CONTRIBUTION OF MULTICRITERIA ANALYSIS AND GIS FOR THE SPECIFIC VULNERABILITY MAPPING TO AGRICULTURAL INPUTS OF GROUNDWATERS IN BONOUA AREA (SOUTHEAST OF CÔTE D'IVOIRE)

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Abstract: This study focuses on the mapping of vulnerable areas to agricultural pollution of Bonoua area where groundwater are envisaged to support the District of Abidjan. Thus to achieve this, the methodological approach adopted involve the use of GIS functionality combined with multi-criteria analysis method. The analysis of groundwater vulnerability map to nitrate in the region of Bonoua highlights five vulnerability classes ranging from very low to very high. The class of "medium vulnerability" is the most dominant and represents 44.21% of the mapped areas. This vulnerability map was validated using the measured nitrate levels in groundwater.

Keywords: pollution, specific vulnerability, GIS, multi-criteria analysis, Bonoua, Côte d'Ivoire

1. INTRODUCTION

In the world, groundwaters represent an important resource used for supplying drinking water, agriculture and industries [1]. Although these waters are in the basement, they are not sheltered from the pollution [2]. They quality are constantly threated by substances from divers natures those can be biologic, chemical or physical. In general, the groundwater contamination is observed after the contaminant has migrated from its initial area and has reached the aquifer systems by charging, in which case it is difficult to be rehabilitated [3]. The prevention against pollution is an important environmental preoccupation that Scientifics accord more effort including the groundwater vulnerability mapping. The establishment of groundwater vulnerability mapping allows better management of groundwater and an execution of effective actions to reduce or prevent pollution [4].

Face to the growth of Abidjan Population (3125890 habitants in 1998 and about 5 million in 2006) [5] associate with dysfunction of some district drillings because of water nitrogen pollution, Bonoua groundwaters exploitation are planned to cope the high needs of this population. Those needs are estimated to about 500000 m^3 per year according to Water Distribution Company of Côte d'Ivoire. Situated in the department of Grand-Bassam, this area possess a water reserve estimated to 13.9 10^9 m^3. Therefore she represents a strategic issue for authorities responsible to the drinking water supply. However this groundwater water is localized in a strongly agricultural area in which fertilizer use is recurrent. The rate of agricultural inputs use is evaluated at about 24% [6].

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Protection of this resource against the agricultural pollutants becomes essential seen the stake it represents. This study was undertaken to develop a vulnerability map related to agricultural inputs of groundwaters in Bonoua area in order to insure best management of it for present and future.

2. MATERIAL AND METHODS

2.1. Study area

The Bonoua region is located in the South-east of Ivory Coast between latitude 5°08’ et 5°31’ N and longitude 3°11’56 et 3°44’ W. She includes the sub-prefectures of Bonoua and Adiake, and a few villages of the sub-prefectures of Aboisso and Alepe. Bonoua is bounded on the North by the cities of Alépé and Aboisso, to the West by Comoe River, to the East by Aby lagoon and Bia River and on the South by Atlantic ocean (Figure 1). This area belongs to subequatorial climate encountered in southern Ivory Coast. She is well watered by an average rainfall of 1710 mm [6].

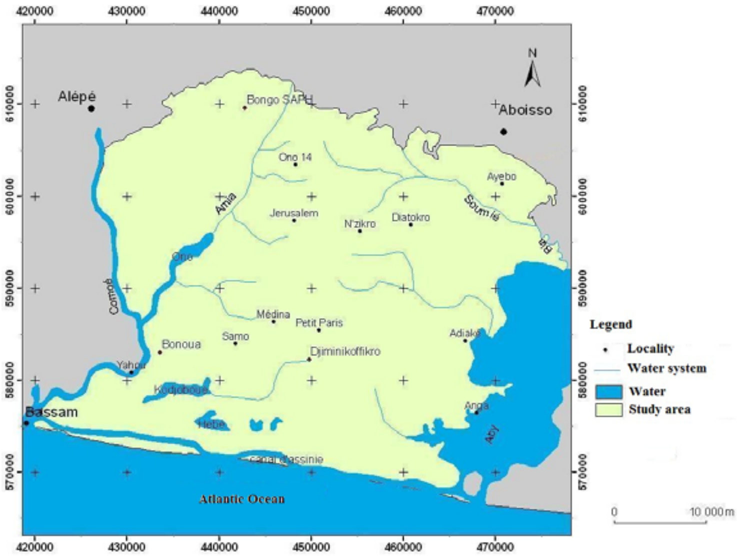

Fig. 1. Location of study area [6].

On geological plan, Bonoua area belongs to the Ivorian coastal sedimentary basin of Cretaceous to Quaternary [7]. Sedimentary formations are made up of sand, clay and sandstone ferruginous dotted of clay-sand and vases along the waterways. The aquifer main of Bonoua exploited for drinking water supply is the Terminal Continental Mio-Pliocene age [7].

2.2. Material

The specific vulnerability mapping of Bonoua area groundwaters to agricultural inputs has necessity the establishment of a dataset. This dataset includes essentially cartography data (geology, landUse of March 2008 and Pedology) and SRTM images (available on the web). Some data such us drilling technical sheets, temperature, rainfall amounts of Adiake station (1980-2006) and drilling chemical data of 2007 were used also. For processing of all these data, software such as MapInfo and ArcGIS were used.

2.3. Methodology

2.3.1. Notion of vulnerability

The term "aquifer vulnerability" is seen from two angles:

- Intrinsic vulnerability based on physical condition of the natural environment;
- Specific vulnerability includes not only the natural parameters but also contaminant properties and the nature of anthropogenic activities [8]. The vulnerability focuses on behavior of potential pollutant, dispersive capacity and purification of the soils, water system quality, landUse typology, sensible points and seawater intrusion [9].

The notion of "specific vulnerability" in this study is used to define the groundwaters vulnerability to a particular pollutant or group of pollutants [10]. Thus, le pollutant considered is nitrate from nitrogen fertilizers.

2.3.2. Methodology approach

The methodology developed for assessing the specific vulnerability to agricultural inputs in the groundwaters of Bonoua region includes the parameters influencing the vertical transfer of pollutants towards groundwaters, behavior and origin of nitrate. This methodology can regroup in 4 stages:

- determination of parameters and ratings assignation;
- elaboration of hierarchy;
- the weighting of criteria and parameters;
- calculation of vulnerability index.

2.3.2. Determination of parameters and ratings assignation

Specific vulnerability includes pollutants properties and its relations with various components of intrinsic vulnerability. Thus the parameters determination of specific vulnerability in groundwater of Bonoua region consisted to add to intrinsic parameters the pollutants properties. For each parameter, a map will be elaborate. A rating varying between 1 and 10 is assigned of each interval. The vulnerability parameters identified are:

- **Effective recharge (R):** It is total quantity of water which reach piezometric surface. The establishment of this parameter requires the calculation of water amount infiltrated during 1980-2006 period from the temperature and rainfall amount. The recharge which is closely bound to the effective infiltration depends of rainfall and its losses by runoff and evapotranspiration. The recharge was estimated from the hydrological equation:

$$P = ETR + R + I; \; I = P - (ETR + R) \tag{1}$$

  with P= annual rainfall (mm); R= runoff (%); I= effective infiltration (mm) and ETR= annual real evapotranspiration (mm). The value of ETR was calculated from formula of Thornthwaite. The height of water infiltrated during 1980 to 2006 period was estimated at 35.589 cm/year. With only this value, the hypothesis wills that recharge is uniform and constant throughout study area. Therefore according to the rating system, the rating assigned to this parameter is 9;
- **Impact of the unsaturated zone (I):** The unsaturated zone is a ground portion between soil (first meter from the surface) and the aquifer surface. The texture of this area determines the time of pollutant transfer [11]. The different geological sections of drillings carried out in this area allowed to define this parameter. The geological layers concerned are those which overcome the aquifer type. The dominant formation in this part was considered representative of unsaturated zone. The lithological formations of unsaturated zone identified are clay, clayey sand, clayey medium sand, and medium and coarse sand. The ratings assigned to these formations taking into account their textures are respectively 3, 6, 7, 8 and 9.
- **Hydraulic conductivity (C):** Hydraulic conductivity of aquifer is defined as the ability of a environment to allow circulation of water through its components. She corresponds to the velocity of liquid substances propagation in the middle. The value of this parameter coming from the works of [12] was estimated at $2\ 10^{-2}$ m/s about 172.8 m/day. The rating 10 was assigned to this parameter taking into account of scoring system adopted.
- **Depth of the water (P):** This is the distance from the ground surface to the top of aquifer. The role of Depth is very important in the assessment of groundwater vulnerability. Indeed, less the distance between aquifer and the ground surface is long, more the resource is vulnerable and less the time of transfer is short [13]. For the determination of this parameter, the water levels of 72 drillings were used. The interpolation of these data allowed drawing the map relative to this parameter. A rating between 1 and 10 was assigned to different values obtained.
- **LandUse (O):** It corresponds to discharges of human activities as industrial, agricultural and urban. This is the set of activities practiced at the ground surface and likely to generate pollutants. The intensity and the nature of these activities favor the pollution or no of the resource. This parameter was obtained from the land use map. Ratings were assigned to main crops according their consumption degree of fertilizer because the pollutant taken in this study is nitrate. Value 1 is assigned to forests and rating 8 and 5 respectively to pineapple crops and rubber.
- **Soil (S):** Soil characteristics control the descendant movements of contaminants [13]. This parameter was found from pedologic map of our study area. Clay soils, ferrallitic soils and hydromorphic soils are encountered in the study area. The scoring given to these soils depend to their capacity to retain water and their power of nitrogen oxidation. These are respectively 1, 6 and 7.
- **Topography (T):** It allows controlling the probability that has a pollutant to flow or to infiltrate into the ground. This parameter comes from digital elevation model (DEM). The later coming from SRTM

image allowed to obtain slopes from tool "slope" of ArcGIS. The slopes vary between 1 and 18.56%. The scores assign to these slope are 1, 3, 5, 9 and 10.

- **The evolution of pollutant:** This parameter concerns the processes those affect a pollutant during its travel through the deep layers. Pollutants are confronted to physical, chemical and biological processes during their leaching [14]. These processes can lead to the delay, reduce and increase the pollutant mobility. The 10 rating was given at this parameter on basis of reaction undergone by nitrate which are solubility, redox and ions exchange.

All these parameters taken in order give acronym **RICPOSTE** to the method.

2.3.3. Prioritization and comparison of criteria

The different parameters involved in specific vulnerability are grouped into a homogeneous set of tree levels. The level (0) corresponds to the general objective, the level (1) to the decision criteria and the level (2) to its characteristics. Three main criteria of decision formed from the parameters identified were retained. These are soil, unsaturated zone (ZNS) and landUse type (TOS). In order to facilitate criteria combination and parameters, some weights were assigned to them (Figure 2).

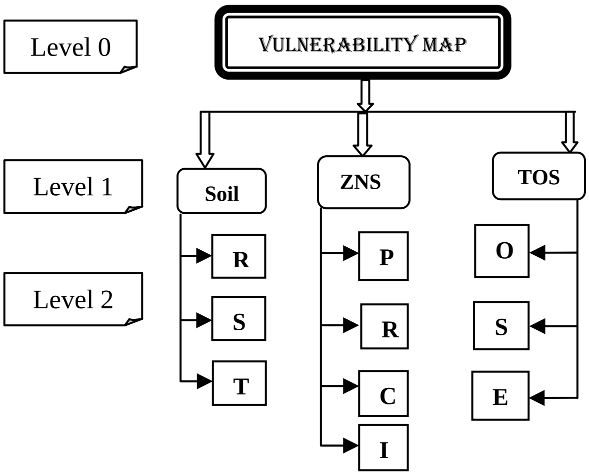

Fig. 2. Hierarchy of parameters retained.

The pair wise comparison method of analytic hierarchy process (AHP) developed by [15] was used for calculating weights. Saaty suggests a scale value from 1 to 9 (Table 1) for the pair wise comparison of criterion [16].

Table 1. Scale of comparison [15].

Value	Comparison	Verbal scale
1	equal importance	both elements are of equal importance
3	moderately important	an element is more little important than the other
5	important	an element is more important than the other
7	very important	an element is more much important than the other
9	extremely important	the dominance of an element is remarkable
2, 4, 6, 8	intermediate values	intermediate values between two judgments is used for refining the judgments

2.3.4. Weighting for criteria and parameters

The values of the criteria decision judgments are presented in matrix (Table 2). For carry out the matrices, the element of left column is successively compared with each elements of the top line of the matrix. If the comparison isn't favorable to left column, appreciation is expressed by a fraction; if not by an integer. The process of comparison begins with the parameters of same criterion. Thus, four matrixes were formed following the prioritization. The first three matrices allow performing comparisons between parameters of a same criterion, and the last between criteria according to the main objective.

The methodology adopted for calculating the weight is summed in 4 stages. The example illustrated in the case of this study is the cell of the first line of the first column:

- The first step consists to sum the values given to different entities compared:

$$\sum Wk \tag{2}$$

with *Wk* = value given to the element and k the le number of elements. Example 1: 1+1/3+3=13/3

Table 2**.** Comparison of criteria.

	SOIL	**ZNS**	**TOS**
SOIL	1	3	1/3
ZNS	1/3	1	1/5
TOS	3	5	1
Tot	13/3	9	23/15

- The second step consists to divide the values of equation 2 by the total of the cell of Table 3 then to sum the values of the relative line.

$$\sum \frac{Wk}{\sum Wk} \tag{3}$$

- Example 2: 3/13+3/9+15/69=0.781

Table 3**.** Weight of criteria.

	SOIL	**ZNS**	**TOS**	**Sum**	**Weight**	**Coherence index**
SOIL	3/13	3/9	15/69	0.781	0.26	0.002
ZNS	3/39	1/9	15/115	0.318	0.11	
TOS	9/13	5/9	15/23	1.9	0.63	
Total	13/3	9	23/15		1	
SOIL	3/13	3/9	15/69	0.781	0.26	

- The third and last step led to the division of the equation 3 value by the number of elements to compare:

$$\sum \frac{Wk}{\sum Wk} \times \frac{1}{3} \tag{4}$$

Example 3: 0.781/3 = 0.26.

- The fourth step led to verify the coherence of judgments. The coherence index measures the logical coherence of judgments [16]. Thus, for each matrix, a coherent index will be calculated. It has to be less or equal to 10%; if not the appreciations may require some revisions [17]. The approach adopted for the judgments verification is subdivided in three groups.

$$\sum \frac{Wk}{\sum Wk} \times \frac{1}{3} \times Tk \tag{5}$$

when *Tk* = total column.

- Example 4: (0.26x13/3) + (9x0.11) + (0.63x23/15) = 3.09.

$$(\sum \frac{Wk}{\sum Wk} \times \frac{1}{3}) - k \qquad (6)$$

- Example 5: 3.09–3 = 0.09.

$$\frac{(\sum \frac{Wk}{\sum Wk} \times \frac{1}{3} - k)}{k - 1} \qquad (7)$$

Example 6: 0.09 / (3–1) = 0.045.

when **0.045** represents the coherence index (*Ci*). This value expresses a good coherence of judgments carry out.

2.3.5. Calculus of vulnerability index
The specific vulnerability index is calculated according this formula:

$$I_{VS} = p_{soil} \times C_{soil} + p_{ZNS} \times C_{ZNS} + p_{TOS} \times C_{TOS} \qquad (8)$$

where P and C are indicates respectively specific vulnerability index, weight and the map of criterion. The vulnerability classes are obtained by grouping *Ivs* [18]; the limits of classes are calculated from the following formula:

$$I(\%) = \frac{(Ivs_i - Ivs_{\min}) \times 100}{Ivs_{\max} - Ivs_{\min}} \qquad (9)$$

with Ivs_i is the class limit, Ivs_{min}= minimum value (2.0986); Ivs_{max}= maximum value (8.418).

$$Ivs_i = \frac{I \times (Ivs_{\max} - Ivs_{\min})}{100} + Ivs_{\min} \qquad (10)$$

when *I* equal 30%, *Ivs* corresponds 3.9944. The grouping of *Ivs* according limits calculated led to different classes of vulnerability.

3. RESULTS AND DISCUSSION

3.1. Map of specific vulnerability indices and degree of vulnerability

The combination of layers on weighting criteria "SOL", "ZNS" and "TOS" gave the map of vulnerability indices (Figure 3). These indices vary from 2.54 to 7.87. The classification of indices following the bounds calculated allows obtaining five classes of vulnerability.

The analysis of this map shows that:

- the very low class represents 27.78% of area mapped. It focuses in northeast of zone, on the east of Ayenoua and a few places scattered in the south;
- the low class representing only 8.58% focuses in the watersides;
- the medium class, more important is seen on the most part of the zone, particularly at Aboutou, Diatokro, Ayenoua, Bongo and N'zikro. It represents 44.21% of zone mapped. The high class was assessed at 12.44%. It is met in the southwest of study area, after the town of Grand Bassam; in the east around the Anga village, located at Aby lagoon side and the plantations of rubber (Bongo-SAPH and SODEPALM);
- the very high class represents 6.99% of study area. It located in the center, in the Bonoua sector, Tchintchébé, Samo, Médina, near Djiminikoffikro and around the lagoon Ono.

The vulnerability map obtained is influenced by landUse criterion so that the high and very vulnerability classes coincides with pineapple crops, oil palm and rubber trees that requires an intense contribution of agricultural inputs.

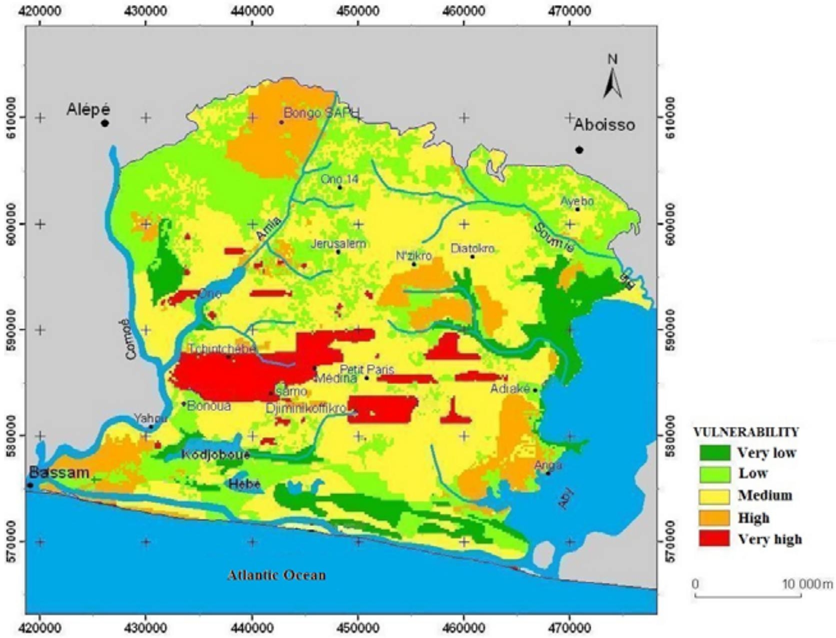

Fig. 3. Map of vulnerability indices.

3.2. Validation of vulnerability map

The superposition of Bonoua's groundwater nitrate concentrations on the vulnerability map performed (Figure 4) allows to establish a spatial relation between the both. The nitrate concentration varies from 0.3 to 24.3 mg/l. they are low and lower than the World Health Organization standard in drinking water which is 50mg/l. they haven't any effect on human health.

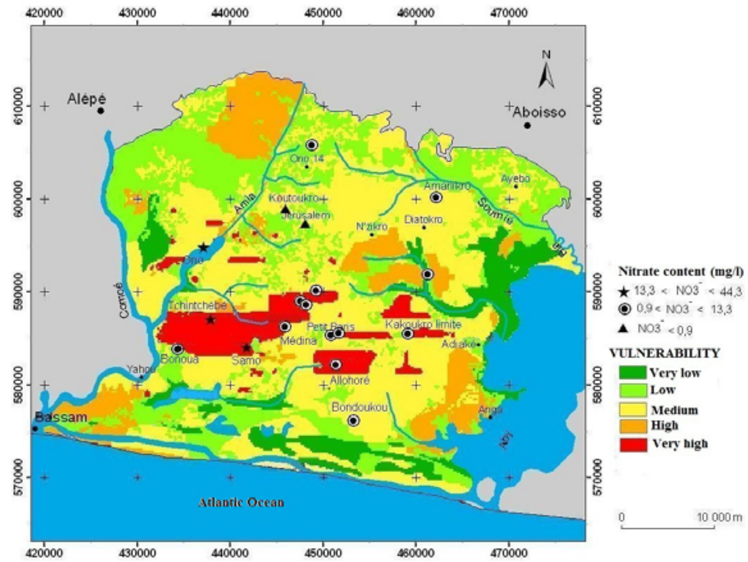

Fig. 4. Content of nitrate.

The rate of overlapping between content with vulnerability map presented by Table 4 shows that 75% values of category 3 coincide with the locality estimated as a zone having a very high vulnerability. Also, 46.62% of the category 2 superimposes with the medium vulnerability and 100% values of category 1 superimpose with the low class. This rate allows expressing that the map performed by RICPOSTE method reflects ground truth.

The results of validity could be improved by an important of nitrate data spread on the whole of study area. This validation type of vulnerability map was used by a few authors like [1, 3, 13] and [19-21]. These authors have showed that the higher content of nitrate overlap with the high vulnerability area.

Although the nitrate content of groundwater with the high vulnerability remain lower than OMS standard, agricultural practice must be regulate and monitor. Also, it would desirable to watch regularly the groundwater quality in the drillings in order to avoid the water contamination. The vulnerability map obtained allows delimiting the sensitive zones that we will have to take into account in the management of Bonoua region. It is therefore a help tool of decision.

Table 4. Degree of nitrates content overlapping on the classes of vulnerability.

	Category 1		**Category 2**		**Category 3**	
Vulnerability	Number of values	Percentage (%)	Number of values	Percentage (%)	Number of values	Percentage (%)
Very low	0	0	1	7.69	0	0
low	**2**	**100**	2	15.38	0	0
medium	0	0	**6**	**46.16**	1	25
high	0	0	0	0	0	0
Very high	0	0	4	30.77	**2**	**75**
TOTAL	2	100	13	100	3	100

4. CONCLUSIONS

The map of specific vulnerability to nitrate in the groundwater of Bonoua region was performing by the combination of GIS method and multicriteria analysis. The analysis of this map shows five vulnerability classes whose the most important is the medium class which covers about 44.21% of study area. The validity of this method was tested by overlapping of 18 values of nitrate with the specific vulnerability map established. It follows that 75% of nitrate values due to human activities coincide with the zone corresponding to the very low vulnerability. This strong rate of coinciding allows to say the map established in this study can be considered as reliable. Nevertheless, if it is true that the nitrate values are for the time being low, an particularly attention must be given to the vulnerable zones in order to preserve as long as possible the quality of Bonoua groundwater.

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