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Assessment of Groundwater Vulnerability by Susceptibility Index (SI) Method in the Niayes Area, Senegal

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Abstract Groundwater vulnerability assessment is a useful tool for groundwater pollution prevention in sahelian countries.

The Quaternary aquifer of Senegal's northern coastline is located in the Niayes area. It offers economic potentialities in the field of industry, farming and fishing. Thus, the anthropic actions combined with pejorative climatological conditions expose it to environmental and social risks, to such a point that the vulnerability of the waters of the aquifer to pollution challenges researchers and decision-makers. The study presented in this paper aims to assess the vulnerability of groundwater to pollution, using the Susceptibility Index (SI) method. Mapping was done using Arc GIS software. The parameters used as input data are, among others, the depth of the groundwater, the soil type, the topographic slope and the groundwater recharge. Several degrees of vulnerability are identified from south to north ranging from "low" to "high". It is noted that further away from the coast, lower is the vulnerability and, the area is moderately vulnerable but with areas of high vulnerability which should attract the attention of decision-makers with the intensification of crops and mining that affect the water table and expose it to pollution of various origins such as nitrates.

To validate our results, we superposed a map of measured nitrates concentration with that of vulnerability. This made it possible to say that the SI method is adequate for assessing vulnerability to nitrate pollution, with a coincidence rate of 70% between nitrates concentration and different classes of vulnerability.

Keywords Niayes, Groundwater, Vulnerability, Susceptibility-Index, Nitrate

Introduction

Senegal's hydrogeology consists of three (3) major aquifer systems, including the Terminal Complex, which groups together the shallower aquifers of the continental terminal and the quaternary that overlap. The most superficial aquifer known as the Quaternary Sands of the North extends from Dakar to Saint Louis along the coast. This region named Niayes area, rich in natural resources (halieutic, pedological, geological and hydrogeological) presents on the economic plan, privileged assets which expose it to pressures, in particular, on its natural resources and its environment. In fact, this formerly sparsely populated area attracts more and more industrialists, farmers, fishermen, tourists whose combined actions disrupt the ecosystem [1]. This disturbance is accentuated with climate change or its negative effects that can weaken the coastline, considering its degree of vulnerability.

The deterioration of climatic conditions noted in recent years is manifested, on the one hand, by an increase in temperatures and consequently on the growing water needs of crops, and on the other hand, a decrease in rainfall that may lead to a decrease in recharge, a drop in piezometry, overexploitation and progress of the salt wedge [2].

Moreover, the rampant urbanization of the area is accompanied by human actions that manifest themselves in the abusive exploitation of marine sands and vegetation; thus accelerating the coastal erosion process [1].

These negative effects raise the issue of the vulnerability of the area to climate change and human actions. In this paper, we question the degree of vulnerability of groundwater resources on the north coast, which deserves further reflection in order to better adapt to the various threats that may affect the water, agricultural and environmental sectors.

In this work, the vulnerability of the groundwater has been studied with the Susceptibility Index method. The vulnerability maps produced using the Arc Gis software have made it possible to determine different vulnerability classes in the area. The hydrogeological parameters needed as input data come from the database of the Directorate of Management and Planning of Water Resources (DGPRE) of Senegal.

Material and Methods

Presentation of the Study Area

The Niayes area registers administratively in the four regions bordering the maritime fringe of northern Senegal including Dakar, Thiès, Louga and Saint-Louis (Figure 1) .It extends over a length of about 180 km and on a 20 to 30 km wide depending on the studies [3], [2]. Figure 1 shows the area with the main municipalities concerned.

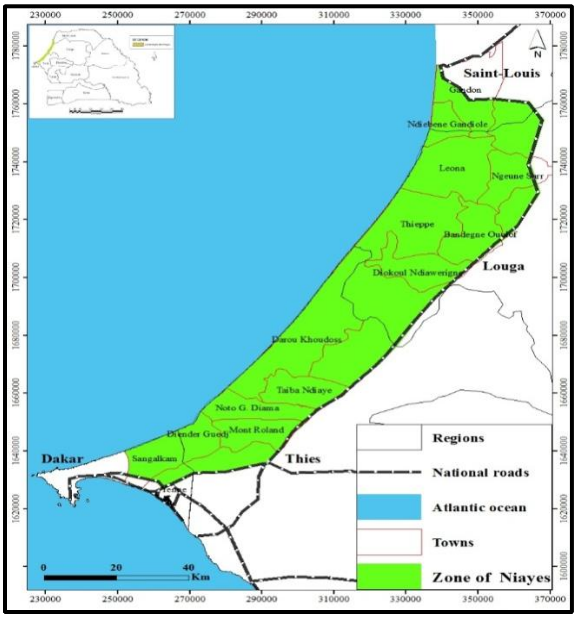

Figure 1: Map of the Niayes area

With decentralization, several municipalities have been built on this coastal strip. They are Sangalcam, Diender, Bayakh, Kayar, Notto Gouye Diama, Mboro, DarouKhoudos, Gandon, Léona and Thieppe, all of them are agricultural.

The "Niayes" are closed inter-dune depressions with a flush or uplifted aquifer and are characterized by a succession of dunes and depressions. The Niayes zone includes several ecological units and contains very important biological and mining resources whose exploitation deserves special attention.

The Climate

The area is located largely in the Sahelo-Sudanian climatic zone. It is subject to the influence of the three winds: the trade wind, the harmattan, hot and dry wind and the monsoon. These winds have an average speed between Dakar and Saint-Louis of 2 to 5 m/s. This relatively high speed makes these winds responsible for the establishment and mobility of the coastal dune system (white dunes).

The average annual temperatures are between 23 and 25 °C

The Relief and The Soils

By observing the area, three sub-zones emerge from north to south: the maritime fringe, the intermediate zone called Niayes and the continental zone. In fact, a cross-section of the northern littoral in several places clearly distinguishes these three parts with distinct characteristics as illustrated in Figure 2.

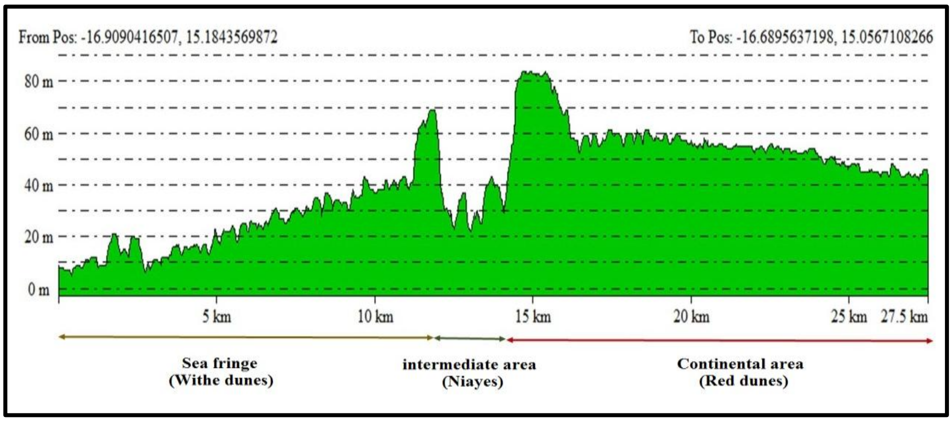

Figure 2: Cross section of the study area

Nowadays, the winds have shaved the dunes to a great extent, favoring the backfilling of the basins.

The intermediate zone or Niayes is identified with hydromorphic soils consisting of sandy loam soils. It is an area of depressions with permanent or temporary pools. There are vegetable basins and many shallows. On the dune slopes, we find mainly euphorbia that fix the soil.

Anthropic Actions

During the last thirty years, the soils of the North littoral have undergone profound transformations on the natural resources and the different ecosystems. These changes, caused by intense wind erosion phenomena combined with the movements of the living maritime and semi-continental dunes, have greatly reduced the agricultural potential of the basins that provide the bulk of vegetable production in Senegal [4]. Soils and traditional wells have become salinized due to the drop of the groundwater's level because of the rainfall deficit which has been installed throughout the area for more than three decades and the anthropogenic action on natural resources (deforestation, extension of mines and quarries, increase in water withdrawals from the aquifer).Since 2012, aware of the importance of this area in the economy of the country, the Government of Senegal, with the support of the Canadian International Development Agency (CIDA), has developed a Master Plan for the Development of the Great Coast (SDAGC) which includes our study area. This opportunity has allowed the establishment of a vast Program of Development and Economic Development of Niayes (PADEN) which is still ongoing. Its overall objective is to contribute to the reduction of the poverty of the populations.

Rainfall

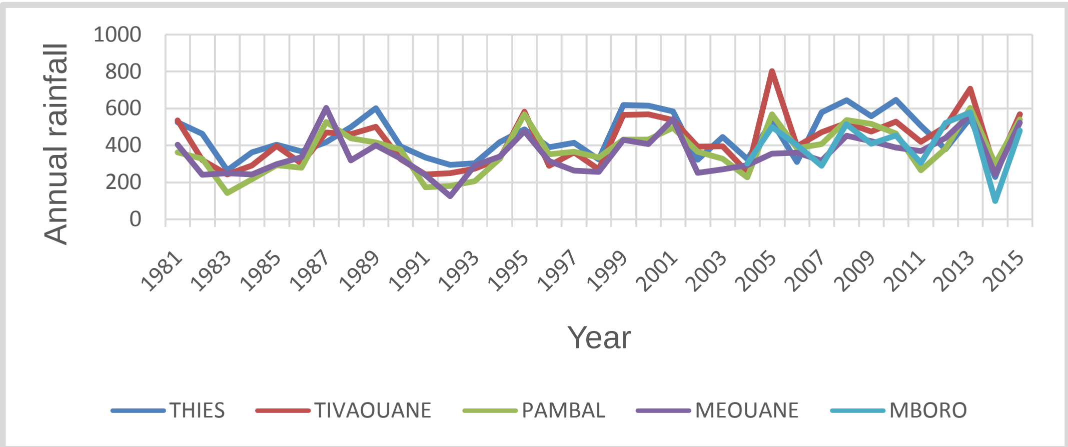

Figure 3: Average annual rainfall in different municipalities in the zone

Recent studies have shown that rainfall has decreased overall by 35% in quantity with a decrease in the duration of the rainy season and a decrease in the frequency of rainy days between the period 1950-1965 and the period 1970-1995 [5]. In fact, in the Niayes area, rainfall has greatly decreased compared to the wet years in Senegal. Moreover, it remains variable in every respect as can be seen in figures 3 and 4.

Figure 3 illustrates quite well the rainfall variability that prevails in the different municipalities of the Niayes area, like almost all Sahelian countries.

In addition, the number of rainy days is very variable as illustrated in Figure 4 in several localities.

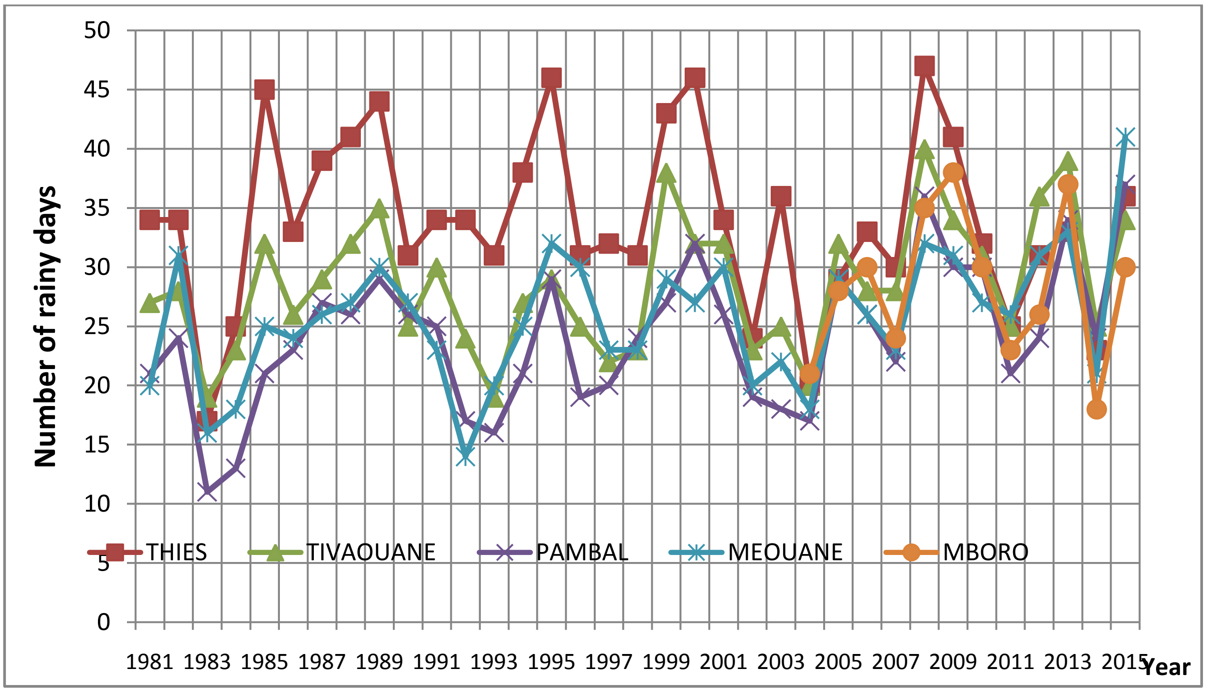

Figure 4: variation of rainy days in some localities in the Niayes area

The number of rainy days is thirty (30) days on average.

Methodology

This vulnerability assessment focuses mainly on the groundwater resources of the northern coastline aquifer. The method used is a variant of the DRASTIC method developed by the United States Environmental Protection Agency (EPA) in 1985 and Aller and al in 1987 to estimate the potential for groundwater pollution [6], [7]. It assesses vertical vulnerability based on seven (7) criteria where **D** is Depth of the groundwater, **R** the groundwater Recharge, **A** the Nature of the aquifer, **S** the nature of the soil, **T** the field Topography, **I** the unsaturated zone Impact and **C** the Hydraulic conductivity (permeability of the aquifer).

Principles of the Susceptibility Index Method

The Susceptibility Index (SI) method is an adaptation of the DRASTIC method [8]. It assesses the vertical vulnerability specific to agricultural pollution (mainly nitrates and also pesticides) and was developed in Portugal [9]. This method takes into consideration five parameters. The first four parameters are identical to the four parameters of the DRASTIC method namely (D: the depth of the aquifer, R: the effective recharge of the aquifer, A: the lithology of the aquifer, and T: the topographic slope of the zone). The dimensions corresponding to the different classes of these parameters, in the DRASTIC method, have also been preserved (Table 1).

Table 1: Ratings given to parameters of the DRASTIC method (Lallemand - Barrès, 1994)

D: Distance to the water table, thickness of the unsaturated zone		**R: Recharge (effective rain)**	
Values in meters	**Rating**	**Values in mm**	**Rating**
0 - 1,5	10	> 25,5	9
1,5 - 4,5	9	17,5 - 25,5	8

4,5 - 9	7	10 - 17,5	6
9 - 15	5	5 - 10	3
15 - 22	3	0 - 5	1
22,5 - 30	2		
> 30	1		
A: Nature of the saturated zone		**S: Nature of the soil**	
Karst limestone	10	shallow or absent	10
Basalt	9	Gravel	10
Sand and gravel	8	Sand	9
Solid sandstone	6	Clay, aggregates or slopes	7
Shales in sequence	6	Sandy Limon	6
Shales in sequence	6	Limon	5
Altered Metamorphic, Grounds, Limestones	4	Silty Limon	4
Metamorphic	3	Clayey silt	3
Solid shale	2	Unaggregated and uncracked clay	1
T: Topography, slopes			
Values in % of slope	**Rating**		
0 -2	10		
2 - 6	9		
6 - 12	5		
12 - 18	3		
> 18	1		

A fifth new parameter has been introduced: the land use parameter (OS). The classification used for this parameter is the CORINE Land Cover classification [10] (Table 2).

A value called land use factor, denoted LU, ranging from 0 to 100, is assigned to each land-use class. It should be noted that the values of the ratings assigned to the classes of the various parameters have been multiplied by 10 to facilitate the reading of the results obtained. These values therefore vary from 0 to 100, ranging from the least vulnerable to the most vulnerable. The weights assigned to the Susceptibility Index parameters vary from 0 to 1 depending on the importance of the parameter in the vulnerability (Table 2).

Table 2: Main land use classes and corresponding values

Land use according to the CORINE Land Cover classification	Land use factor (LU)
Industrial landfill, garbage dump, mines	100
Irrigated areas	90
Quarry, shipyard	80
Covered artificial areas, green areas	75
Permanent crops	70
Discontinuous urban areas	70
Pastures and agro-forestry areas	50
Aquatic environments (swamps, salt marshes, etc.	50
Forests and semi-natural areas	0

Table 3: Weight Assigned to SI Parameters

Parameters	D	R	A	T	OS
Weight	0,186	0,212	0,259	0,121	0,222

The SI method presents four degrees of vulnerability according to the values of the indices obtained (Table 4).

Table 4: SI indices classes and degrees of vulnerability

Degrees of vulnerability	Indices of vulnerability
low	< 45
average	45-64
high	65-84
Very high	85-100

Results and Discussion

1. MAP OF VULNERABILITIES BY THE SI METHOD

This method requires the prior establishment of a land use map that estimates the value of land use factor "LU". Figure 5 shows the land cover map.

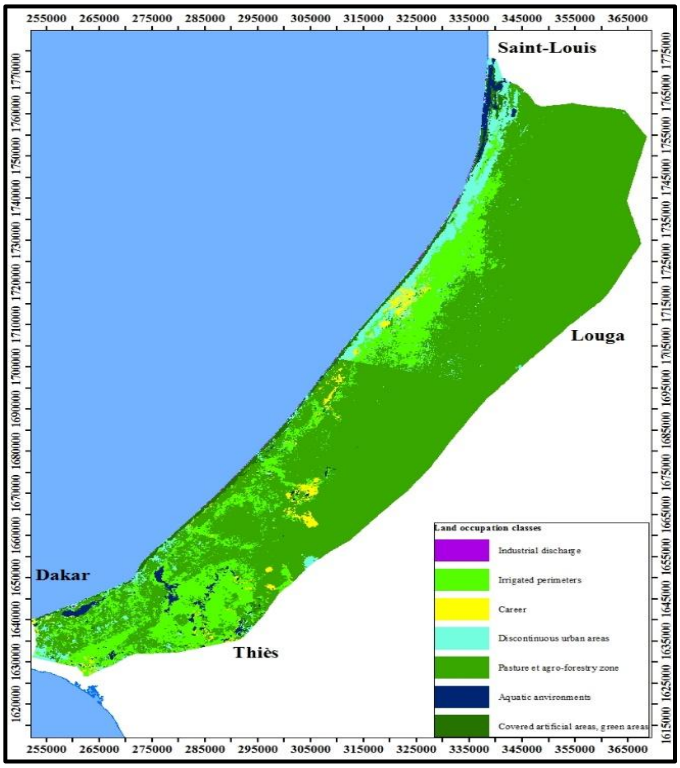

Figure 5: Land Cover Map

This map shows seven (7) land use classes whose areas are shown in Table 5

Table 5: Different classes of land use with their areas

Land occupation	Area (Km²)	Area (%)
Industrial discharge	17	0,4
Irrigated areas	1539	32,9
Career	96	2,0
Discontinuous urban areas	285	6,1
Pastures and agro-forestry zones	2670	57,0
Aquatic media	39	0,8
Covered artificial areas, green areas	37	0,8
Total area	**4683**	**100**

The most dominant is grazing and agro-forestry. However, irrigated perimeters occupy a significant place. Figure 6 shows the vulnerability map with the SI method.

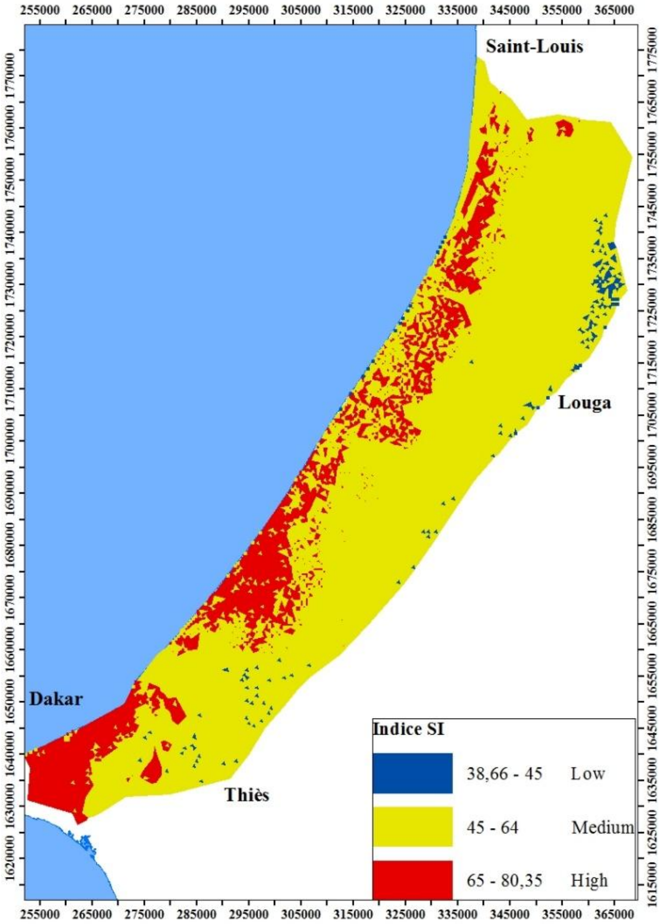

Figure 6: map of vulnerability by SI method

This method highlights two distinct classes of vulnerability. High vulnerability along the coastline occupying 21% of the area considered and medium vulnerability throughout the southern part occupying 77% of the area.

Table 6 gives results in a comparison of the areas occupied by the degrees of vulnerability of the different methods.

Table 6: Areas occupied by the degrees of vulnerability

METHOD	Vulnerability indices	Degree of vulnerability	Area (Km²)	Area (%)
	< 45	Low	36.21	0.77
SI	45 -64	Average	3651.89	77.96
	65 - 84	High	995.90	21.27
		Total	4683	

These cards have several vulnerability classes. All areas (south, center and north) of the study area have areas of high vulnerability. In any case, we note that the further we get off the coast, the lower the vulnerability and that, overall, the Niayes area is moderately vulnerable, but with sectors of high vulnerability that must attract the attention of decision-makers. With intensification of crops and mining that affects the aquifer and exposes it to different pollutants including nitrates. In fact, the uncontrolled growth of recent decades has resulted in massive urbanization of this area. Thanks to its cool climate and the presence of a shallow underground water table, this fairly populated region provides nearly 95% of horticultural production and most of Senegal's vegetable production.

Because of the necessity to satisfy the needs of the local and foreign market, the peasants are engaged in a policy of intensification of agricultural production. This requires the use of certain substances such as fertilizer, pesticides or raw wastewater rich in nitrate for watering plants [3]. Then the vulnerability of the sheet facing this pollutant (nitrate) deserves to be studied.

2. RESULTS OF THE SUPERPOSITION OF THE CARD OF VULNERABILITY WITH THE CARD OF CONCENTRATION OF NITRATES

In this work, we use data in 21 piezometers (figure 7).

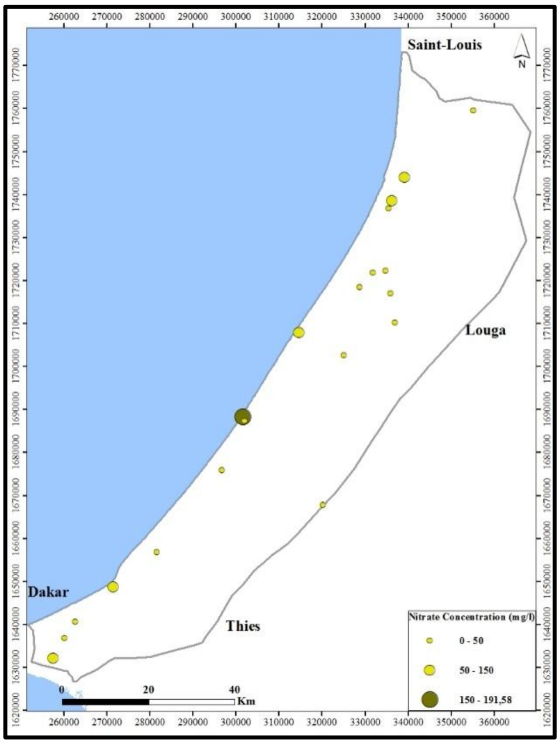

Figure 7: Distribution of the different sampling points

Figure 8 is the map giving the distribution of nitrate concentrations in the study area.

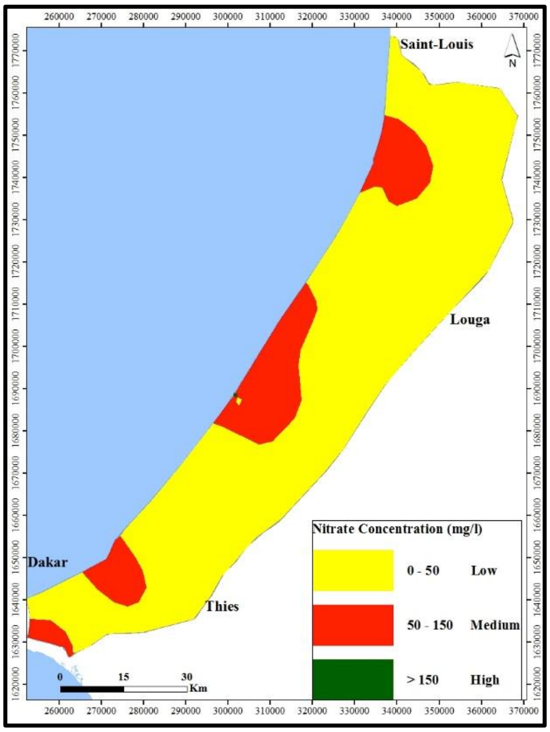

Figure 8: Map of distribution of nitrate concentrations in mg/l

Figure 9 is the result of superposition maps of nitrate concentration and pollution vulnerability

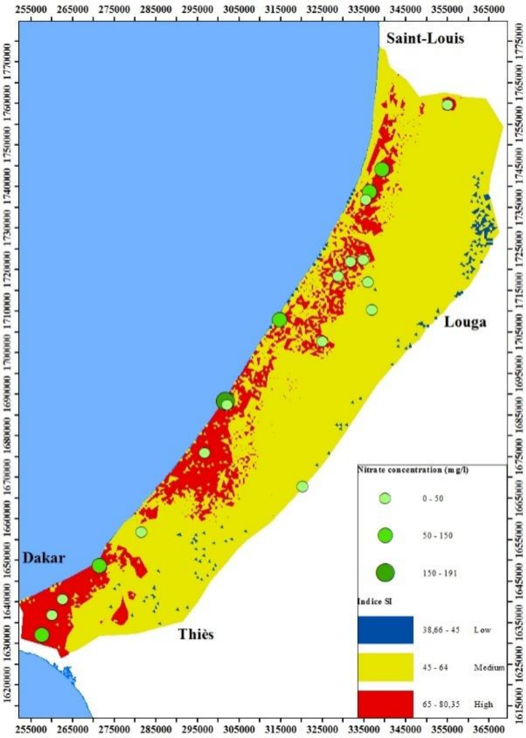

Figure 9: Superposition of the cards (SI / Nitrate)

3. DISTRIBUTION OF POINTS BY CLASS OF CONCENTRATION AND DEGREES OF VULNERABILITY

Table 7 gives the distribution of points by class of concentration and degrees of vulnerability.

Table 7: Breakdown of points by concentration class and degree of vulnerability

METHODS	Degree of vulnerability	Classification of nitrate concentrations (mg / l)		
		< 50 mg/l	50 à 150 mg/l	> 150 mg/l
		Number of points / concentration class		
SI	Low	0	0	0
	Average	6	0	0
	High	8	5	1
TOTAL		14	5	1

- The single value above 150 mg/l coincides 100% with the area of high vulnerability;
- The five values between 50 and 150 mg/l coincide 100% with the zone of high vulnerability;
- Of the fourteen values below 50 mg/l, none coincide with the low vulnerability zone, six (42.9%) coincide with the medium vulnerability zone and eight (57.1%) coincide with the vulnerable zone. high.

So, we have a 70% coincidence rate between available nitrate concentrations and different vulnerability classes (14 out of 20 values). This coincidence rate can be detailed as follows, a 100% coincidence rate between high nitrate concentrations (greater than 150 mg/l) and areas of high vulnerability; a coincidence rate of 100% between mean concentrations (between 50 and 150 mg/l) and areas of high vulnerability; and a 57.1% coincidence rate between low (<50 mg/l) and high vulnerability areas.

The SI method gives a 70% coincidence rate between nitrate concentrations and areas of high vulnerability. This method addresses a specific vulnerability related to pollution sources and takes into account the properties of pollutants and the various components already considered in the intrinsic vulnerability [11], [12]. It is therefore an evolutionary vulnerability more adapted to the study area. Indeed, the latter is constantly subjected to anthropogenic pressures whose harmful actions combined with pejorative climatological conditions, expose it to environmental and social risks. Therefore the SI method very well assesses the vulnerability to nitrate pollution of Niayes groundwater.

Conclusion

The vulnerability to pollution of the free groundwater of the Niayes zone is evaluated in this study with the susceptibility index method. The results show several vulnerability classes that occur in the north, center and south of the study area. In all sectors of the northern coast of Senegal, there are low and high vulnerability classes. This shows another point of view of the variable characteristics of this coastal strip, which is under increasing human pressure.

A superposition of the general vulnerability maps with a nitrate concentration map has shown that this method is adequate with this type of pollutant with a coincidence rate of 70% between the available nitrate concentrations and the various classes of vulnerability, notably high. However, a comparative study using other methods such as DRASTIC and SINTACS can be considered in order to see the most appropriate method to study the vulnerability of the Niayes aquifer.

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