INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 10, Issue 3, July-September 2019: 493-506 www.ijcs.uaic.ro

# MAPPING GROUNDWATER VULNERABILITY TO POLLUTION IN THE REGION OF ADIAKE, SOUTHEAST COASTAL OF CÔTE D'IVOIRE: A COMPARATIVE STUDY OF THREE (3) METHODS

Sampah Georges EBLIN[1], Kouao Armand ANOH[1], Affoué Berthe YAO[1], Nagnin SORO[2], Valentin NEDEFF[3*], Emilian MOSNEGUTU[3], Andrei Victor SANDU[4,5*]

[1] Jean Lorougnon Guédé University of Daloa, Department of Earth Sciences, Laboratory of Environmental Science and Technology, BP 150 Daloa, Côte d'Ivoire
[2] Félix Houphouët Boigny University of Abidjan, Laboratory of Science and Technology of Water and Environment, 22 BP 582 Abidjan 22, Côte d'Ivoire
[3] Vasile Alecsandri University of Bacau, Faculty of Engineering, Department of Environment Engineering and Mechanical Engineering, Calea Marasesti 156, 600115 Bacau, Romania
[4] Gheorghe Asachi Technical University of Iasi, Faculty of Material Science and Engineering, 61A D. Mangeron Blvd., 700050 Iasi, Romania
[5] Romanian Inventors Forum, 3 Sf. Petru Movila, Str. Bl. L11, Sc. A, Et. III, Ap.3, 700089 Iasi, Romania

***Abstract***

*This study aims to map the vulnerability to groundwater pollution in the region of Adiaké subjected of intense agricultural activities. The application of intrinsic vulnerability methods (DRASTIC and SINTACS) gives high vulnerability in the South while the Susceptibility Index (SI) shows a potentially high (40%) and very high (60%) vulnerability across the region. The superposition of nitrate concentrations in groundwater and vulnerability classes gave a high coincidence rate (71.74%) with the susceptibility index. The very low margins of error: 1.52% (SI), 2.35% (SINTACS) and 2.90% (DRASTIC) prove that the applied methods are reliable; the SI method is the most appropriate and, DRASTIC and SINTACS are in phase with DRASTIC overestimating vulnerability.*

***Keywords**: Adiaké; Cartography; Côte d'Ivoire; Intrinsic vulnerability methods, Susceptibility Index*

## Introduction

The modernization and intensification of agriculture, the development of industrialization and the parallel growth of consumption are accompanied by a further deterioration of the environment [1-12]. The impact of these pollutions appears in the deterioration of the quality of the water resources which become not drinkable for the population in the majority of the cases and even unusable for the other uses in certain cases [9-18].

The excellent natural conditions enjoyed by the region of Adiaké have favoured a high local urban density, a development of agricultural, agro-industrial, mining and fishery activities [19]. Anthropogenic pressures in this region raise concerns about the risk of pollution of water resources and particularly of groundwater. Preventing water pollution, especially groundwater, is an important step in the management of aquifers, to which scientists are giving more and more effort, studying the vulnerability of groundwater [12]. The vulnerability study consists of

* Corresponding author: vnedeff@ub.ro or euroinvent@yahoo.com

assessing the sensitivity of the resource to any form of pollutant introduced from the soil surface based on the physical properties of the environment. Indeed, the qualitative management of groundwater aims to preserve the overall quality of the water table with a systematic prevention principle that is far better than that of treating water for drinking water supply when their quality is deteriorated [20, 21]. For sustainable management of water resources, it is necessary to develop methodologies to provide decision-makers with decision support tools. They are tools for preventing and protecting water resources against all sources of pollution.

The mapping of vulnerability and risks of groundwater pollution is a methodology that has become necessary to ensure a qualitative management of water resources. This study aims to map the vulnerability to groundwater pollution in the region of Adiaké. The accuracy of its evaluation depends essentially on the nature, quantity and reliability of the data used. For the sake of comparison, the study was based on two intrinsic vulnerability methods (DRASTIC and SINTACS) and one of specific vulnerability (SI).

## Materials and Methods

### *Study area*

The region of Adiaké is located in the extreme south-east of Côte d'Ivoire, between longitudes 2°43' and 3°32' West and latitudes 5°04' and 5°28' North. It is a coastal plain of less than 200m altitude (Fig. 1). It covers an area of over 3,000km$^2$ with an estimated population of around 400,000 [22].

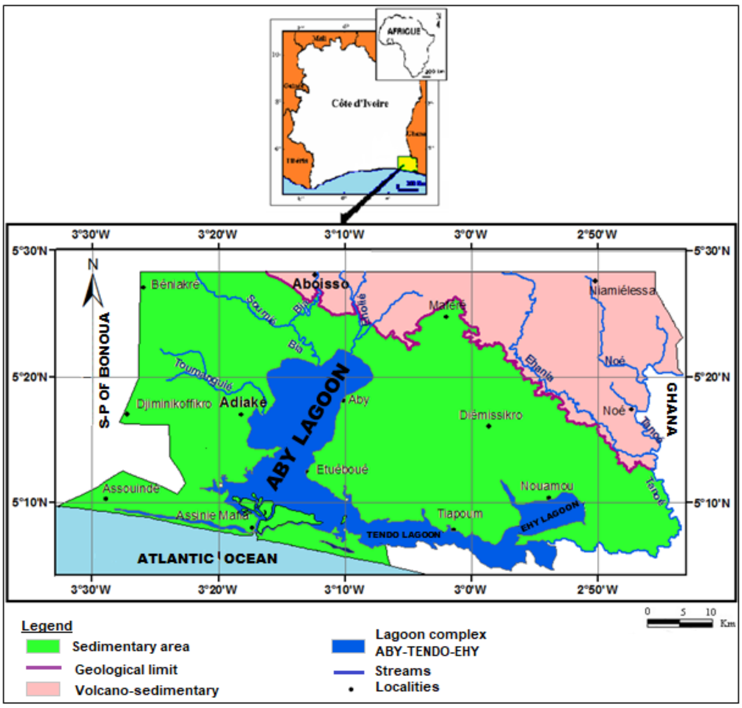


**Fig. 1.** Location of the region of Adiaké

This region belongs to the ombrophilous sector of the Guinean domain subjected to an equatorial climate of transition which is characterized by four seasons in the year: two rainy

(April to July and October to November) and two dry (December to March and August to September). It is a very humid area with average annual rainfall greater than 2000mm [23].

The region is drained by two watersheds represented by the coastal rivers: Bia and Tanoé, their tributaries and many other streams associated with the lagoon complex Aby-Tendo-Ehy, 427km$^2$ wide.

Soils belong to three distinct types of soils from different geological terrains: ferrallitic soils highly leached under heavy rainfall, hydromorphic soils and poorly developed soils of the littoral [24]. This diversity of soils has favored the diversification and development of agriculture, the main economic activity of the populations of the region, with 60% to 80% of the active members and more than 50% of the area of the region [19, 25].

The region of Adiaké straddles two geological domains consisting of the formations of the coastal sedimentary basin (in the South) and those of the crystalline and crystallophyllian basement (in the North). To the south of the Aby-Tendo-Ehy lagoon complex, the sedimentary basin consists of "low plateaux" of sandy-clay nature, sandy coastlines, swamp vases and washed-out sands of the fluvio-lagoon depressions. To the north of this complex, the sedimentary basin is represented by the "Highlands" consisting of sands, clays and ferruginous sandstones.

The Precambrian basement consists of shales and granitoids interspersed with quartz veins and dykes [26]. In terms of hydrogeology, the region has two types of aquifers: the continuous aquifers of the sedimentary basin consisting of Quaternary and Mio-Pliocene aquifers (Continental Terminal) and the discontinuous aquifers of the Precambrian basement consisting of aquifers of the alterites and cracked base.

***Data and material***

This study was based on multisource data; those are:

- Cartographic data composed of the geological maps at 1/200 000 of the Grand-Bassam square [26] and the Côte d'Ivoire soil sketch at a scale of 1:500000 (sheet South-East) prepared by [11];
- Shuttle Radar Topography Mission (SRTM) and Landsat 7 Enhancement Thematic Mapper Plus (ETM+) satellite images. They are from 2000 and from the scene p195 - r056;
- Data from about 100 hydraulic drilling implanted in the different geological formations of the region;
- Nitrate concentrations in 46 drilling in the study area.

Data processing is made possible by:

- MAPINFO 10.0 mapping software, used for geographic analysis and highlighting attributes (maps) for other applications and ArcGIS 10.1 used for the production and combination of thematic maps;
- ENVI 4.3, satellite image processing software, to highlight the slope map and the land use map of the study area.

• *Application of methods*

Since the introduction of the concept of vulnerability to groundwater pollution, many methods for determining groundwater vulnerability have been developed around the world [27]. All are a function of the aquifer types in the study area: porous aquifers, fissure aquifers and karstic aquifers. However, some were tested on different media and gave satisfactory results: this is the case of the DRASTIC and SINTACS methods used in this study. The choice of the Susceptibility Index (SI) method is justified by the fact that this method estimates the vertical vulnerability specific to agricultural pollution.

▪ *DRASTIC method*

The DRASTIC method proposes two weighting systems according to land use conditions: "normal" occupation or occupation by intensive agricultural activity using, for example, phytosanitary products [28]. The importance of each factor is evaluated by a fixed "Weight", varying between a value of 5 for the most significant factors and a value of 1 and 2 for the least significant factors, respectively for the "normal" and "phytosanitary products" impacts (Table 1).

**Table 1.** DRASTIC parameters with their respective weights [29]

| **Hydrogeological parameters** | **Weighting factor** | |
|---|---|---|
| | **"normal or standard"** | **"Pesticides"** |
| **D :** depth to water | 5 | 5 |
| **R :** efficient or net recharge | 4 | 4 |
| **A :** aquifer media | 3 | 3 |
| **S :** soil media | 2 | 5 |
| **T :** topography | 1 | 3 |
| **I :** impact of the vadose zone | 5 | 4 |
| **C :** hydraulic conductivity of the aquifer | 3 | 2 |

Each parameter is assigned a "rating" ranging from 1 to 10, depending on the particularity of the environment. Conditions of lower vulnerability provide low ratings, while those that increase them provide high ratings. Vulnerability assessment involves calculating the DRASTIC (ID) Index. It is a numerical index representing the weighted sum of the products of the scores corresponding to the seven hydrogeological parameters by their weight (equation 1).

$$\mathrm{ID} = \mathrm{D_C} \times \mathrm{D_P} + \mathrm{R_C} \times \mathrm{R_P} + \mathrm{A_C} \times \mathrm{A_P} + \mathrm{S_C} \times \mathrm{S_P} + \mathrm{T_C} \times \mathrm{T_P} + \mathrm{I_C} \times \mathrm{I_P} + \mathrm{C_C} \times \mathrm{C_P}, \quad (1)$$

where: D, R, A, S, T, I and C are the seven parameters and the subscripts "c" and "p" are the corresponding "rating" and "weights" respectively.

The DRASTIC index values obtained represent the measurement of hydrogeological vulnerability of the aquifer [20]. They vary from 23 (minimum value) to 226 (maximum value) in the case of the standard version considered in this study. These theoretical extremes are however very rare and the calculated indices are rather in the range 50 to 200 [29]. The values obtained are grouped according to [30], in four classes each of which corresponds to a degree of vulnerability (Table 2).

***Table 2.*** Criteria for vulnerability assessment in the DRASTIC method [30]

| **Vulnerability index** | **Vulnerability degree** |
|---|---|
| < 101 | Low |
| 101 - 140 | Medium |
| 141 - 200 | High |
| > 200 | Very high |

- *SINTACS method*

The SINTACS method is derived from the DRASTIC method [31]. This method was developed in Italy in the early 1990s to adapt to larger-scale mapping, given the high hydrogeological diversity of Italy [31]. It takes into account the same hydrogeological parameters as the DRASTIC method, with different weights and dimensions [32]. In this method, the "Weights" assigned to the hydrogeological parameters depend on the different scenarios proposed by the method. The importance of each factor is evaluated by a fixed "Weight", varying from 5 for the most significant factors in the vulnerability to 1 and 2 for the factors that are least (Table 3).

Mapping begins with the rating of each parameter according to the practical guide of the SINTACS method [33]. This rating runs from 0 to 10 according to its importance in the definition of vulnerability which is depending on the lithological, morphological, hydrogeological, hydraulic, soil and anthropogenic features of the concerned area [32]. Unlike DRASTIC, the SINTACS method makes it possible to use, at the same time and in different cells, variable weighting factors according to the situations [31].

**Table 3.** Weight assigned to parameters in SINTACS method scenarios

| Scenario<br>Parameters | Standard Impact | Severe Impact | Major Drainage | Karst | Cracked Lands |
|---|---|---|---|---|---|
| **S :** depth to water | 5 | 5 | 4 | 2 | 3 |
| **I :** efficient or net recharge | 4 | 5 | 4 | 5 | 3 |
| **N :** impact of the vadose zone | 5 | 4 | 4 | 1 | 3 |
| **T :** soil media | 4 | 5 | 2 | 3 | 4 |
| **A :** aquifer materials | 3 | 3 | 5 | 5 | 4 |
| **C :** hydraulic conductivity | 3 | 2 | 5 | 5 | 5 |
| **S :** topography slope | 2 | 2 | 2 | 5 | 4 |

Vulnerability assessment involves calculating the SINTACS Index (SI). It is a numerical index representing the weighted sum of the products of the ratings attributed to the hydrogeological parameters by the corresponding weights (equation 2).

$$\mathrm{IS} = S_C \times S_P + I_C \times I_P + N_C \times N_P + T_C \times T_P + A_C \times A_P + C_C \times C_P + S_C \times S_P, \qquad (2)$$

where: S, I, N, T, A, C and S are the seven parameters and the subscripts "c" and "p" are the corresponding "rating" and "weights" respectively.

The final SINTACS vulnerability map obtained is the sum of the thematic maps of each SINTACS parameter; each having already been multiplied by its corresponding weight in the scenario describing the environmental and anthropogenic conditions of the study area. The region of Adiaké is a highly anthropized area that reflects the conditions foreseen in the "Severe Impact" scenario. The SINTACS index (IS) values obtained are classified into six vulnerability classes (Table 4).

**Table 4.** Criteria for vulnerability assessment in the SINTACS method [34].

| Vulnerability index | vulnerability degree |
|---|---|
| 26 - 80 | Very low |
| 80 - 105 | Low |
| 106 - 140 | Medium |
| 141 - 186 | High |
| 187 - 210 | Very high |
| 211 - 260 | Extreme |

▪ *Susceptibility Index (SI) method*

The SI method, which estimates the vertical vulnerability specific to agricultural pollution (mainly by nitrates and also by pesticides), was developed in Portugal by Ribeiro (2000) in [31]. It takes into consideration five parameters, the first four of which are identical to those used in the DRASTIC method: the depth of the aquifer (D), the effective recharge of the aquifer (R), the aquifer lithology (A) and the topographic slope of the ground (T). Furthermore, the classification used is similar to that of DRASTIC. Only the fifth parameter: "land use" (LU) undergoes another classification; that adopted by the program of the Coordination of Information on the Environment (CORINE Land Cover, 1993) indicated in Table 5. A value called land use factor, denoted LU, ranging from 0 to 100, is assigned to each land use class. The dimension values therefore vary from 0 to 100, ranging from the least vulnerable to the most vulnerable. To facilitate the reading of the results obtained, the values of the ratings assigned to the classes of the various parameters have been multiplied by 10.

**Table 5.** Main land use classes and corresponding Land Use (LU) values

| Land use according to the CORINE Lander Cover classification | LU rating |
|---|---|
| Industrial discharge, garbage dump, mines | **100** |
| Irrigated areas, paddy fields, annual irrigated and non-irrigated crops | **90** |
| Quarry, shipyard | **80** |
| Covered artificial areas, green areas, continuous urban areas | **75** |
| Permanent cultures (vines, orchards, olive, etc.) | **70** |
| Discontinuous urban areas | **70** |
| Pastures and agro-forestry areas | **50** |
| Aquatic environment (marsh, saline, etc.) | **50** |
| Forests and semi-natural areas | **0** |

From Table 5, another classification that takes into account the realities of the region (humid tropical area) was carried out to adapt this method in the region (Table 6).

**Table 6.** Notes for Land Use classes in the region of Adiaké

| Land use according to the CORINE Lander Cover classification | LU rating |
|---|---|
| Mines (Aféma gold deposit at Maféré) | **100** |
| Permanent crops 1 (Oil palm and rubber) | **70** |
| Permanent crops 2 (Mosaic crops / fallow) | **60** |
| Permanent crops 3 (Coconut) | **50** |
| Discontinuous urban areas (Bare soil and artificialized areas) | **70** |
| agro-forestry areas (Mosaic forest / crops (Cocoa, Coffee, Banana, Pineapple)) | **50** |
| Aquatic environment (Lagoon, rivers, wetlands) | **50** |
| Forests and semi-natural areas (Dense forest) | **0** |

Weights assigned to SI parameters vary from 0 to 1 depending on the importance of the parameter in the vulnerability (Table 7).

**Table 7.** Weight assigned to SI parameters

| SI parameters | D | R | A | T | LU |
|---|---|---|---|---|---|
| **Weight** | 0,186 | 0,212 | 0,259 | 0,121 | 0,222 |

The vulnerability index SI (ISI) is the result of the sum of the products of the odds by the weights of the corresponding parameters (Equation 3):

$$ISI = D_C \times D_P + R_C \times R_P + A_C \times A_P + \mathrm{T_C} \times \mathrm{T_P} + \mathrm{LU_C} \times \mathrm{LU_P}, \qquad (3)$$

where: D, R, A, T and LU are the five parameters and the subscripts "c" and "p" are the corresponding "rating" and "weights" respectively.

The SI method has four degrees of vulnerability according to the values of the indices obtained (Table 8).

**Table 8.** Criteria for vulnerability assessment in the SI method

| Vulnerability index | Vulnerability degree |
|---|---|
| 30 - 45 | Low |
| 45 - 64 | Medium |
| 65 - 84 | High |
| 85 - 100 | Very high |

- *Description of vulnerability parameters*

*Depth to water*

It is represented by the water level in aquifers. The classification of the different values of the depth to water takes into account the rating system of the different methods. In the region, it varies from 1.2m in Assinie Mafia (in the quaternary sands) to 84.5m in Abou-Carrefour (in the tertiary sands).

*Efficient or net recharge*

Effective infiltration is the fringe of water that will actually feed aquifers. It is determined from the water balance. The application of the GR2M rain flow model by [35] in Aboisso gave 386mm. The rainfall is considered homogeneous for a station, this value has been generalized throughout the region. The rating given to this value depends on the rating system of each method.

*Aquifer materials*

They represent the type of aquifer. The saturated zone in the region of Adiaké is represented by sedimentary formations (South), a reduced layer of metamorphic and igneous rocks (North), and shale volcano-sedimentary (East) [26]. The classification of this parameter took into account the rating system of applied methods.

*Soil media*

Soil type refers to the nature of the topsoil layer that is the first formation traversed by pollutants. The diffusion of these pollutants will depend on the nature of the soils encountered in the region. According to the soil map of the region [27], there are: hydromorphic soils, tertiary sands, marine and quaternary sands, sandy loams and typical ferralitic soils on granite or reworked on shale. The ratings assigned to this parameter take into account the rating system of the two intrinsic methods.

*Topography*

It is characterized by the slope. It is derived from the Digital Elevation Model (DEM) obtained from the SRTM image, from which the slope map was generated. In the region of Adiaké, the relief is generally monotonous and characteristic of the Ivorian coastline. Altitudes are less than 200m and slopes between 0 and 12%. The ratings assigned to the different classes depend on the rating system of each method.

*Impact of the vadose zone or unsatured zone*

It determines the pollutant transfer time. In the region of Adiaké, water is exploited in both sedimentary and Precambrian basement aquifers. Based on the vadose zone type classes defined by DRASTIC and SINTACS methods, ratings have been assigned to the rock formations. The attribution of ratings was done considering the dominant tendency of a frequently encountered lithology in a hydrogeological log.

*Hydraulic conductivity of the aquifer*

Hydraulic conductivity is likened to the apparent average permeability characterizing the entire studied area. It was determined from the transmissivity obtained from the "well test" data. Ratings were assigned based on DRASTIC and SINTACS methods rating system.

*Land use*

It is the distribution (qualitative and quantitative) and the spatial organization of natural or human formations on a given area [36]. It conditions the degree of anthropogenic pollution of groundwater.

- *Validation of vulnerability maps*

Several authors including [37, 38], verified the validity of pollution vulnerability assessment methods based on groundwater chemical data from the study area. The physicochemical parameters generally used are nitrates, global mineralization (or electrical conductivity). In this study, nitrate concentrations were used for the validation of pollution vulnerability maps produced. It consists of calculating the coincidence rate between the spatial distribution of nitrate concentrations in the aquifer and the distribution of vulnerability classes. It distinguishes vulnerable regions from those that are protected. Indeed according to [39], the actual contaminated areas correspond to those with the highest vulnerability indices.

- *Comparison of vulnerability mapping methods*

It consists of determining the margin of error on each vulnerability map. This involves calculating the uncertainties on the average index of the parameters of each method according to equation 4 [40].

$$\Delta\bar{x} = \frac{\sigma}{\sqrt{m}} = \sqrt{\frac{1}{m(m-1)}\sum_{i=1}^{m}|(x_i - \bar{x})|^2} \tag{4}$$

were: $\Delta\bar{x}$: Uncertainty on the average index of each parameter; $\sigma$: Standard deviation of the vulnerability indices of the hydrogeological parameter; m: Number of drilling considered; $x_i$: Hydrogeological parameter vulnerability index at the drilling I; $\bar{x}$: Average vulnerability index of the hydrogeological parameter.

The actual margin of error is calculated from equation 5.

$$Er = \frac{\sum\Delta\bar{x}}{I_{V\_A}} \tag{5}$$

with: $\mathbf{I_{V\_A}}$, the average vulnerability index for each method.

## Results and Discussion

### *Vulnerability maps to groundwater pollution*

The resulting maps present several vulnerability classes, ranging from low degree (DRASTIC) to extreme (SINTACS) (Fig. 2).

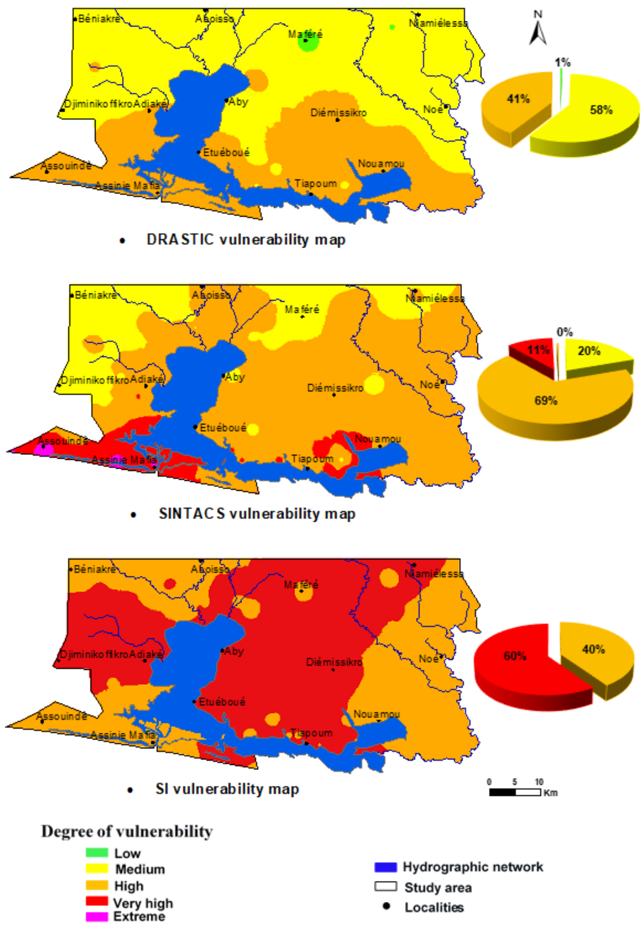


**Fig. 2.** Maps and spatial distribution of vulnerability to groundwater pollution

DRASTIC set up 58% of the region of medium vulnerability while SINTACS considers 69% of the area of high vulnerability to pollution. On the SI map, the very high vulnerability class covers 60% of the study area (Fig. 2). This study revealed several trends of vulnerability to pollution: "medium to high" with DRASTIC and SINTACS and, "high to very high" with the SI method. Areas with high vulnerability are generally located in the south of the region and particularly in the south-west characterized by a natural predisposition favorable to pollution [41]. It is in this area that [42] obtained high and very high degrees of vulnerability. According to studies carried out on coastal localities of Côte d'Ivoire such as Abidjan and Bonoua, vulnerability maps to groundwater pollution revealed that the most vulnerable areas are located in the South, with a gradient in the North [38, 42]. This study confirms the results of these studies. Only the SI map shows a potentially high (40%) and very high (60%) vulnerability, covering the entire region.

### *Validity of vulnerability cards*

Nitrates chosen as indicators of pollution of superficial origin, have generally very low concentrations in the groundwater of the region, with an average of 7.996±18,024mg/L (Fig. 3). However, there is a high concentration of Adiaké (38.9 mg/L) and abnormal concentration in Krindjabo (88.7mg/L).

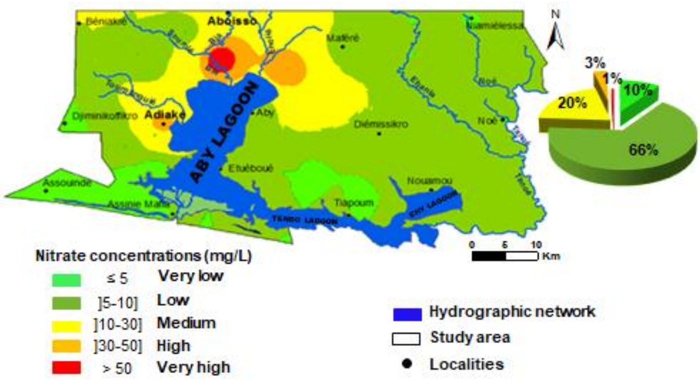


**Fig. 3.** Spatial distribution of nitrate concentrations in groundwater

This sector of abnormal concentration of nitrate does not coincide with a very high or extreme degree of vulnerability, but rather with a moderate vulnerability zone (according to DRASTIC) or a high vulnerability zone (according to SINTACS and SI). This shows that the SINTACS and SI methods are closer to reality than DRASTIC. The coincidence rates obtained are 71.74% with SI, 60.87% with DRASTIC and 52.17% with SINTACS. However, according to [43], maximum nitrate concentrations are not necessarily located under agricultural parcels. In some cases, the contributions of septic tanks can lead to more nitrate pollution than agriculture. The hydrochemical surveys carried out in favor of this study have generally shown that the groundwater of the region are not polluted by nitrates. Apart from Krindjabo, which has an abnormal nitrate content (88.7mg/L) and Adiaké, which has a high concentration of 38.9 mg/L, the situation is not alarming in terms of groundwater (with an average content of about 8 mg/L). These results are in perfect agreement with the study of [23] which showed that nitrate concentrations in the region remain insignificant in groundwater, with the exception of Krindjabo (88mg/L). The study of [42] in the region of Bonoua supports these claims. These authors found nitrate levels ranging from 0.4 to 24.3mg/L, well below the WHO drinking standard (50mg/L).

***Margins of error on vulnerability maps***

The margins of error are 2.90%, 2.35% and 1.52% respectively on DRASTIC, SINTACS and SI maps (Fig. 4).

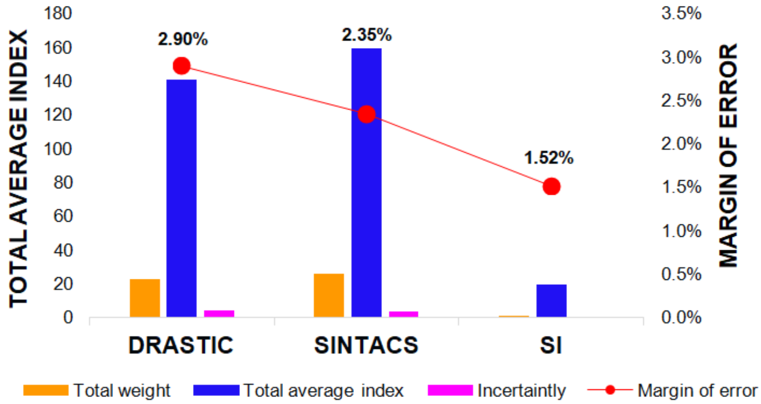


**Fig. 4.** Parameters for comparing vulnerability methods

DRASTIC and SINTACS have margins of error that are significantly closer and higher than SI method. These low values of the margin of error on each map reflect both the good quality of ratings attributed to the different parameters and the adaptation of these methods to the mapping of the vulnerability to groundwater pollution in the study area. These values are much lower than those obtained by [40] (16.7% and 18.07% respectively for DRASTIC and SINTACS). Furthermore, these results reveal that, of the three vulnerability methods applied, the SI method (1.52%) remains the most appropriate. This supports the hypothesis that intrinsic vulnerability tends to overestimate the degree of vulnerability [37]. This result is confirmed by [44] who proved that vulnerability to nitrate pollution is best expressed through the SI method. According to [45], as part of a land use planning program, it is recommended that a specific vulnerability study be applied following an intrinsic vulnerability assessment to assist in locating a potentially polluting human activity.

Values close to the error margins on the DRASTIC and SINTACS cards confirm the similarity of the two methods. Indeed, the SINTACS method is the Italian version of the DRASTIC method. However, the SINTACS method offers more flexibility in the indexing and weighting system [46]. In its "Severe Impact" scenario, it is the second most appropriate pollution vulnerability method for the region, after the SI method. The results obtained by [47] in a statistical comparison of vulnerability maps showed the similarity between the results obtained by SINTACS and SI methods.

## Conclusion

The application of intrinsic vulnerability (DRASTIC, SINTACS) and Susceptibility Index (SI) methods allowed to assess and map the vulnerability to groundwater pollution in the region of Adiaké. The spatial distribution of vulnerability degrees set 58% of the region of medium vulnerability, according to the DRASTIC method; 69% of the region of high vulnerability, according to the SINTACS method and 60% of the region of very high vulnerability to pollution, according to the SI method. The coincidence rate between nitrate concentrations in groundwater and different vulnerability classes is 71.74% with SI, 60.87%t with DRASTIC and 52.17% with SINTACS.

The very low margins of error on the vulnerability maps produced show that methods used are well suited to mapping the groundwater vulnerability to pollution in the region.

Nevertheless, with 1.52%%, the SI specific vulnerability method seems the most appropriate. Moreover, the margins of error on the substantially similar DRASTIC (2.90%) and SINTACS (2.35%) maps confirm the analogy between the two methods. However DRASTIC tends to overestimate the vulnerability that SINTACS.

## References


[1] A.D. Chitimus, E. Mosnegutu, M.C. Nicolescu, M. Turcu, M.C. Belciu, G. Ardeleanu, *Mathematical modelling of water migration time in soil*, **Environmental Engineering & Management Journal**, **13**(7), 2014, pp. 1581-1586.

[2] A.D. Chitimus, C.Radu, V.Nedeff, E.Moşnegutu, N.Barsan, *Studies and Researches on Typha Latifolia's (bulrush) Absorption Capacity of Heavy Metals From the Soil*, **Scientific Study & Research Chemistry & Chemical Engineering, Biotechnology, Food Industry**, **17**(4), 2016, pp. 381 – 393.

[3] A.D. Chitimus, N.Barsan, V., Nedeff, E.Mosnegutu, O. Muscalu (Plescan), *Studies and research concerning the influence of liquid pollutants' leaching speed in the soil on the process of cleaning and self-cleaning*, **17th International Multidisciplinary Scientific GeoConference SGEM** 2017, **17**(51), 2017, pp. 859-866.

[4] C. Radu, A.D. Chitimus, M. Turcu, G. Ardeleanu, M. Belciu, *Impacts of Anthropogenic Activities in Bacau Area Upon Heavy Metals Concentration on Bistrita River Sides*, **Environmental Engineering and Management Journal**, **13**(7), 2014, pp. 1687-1691.

[5] A.D. Chitimus, V. Nedeff, E. Mosnegutu, M. Panainte, *In situ soil flushing studies on remediation efficiency of polluted sandy soils with organic acids*, **Environmental Engineering and Management Journal**, **11**(12), 2012, pp. 2163-2168.

[6] O.M. Muscalu (Pleșcan), V.Nedeff, A.D. Chițimus, E. Partal, E. Mosnegutu, I.D. Rusu, *Influence of Soil Fertilization Systems on Physical and Chemical Properties of the Soil*, **Rev. Chim. (Bucharest)**, **69**(11), 2018, pp. 3106-3111.

[7] D. Chițimus, A. Cochiorca, V. Nedeff, O. Muscalu, N. Barsan, *Studies and Research on Phragmites Australis' (Common Reed) Absorption Capacity of Heavy Metals From the Soil in Roman City, Romania*, **Proceeding of the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management**, SGEM, **18**, 2018, pp. 671-678.

[8] O.M. Muscalu (Pleșcan), V. Nedeff, A.D. Chitimus, E. Partal, N. Barsan, I.D. Rusu, *Influence of Soil Fertilization Systems and Crop Rotation on Chemical Properties of the Soil*, **Rev. Chim. (Bucharest)**, **70**(2), 2019, pp. 536-542.

[9] E.F. Mosnegutu., V. Nedeff, A.D. Chitimus, D.I. Rusu, *Aspects regarding the siret river direction-changing in the Bacau county region, Romania*, **International Journal of Conservation Science**, **10**(1), 2019, pp. 131-138.

[10] A. Cochiorca, V. Nedeff, N. Barsan, M. Panainte-Lehadus, E.F. Mosnegutu, *Aspects related to water quality assessment in a mining activity area. Case study, mining area Tg. Ogna, Romania*, **Proceeding of the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management**, SGEM, **18**(3.1), 2018, pp. 87-94.

[11] A. Cochiorca, V. Nedeff, N. Barsan, E.F. Mosnegutu, M. Panainte-Lehadus, C. Tomozei, *Analysis of water quality for two rivers located near a mining area*, **Chemistry & Chemical Engineering, Biotechnology, Food Industry**, **19**(4), 2018, pp. 455 – 463.

[12] L. Idrissi, *Nitrates et nitrites: Polluants qui menacent la santé et l'environnement*, **Les Technologies de Laboratoire**, (1), 2006, pp. 10-14.

[13] * * *, **Agriculture et environnement: Enseignements tirés de dix ans (1993-2003) des travaux de l'OCDE**, Organisation pour la Coopération et le Développement Economique (OCDE), 2004, p. 41.

[14] V. Vasilache, C. Filote, M.A. Cretu, I. Sandu, V. Coisin, T. Vasilache, C. Maxim, *Monitoring of Groundwater Quality in Some Vulnerable Areas in Botosani County for Nitrates and Nitrites Based Pollutants*, **Environmental Engineering and Management Journal, 11**(2), 2012, pp. 471-479, DOI: 10.30638/eemj.2012.059.

[15] D.G. Cozma, C.L. Costuleanu, I. Sandu, D. Lutic, *Statistical Analysis of Raw and Potable Water Quality from a Preparation Plant, as a Basis to Purpose the Re-schedule of the Physico-Chemical Current Routine Analysis Periodicity*, **Revista de Chimie, 69**(1), 2018, pp. 214-221.

[16] D. Bociort, C. Gherasimescu, R. Berariu, R. Butnaru, M. Branzila, I. Sandu, *Research on the Degree of Contamination of Surface and Groundwater used as Sources for Drinking Water*, **Revista de Chimie, 63**(11), 2012, pp. 1152-1157.

[17] T. Lupascu, M. Ciobanu, V. Botan, I.G. Sandu, I. Dragalin, T. Mitina, I. Sandu, *Removal of Ammonium Ions and Ammonia from Groundwater by Oxidation Processes*, **Revista de Chimie, 69**(11), 2018, pp. 3082-3086.

[18] C.P. Papadatu, M. Bordei, G. Romanescu, I. Sandu, *Researches on Heavy Metals Determination from Water and Soil in Galati County, Romania*, **Revista de Chimie, 67**(9), 2016, pp. 1728-1733.

[19] C. Hauhouot, *Les pressions anthropiques sur les milieux naturels du sud-est ivoirien*, **Geology-Ecology-Tropical**, **28**(1-2), 2004, pp. 69-82.

[20] M.H. Hamza, A. Added, A. Frances, R. Rodriguez, M. Ajmi, S. Abdeljaoued, *Évaluation de la vulnérabilité à la pollution potentielle de la nappe côtière alluvionnaire de Meltine-Ras Jebel-Raf Raf (Nord-Est tunisien) selon les méthodes paramétriques DRASTIC, SINTACS et SI*, **Revue des sciences de l'eau**, **21**(1), 2008, pp. 75-86.

[21] V. Mourey, J. F. Vernoux, *Les risques pesant sur les nappes d'eau souterraine d'Ile-de-France*, **Annales des mines**, 2000, pp. 32-40.

[22] JICA (Japan International Cooperation Agency), **Plan Directeur de Gestion intégrée des ressources en eau en Côte d'Ivoire** - Rapport Final, 2001, p. 949.

[23] B. Dibi, I. Doumouya, K. Koffi, N. Soro, I. Savane, K. Kouame, *Evaluation et cartographie de la vulnérabilité à la pollution en aquifère confiné selon la méthode DRASTIC: cas de la région d'Aboisso, Sud-est de la Côte d'Ivoire*, **European Journal of Scientific Research**, **18**(3), 2007, pp. 500-513.

[24] B. Dabin, N. Leneuf, G. Riou, Notice explicative de la carte pédologique de la Côte d'Ivoire à l'échelle de 1/2.000.000**,** ORSTOM, Institut d'Enseignement et de Recherches Tropicales d'Adiopodoumé (Côte d'Ivoire), 1960, p. 31.

[25] A.H.G. Koua, *Situation de la production de café en côte d'ivoire: cas du département d'Aboisso, état des lieux et perspectives*, 2007, **Mémoire de fin d'étude pour l'obtention du Diplôme d'Agronomie Approfondie**, Ecole Supérieure d'Agronomie. http://www.memoireonline.com/10/07663/m_situation-production-café-cote-d-ivoire-aboisso.html. [Accessed 21.3.2018]

[26] C. Delor, I. Diaby, B. Yao, Y. Simeon, J-P. Tastet, M. Vidal, J-C. Chiron, A. Dommanget, *Notice explicative de la carte géologique de la Côte d'Ivoire à 1/200 000, feuille Grand-Bassam*, **Mémoire de la Direction de la Géologie** (Abidjan/Côte d'Ivoire), **4**, 1992, p. 30.

[27] A. Perraud, P. De La Souchère, Esquisse pédologique de la Côte d'Ivoire à l'échelle de 1/500 000**, Feuille Sud-Est**, Ed. ORSTOM, Centre d'Adiopodoumé, 1971.

[28] L. Aller, T. Bennet, J.H. Lehr, R. Petty, G. Hackett, **DRASTIC: A Standardized System to Evaluate Ground Water Pollution Potential Using Hydrogeologic Settings**, U.S EPA-600/2-87-035, 1987, p. 455.

[29] D. Isabel, P. Gelinas, F. Aubre, *Cartographie de la vulnérabilité des eaux souterraines au Québec*, **Revue des Sciences et Techniques de l'Eau**, 1990, p. 23.

[30] B.A. Engel, K.C.S. Navulur, B.S. Cooper, L. Hahn, *Estimating groundwater vulnerability to non-point source pollution from nitrates and pesticides on a regional scale Proc* **HydroGIS'96: Application of Geographic Information System in Hydrology and**

**Water Ressources Management**, (Editors: K. Kovar, and H.P. Nachtnebel),, International Association of Scientific Hydrology, **235**, 1996, pp. 521-526.

[31] N. Schnebelen, J.P. Platel, Y. Lenindre, D. Baudry, **Gestion des eaux souterraines en Aquitaine** - *Année 5. Etude Sectorielle - Protection de la nappe de l'Oligocène en région bordelaise. Nouvelles connaissances hydrogéologiques. Cartographie de la vulnérabilité aux pollutions*, Rapport BRGM/RP-51178-FR, 2001, p. 75.

[32] M. Al Kuisi, A. El-Naqa, N. Hammouri, *Vulnerability mapping of shallow groundwater aquifer using SINTACS model in the Jordan Valley area*, **Jordan Environmental Geology**, **50**, 2006, pp. 651-667.

[33] M. Civita, M. De Maio, **SINTACS. Un sistema parametrico per la valutazione e la cartografia per la valutazione della vulnerabilità degli acquiferi all'inquinamento,** Metodologia ed automazione, Quaderni di tecniche di protezione ambientale, Pitagora Editrice, Bologna, 1997, p. 191.

[34] S. Kapelj, J. Loborec, J. Kapelj, *Assessment of aquifer intrinsic vulnerability by the SINTACS method*, **Geologia Croatica**, **66**(2), 2013, pp. 119-128.

[35] B. Dibi, *Cartographie des sites potentiels d'implantation des points d'eau dans la région d'Aboisso (Sud-est de la Côte d'Ivoire) : Apport du SIG et de l'analyse multicritère*, **PhD Thesis,** Université de Cocody-Abidjan (Côte d'Ivoire), 2008, p. 167.

[36] A. Kangah, *Utilisation de la télédétection et d'un système d'information géographique (SIG) pour l'étude des pressions anthropiques sur les paysages géomorphologiques des savanes sub-soudanaises : exemple du degré carré de Katiola (centre-Nord ivoirien)*, **PhD Thesis,** Université de Cocody-Abidjan, Côte d'Ivoire, 2006, p. 186.

[37] J.P Jourda., K.J. Kouamé, M.B. Saley, K.F. Kouamé, B.H. Kouadio, Kouamé K., *A new cartographic approach to determine the groundwater vulnerability of the Abidjan aquifer.* **In Groundwater Pollution in Africa**, Xu Y, Usher B (eds). Taylor & Francis/Balkema: Leiden, 2006, pp. 103-114.

[38] K.S. Deh, K.J. Kouame, B.M. Saley, K.J.J. Tanoh, T.A. Anani, K.H. Signo, J.P. Jourda, J. Biémi, *Evaluation de la vulnérabilité spécifique aux nitrates (NO3) des eaux souterraines du District d'Abidjan (Sud de la Côte d'Ivoire)*, **International Journal of Biology, Chemistry and Science**, **6**(3), 2012, pp. 1390-1408.

[39] V. Murat, D. Paradis, M.M. Savard, M. Nastev, É. Bourque, A. Hamel, R. Lefebre, R. Martel, *Vulnérabilité à la nappe des aquifères fracturés du sud-ouest du Québec : évaluation par les méthodes DRASTIC et GOD*, **Ressources Naturelles Canada**, Commission Géologique, 2003, p. 16.

[40] B. Dibi, K.L. Kouassi, K.I. Kouamé, K.S. Konan, M. Soumahoro, A.B. Konan-Waidhet, D. Gnakri, *Evaluation de la vulnérabilité à la pollution des aquifères des formations altérites à partir des méthodes DRASTIC et SYNTACS : Cas de la ville de M'bahiakro, Centre de la Côte d'Ivoire*, **International Journal of Innovation and Applied Studies**, **2**(4), 2013, pp. 464-476.

[41] N. Aghui, J. Biemi, *Géologie et hydrogéologie des nappes de la région d'Abidjan et risques de contamination*, **Annales de l'Université Nationale de Côte d'Ivoire**, Série c, **Tome 20,** 1984, pp. 331-347.

[42] G.E. Aké, B.H. Kouadio, K. Dongo, B. Dibi, K.F. Kouamé, J. Biemi, *Application des méthodes DRASTIC et SI pour l'étude de la vulnérabilité à la pollution par les nitrates ($NO_3^-$) de la nappe de Bonoua (Sud-Est de la Côte d'Ivoire)*, **International Journal of Biology, Chemistry and Science**, 4(5), 2009, pp. 1675-1692.

[43] F. Barrez, *Essais de caractérisation hydrochimique verticale de la nappe de la Craie dans le secteur minier Carvin-Douai-Hénin Beaumont*, **PhD Thesis**, Université de Lille 1 (Université des Sciences et Technologies de Lille)-France, 2006, p. 144.

[44] M.H. Hamza, A. Added, R. Rodriguez, S. Abdeljaoued, A. Ben Mammou, "*A GIS-based DRASTIC vulnerability and net recharge reassessment in an aquifer of a semi-arid region*

*(Metline-Ras Jebel-RafRaf aquifer, Northern Tunisia)*," **Journal of Environmental Management**, **84**, 2007, pp. 12‐ 19.
[45] É. Boisvert, E. Bourque, V. Cloutier, D. Kirkwood, K. Lauziere, R. Lefebvre, R. Martel, Y. Michaud, M. Nastev, M. Ouellet, D. Paradis, M. Ross, N. Rousseau, M.M. Savard, **Guide méthodologique pour la caractérisation régionale des aquifères en roches sédimentaires fracturées**, 2008, p. 162.
[46] D. Allier, B. Vittecoq, V. Mardhel, *Evaluation de la vulnérabilité intrinsèque des eaux souterraines de la Martinique*, **BRGM/RP/FR-56283-Rapport final**, 2008, p. 78.
[47] M.H. Hamza, A. Added, A. Frances, R. Rodriguez, M. Ajmi, S. Abdeljaoued, *Évaluation de la vulnérabilité à la pollution potentielle de la nappe côtière alluvionnaire de Meltine-Ras Jebel-Raf Raf (Nord-Est tunisien) selon les méthodes paramétriques DRASTIC, SINTACS et SI*, **Revue des sciences de l'eau**, **21**(1), 2008, pp. 75-86.

*Received: February 21, 2018*
*Accepted: July 22, 2019*