Comparative Analysis Of The Mapping Of The Vulnerability To Pollution Of Fissured Aquifers In Agboville Department By Drastic And SI Methods (South-East Of Côte d'Ivoire)

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Abstract:

The study aims to establish vulnerability maps of groundwater pollution in Agboville department due to anthropogenic pressures, with a view to their sustainable management. The methods used are DRASTIC and SI. They use four common vulnerability parameters (groundwater depth, recharge, aquifer materials and topography) that are intrinsic to the aquifer. To these parameters, the DRASTIC method associates three others (soil type, unsaturated zone and hydraulic conductivity), while the SI method associates a fifth extrinsic parameter (land use). Their thematic mapping, followed by their combination in a GIS, made it possible to draw up the various pollution vulnerability maps using both methods. Each map highlights five classes of vulnerability. The dominant vulnerability classes in terms of surface area occupied are: low (32%) and high (36%) for the DRASTIC method, and medium (42%) and high (26%) for the SI method. The superimposition of the map of spatial distribution of nitrate levels in groundwater with the established vulnerability maps shows that the areas with low levels coincide with the low vulnerability classes, thus allowing their validation. The results of the Kappa test and the surface analysis to examine the vulnerability maps reveal that the Kappa coefficient (K = 0.29) is reliable and gave a fair agreement between the two methods. This agreement is confirmed by the surface analysis (45,25 %). The SI method appears to be the most appropriate for assessing the vulnerability to groundwater pollution in this area.

Key Words: Vulnerability to pollution, discontinuous aquifers, DRASTIC, SI, Agboville, Côte d'Ivoire.

Introduction

Anthropogenic activities (urbanization, intensive agriculture and industrialization) and their environmental impacts are major issues in our ever-growing civilizations (Ducommun, 2010). One of its impacts is water pollution, in this case groundwater. Indeed, the quality of this water is deteriorating due to the increase in diffuse sources of pollution from agricultural activities and point sources from industrial activities, accidental spills of toxic substances, waste burial sites and wild deposits of garbage (Murat, 2000). This is a very alarming situation of about two billion people worldwide depend on groundwater for drinking and irrigation water (United Nations, 2017). As a result, the issue of access to water has become an important challenge for all humanity and international bodies have included it in the Sustainable Development Goals (SDGs) to guarantee access to water and sanitation for all and to ensure sustainable management of water resources (WHO, 2000). Since 2000, the State of Côte d'Ivoire has had a national water policy oriented towards Integrated Water Resources Management (IWRM) to ensure sustainable management of the available resource. In addition, the localities of the Agnéby watershed, including the Agboville department, are experiencing environmental problems affecting drinking water supply (Assoma, 2013). In fact, the drinking water supply of the populations is carried out by the Water Distribution Company of Côte d'Ivoire (WDCCI) exclusively through the catchment of the "Agbô" river, whose quality has considerably deteriorated and no longer responds efficiently to conventional physico-chemical treatments (PREMU, 2017). The aftertaste left by these waters distributed in households encourages the population to resort to mineral water for those with a high income level or to purchase water in "packets" from water sources and wells of doubtful quality for the most modest. However, the work of N'go et *al.,* (2005) and Ahoussi (2008) indicates that this area is densely fractured and represents a real groundwater reserve, which would constitute an undeniable recourse to alleviate this problem of drinking water supply for the populations of these localities. In addition, the excessive use of fertilizers, pesticides and effluents from sewage systems, septic tanks and solid waste, linked to the density of agricultural activities, galloping demographics are a threat to these groundwater resources. In Azaguié for example, the contamination of groundwater by pesticides was revealed (Touré et *al.,* 2015) showing the impact of anthropogenic activities on these resources. Groundwater in this department is then threatened by this worrying situation. To prevent the risks of groundwater pollution, one of the adapted approaches is the knowledge of areas vulnerable to pollution.

However, no groundwater vulnerability mapping studies have been undertaken in this department to show the main trends in vulnerability and the allocation of activities at risk. Thus, the present study includes the assessment of the intrinsic vulnerability to pollution of the fissured aquifers of the Agboville department by the DRASTIC method. It also combines the SI method, which assesses the specific vulnerability to nitrate pollution, to highlight these impacts. These two methods are then compared by the Kappa test and surface analysis to determine which one best assesses vulnerability to pollution. The objective of this study is to highlight the areas vulnerable to groundwater pollution in Agboville department in order to guide the choice of policies for the prevention and management of pollution risks to the groundwater resources of this region in a sustainable management perspective.

I. Presentation of the study area

The department of Agboville is situated in southeastern Côte d'Ivoire, between latitudes 5°35’N and 6°15’N, and longitudes 3°55’W and 4°40’W. It covers an area of about 3,850 km^2 (Figure 1) within the square degree of Abidjan. This department is located about 82 km from Abidjan.

The geomorphological model of the department is characterized by a very monotonous set. It consists of a peneplain composed of a succession of interfluves with convex summits. The landscape as a whole is dotted with rounded hills culminating at 200 m, with an average of 108 m (Géomines, 1982). The plateaus are opened by numerous flared thalwegs and the difference in height between plateaus and thalwegs varies from 20 to 40 m.

The Agnéby river and its tributaries create multiple valleys giving rise to abundantly drained low plateau (Dembélé, 1989).

The soils in the study area are ferralitic. In the south of the department, soils are moderately desaturated and in the north, they are strongly desaturated with humiferous horizons. The hydromorphic gley and pseudogley soils are located along the Agnéby river (Rieffel, 1967). Peat bogs are also found in marshy valleys. The department of Agboville has a vegetation cover marked by the ombrophilic type for the southern third and the rest by the mesophilic type dominated by Gabonese tulip trees and cheese makers. This vegetation is characterized by numerous stretches of forest, several of which have been classified by the colonial administration (Seguié, Gorké, Kavi, Mafé, Loviguié, Seddy, Bamo, Bebasso and Yapo Abbé). There are areas of clearings due to agricultural activities. It is under the influence of the transitional equatorial climate marked by four seasons (02 rainy seasons and 02 dry seasons). Nowadays, this distribution of seasons is disturbed by climate variability (Orou, 2017).

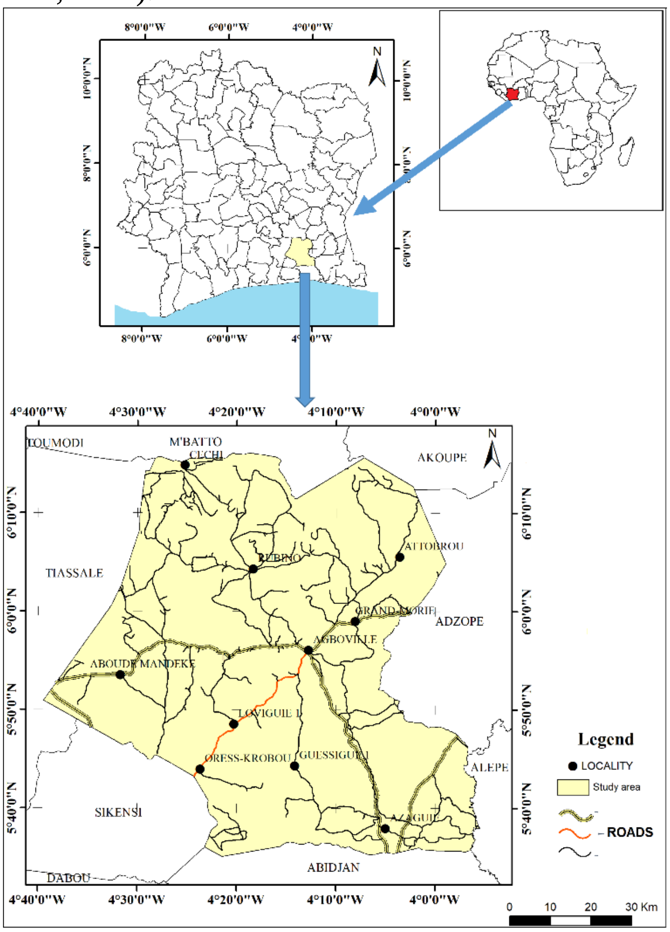

Figure 1. Location of Agboville departmen

This department is characterized by a climate without much temperature variation; the hottest month is March with an average of 28.5°C, and August is the coldest with 24.5°C (Ahoussi, 2008).
This area is sufficiently drained by many watercourses (Figure 2). Surface waters are dominated by rivers and numerous small reservoirs. The Agnéby, the most important river, has its source in the department of Bongouanou in the north and is 250 km long (Pierre, 1993). This river has three main tributaries: the Kevi, the Gorké and the Seguié.

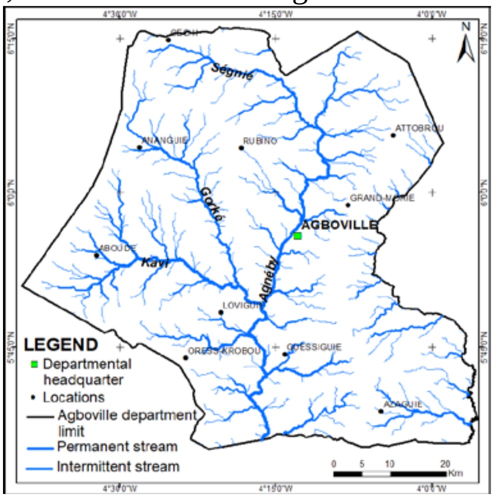

Figure 2. Hydrographic network of the Agboville department

The study area is an agricultural area. Rice, vegetables, fruit, cocoa, oil palm, rubber and to a lesser degree horticulture is cultivated (Orou, 2017). There are also some agro-industrial units. The geological formations consist of crystalline, mainly schistose, strongly folded and metamorphosed rocks interspersed with granitic intrusions. The schists present important lateral variations related to a very heterogeneous lithology. Their alteration produces a thick layer of alteration whose strength varies between 4 and 40 m (N'go et *al.*, 2005).

The granitoids are intruded by quartz veins and affected by several fracture networks of variable direction (NS, N75°, N30°, N85° and N155°). These fractures and veins are of great interest in the recharge of aquifers in the region (Ahoussi et *al.*, 2010) and could constitute preferential zones for the circulation of pollutant towards groundwater aquifers.

II. Material and Method

2.1. Material and data

The data used in this study consist of :

- a Shuttle Radar Topographic Mission (SRTM) satellite image with a resolution of 30 m, downloaded via the http site : //

www.glcf.umiacs.umd.edu, covering the study area dealing with altitudes and used to assess the altimetry of the study area and to draw up its slope map;
- the scenes (196-056, 195-056 and 194-055) of the Landsat 8 OLI satellite image, acquired on 20 April 2019, on the american http site : // earthexplorer.usgs.gov/images for land use mapping;
- a soil sketch map of Côte d'Ivoire South-East sheet at a scale of 1/500,000 for the realization of the soil map;
- technical data sheets of boreholes (88 in number) carried out in the Agboville department covering the period from 1978 to 2000, from the Directorate of Rural and Peri-urban Hydraulics, the National Drinking Water Office and the works of Ahoussi et *al.,* (2010). They were used to produce maps of depth, aquifer material, soil type and the impact of the vadose zone in the study area;
- nitrate chemical data from groundwater (29 in number) in the Agbovillle department extracted from the work of Orou (2017) to validate the vulnerability maps;
- rainfall data from the Agboville station acquired from the Development and Operation, Airport, Aeronautical and Meteorological Society (DOAAMS) over the period from 1901 to 2000 for the evaluation of annual rainfall in the Agboville department.

2.2. Method

The DRASTIC method is intended for mapping the intrinsic vulnerability of aquifers. It has already been the subject of several applications through the literature (Mohamed, 2001; Murat et *al.,* 2003; Jourda et *al.,* 2007; Aké et *al.,* 2010, Deh et *al.,* 2012). Although often modified, such as the Susceptibility Index (SI) method for example (Hamza et *al.,* 2007), it remains effective in vulnerability assessment. The SI method or Susceptibility Index is a specific vertical vulnerability method developed by Ribeiro (2000) to take into account the behaviour of pollutants of agricultural origin, mainly nitrates (Aké et *al.,* 2010).

The joint application of the DRASTIC and SI methods has the advantage of ensuring a certain complementarity in the assessment of the vulnerability of a slick to nitrate pollution (Aké et *al.,* 2010). These different methods take the form of a numerical rating system, based on consideration of the various factors influencing the hydrogeological system. Their application was then followed by a correlation test (Kappa test, surface analysis) in order to determine the one that best assesses the vulnerability to pollution of aquifers in Agboville department.

2.2.1. Assessment of vulnerability to pollution using the DRASTIC method

The acronym DRASTIC corresponds to the initials of seven factors determining the value of the vulnerability index (Bézèlgues et *al.*, 2002): depth of the water table (D); effective recharge (R); aquifer materials (A); soil type (S); topography or slope (T); the impact of the vadose zone or unsaturated zone (I) and the permeability or hydraulic conductivity of the aquifer (C). Each parameter is assigned a scale with intervals where a rating is given according to the particularity of the environment. Each thematic map was classified into classes associated with ratings ranging from 1 to 10, and each of the seven parameters was then assigned a fixed multiplier factor (Dp) ranging from a value of "5" for the most significant factors to a value of "1" for the less significant factors.

The DRASTIC vulnerability index (ID) was determined according to equation (1) (Osborn et *al.*, 1998) :

$$ID = Dc \times Dp \ + Rc \times Rp + Ac \times Ap + Sc \times Sp + Tc \times Tp + Ic \times Ip + Cc \times Cp \quad (1)$$

(Where D, R, A, S, T, I and C are the seven parameters of the DRASTIC method, "p" being the weight of the parameter and "c" the associated coordinate). After the index calculation, the vulnerability classes are matched to the different ranges of DRASTIC indices calculated. Equation (2) is used to convert the DRASTIC indices into percentages (Jourda et *al.*, 2007).

$$Index\ in\ \% = \frac{ID-23}{203} \times 100 \quad (2)$$

These percentage indices correspond to degrees of vulnerability as shown in table 1.

Table 1. DRASTIC Index and degree of vulnerability according to Jourda et *al.*, (2007)

DRASTIC Index in %	Degree of vulnerability
0 - 30 %	Very low
31 - 45 %	Low
46 - 60 %	Medium
61 - 75 %	High
76 - 100 %	Very high

2.2.2. Assessment of vulnerability to pollution using the SI method

The particularity of this five parameter method is that it has four parameters which are identical to the DRASTIC method and a fifth one which is the land use (LU). The ratings assigned to the four parameters in the DRASTIC method have been retained.

The land use parameter was obtained by processing the Landsat 8 OLI image acquired on April 20, 2019.

The digital processing consisted in the creation of multi-band images which served as a basis for the realization of the coloured compositions. In this study, Landsat OLI bands 5, 6 and 7 were combined because they present a better discrimination between geographical objects (Sarr, 2009). This step generated six land cover types based on the colour composition. In order to compare these classes defined on the image with the reality on the ground, the investigations were continued by selecting training sites. They were chosen according to their accessibility and spatial distribution. It was a question of having control points for the different types of land use. Subsequently, a mission carried out on 08 and 09 October 2019 in the city of Agboville and its surroundings, allowed to take the bitter points with the GPS of various useful and even essential data in the realization of the land use map. This was followed by the directed classification. The control of the area made it possible to opt for a supervised classification using the maximum likelihood algorithm. This algorithm is widely used in supervised classifications and is considered to be the most efficient algorithm in the production of thematic maps in the field of land cover (Bonn et Rochon, 1992). The information collected was then compared with the field data and the confusion matrix, characterized by the overall precision, the Kappa coefficient, to obtain an acceptable overall precision. An improvement of the classification by a 3x3 median filter was used and allowed the elaboration of the 2019 land use map of the Agboville department. The "land use" parameter underwent a subsequent classification, specifically that of Corine Land Cover (1993) as shown in table 2.

A value called the land use factor and noted LU, ranging from "0" to "100", is assigned to each land use class (Aké et *al.*, 2010).

Thus, a value of "0" corresponds to forests and semi natural areas while a value of "100" is assigned to industrial landfills, garbage dumps and mines. The values of the scores assigned to the classes of the different parameters were multiplied by "10" to facilitate the reading of the results obtained. Thus, they range from "0" to "100", from the least vulnerable to the most vulnerable (Table 2). The weights assigned to the SI parameters vary from "0" to "1" depending on the importance of the parameter in terms of vulnerability (Table 2). The calculation of the SI index is carried out using the equation noted 3 of (Hamza et *al.*, 2007) :

$$ISI = Dc \times Dp + Rc \times Rp + Ac \times Ap + Tc \times Tp + OSc \times OSp \qquad (3)$$

With:

ISI: SI index, c = parameter rating and p = the associated weight.

Based on the classification in table 2, another classification, which takes into account the realities of the Agboville department, was carried out to adapt the SI method to the context of the study area (Table 3). In this way, it was possible to establish a correspondence between the classes of SI indices and those of degree of vulnerability obtained (Table 4).

Table 2. Land use classification according to Corine land Cover (1993) and weight of SI parameters

Land use classes				Value of the factor (LU)	
Industrial landfills, garbage dumps, mines				100	
Irrigated perimeters, rice fields, irrigated and non-irrigated annual crops				90	
Careers, Shipyard				80	
Artificial covered areas, green areas, continuous urban areas				75	
Permanent crops (vines, orchards, olive trees, etc.)				70	
Discontinuous urban areas				70	
Pastures and agro-forestry areas				50	
Aquatic environments (marshes, salt marshes, etc.)				50	
Forests and semi-natural areas				0	
Parameters	**D**	**R**	**A**	**T**	**OS**
Weight	0.186	0.212	0.259	0.121	0.222

It is excluded from the new classification (Table 3), the first four land use classes (see Table 2) being non-existent in Agboville department.

Table 3. Classes and land use ratings according to the SI method in Agboville department

Land use	Land use factor value
Industrial crops	70
Bare ground / disparate urban areas	70
Mosaic fallow - culture	60
Mosaic forest - culture	50
Water	50
Islands of dense forest	0

Table 4. SI indexes and degree of vulnerability (Jourda et *al.*, 2007)

SI Index	Degree of vulnerability
0 – 30 %	Very low
30 – 45 %	Low
45 – 60 %	Medium
60 – 75 %	High
75 – 100 %	Very high

In this approach, and following the work of Jourda et *al.*, (2007); Aké et *al.*, (2010), the minimum rating that a parameter is likely to have in the study area is 1 and the maximum rating is 23. The equation for converting the SI indexes to percentages is as follows equation 4 :

$$ISI = \frac{ISIi - ISImin}{ISImax - ISImin} \times 100 \quad (4)$$

With ISIi: SI index to be identified, ISImin = 1 and ISImax = 23
By replacing the various unknowns in equation (4) with their values, we obtain equation 5 below :

$$ISI = \frac{(ISIi-1)}{22} \times 100 \quad (5)$$

2.2.3. Vulnerability map validation

The vulnerability maps developed were validated by the groundwater chemical test. Several authors including Mohamed (2001), Jourda et *al.*, (2006), Hamza et *al.*, (2007), Kouamé (2007), Aké et *al.*, (2010) have verified the validity of pollution vulnerability assessment methods based on groundwater chemistry data in their studies. The different vulnerability maps, in the case of the present study, were tested by the distribution of nitrate levels in groundwater (Orou, 2017), from the department of Agboville. The map of nitrate contents in groundwater was superimposed on the different vulnerability maps established. A vulnerable zone is not synonymous with current pollution. However, it calls for predispositions to be taken to strengthen policies for the protection of these resources.

2.2.4. Correlation test between the methods used

The objective of this test is to evaluate the adequacy of the results obtained or the degree of agreement of the vulnerability maps by the DRASTIC and SI methods. A classification of the methods has been carried out using the results of this test, which consists of the Kappa test and surface analysis.

2.2.4.1. Kappa test

The Kappa coefficient developed by Cohen in 1960 (Murat et *al.*, 2000) is the proportion of agreement among observers, attributable to the reproducibility of classifications rather than chance.

Reproducibility is therefore observed when a measurement gives the same result regardless of the measurement method (Kouamé, 2007). This coefficient represents the statistical index that measures the degree of agreement of a measure between two or more observers who have to judge the same phenomenon. The elements taken into account to adapt the kappa test to the study are :

- the number of subjects "n" corresponding to the number of pixels in the study area ;
- the nominal categories "L" corresponding to the vulnerability indices;
- the two observers corresponding to the methods used (DRASTIC and SI).

These make it possible to determine the agreement and association of the classifications carried out by the two methods. The test is summarized as described in table 5

Table 5. Schematization of the Kappa test (Bernard, 1993)

My \ Mx	C1	C2	C3	C4	C5	Total
C1	**C11**	**C21**	**C31**	**C41**	**C51**	**Y1**
C2	**C12**	**C22**	**C32**	**C42**	**C52**	**Y2**
C3	**C13**	**C23**	**C33**	**C43**	**C53**	**Y3**
C4	**C14**	**C24**	**C34**	**C44**	**C54**	**Y4**
C5	**C15**	**C25**	**C35**	**C45**	**C55**	**Y5**
Total	**X1**	**X2**	**X3**	**X4**	**X5**	**N**

With
Ci: representing the possible categories or classifications (i = 1, 2, 3) ;
Xi: sum of the elements classified in categories i by the observer Mx ;
Yi: sum of the elements classified in the categories i by the observer My;
Mx: DRASTIC method;
My: SI method.

The Kappa coefficient is calculated by the following formulae summarised in table 6 :

Table 6. Calculation of the Kappa coefficient (K)

Probability of observer agreement	$H0 = \frac{D11 + D22 + D33 + D44 + D55}{n}$
Probability of agreement among observers under the assumption of non-association	$Hc = \frac{1}{n^2}\sum_i Xi \times Yi$
Probability of agreement among observers due to reproducibility of classifications rather than chance	$K = \frac{H0 - Hc}{1 - Hc}$

The range of possible values of the Kappa coefficient is between "-1" and "1" and the different values of this coefficient give the following interpretations:
- K = 0, H0 = Hc: the agreement is null or simply due to chance;
- K = 1, H0 =1: the match is perfect;
- K < 0, then discordance.

The interpretation of the results given by the Kappa coefficient can be made using the Kappa interpretation scale developed by Landis and Koch (1977) which determines the concordance rate according to the observed Kappa value (Table 7). Coefficient values may exceed threshold values.

Table 7. Kappa (K) scale of interpretation (Landis and Koch, 1977)

Observed Kappa values	Interpretation
< 0	Virtually non-existent agreement
0 – 0.20	Weak agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Important agreement
0.81 – 1.00	Near perfect tuning

2.2.4.2. Surface analysis

It consists in reducing the vulnerability classification scales of the methods used (DRASTIC and SI) to a scale common to both methods. It is evaluated by the difference between the DRASTIC and SI maps. This method makes it possible to calculate the area of each index variation from one method to the other and to determine the frequency of concordance and discordance observed (Murat et *al.,* 2000).

The DRASTIC and SI maps are subtracted after classification and the indices are assigned to each vulnerability class according to Table 8. The subtraction operation is performed using the "raster calculator" menu of the ArcGIS software with "D" the DRASTIC method and "S" the SI method.

Table 8. Principle of surface analysis (Anani, 2006)

Expected result	Interpretation
D – S > 0	DRASTIC overestimates the vulnerability compared to SI
D – S < 0	DRASTIC under evaluates the vulnerability in relation to SI
D – S = 0	The two methods DRASTIC and SI are identical

III. Results and Discussion

III.1. Vulnerability to pollution according to the DRASTIC method

Vulnerability indices according to the DRASTIC method range from 58 to 215. The localities of Attobrou in the northeast and the Ananguié area in the northwest have the lowest values (58-84). The highest values are located in the North, centre and south respectively in the Cechi, Agboville and Azaguié zones. Indices with average values are found throughout the study area with values ranging from (112-156). Their conversion into percentages resulted in five vulnerability classes: very low, low, medium, high and very high (Figure 3).

The "very low" vulnerability class, with a percentage of 5.3% of the study area, is divided into a strip in the north-eastern part, the extreme north-western part and an islet in the southern zone in the sectors of the localities of Attobrou, Ananguié and lovigué, respectively. This class contains the zones of unsaturated layers consisting of lateritic clay combined with a hydraulic conductivity ranging from $2.77.10^{-8}$ to $9.29.10^{-5}$ m/s, at the great depth of the static level of the sector (higher than 20 m) and a strong slope (higher than 12 %).

The "low" vulnerability class represents 31.9% of the study area. It mainly occupies the southern part of the study area in strips and islands in the centre, and the extreme east and west in the localities of Grand Morié, Attobrou and Ananguié. It is thought to be due to a water depth of between 9 and 20 m, a thickness of alteration generally consisting of lateritic clay and a slope of between 2 and 12%.

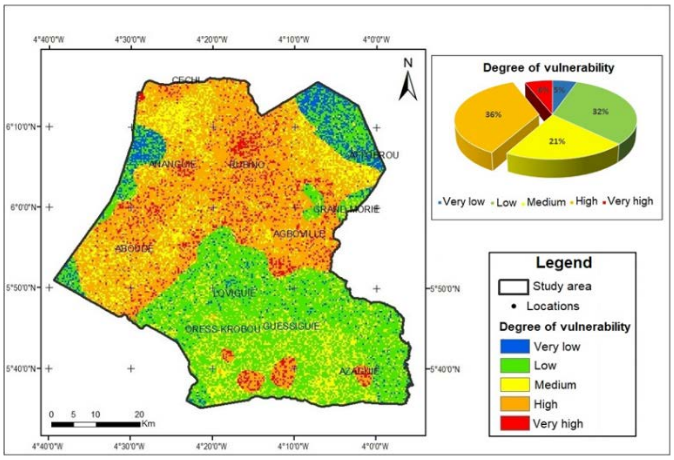

Figure 3. Map of vulnerability to pollution of the aquifers of the Agboville department according to DRASTIC

The "medium" vulnerability class represents 20.80% of the study area. It is found in the localities of Rubino and Cechi in the northern part, in the east at the bottom of the locality of Attobrou and in a band in the southern part. It can be explained by the presence of gravelly soil, water depths between 9 and 15 m and a slope of between 6 and 12%.

The "high" vulnerability class represents the largest proportion (36%). It covers the central, northern and western zone in strips in the localities of Agboville and Rubino, Cechi and Aboudé, respectively, and in islets in the south in the locality of Azaguié. It can be explained by the fact that the thickness of alteration is dominated by gravelly soil combined with a hydraulic conductivity lower than 5.10^{-5} m/s and a depth of the static level between 4.5 and 15 m.

Finally, the "very high" class occupies 6% of this area. This class is found in the sectors of Rubino, Agboville in the centre, Cechi in the North, in the West in the vicinity of Ananguié and in the South interspersed in the Azaguié zone.

This very high vulnerability class is reflected by the predominance of alteration thickness consisting mostly of gravelly soil combined with a hydraulic conductivity below 5.10^{-5} m/s and a shallow water depth (1.5 to 9 m).

III.2. Vulnerability to pollution according to the SI method

The values of the vulnerability indices for groundwater pollution according to the SI method range from 2.42 to 13.57. They also highlight five classes of vulnerability to pollution. These are: "very low", "low", "medium", "high" and "very high" (Figure 4).

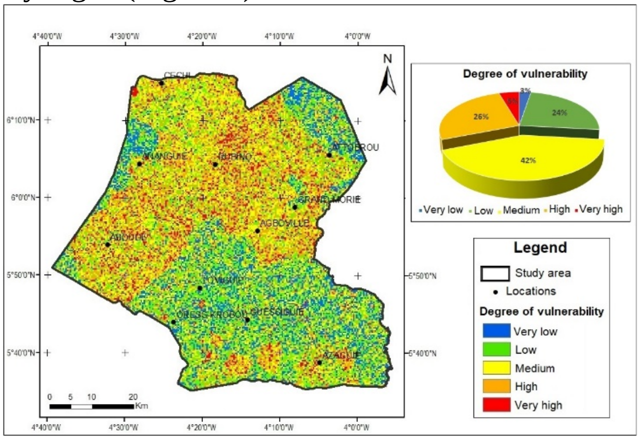

Figure 4. Map of vulnerability to pollution of aquifers in Agboville department according to SI

The "very low" class, covers 2.63% of the study area and occurs in the south, extreme north-west and east respectively in the localities of Loviguié, Ananguié and Attobrou. It characterizes a low vulnerability to pollution and would be due to the depth of the water (over 23 m), the thickness of alteration consisting of lateritic clay and a slope of over 12%.

The "low" class covers 24.07% of the study area and is widespread over most of the study area. It is mostly located throughout the southern zone, in the localities of Guessiguié and Oress-Krobou, at the eastern and western extremes respectively in the localities of Attobrou and Aboudé. This class is also found in the area of Cechi (North) and Grand Morié (centre). It could result from an average water depth of 15 m, clayey soil and a slope of more than 18%.

The "medium" class covers almost the entire study area (42.4%). It reflects moderate vulnerability and is increasing in almost the entire study area.

It would be due to the dominance of water depths between 9 and 15 m, high population density, agricultural practice, the presence of gravelly soils and average slopes (2 to 12 %).

The "high" class represents a high vulnerability and covers 26.30% of the study area. It is found in the Agboville and Rubino (central) areas, and in a few areas in the south around Azaguié.

This class may be linked to the shallow depth of the water table (1.5 - 9 m), the strong preponderance of industrial crops (rubber, oil palm and cocoa) and the predominantly gravelly soil.

The "very high" class represents 4.6% of the study area. It is located in the areas of Agboville, Rubino, Cechi and Azaguié where agricultural activity is intense. The Azaguié area in particular is an area with a high production of industrial crops (rubber tree, cocoa, oil palm, sweet banana) reflecting intensive use of agricultural inputs. The very high degree of vulnerability is therefore linked to intensive agricultural activity and the predominance of gravelly soil in these sectors.

III.3. Vulnerability map validation

Nitrate values in Agboville ranged from 2.14 mg/L to 22.78 mg/L. The highest value (22.78 mg/L) was recorded in the Bethel well (Rubino). These values are below the WHO standard (50 mg/L).

Thus, the overlay of these two types of vulnerability map by DRASTIC and SI methods and nitrate rate, (Figures 5 and 6) shows that the samples with very low nitrate values coincide with the low vulnerability zones and the high nitrate values occur mostly in the high vulnerability zones. This overlay indicates that the maps produced reflect the reality of the terrain.

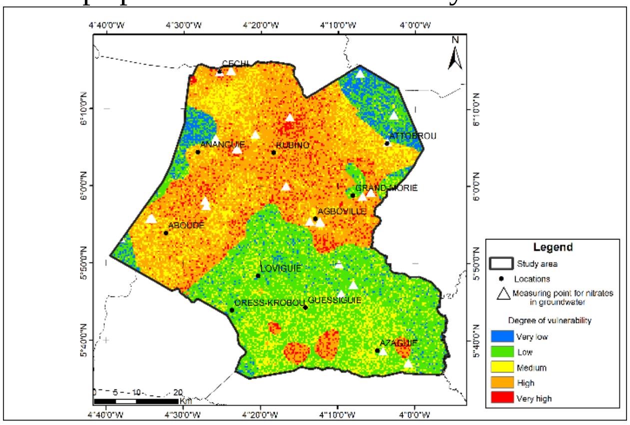

Figure 5. Superimposition of the DRASTIC vulnerability map to the spatial distribution of nitrate levels in the groundwater of the Agboville department

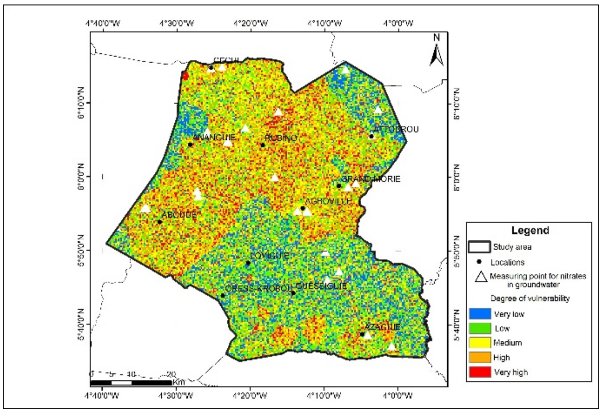

Figure 6. Superimposition of the SI vulnerability map to the spatial distribution of nitrate levels in the groundwater of the Agboville department

III.4. Comparison of DRASTIC and SI methods by Kappa test and surface analysis

III.4.1. Kappa conformity test

The kappa compliance test measured the degree of agreement between the DRASTIC and SI methods. The number of subjects "n" corresponding to the number of pixels in Agboville department is equal to 34 564. The results of the combination of the two methods are given in table 9.

Table 9. **Combination of DRASTIC and SI method indices**

DRASTIC / SI	D1	D2	D3	D4	D5	Total
S1	1 641	3 190	459	10	0	5 300
S2	213	5 114	2 471	1 125	0	8 923
S3	0	2 454	2 178	5 438	2	10 072
S4	0	245	1 712	4 888	250	7 095
S5	0	1	374	976	1 823	3 174
Total	1 854	11 004	7 194	12 437	2 075	34 564

The pixels observed in each class indicate an inequal distribution. The parameter values for this test are as follows: Ho (0.45); K (0.22) and Hc (0.29). The results of the calculations reveal that the test is reliable since the value of the Kappa coefficient is positive and therefore interpretable. Furthermore, the observed Kappa value is between 0.21 and 0.4 showing fair agreement.

III.4.2. Surface analysis

The results of the subtraction between the vulnerability indices of the two vulnerability maps DRASTIC and SI are summarized in table 10.

Table 10. Percentage of surfaces according to differences in DRASTIC and SI indices

Difference	Number of pixels	Percentage
-3	1	0.003
-2	619	1.79
-1	5 355	15.49
0	15 646	45.25
1	11 354	32.84
2	1 586	4.59
3	10	0.03

This table shows a small proportion (0.003) of the index class "-3" and the difference in index "0" shows the largest proportion (45.25%). The histogram and the index variation map resulting from this crossing are shown in figures 7 and 8 respectively.

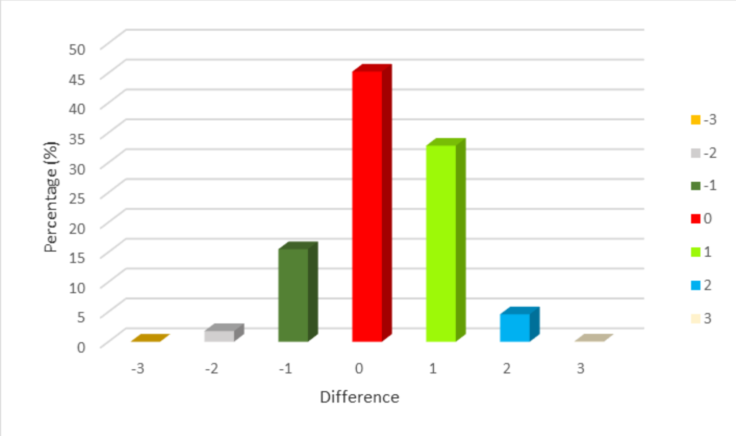

Figure 7. Histogram of the index variation between DRASTIC and SI

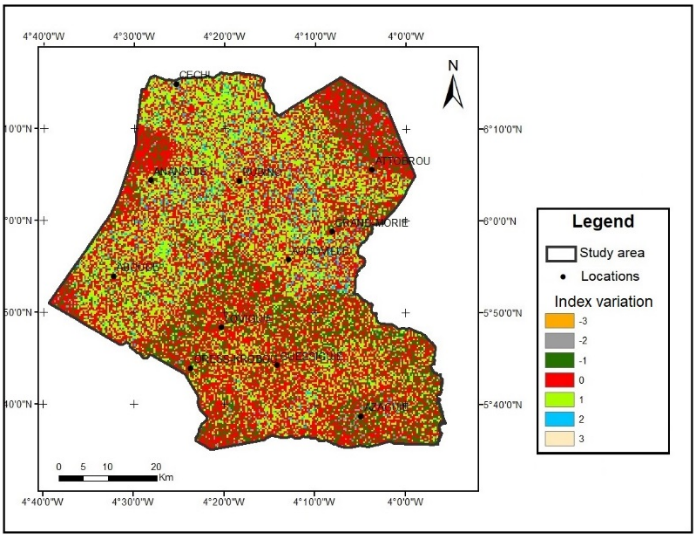

Figure 8. Map of surface index variation between DRASTIC and SI

The DRASTIC and SI methods show homogeneity over 45.25% and some variation over 37.46% and 17.28% of the study area. The overvaluation between the methods used is as follows :

- classes "-3", "-2" and "-1" reflect an overestimation of DRASTIC's vulnerability compared to SI and represent 17.28% of the study area ;

- classes "3", "2" and "1" reflect an overevaluation of the vulnerability of SI compared to DRASTIC representing 37.46% of the Agboville department.

This high proportion of overvaluation of the SI method implies that it tends to overestimate vulnerability to pollution compared to the DRASTIC method. This would be due to the introduction of land use, a parameter external to the aquifer. The application of these statistical methods shows a fair agreement between the DRASTIC and SI methods using a Kappa coefficient between

0.21 and 0.4. Moreover, they indicate that the SI method is the most suitable for assessing the vulnerability to pollution of the aquifers of the Agboville department.

III.5. Discussion

The DRASTIC method is the method that was used as the reference for determining changes in vulnerability in this study. The index values obtained by this method range from 58 to 215. They differ slightly from the other ranges of indices encountered in southern Côte d'Ivoire by this method. Indeed, the work of Djemin (2016) in the Dabou region; Aké et *al.,* (2010) in the Bonoua region and Kouamé (2007) in the District of Abidjan, indicate indices ranging between 100 and 210. This difference could be explained by the extent of the different study sites.

The mapping of the vulnerability to groundwater pollution in Agboville department using DRASTIC and SI methods resulted in the same classes (five) of degree of vulnerability. They reveal classes of very low to very high vulnerability.

The dominant vulnerability classes in terms of surface area occupied are: low (32%) and high (36%) by the DRASTIC method, and medium (42%) and high (26%) by the SI method.

The use of a large number of parameters by the DRASTIC method allows a better knowledge of the environment. In addition, too many parameters create difficulties in obtaining the required information and high costs for data collection (Murat, 2000). In fact, the realization of the vulnerability map by the DRASTIC method requires the use of seven (07) parameters whose reliability depends on the data used for their realization. Due to a lack of data covering the entire study area, all point data used in this study (infiltration, groundwater depth, hydraulic conductivity) were interpolated (IDW), thus assigning values to areas where no data are known.

The interpolation used can lead to errors in the realization of the parameters, as it is only reliable within the intervals delimited by the point data (Jourda et *al.,* 2006). One of the difficulties in applying vulnerability methods is also the limits of the classes and the ratings that are assigned to the different parameters (Murat, 2000). The boundaries of the different classes are therefore not absolute values, but rather relative values (Jourda et *al.,* 2006). They may then vary from one study to another and from one region to another. The maps of vulnerability to pollution by this intrinsic method nevertheless reveal results that are interpretable and capable of giving an idea of the level of pollution. Several works carried out in different contexts have verified and supported this conclusion (Murat, 2000; Murat et *al.,* 2003; Kouamé, 2007, Hamza et *al.,* 2008, Aké et *al.,* 2010).

With regard to the mapping of vulnerability to pollution using the SI method, it indicates indices ranging from 2.25 to 13.57. They are far from the SI classes defined by Ribeiro (2000). As well as the classes defined by Aké et *al.,* (2010) and Tivoli (2018), whose SI indices vary respectively from 2.23 to 23.03 and 3.7 to 28.05. This situation could be explained by the adaptation made on the parameters taking into account the local realities specific to the context of the Agboville department. This would also be explained by the fact that classes: industrial waste dumps, garbage dumps, mines; irrigated perimeters, irrigated and non-irrigated annual crops; quarries, shipyards and covered artificial areas, green areas, continuous urban areas are absent for the moment in this department. While these classes have the highest "LU" ratings because they vary from 100 to 75 and the adaptation that has been made with the realities of the county region does not allow to have the range of Ribeiro's classes.

Nevertheless, the adaptation method of Jourda et *al.*, (2007) by converting the SI indices into percentages gives five classes of SI vulnerability which are distributed as follows: very low (2.63%), low (24.07%), medium (42.4%), high (26.30%) and very high (4.6%) of the occupied surface area. The SI method best assesses vulnerability due to the combination of intrinsic (groundwater depth, recharge and aquifer material) and extrinsic (land use) parameters. This land use factor reflects the impact of anthropogenic activities that may threaten the viability of the groundwater resource in the Agboville department.

The predominance of agriculture in this area implies an intensive use of agricultural inputs that could threaten water resources. Indeed, the analysis of the groundwater of the agricultural areas of the Agboville department indicates a high level of agricultural contamination index (Orou, 2017).

They are observed in rubber, oil palm, food crops and rice plantations. This agricultural contamination is all the more important in wells where the planting-well distance is less than 20 m and/or the age of the planting is more than 15 years (Orou, 2017). Although this zone is densely fractured, N'go et *al.,* (2005); Ahoussi et *al.,* (2010) and represents an important groundwater reserve, it could be a risk factor contributing to making these aquifers vulnerable to pollution.

Indeed, the work of Touré et *al.*, (2015), already reveals a contamination of groundwater by pesticides in Azaguié, showing the impact of anthropogenic activities on these resources.

The different classes of vulnerability to groundwater pollution by both methods in Agboville department were confirmed by chemical analysis values (nitrate levels) in boreholes and wells in the study area. The levels obtained in this zone are below the WHO standard (50 mg/L) for drinking water for the time being. High and low nitrate rate coincide with the high and low vulnerability zones respectively. This concordance made it possible to validate the vulnerability maps and to show that the maps established could reflect the reality of the terrain.

Comparison of the vulnerability maps from the Kappa test and the statistical analysis showed that the agreement coefficient (K coefficient) is reliable and gave a fair agreement (K = 0.22) between the two methods. This result is different from that obtained by Kouamé (2007), in the District of Abidjan (K = 0.418) and Allechy (2015), in the region of Oumé (K = 0.43). The surface analysis shows average agreement (45.25%). The results of the surface analysis confirm those of the Kappa test in both studies. The vulnerability maps are therefore different, showing that the association between the two methods is not perfect.

The over-evaluation of the SI method in surface analysis implies that this method tends to overestimate the vulnerability to pollution compared to the DRASTIC method.

Therefore, it indicates the SI method as the most suitable for assessing the vulnerability to pollution of the aquifers of the Agboville department.

The vulnerability maps drawn up by the DRASTIC and SI methods are reliable in that they provide a fairly accurate picture of the department's sensitive areas so that the necessary protective measures can be taken. These maps will thus give the authorities an idea of the areas vulnerable to pollution that will have to be taken into account when developing the Agboville department.

Conclusion

The mapping of the vulnerability to pollution of the aquifers of the Agboville department by DRASTIC and SI methods highlighted five classes : very low, low, medium, high and very high. The dominant vulnerability classes in terms of surface area occupied are : low (32%) and high (36%) for the DRASTIC method, and medium (42%) and high (26%) for the SI method. Anthropogenic activities dominated by agriculture coupled with strong fracturing in Agboville department are factors threatening the sustainability of groundwater resources. The nitrate rate obtained for the moment in this zone are below the WHO standard (50 mg/L) for drinking water.

Comparison between the methods used reveals that the SI method is the most suitable for assessing the vulnerability to pollution of the aquifers of this department. The Kappa compliance test shows for this purpose a fair agreement (K = 0.22) between the methods used with a Kappa coefficient between 0.21 and 0.40. In addition, the surface analysis shows an overestimation of the SI method over the DRASTIC method.

Thus, the SI method tends to better assess the vulnerability to pollution compared to the DRASTIC method in Agboville department. The knowledge of sensitive areas allows to better guide the authorities in the development of the Agboville department and to indicate the adequate choice of groundwater, in order to solve the problem of quality drinking water supply.

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