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Use of Multicriteria Analysis (MCA) to Map the Specific Vulnerability of Groundwater in the City of Daloa (Central-Western Ivory Coast)

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Abstract

In Daloa, the waters from wells and springs from shallow aquifers are used for drinking, given the low water coverage and organoleptic quality of water from the public network. However, the lack of an adequate sewage system and human activities could lead to a risk of chemical contamination of this water table. Yet, the vulnerability and contamination of groundwater in urban areas are a major concern that requires greater attention. It therefore seems necessary to map the specific vulnerability linked to chromium in order to identify the areas requiring special attention. To do this, we opted for Multi-Criteria Analysis, which takes many parameters into account and is suitable for porous media. This method is based on a numerical rating system, which takes into account hydrogeological, human and pollutant characteristics. Field data, laboratory data and maps were used. Using ArcGis software, the data was interpolated, reclassified and rated. The combination of maps indicates three classes of vulnerability: average (0.79%), high (97.53%) and very high (1.68%), with satisfactory validation criteria (coincidence rate: 78.26% and margin of error 0.68%). Consequently, there is a potential risk of contamination of alterite aquifers throughout the city. The MCA has produced satisfactory results, but these can be supplemented by a numerical mass transport model to validate the degree of vulnerability.

Keywords

Shallow Aquifers, Specific Vulnerability Index, Chemical Pollution, Margin of Error, Daloa

1. Introduction

The contamination and vulnerability of groundwater in urbanised areas are a major concern that requires greater attention (Mfonka et al., 2018), because preserving groundwater quality is all the more important given that this resource, once contaminated, becomes unsuitable for consumption (Jourda et al., 2006). However, in recent years, some studies have shown that groundwater resources undergo serious impacts in terms of quality and quantity (Aydi, 2018; Kirlas et al., 2022). This is attributable to growing demand and pollution caused by anthropogenic pressures (Blanchard et al., 2016). Indeed, rapid population growth, inadequate sanitation, agriculture, industrial operations and inappropriate waste disposal contaminate and pollute groundwater reserves for human consumption, compromising their safety and purity (Babuji et al., 2023). This is a problem that affects many urban areas in developing countries. In Daloa, the problem is marked by the discharge of waste water, uncontrolled household waste dumps, faulty septic tanks located less than 15 m from water points and low well depths. All of these factors make us fear any risk of chemical contamination of the alterite aquifers used by the majority of the population for their drinking water. However, for their own consumption, local people have recourse to water from these aquifers, given the low drinking water coverage (Awomon et al., 2018) and organoleptic quality of water from the public network (Kouassi et al., 2023). And to date, no specific vulnerability study has been carried out on these water tables. So prevention against any pollutant appears essential. As a result, different methods (DRASTIC, GOD, SINTACS, EPIK, SI, PaPRI, AMC, etc.) have been developed to assess the vulnerability of aquifers.

However, most of them present errors and uncertainty in the determination of rating scales and weighting coefficients (Goyal et al., 2021). Multi-criteria analysis (MCA), on the other hand, seems to perform better, because it is a method in which the importance of each factor is assessed by means of the consistency ratio. This method was used in the present study because it takes many parameters into account and is suitable for porous media such as the alterite aquifers in the city of Daloa.

This method has been the subject of several applications worldwide, particularly for identifying potential recharge zones (Makonyo & Msabi, 2021) and locating water points (Mangoua et al., 2014; Abdelouhed et al., 2021). It has been successfully used to map the best sites for municipal waste storage (Karimi et al., 2019; Bilgilioglu et al., 2022) and medical waste incineration (Husna et al., 2017). Kumar et al. (2017) and Aydi (2018) used it to assess vulnerability to groundwater pollution in India and Tunisia respectively. In Ivory Coast, Kouadio (2019) used it to assess vulnerability to pollution of alterite aquifers. However, all these authors only studied intrinsic vulnerability and only considered hydrogeological and/or human parameters. Therefore, this study sheds light on the mapping of the specific vulnerability to pollution of alterite aquifers in order to prevent potential pollution risks. In addition to hydrogeological and human parameters, taking into account the characteristics of the pollutant could provide a better understanding of the sensitivity of aquifers. The response of the system (soil-unsaturated zone-saturated zone) could also depend on the pollutant considered. Emphasis is also placed on the specific vulnerability of chromium, as the chromium analysed has high concentrations in all seasons compared with other chemical parameters in Daloa's well and spring waters. This parameter, in its Cr^{6+} form, can cause toxic and carcinogenic effects in consumers of these waters.

2. Material and Methods

2.1. Description of the Study Area

The study was carried out in the town of Daloa, which is located in central-western Ivory Coast and covers an area of 97.28 km². It is situated between 6˚22' and 6˚29' west longitude and between 6˚49' and 6˚56' north latitude (Figure 1). It is the country's third most populous city after Abidjan and Bouaké, with an estimated

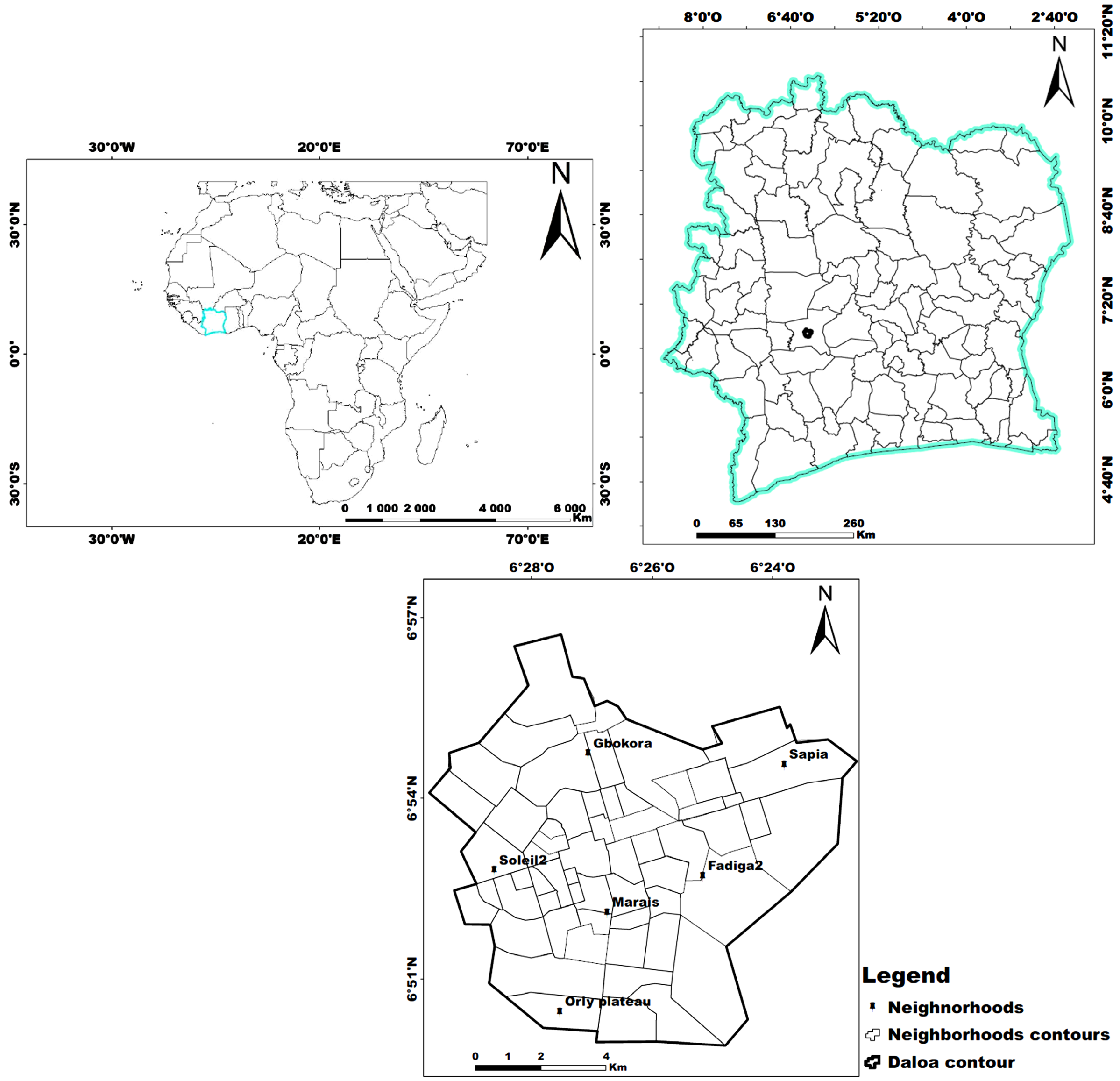


Figure 1. Map of daloa city.

population of 421,879 (INS, 2021). It has a transitional tropical climate, with a rainy season from March to October and a dry season from November to February (Kouadio, 2022). The Daloa formations belong to the Precambrian basement and there are generally composite aquifers in this environment: alterite aquifers (superficial) and fractured aquifers (Lachassagne et al., 2011). Alterite aquifers are subdivided into two layers (**Figure 2**): alloterites and isalerites (Kouassi et al., 2024). The city of Daloa is located in a single geological domain, namely migmatites on heterogeneous granitoids.

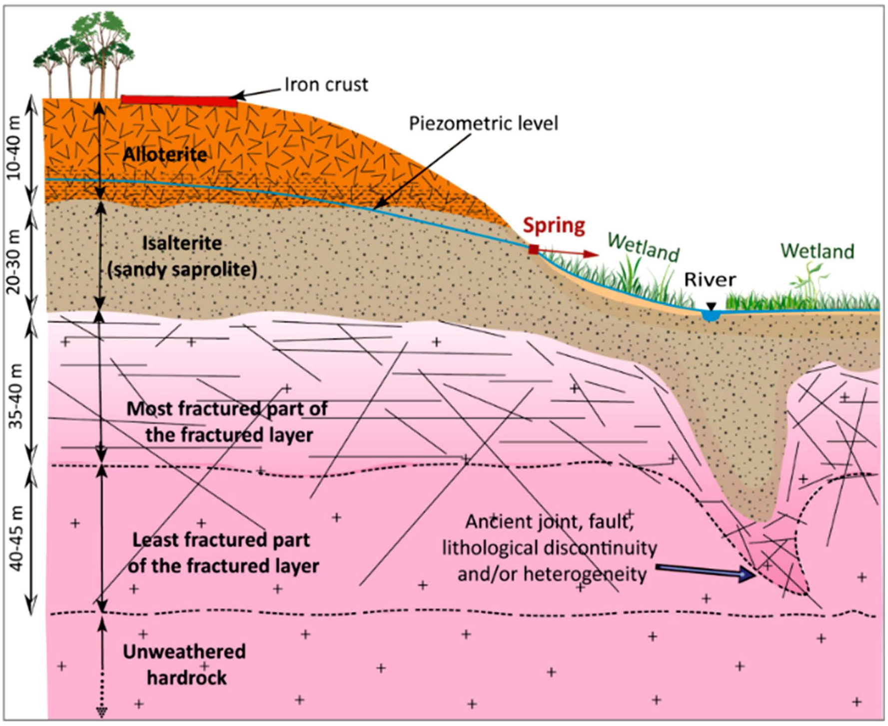


Figure 2. Generalized conceptual model of the hydrogeological context of Daloa (Kouassi et al., 2024).

2.2. Data Collection Methodology

2.2.1. Collecting of Hydrogeological Data

The majority of hydrogeological parameters control water flow and permit assessment of the vertical vulnerability of groundwater. It is about the physical properties that play a role in the migration and attenuation of a contaminant within the soil-unaerated zone-aerated zone complex. There are many hydrogeological parameters, but we have chosen to focus on:

Well depth: this represents the distance (in metres) from the soil surface to the piezometric surface. It determines the thickness of the unsaturated zone and conditions the pollutant transfer time to the water table (Patel et al., 2023; Fusco et al., 2024). For this study, campaigns to measure the water level in 30 wells were carried out in March and November 2022, which mark the start of the rainy and dry seasons, using an OTT 150 m light and sound piezometric probe. In practice, this involved undoing the graduated tape until the tip touched the surface of the water and a sound was emitted before the value was taken. It should be noted that this value is used to calculate the water's edge.

Annual recharge: this is the main vehicle for transferring pollutants to groundwater. The greater the recharge, the greater the risk of contamination (Maqsoom et al., 2021). In this study, recharge was determined on the basis of the piezometric fluctuation method (Equation 1):

$$R = \theta \times \Delta H \qquad \text{(Equation 1)}$$

with R: total recharge (mm/an); θ: total porosity determined from soil samples taken with an auger around the wells using the saturation method; ΔH: seasonal water level variation.

Hydraulic conductivity of alterites: this is a physical characteristic that represents the ease with which a material allows fluid to be transferred through a connected network.

It controls the propagation speed of the pollutant in the aquifer. In the field, Porchet's method, based on the principle of constant-load infiltration, was applied using a double-ring infiltrometer.

The principle is to follow the evolution of the water level as a function of time in the inner ring to determine the rate of infiltration at each time step. After a certain time, a steady state is established. The conductivity is then calculated on the basis of equation 2:

$$C = \frac{r \times h'}{t \times (2h + r)} \qquad \text{(Equation 2)}$$

where r: radius of the hole (m) in relation to the inner ring; h'. height of the percolated water (m); t: elapsed time (s); h: height of the water column (initial value, in m).

Aquifer material: This is the lithology of the saturated zone. This parameter intervenes in the trapping of the pollutant, which can escape due to the absorption capacity of the soil (Mbuluyo et al., 2017). Thus, the data collected from logs and lithological sections of boreholes in the study area give a more or less detailed idea of this parameter. To determine the 'Aquifer material' parameter, the layers representative of the saturated zone were considered.

Slope: This parameter indicates whether the water will run off at the surface or infiltrate into the ground. Indeed, the steeper the slope, the greater the runoff and the less the water will infiltrate (Farah et al., 2021). On the other hand, an area with a weak slope favours infiltration and increases the potential for contaminant migration. To determine this, we used a digital terrain model (DTM) that can be downloaded from the Earth Explorer website.

Soil type: Soil is a hydraulic property that controls recharge during the water infiltration process (Mboudou et al., 2016; Maqsoom et al., 2021). Its characteristics are of considerable importance in the path of water and therefore in the transfer time of pollutants from the soil surface to water. For this reason, the soil map of Côte d'Ivoire produced by Perraud & De La Souchère (1969) was used, revealing that the soil in Daloa is sandy-clayey.

Unsaturated zone: this is located between the soil layer and the water table. The nature of this zone is an important parameter, because it influences the speed at which pollutants propagate towards the aquifer. The influence of this zone on the potential pollution of the aquifer depends essentially on either the thickness, lithology or transit time (Gourcy, 2022). For the present study, only lithology was considered. This parameter was determined on the basis of logs and lithological sections from boreholes.

2.2.2. Collecting of socio-Environmental Data

In order to acquire socio-environmental data, it was necessary to carry out surveys of state structures and households. The information sought concerned:

Population density: this refers to the number of individuals per square kilometre. This parameter influences all human activities carried out on the surface of the soil, which are likely to produce pollutants directly or indirectly. For this study, the population data provided by the National Statistics Institute (INS) during the general population census in 2021 were used.

Management of wastewater and household waste: these parameters refer to the type of sanitation system used by the population. For these data, a survey was conducted among households in Daloa in 2021. The questions concerned the type of sanitation system used (septic tanks, refuse bins, nature). The proportions of households discharging wastewater and household waste into the environment were calculated.

2.2.3. Collecting Chemical Data on Well and Spring Water

Seasonal chemical analysis of well and spring water has enabled chemical parameters to be identified and quantified. It was revealed that heavy metals, particularly chromium, are present in high concentrations, regardless of the season.

The characteristics of chromium have therefore been taken into account in order to better explain all the physico-chemical interactions between the aquifer and the pollutant. These are the degree of adsorption (Ad) of the pollutant by the unsaturated zone and its solubility (So) in water, the information for which comes from documentary research.

2.3. Methodology for the Elaboration of the Specific Vulnerability Map

This study consists to present the areas of high vulnerability linked to a specific pollutant on a map. The assessment and mapping of areas vulnerable to chromium pollution was made possible by the application of Multi-Criteria Analysis (MCA) based on the AHP method. This technique has proved effective in other studies of groundwater contamination. The map is drawn up in several steps. For this reason, a simplified conceptual model was developed to facilitate the work (**Figure 3**).

2.3.1. Identification of Vulnerability Factors

The identification of factors relating to the study of the specific vulnerability of aquifers is conditioned by several criteria such as the hydrogeological criterion, the human criterion and the pollutant criterion. As part of this study, twelve (12) factors were selected (Table 1), namely: depth (D), recharge (R), aquifer material (A), lithology of the unsaturated zone (LUZ), conductivity (C), slope (Sl) and soil (S), which constitute the hydrogeological factors. As for human factors, the population density (PD), the household waste management method (Hw) and the waste water management method (Ww) were retained. The pollutant factors are the degree of adsorption (Ad) of the pollutant in the unsaturated zone and its solubility (So) in water.

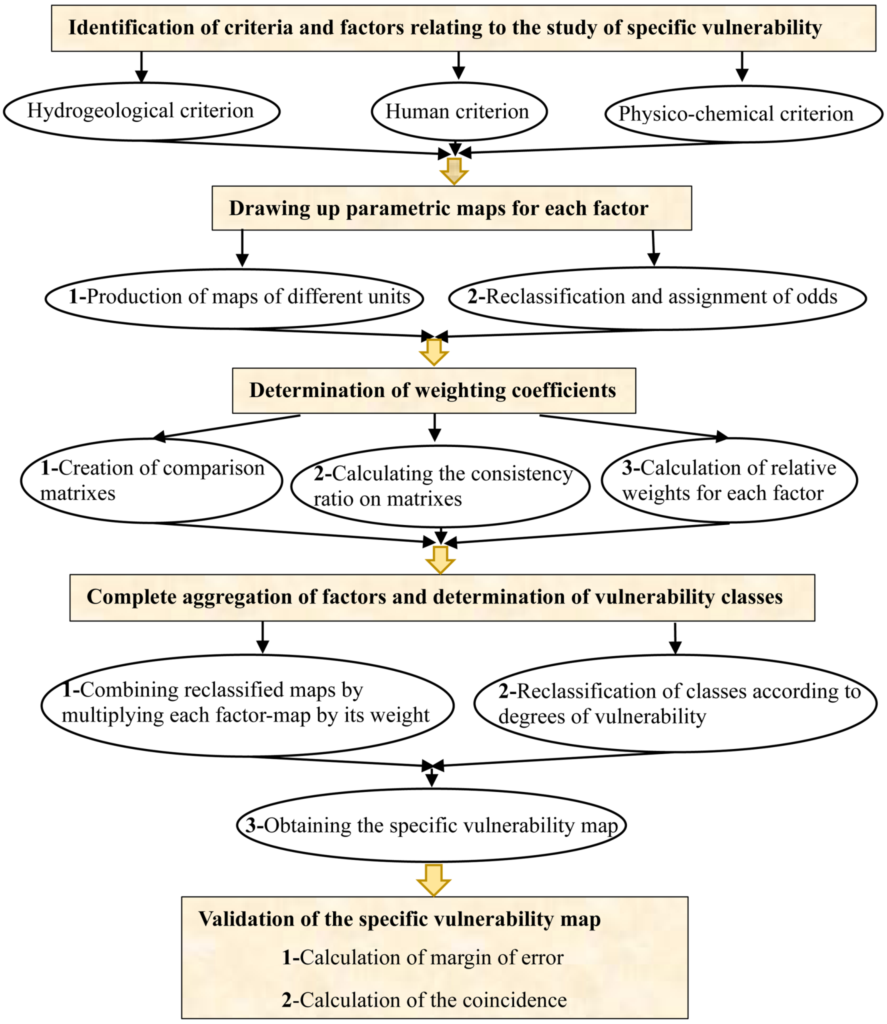


Figure 3. Conceptual model showing the steps involved in elaborating a vulnerability map.

Table 1. Factors relating to the study of specific vulnerability to pollution.

	Units	Values	Sources
P	m	1.04 - 20.42	Piezometric measurement
R	mm/years	5.5 - 484.9	Piezometric fluctuation method

Continued

A		Coarse sand	Borehole logs
LUZ		Clayey sand	Borehole logs
C	m/s	$5.44 * 10^{-6}$ - $1.79 * 10^{-4}$	Measurement using the Porchet method
Sl	%	0 - 170.09	DTM
S		Clayey sand	Pedological sketch
PD	Inhbts/Km^2	1182 - 83 119	INS (2021)
Hw	%	50	Survey data
Ww	%	50	Survey data
So		Oui	Bibliography
Ad		Non	Bibliography

2.3.2. Drawing Up Parametric Maps of Factors

All the field data obtained was compiled and interpolated. Qualitative data (aquifer material, slope, unsaturated zone lithology, soil type, solubility and adsorption) were transformed into raster and quantitative values before being interpolated to the entire study area. They were then reclassified and rated. In practice, the data was interpolated in the ArcGIS environment. This was done using the Inverse Distance Weighting (IDW) method, known as the local deterministic method in the 'Spatial Analyst tools' module. The values were then reclassified on the basis of the several-author rating system shown in **Tables 2-4**. Finally, as the factors were measured on different scales, they had to be standardised. As a result, each factor was associated with an entire scale with a score ranging from 1 to 10 in the 'Reclassify' tool.

Table 2. Ratings linked to hydrogeological factors.

Parameters	Classes	Ratings	Authors
P (m)	0 - 1.5	10	Aller et al. (1987)
	1.5 - 4.5	9	
	4.5 - 9	7	
	9 - 15	5	
	15 - 23	3	
	23 - 31	2	
R (mm/year)	0 - 50	4	Aller et al. (1987)
	50 - 100	6	
	100 - 180	8	
	>180	10	

Continued

C (cm/d)	<4	1	Aller et al. (1987)
	4 - 12	2	
	12 - 29	4	
	29 - 41	6	
	41 - 82	8	
	>82	10	
A LUZ	Chippings	9	Majolagbe et al. (2016)
	Coarse sand	8	
	Middle sand	7	
	Fine sand	6	
	Clayey sand	5	
Sl (%)	0 - 10	10	Mbuluyo et al. (2017) Modified
	10 - 20	9	
	20 - 30	5	
	30 - 50	3	
	50+	1	
S	Thin soil	10	Mbuluyo et al. (2017)
	Sandy-clay	4	
	Clay	1	

Table 3. Ratings linked to human factors.

Parameters	Classes	Ratings	Authors
PD (Inhbts/Km^2)	<1000	1	Deh (2013) modified
	1000 - 3000	2	
	3000 - 5000	4	
	5000 - 10,000	6	
	10,000 - 20,000	8	
	>20,000	10	
Hw (%) Ww (%)	0 - 25	4	Kouadio (2019)
	25 - 50	6	
	50 - 75	8	
	75 - 100	10	

Table 4. Ratings assigned to pollutant characteristics.

Parameters	Classes	Ratings	Authors
Ad	Null	10	Deh (2013)
	Very low	8	
	Low	7	
	Moderate	5	
So	High	7	

2.3.3. Determining the Weighting Coefficients

Given the large amount of data to be processed and the complexity of the problem to be studied, the method developed by Saaty (1977) was used to quantify and rank the criteria and factors characterising vulnerability to pollution. It is a simple method whose backbone is consolidated by mathematical calculations that generate weighting coefficients whose sum is equal to 1. The methodological approach can be summarised in four (4) steps.

Construction of the hierarchy: this has consisted of structuring the problem to be solved into three levels (**Figure 4**). Level 0 represents the main objective to be achieved. Level 1 corresponds to the three (3) criteria taken into account in this study. Finally, level 2 presents the twelve (12) evaluation factors.

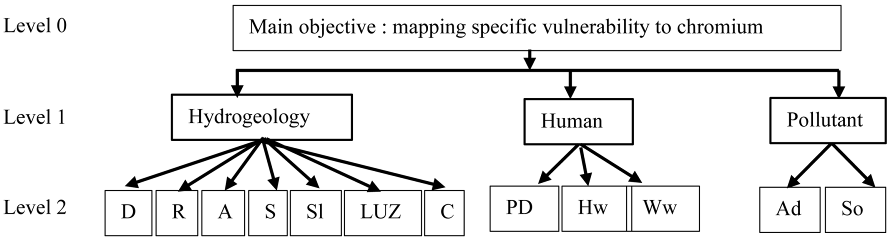


Figure 4. Hierarchical structure according to Saaty (1977) modified for the present study.

Binary combination: this consisted in comparing the relative importance of all the elements taken two by two to configure reciprocal square matrices based on the model established by Saaty (1980) and on the numerical scale of El Majorni (2002). Firstly, the various factors were established in a precise order based on actual information on the alterite aquifers in the city of Daloa. The order of classification is as follows: P-Sl-A-R-S-LUZ-C, Ww-Hw-PD and So-Ad. Thereafter, when two factors have the same importance in the study of vulnerability to pollution, the value 1 is given to them. However, if one factor is more important than the other, then it is given the value 5. Otherwise, it is given the opposite value.

Determining logical consistency: this involves calculating the RC consistency ratio. This operation is composed of seven (7) steps:

Normalisation of the original matrix: this step consists of dividing each numerical scale of each parameter following each column by the total for that column. In this matrix, a total is determined for each line.

Calculating the priorities of the parameters according to the lines: this involves dividing each total of the lines by the total of the totals of the lines.

Creating a new matrix by multiplying each priority by the columns of the original matrix. A total is then determined for each line.

Ratio of each line total by each priority.

Calculation of the maximum eigenvalue of the elements compared ($\lambda_{\max}$) based on the following formula:

$$\lambda_{\max} = \frac{\sum \mathrm{RV}}{n} \qquad \text{(Equation 3)}$$

With: RV_k, report values and n, number of elements compared.

Determination of the coherence index (CI) by the following formula:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \qquad \text{(Equation 4)}$$

Calculation of the coherence ratio. Saaty defined, by experiment, a coherence ratio as the ratio of the coherence index (CI) to the random index (RI) of a matrix of the same dimension. The RI values are 1.35, 0.52 and 0 respectively for the hydrogeological, human and pollutant matrices (Saaty, 2000; Alonso & Lamata, 2006).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad \text{(Equation 5)}$$

The consistency ratio provides information on the consistency of the judgements, because the values assigned can present a certain degree of inconsistency. This ratio is compared to 10% (Saaty, 2000).

If RC ≤ 10%, then the matrix is said to be coherent;

If RC > 10%, then the matrix is not consistent and should be revised.

Calculation of factor weights: the eigenvectors and weighting coefficients by line were determined according to the equations below:

$$\mathrm{Ev} = \sqrt[n]{W_i \times \cdots \times W_n} \qquad \text{(Equation 6)}$$

$$\mathrm{WC} = \frac{\mathrm{Ev}_i}{\mathrm{Ev}_i + \cdots + \mathrm{Ev}_n} \qquad \text{(Equation 7)}$$

with WC: weighting coefficient; Ev: eigenvector for each parameter; W_n: main scores assigned to the parameters.

2.3.4. Complete Aggregation of Factors and Determination of Vulnerability Classes

Complete aggregation of the factors involved multiplying each reclassified factor map by its respective weighting coefficient and adding the results to produce a suitability index on a scale of 1 to 10.

Mena (2000) considers that this method is the only one applicable when there are several criteria which vary continuously in space. By adapting the vulnerability index formula established by Gogu & Dessargue (2000), we can write:

$$\mathrm{SAI} = \sum_{i=1}^{n} \mathrm{WC}_i \times \mathrm{RM}_i \qquad \text{(Equation 8)}$$

with SAI: specific ability index; WC_i: weight of factor *i*; RM_i: reclassified map of factor *i*.

This equation was used individually for the three decision criteria. Subsequently, the specific chromium vulnerability index noted (SVI) was obtained according to the following formula:

$$\mathrm{SVI} = \mathrm{WC\_Hg} \times \mathrm{SAI\_Hg} + \mathrm{WC\_Hu} \times \mathrm{SAI\_Hu} + \mathrm{WC\_P} \times \mathrm{SAI\_P} \quad \text{(Equation 9)}$$

with WC_Hg, WC_Hu and WC_P the weighted coefficient of the different criteria considered.

Next, the equal interval classification method of Aydi (2018) was used to classify the vulnerability to specific pollution into five classes (**Table 5**).

Table 5. Specific vulnerability indices and classes according to Aydi (2018).

Indices	Classes of vulnerability
[1 - 2[	Very low
[2 - 4[	Low
[4 - 6[	Medium
[6 - 8[	High
[8 - 10]	Very high

2.3.5. Validation of the Specific Vulnerability Map

To affirm the reliability of the specific pollution vulnerability map of the city of Daloa and to appreciate the relevance of each variable on this map, two (2) verification tests were carried out. The first test consisted in determining the margin of error on the final pollution vulnerability map. The second test, which is an empirical validation criterion, consisted of calculating the coincidence rates of high chromium concentrations analysed in well and spring water in Daloa and in highly vulnerable areas. This is one of the approaches (Superimposing existing groundwater chemical data on the map) widely used to empirically validate a vulnerability map.

Calculation of the margin of error: the margin of error permits to appreciate the quality of the information obtained from the vulnerability map. It was calculated on the basis of the equations bellow:

$$\Delta\bar{X} = \frac{\sigma}{\sqrt{m}} \quad \text{(Equation 10)}$$

$$\mathrm{Er} = \frac{\sum \Delta\bar{X}}{\mathrm{IvM}} \quad \text{(Equation 11)}$$

with $\Delta\bar{X}$: uncertainty on the average index; σ: standard deviation of vulnerability indices; *m*: number of data considered; IvM: average vulnerability index.

Determination of coincidence rates: chromium concentrations were projected onto the pollution vulnerability map, and the coincidence rate was determined by calculating the ratio of the number of wells whose pollution level was consistent with the vulnerability level over the total number of wells sampled. To do this, 27 wells with chromium values greater than 0.05 mg/L were considered. In validating the vulnerability map, the areas that are really contaminated must correspond to those with the highest vulnerability indices. This verification technique has been adopted by several authors, including Deh (2013), Gougo (2016), Kumar et al. (2017) and Kouadio (2019).

3. Results

3.1. Weighting Coefficients

The obtaining of the different thematic maps has involved multiplying each factor map by its weight (Cp).

Thus, **Tables 6-9** show the weighting coefficients based on the numerical values assigned (see square matrices) and the consistency ratio. These tables show ratio values between 0% and 0.05%. This shows that the matrices are consistent. On the basis of the order of importance of each factor established, the weighting coefficients decrease from the most important to the least important factors.

Table 6. Weight of hydrogeological factors according to matrix.

	P	Sl	A	R	S	LUZ	C	CR	WC
P	1	2	3	5	5	6	6	0.05	0.35
Sl	1/2	1	3	5	4	4	5		0.26
A	1/3	1/3	1	4	3	3	5		0.16
R	1/5	1/5	1/4	1	2	2	3		0.08
S	1/5	1/5	1/3	1/2	1	2	2		0.06
LUZ	1/6	1/4	1/3	1/2	1/2	1	2		0.05
C	1/6	1/4	1/5	1/3	1/2	1/2	1		0.04

Table 7. Weight of human factors according to matrix.

	Ww	Hw	PD	CR	WC
Ww	1	3	4	0.01	0.62
Hw	1/3	1	2		0.24
DP	1/4	1/2	1		0.14

Table 8. Weight of pollutant factors linked to the matrix.

	So	Ad	CR	Cp
So	1	2	0	0.67
Ad	1/2	1		0.33

Table 9. Weight of criteria.

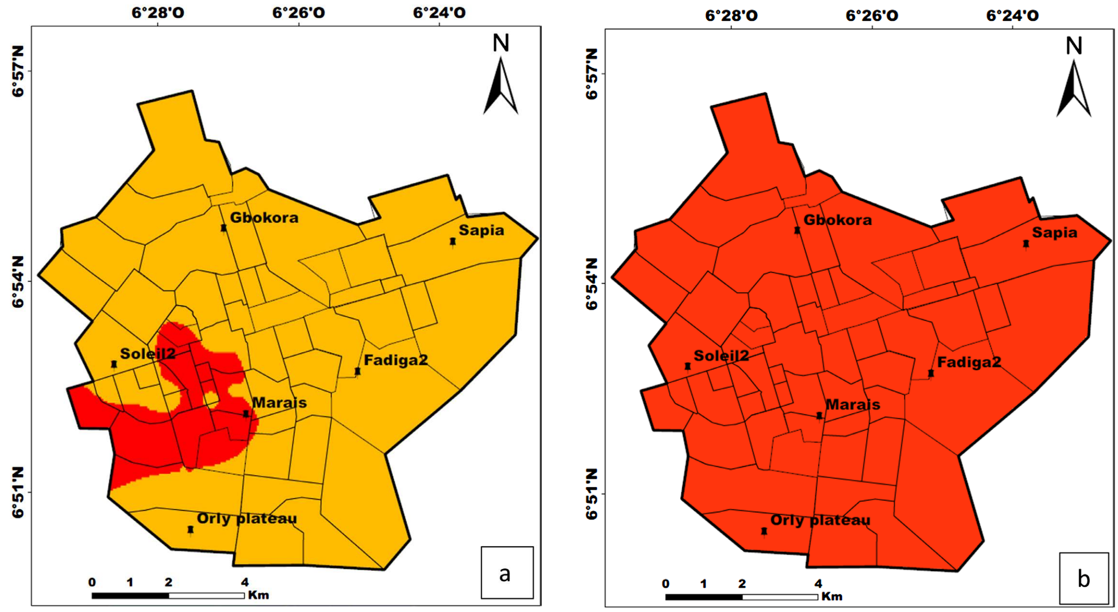
	Hydrogeology	Human	Pollutant	CR	WC
Hydrogeology	1	3	5	0.04	0.62
Human	1/3	1	3		0.24
Pollutant	1/5	1/3	1		0.14

3.2. Analysis of Specific Suitability Maps

Human vulnerability map: Figure 5(a) shows two (2) classes of vulnerability to pollution, namely high and very high, on the human vulnerability map. These two (2) occupy 89.37% and 10.63% respectively. As a reminder, drawing up this map was made possible thanks to data on population density, wastewater management and household waste. Thus, it is clear that the human activities carried out in the area seem to be crucial in terms of the vulnerability of the alterite aquifers.

Pollutant criteria map: The sensitivity map linked to the characteristics of chromium (Figure 5(b)) indicates a very high vulnerability class throughout the study area. This indicates that chromium or all non-reactive and soluble pollutants could migrate towards the groundwater of the city of Daloa.

Hydrogeological criterion map: It shows four (4) classes of vulnerability to pollution (low, medium, high and very high) in the study area after superimposing the thematic maps (Figure 5(c)). However, the high class predominates, and represents 86.81% of the surface area. Then come the medium, very high and low classes, which occupy 11.64%, 1.52% and 0.03% respectively. The latter are poorly represented on the map. Consequently, this situation indicates that hydrogeological factors would favour the progression of certain pollutants towards the water table if they were present in these areas.



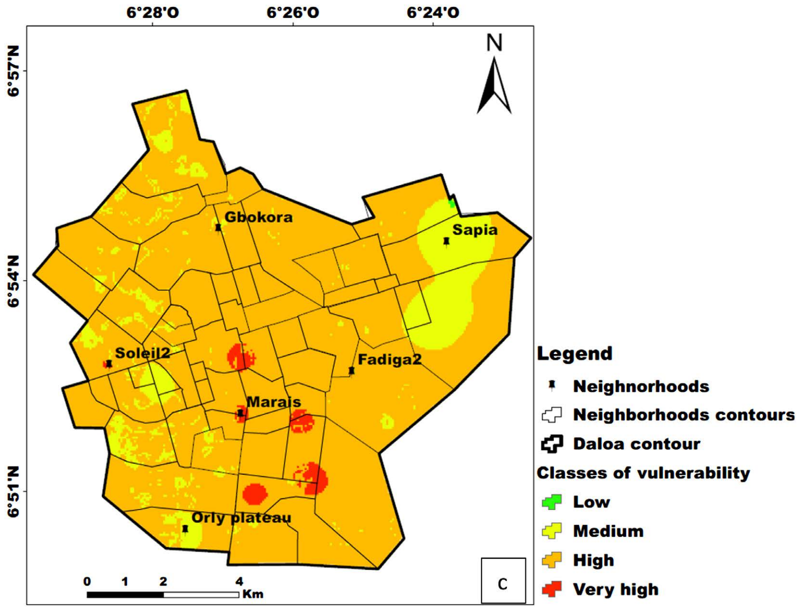


Figure 5. Vulnerability map: human criteria (a), pollutant criteria (b) and hydrogeological criteria (c).

3.3. Analysis of the Final Chromium-Specific Vulnerability Map

The specific vulnerability map based on the AMC method, obtained by combining the maps, shows three classes of vulnerability (medium, high and very high) (Figure 6). Analysis of this map shows that the medium and very high vulnerability classes hardly exist in the study area (0.79% and 1.68% of the total surface area of the study area); instead, it is dominated by the high class (97.53%). In this case, a very close eye must be kept on any intense anthropogenic activities that tend to pollute groundwater.

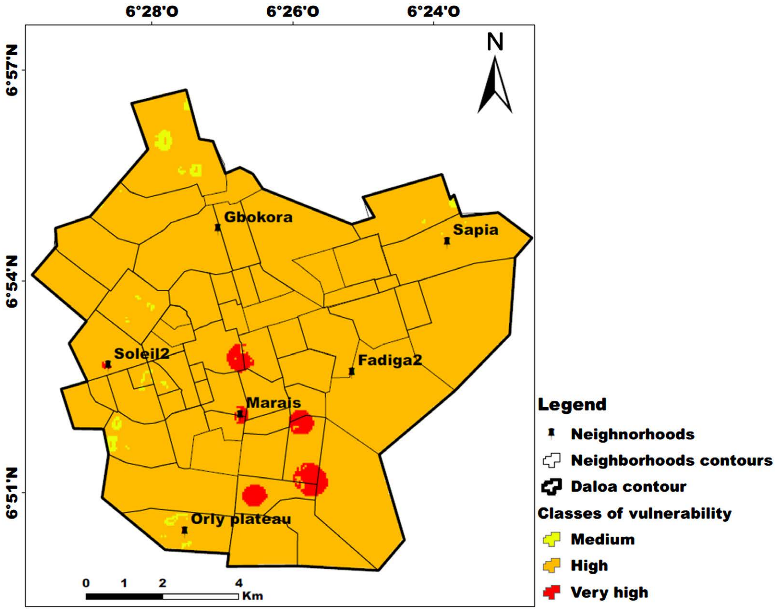


Figure 6. Specific vulnerability map of the city of Daloa.

3.4. Criteria for Validating the Vulnerability Map

The validity of this map was made possible by the margin of error and the coincidence rates of high chromium concentrations. The margin of error obtained on the map is 0.68% (Table 10), showing that the information on the map is reliable. This error value was obtained by considering only those factors for which the data came from the field missions. In terms of uncertainties, the depth factor has the highest value (0.08).

Table 10. Margin of error on the final vulnerability map.

	P	R	A	LUZ	C	PD	Ww	Hw	Ad	So
σ	0.46	0.14	0.00	0.00	0.02	0.19	0.00	0.00	0.00	0.00
I_{vi}_M	1.92	0.53	1.27	0.25	0.05	1.04	5.04	1.84	2.63	6.03
m	30	30	11	11	42	44	44	44	44	44
$\Delta\overline{x}$	0.08	0.03	0.00	0.00	0.003	0.03	0.00	0.00	0.00	0.00
Er	0.0068 = 0.68%									

As for the coincidence rate, the distribution of chromium concentrations on the vulnerability map reveals that 78.26% of chromium concentrations > 0.05 mg/L coincide with areas of high vulnerability (Figure 7).

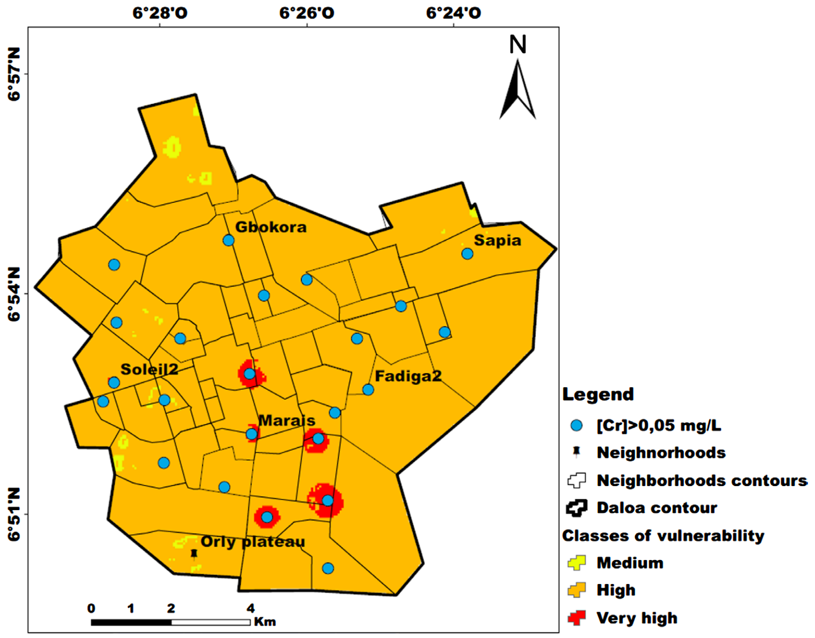


Figure 7. Distribution of chromium concentrations on the vulnerability map.

4. Discussion

In the study of specific vulnerability, Geographic Information Systems (GIS) and Multicriteria Analysis (MCA) remain a well indicated alternative for accurately mapping the sensitivity of an environment through the participation of multiple parameters.

In the present study, the vulnerability map of the alterite aquifers to pollution shows three (3) classes of vulnerability: medium (0.79), high (97.53%) and very high (1.68), with the high class predominating. Analysis of this map indicates that there is a potential risk of groundwater contamination in the entire town. This high level of vulnerability obtained in the present study could be linked to certain hydrogeological factors, namely the low depth of the water table (1.05 - 20.41 m). The depth of the water table determines the distance the pollutant has to travel before reaching the water table (Kouadio, 2019). The higher the water level, the faster the pollutant could reach the water table (Maqsoom et al., 2021; Patel et al., 2023). The importance of this parameter in assessing vulnerability to pollution has already been underlined by several authors (Maqsoom et al., 2021; Poromna et al., 2022). Also, the vulnerability of these areas could be explained by the presence of low slopes (0 to 26.01%) that cover practically the entire area. Slope is a factor that favours either the infiltration of surface water into groundwater or run-off (Poromna et al., 2022). This result corroborates the work of Kamenan et al. (2020) in the Lobo basin. They have stated that, in general, the basin presents 76.90% of low slopes. On the other hand, this vulnerability is reinforced by human factors. The precarious sanitation system in the city of Daloa could lead to high production of pollutants that could infiltrate and contaminate the water table, as shown in the study by Kouadio (2019).

Furthermore, the vulnerability classes obtained in the present study are similar to those obtained by Kouadio (2019), Kamenan et al. (2020) and Pouye et al. (2022), who assessed the intrinsic vulnerability to pollution of the Agboville sand-clay aquifer, the Lobo basin and the Dakar sand aquifer. Indeed, their work revealed a dominance of the high class of 56%, 89% and 45% respectively based on the AMC, PaPRI and SI methods. This similarity could be attributable to factors such as the low depth of the water table, the low slope and the lithology. It is therefore understandable that hydrogeological and human criteria seem to be the most important in assessing the degree of vulnerability of groundwater. However, this is not what is observed in the work of Deh (2013) and Kirlas et al. (2022) with the AMC and SI respectively. Instead, they found the low vulnerability class for the sandy water table in Abidjan (39%) and the sandy-clay water table in Nea Moudiana in Greece (32%). This difference could be attributable to geological formation and depth. Indeed, Deh (2013) worked on a sand table with dominant depths between 39.85 and 88.40 m. For Kirlas et al. (2022), on the other hand, it is a sandy-clay water table with a shallow depth (0 to 10 m).

In addition, determining the margin of error and the coincidence rates are validation criteria that make it possible to assess the relevance of the information in the pollution vulnerability map. Indeed, the production of parametric pollution maps is very complex and presents errors linked to the important number of data taken into account. Several factor maps, concerning recharge, hydraulic conductivity, depth of the water table, lithology of the unsaturated zone, aquifer material, population density, wastewater and household waste management methods, were produced by interpolation, thus assigning values in areas where no data is known or exists. Despite this limitation, the vulnerability maps remain reliable. It should be noted that field measurements and analysis of groundwater chemical parameters are used extensively for validation of the final vulnerability map. As a result, Kumar et al. (2017) considered 10 parameters (total alkalinity, pH, TDS, hardness, magnesium, sulphate, calcium, iron, fluoride and nitrate) from 241 water samples to validate and assess the accuracy of the results. Poromna et al. (2022) validated their map by measuring the distance between sewage works and wells; physico-chemical parameters (pH, EC, TAC, Ca^{2+}, K^+, Na^+, Mg^{2+}, Mn^{2+}, Cl^-, SO_4^{2-} and NO_3^-) and indicator germs of faecal contamination (faecal coliforms, Escherichia coli, faecal streptococci and sulphate-reducing anaerobic germs). On the other hand, nitrate concentrations alone have been used by many authors to validate pollution vulnerability maps (Amrani et al., 2019; Kouadio, 2019; Kamenan et al., 2020; Benmoussa et al., 2023). For the present study, the margin of error of 0.68% and the coincidence rate of 78.26% obtained seem satisfactory. The strong coincidence of high chromium levels with areas of high vulnerability shows the gravity of the groundwater pollution. This situation is all the more critical given that water from traditional wells and natural springs is consumed by the majority of the population of Daloa. Consequently, the information on the map can be used for decision-making and management of groundwater resources. Even if these values do not reach the desired ones, they remain important to justify the reliability of the vulnerability map. Thus, compared with other studies, the value of the margin of error is lower than 1.52% found by Eblin (2014) and 2.1% by Kamenan et al. (2020) with the SI and PaPRI methods. These margins of error obtained by these authors could be due to the large surface areas of their study zones and to the interpolation of data where these are not known. Concerning the chromium coincidence rate, the results are close to those of Kouadio (2019) who have found a nitrate coincidence rate with high vulnerability zones of 80%. This comparison can be explained by the fact that nitrates and chromium are both water-soluble substances and are not reactive. Thus, the AMC method seems better to express the specific vulnerability of groundwater.

5. Conclusion

The aim of this study is to map the degree of specific vulnerability of the alterite aquifers in the city of Daloa on the basis of multi-criteria analysis (MCA). Thus, using this method, it was necessary to consider seven (7) hydrogeological factors (P-Sl-A-R-S-LUZ-C), three human factors (Ww-Hw-PD) and two pollutant factors (So-Ad). The final vulnerability map obtained indicates potential risks of groundwater contamination. In fact, it reveals three classes of vulnerability: average (0.79), high (97.53) and very high (1.68), with the high class predominating. This strong vulnerability is marked throughout the city of Daloa, and the medium and very high classes are located in a few places. The risk of contamination is considerable, given the presence of several sources of pollution in the city, namely domestic and hospital discharges, failure to respect the distance between water points and septic tanks, and the lack of hygiene measures for collection containers. A margin of error of 0.68% and a coincidence rate of 78.26% were obtained, both of which are satisfactory. In reality, the areas contaminated by heavy metals correspond to those where high vulnerability has been observed. These criteria indicate that the data interpolated from those collected are good enough to assess the vulnerability of those areas where it was not possible to measure the data. As a result, the entire city of Daloa needs to be monitored for intense human activity that tends to pollute groundwater. However, a solute transport model would give the vertical transfer time of the pollutant from the soil surface to the piezometric surface.

Ethical Approval of Authors

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Consent to Participate

The authors express their consent to have participated in the submitted work.

Consent to Publish

The authors express their consent to have published the manuscript.

Author Contribution Statement

YEK, YT, OMJM, YMK and BD contributed to the study conception and design. Thus, material preparation, data collection and analysis were performed by YEK, YT and OMJM. All versions of the manuscript were written by YEK. YT, OMJM, YMK and BD commented on previous versions of the manuscript, suggested corrections and approved the final manuscript.

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Availability of Data and Materials

The authors confirm that the data supporting the results of this study are available in the article. However, if these are the raw data, readers can contact the corresponding author [Yon Edwige Kré], on reasonable request.

Conflicts of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

Abdelouhed, F., Ahmed, A., Abdellah, A., Yassine, B., & Mohammed, I. (2021). Using GIS and Remote Sensing for the Mapping of Potential Groundwater Zones in Fractured Environments in the Chaouia-Morocco Area. *Remote Sensing Applications: Society and Environment, 23,* Article ID: 100571. https://doi.org/10.1016/j.rsase.2021.100571

Aller, L., Lehr, J. H., Petty, R., & Bennett, T. (1987). Drastic: A Standardized System to Evaluate Groundwater Pollution Potential Using Hydrogeologic Setting. *Journal Geological Society of India, 29,* 23-37. https://doi.org/10.17491/jgsi/1987/290112

Alonso, J. A., & Lamata, M. T. (2006). Consistency in the Analytic Hierarchy Process: A New Approach. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 14,* 445-459. https://doi.org/10.1142/s0218488506004114

Amrani, S., Hinaje, S., & Gharmane, Y. (2019). Application des méthodes paramétriques (drastic et si) pour l'étude de la vulnérabilité à la pollution potentielle par les nitrates de la nappe d'eau superficielle de Timahdite-Almis Guigou (Moyen Atlas, Maroc). *Revue des Sciences de l'Eau, 32,* 237-252. https://doi.org/10.7202/1067307ar

Awomon Née, A. D. F., Coulibaly, M., Niamke, G. M., & Santos, D. S. (2018). La problématique de l'approvisionnement en eau potable et le développement des maladies à transmission hydrique dans les quartiers d'extension Orly de la ville de Daloa (Côte d'Ivoire). *Revue Espace, Territoires, Sociétés et Santé, 1,* 91-108.

Aydi, A. (2018). Evaluation of Groundwater Vulnerability to Pollution Using a GIS-Based Multi-Criteria Decision Analysis. *Groundwater for Sustainable Development, 7,* 204-211. https://doi.org/10.1016/j.gsd.2018.06.003

Babuji, P., Thirumalaisamy, S., Duraisamy, K., & Periyasamy, G. (2023). Human Health Risks Due to Exposure to Water Pollution: A Review. *Water, 15,* Article 2532. https://doi.org/10.3390/w15142532

Benmoussa, A., Wafik, A., Abdsamad, N., & Khrmouch, S. (2023). Nouvelle Approche d'Etude de la Vulnérabilité à la Pollution des Eaux Souterraines: Cas de la Nappe Mio-PlioQuaternaire du Bassin du Tadla (Maroc). *European Scientific Journal, ESJ, 19,* 49-73. https://doi.org/10.19044/esj.2023.v19n40p49

Bilgilioglu, S. S., Gezgin, C., Orhan, O., & Karakus, P. (2022). A GIS-Based Multi-Criteria Decision-Making Method for the Selection of Potential Municipal Solid Waste Disposal Sites in Mersin, Turkey. *Environmental Science and Pollution Research, 29,* 5313-5329. https://doi.org/10.1007/s11356-021-15859-2

Blanchard, A. F., Théophile, L., Marc, Y. T., François, Y. K. A., Suzane, K. O., Raphaël, O. K. A. et al. (2016). Cartographie DE La Vulnérabilité à la Pollution DEs Aquifères du Socle Précambrien: Cas de la Région D'oumé (Centre-Ouest De La Côte d'Ivoire). *European Scientific Journal, ESJ, 12,* 374-394. https://doi.org/10.19044/esj.2016.v12n20p374

Deh, S. K. (2013). *Contribution de l'évolution de la vulnérabilité spécifique aux nitrates et d'un modèle de transport des organochlorés à la protection des eaux souterraines du district d'Abidjan (Sud de la Côte d'Ivoire).* Master's Thesis, Université Nangui Abrogoua.

Eblin, S. G. (2014). *Dégradation des écosystèmes environnementaux dans la région d'Adiaké (Sud-Est côte de la côte d'ivoire) et risque de pollution des eaux: Apport d'un SIG.* Master's Thesis, Université Félix Houphouët Boigny de Cocody.

El Majorni, Z. (2002). *Conception d'un système d'information à référence spatiale pour la gestion environnementale; application à la sélection de sites potentiels de stockage de déchets ménagers et industriels en région semi-aride (Souss, Maroc).* Master's Thesis, Université de Genève.

Farah, A., Algouti, A., Algouti, A., Baiddane, Y., & Ifkirne, M. (2021). Using GIS and Remote Sensing for the Mapping of Potential Groundwater Zones in Fractured Environments in the CHAOUIA-Morocco Area. *Remote Sensing Applications: Society and Environment, 23,* 1-16.

Fusco, F., Allocca, V., Bancheri, M., Basile, A., Calcaterra, D., Coppola, A. et al. (2024). Corrigendum to "A Multi-Method Approach for Assessing Groundwater Vulnerability of Shallow Aquifers in the Marchfeld Region (Austria)". *Journal of Hydrology: Regional Studies, 54,* 1-17.

Gogu, R. C., & Dassargues, A. (2000). Current Trends and Future Challenges in Groundwater Vulnerability Assessment Using Overlay and Index Methods. *Environmental Geology, 39,* 549-559. https://doi.org/10.1007/s002540050466

Gougo, A. K. (2016). *Etude de la vulnérabilité à la pollution agricole de l'aquifère alluvial Karfuguela (Banfora, Burkina Faso).* Ph.D. Thesis, 2IE de Burkina Faso.

Gourcy, L. (2022). *La vulnérabilité des eaux souterraines* (p. 72). Support de presentation, Journée mondiale de l'eau «Les eaux souterraines, rendre visible l'invisible sous nos pieds».

Goyal, D., Haritash, A. K., & Singh, S. K. (2021). A Comprehensive Review of Groundwater Vulnerability Assessment Using Index-Based, Modelling, and Coupling Methods. *Journal of Environmental Management, 296,* Article ID: 113161. https://doi.org/10.1016/j.jenvman.2021.113161

Husna, A. H., Cem, Ç. D., & Bahar, S. (2017). Sitting of a Central Healthcare Waste Incinerator Using GIS-Based Multi-Criteria Decision Analysis. *Journal of Cleaner Production, 166,* 1031-1042.

INS (Institut National de la Statistique) (2021). *Recensement général de la population et del'habitat (RGPH) Résultats globaux. (Abidjan-côte d'Ivoire)* (p. 26).

Jourda, J. P., Saley, M. B., Djagoua, E. V., Kouamé, K. J., Biémi, J., & Razack, M. (2006). Utilisation des données ETM+ de Landsat et d'un SIG pour l'évaluation du potentiel en eau souterraine dans le milieu fissuré précambrien de la région de Korhogo (nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Revue de Télédétection, 5,* 339-357.

Kamenan, Y. M., Mangoua, O. M. J., Dibi, B., Georges, S. E., Kouassi, K. L., & Kouassi, K. A. (2020). Assessment of Vulnerability to Groundwater Pollution in the Lobo Watershed at Nibéhibé (Central-West, Côte d'Ivoire). *Journal of Water Resource and Protection, 12,* 657-671. https://doi.org/10.4236/jwarp.2020.128040

Karimi, H., Amiri, S., Huang, J., & Karimi, A. (2019). Integrating GIS and Multi-Criteria Decision Analysis for Landfill Site Selection, Case Study: Javanrood County in Iran. *International Journal of Environmental Science and Technology, 16,* 7305-7318. https://doi.org/10.1007/s13762-018-2151-7

Kirlas, M. C., Karpouzos, D. K., Georgiou, P. E., & Katsifarakis, K. L. (2022). A Comparative Study of Groundwater Vulnerability Methods in a Porous Aquifer in Greece. *Applied Water Science, 12,* Article No. 123. https://doi.org/10.1007/s13201-022-01651-1

Kouadio, A. N. B. (2019). *Évaluation des risques sanitaires liés à la consommation des eaux de puits traditionnels par les ménages à faibles revenus en milieu urbain: Cas de la ville d'Agboville (Côte d'Ivoire).* Master's Thesis, Université Nangui Abrogoua d'Abidjan.

Kouadio, K. J. O. (2022). *Modélisation du mode de recharges et du transfert de polluant vers leseaux souterraines du bassin versant de la Lobo à Nibéhibé (Centre-Ouest de la Côte d'Ivoire).* Master's Thesis, Université Jean Lorougnon Guédé de Daloa.

Kouassi, A. A. M., Kouassi, K. L., & Gnagne, T. (2023). Impact of the Condition of Drinking Water Supply Networks on the Quality of Water Intended for Consumption: The Case of the Network in the Commune of Daloa (Central West of Côte d'Ivoire). *Journal of Water Resource and Protection, 15,* 677-691. https://doi.org/10.4236/jwarp.2023.1512036

Kouassi, K. J., Lachassagne, P., Mangoua, O. M. J., Sombo, A. P., & Dibi, B. (2024). Identifying the Origin of Springs in Weathered-Fractured Crystalline Aquifers Using a Hydrogeophysical Approach. *Scientific Reports, 14,* Article No. 12977. https://doi.org/10.1038/s41598-024-63748-8

Kumar, P., Thakur, P. K., Bansod, B. K., & Debnath, S. K. (2017). Multi-criteria Evaluation of Hydro-Geological and Anthropogenic Parameters for the Groundwater Vulnerability Assessment. *Environmental Monitoring and Assessment, 189,* Article No. 564. https://doi.org/10.1007/s10661-017-6267-x

Lachassagne, P., Wyns, R., & Dewandel, B. (2011). The Fracture Permeability of Hard Rock Aquifers Is Due Neither to Tectonics, Nor to Unloading, but to Weathering Processes. *Terra Nova, 23,* 145-161. https://doi.org/10.1111/j.1365-3121.2011.00998.x

Majolagbe, A. O., Adeyi, A. A., & Osibanjo, O. (2016). Vulnerability Assessment of Groundwater Pollution in the Vicinity of an Active Dumpsite (Olusosun), Lagos, Nigeria. *Chemistry International, 2,* 232-241.

Makonyo, M., & Msabi, M. M. (2021). Identification of Groundwater Potential Recharge Zones Using GIS-Based Multi-Criteria Decision Analysis: A Case Study of Semi-Arid Midlands Manyara Fractured Aquifer, North-Eastern Tanzania. *Remote Sensing Applications: Society and Environment, 23,* Article ID: 100544. https://doi.org/10.1016/j.rsase.2021.100544

Mangoua, O. M. J., Dibi, B., Koblan, E. W., Douagui, G. A., Kouassi, K. A., Savané, I., & Biémi, J. (2014). Map of Potential Areas of Groundwater by the Multi-Criteria Analysis for the Needs for Water of the Baya's Catchment Basin (East of Côte d'Ivoire). *African Journal Agricultural Research, 9,* 3319-3329.

Maqsoom, A., Aslam, B., Alwetaishi, M., Awais, M., Hassan, U., Maqsoom, S. et al. (2021). A GIS-Based Groundwater Contamination Assessment Using Modified DRASTIC Geospatial Technique. *Water, 13,* Article 2868. https://doi.org/10.3390/w13202868

Mboudou, E. G., Ombolo, A., Bon, A. F., Ntep, F., & Bineli, E. (2016). Apport des méthodes paramétriques DRASTIC, GOD et SI à l'évaluation de la vulnérabilité intrinsèque dans les aquifères du bassin versant de l'Abiergué (région de Yaoundé). *Review CAMES Science de la vie, de la terre et agronomie, 4,* 67-78.

Mbuluyo, M., Mashauri, F., & M'Putu, P. (2017). Cartographie de la vulnérabilité à la pollution de la nappe souterraine d'Isiro (Nord-est de la RD Congo) à partir de la méthode DRASTIC. *Afrique Science, 13,* 125-139.

Mena, B. S. (2000). Introduction aux méthodes multicritères d'aide à la décision. *Biotechnology, Agronomy, Society and Environment, 4,* 83-93.

Mfonka, Z., Ndam Ngoupayou, J. R., Ndjigui, P., Kpoumie, A., Zammouri, M., Ngouh, A. N. et al. (2018). A GIS-Based DRASTIC and GOD Models for Assessing Alterites Aquifer of Three Experimental Watersheds in Foumban (Western-Cameroon). *Groundwater for Sustainable Development, 7,* 250-264. https://doi.org/10.1016/j.gsd.2018.06.006

Patel, P., Mehta, D., & Sharma, N. (2023). Assessment of Groundwater Vulnerability Using the GIS Approach-Based GOD Method in Surat District of Gujarat State, India. *Water Practice and Technology, 18,* 285-294. https://doi.org/10.2166/wpt.2023.004

Perraud, A., & De La Souchère, P. (1969). *Esquisse pédologique de la Côte d'Ivoire. Ech.*

1/500000e feuille Sud-Ouest. ORSTOM.

Poromna, H., Gado, A. R., Kangni-Dossou, M., Gnandi, K., & Ameyapoh, Y. (2022). Evaluation de la Vulnérabilité des Nappes Phréatiques à la Pollution engendrée par la Mauvaise Gestion des boues de Vidange dans la Ville d'Aného au Togo. *European Scientific Journal, ESJ, 18,* 208-244. https://doi.org/10.19044/esj.2022.v18n21p211

Pouye, A., Faye, S. C., Diédhiou, M., Gaye, C. B., & Taylor, R. G. (2022). An Evaluation of Groundwater Vulnerability Assessment Methods in a Rapidly Urbanizing City: Evidence from Dakar, Senegal. *Environmental Earth Sciences, 81,* Article No. 410. https://doi.org/10.1007/s12665-022-10531-5

Saaty, T. L. (1977). A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology, 15,* 234-281. https://doi.org/10.1016/0022-2496(77)90033-5

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation.* Mc Graw-Hill.

Saaty, T. L. (2000). The Scale, Consistency and the Eigenvector. In T. L. Saaty (Ed.), *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process* (pp. 49-60). RWS Publications.