ended in such a conclusion. This map allows having an idea on the sensitive zones which it is necessary to take into account during the town planning [11].

CONCLUSION

The application of DRASTIC method has allowed realizing the maps of groundwater intrinsic vulnerability of Abidjan district and Korhogo department. The analysis of these maps highlights vulnerability classes of unequal spatial distribution. These various maps of vulnerability were confronted with the maps of spatial distribution of nitrate values. It stood out from this confrontation an overlapping of the high vulnerabilities zones to the high nitrate values zones; validating also the vulnerability maps. The

overlapping of these two types' maps (high vulnerability and high nitrate values) allows saying that the maps established by this method reflect the reality. DRASTIC method can be thus applied in Côte d'Ivoire whatever the hydrogeological environment is (sedimentary or crystalline) for the mapping of groundwater vulnerable zones to pollution.

ACKNOWLEDGEMENT

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