Evaluation of the vulnerability of groundwater to nitrogen pollution in the commune of Mananara Avaratra by the SINTACS method

Elando Fréda ZAMANILEHA, Yves Jean Michel MONG and Pierre RAVELONANDRO

Abstract— The urban commune of Mananara Avaratra, located on the east coast of Madagascar in the Analanjirofo region, is characterized by alluvial soils, mainly sandy and ferruginous, and a tropical climate. Groundwater is considered as the main source of drinking water for the local population although the presence of pollution by nitrogen compounds has been a serious environmental problem for more than a decade This study aimed at developing a groundwater vulnerability model for nitrate and ammonium as a protective measure. Based on the intrinsic vulnerability determined by the SINTACS model, the influence of anthropogenic parameters related to nitrogen sources and groundwater use on contamination was verified using GIS. Chemical analyses showed high concentrations of nitrate (136.987 mg.l^{-1}) and ammonium (1.120 mg.l^{-1}) in the samples. The high nitrate and ammonium concentrations were found in the northern subwatershed, probably due to the area impacted by urbanization by urbanization, where the groundwater vulnerability index is high (high index is 197 - 210 and for the very high ones 215 - 223). On the other hand, the concentrations in the southern subwatershed are lower, and the index is moderate (137 - 178). In order to prevent the contamination of groundwater by nitrogen, it is necessary to develop management policies on surface land use and groundwater, as well as to continuously monitor the latter.

Index Terms— Ammonium, Mananara Avaratra, Nitrate, SINTACS, Subwatershed, Vulnerability.

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1 INTRODUCTION

WATER is the most abundant substance on the planet Earth. Since the beginning, human life has been linked to water, so it is life. However, its availability varies in space and time (Peter et Meena, 2010). It is closely related to the climate and geomorphology of the continent or country considered (Abdeslam et al., 2017). Today, more than 800 million people in the world do not have access to safe drinking water or water of sufficient quality for their subsistence and for sanitary services.

Nitrogen contamination of surface water and groundwater is a typical problem for urbanization, agriculture in the regions and all over the world (Fraser et Chilvers, 1981), (Soldatova et al., 2017). In this respect, the prevention of groundwater pollution is an important issue to which scientists are making more effort. This contamination is evidenced in several countries regardless of the level of economic development of the countries. In recent years, the international scientific community has shown great interest in this subject. Thus, numerous researches have focused on environmental management, land use (Fabbro Neto et Gómez-Martín, 2020, Gerssen-Gondelach et al., 2017) and the study of groundwater vulnerability (Yu et al., 2022, Taghavi et al., 2022, Dhaoui et al., 2022, Elzain et al., 2022, Rahman et al., 2021, Siarkos et al., 2021, Kwon et al., 2022, Vu et al., 2021).

The potential impact of nitrogen fertilizer contamination on groundwater was used to develop a mechanistic model capable of predicting water flow, transport, and transformations of nitrogen in the unsaturated zone of agricultural soils in the regions. The specification of nitrogen in groundwater and the vulnerability of groundwater to nitrogen contamination are determined by factors such as bacterial activity, soil organic matter and soil physicochemical characteristics, mineral compositions, intense agricultural activities with fertilizer application, population density, increasing rate of urbanization, runoff and irrigation.

Human consumption of nitrate-contaminated water can lead to the development of serious diseases such as methemoglobinemia, while nitrite, an intermediate form of nitrogen generated during the denitrification process, has been correlated with carcinogenicity (Coss et al., 2004, (Pawełczyk, 2012). Based on these premises, the aim of this study was to numerically model the occupation of soil, the migration of nitrogen compounds through the unsaturated zone, and the approaches commonly used to assess the vulnerability and pollution risk of groundwater resources in aquifers of the urban commune of Mananara Avaratra. Thus, this study clarifies the characteristics of groundwater nitrogen pollution and model groundwater vulnerability using the SINTACS method.

2 MATERIALS AND METHODS

2.1 Description of the study area

The study was conducted in the urban commune of Mananara Avaratra, the chief town of the district of Mananara Avaratra on the east coast of Madagascar, located in the central-eastern part of the Analanjrirofo region, about 637 km from the capital Antananarivo, with an area of about 104,724 km^2 (Fig. 1). The population is 35,148 inhabitants (INSTAT, 2020). The climate of

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Mananara Avaratra is tropical and equatorial, with high rainfall throughout the year. The average annual temperature is 24.4°C and the average rainfall is 3415.5 mm. The hot season extends from January to April. Cyclones can occur during this period. Regarding the winds, the trade winds are intertropical and blow almost all year round (DGM, 2019). The first layer of topsoil in the northern part of the commune of Mananara Avaratra is hydroalluvial and mainly sandy. On the forested hills, the second surface layer is made up of yellow and yellow-red ferralitic type soils, slightly acidic, and the communal soil comes from a matrix with a pH of about 5, variable according to its characteristics.

The geomorphology of the area is characterized by the set of reliefs that limit the lines of distribution of runoff and infiltration water that flow from high to low altitudes, and feed the effluents. Mananara Avaratra is located in the sedimentary basin of the east coast of Madagascar, from which it is cratered by alluvial groundwater (Rakotondrainibe, 2016).

From the temperature and precipitation data, the water balance was calculated using the Thornthwaite equation by $\boldsymbol{P} = \boldsymbol{E} + \boldsymbol{R} + \boldsymbol{I} \pm \Delta\boldsymbol{S}$ (Pereira et Pruitt, 2004).

Where *P: Precipitation, E: Evapotranspiration, R: Runoff, I: infiltration, ±ΔS: change in soil water stock.*

The 2019 registration calculations resulted in the following values:

$\boldsymbol{P} = \boldsymbol{3415,5mm}$; $\boldsymbol{R} = \boldsymbol{117,73mm}$; $\boldsymbol{E} = \boldsymbol{2981,86mm}$; $\boldsymbol{I} = \boldsymbol{315,73mm}$; $\pm\Delta\boldsymbol{S} = \boldsymbol{0}$.

2.2 Research Methodology

The fieldwork was conducted in March 2019, in the urban commune of Mananara Avaratra, including seventeen sampling points. The first part of the work was focused mainly on land use surveys and the collection of information available in the study area, such as the characterization of loose sediments and the measurement of water levels in the catchment points. During sample collection, a household survey was conducted around the sampling points. A questionnaire was used to highlight the vulnerability of the water to possible groundwater contamination. The second part of the work consisted in the analysis of the physico-chemical parameters of the groundwater samples, which was carried out in the laboratory of LACAE-CNRE. The analyses consisted of testing the following parameters: pH, color, turbidity, salinity, conductivity, nitrate, nitrite and ammonium. The reference standards for the analyses are described in the table 1.

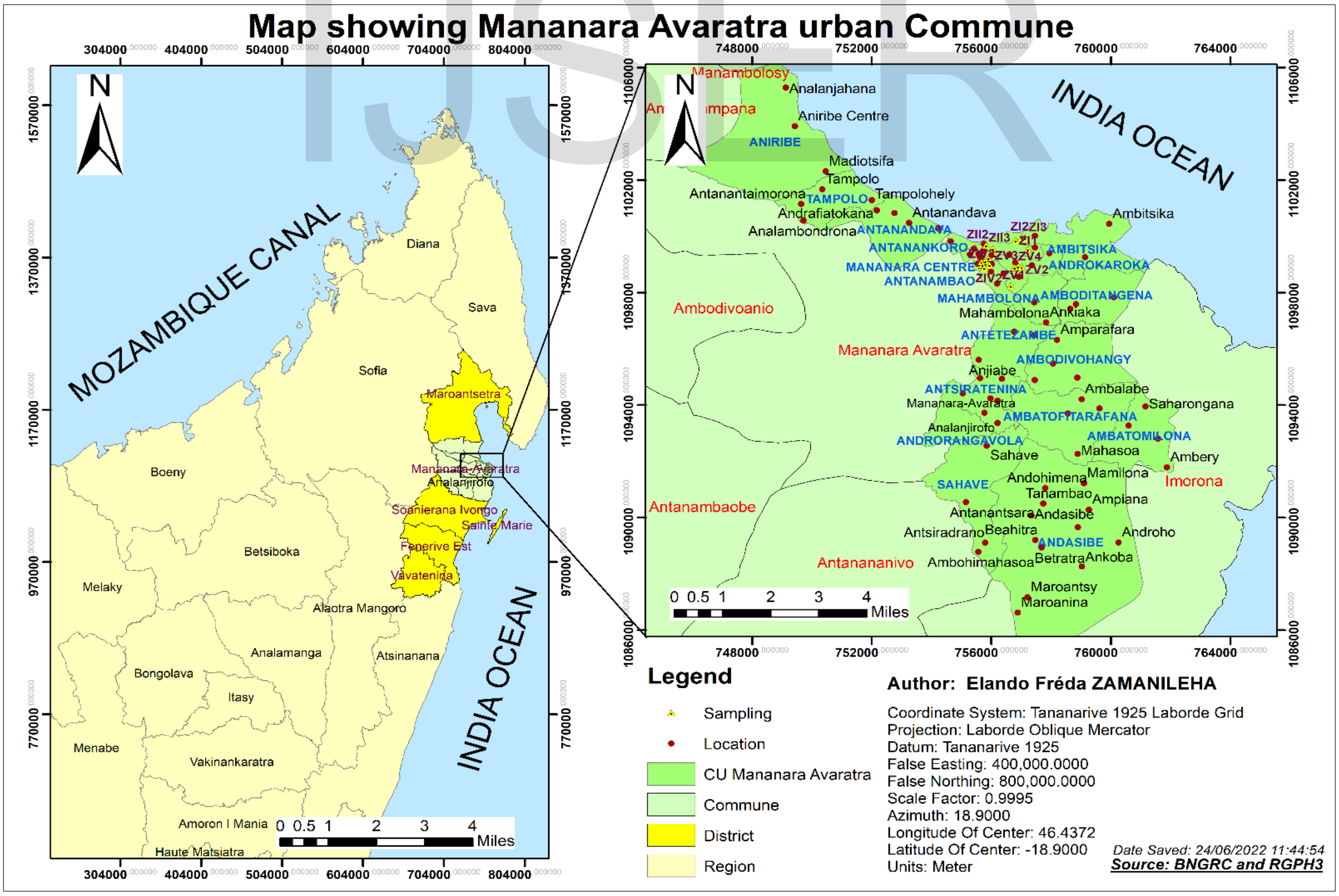

Fig. 1 : Map showing Mananara Avaratra urban Commune

TABLE 1 : PARAMETER VALUES FOR EACH CLASS OF PHYSICO-CHEMICAL COMPLIANCE OF WATER.

Parameter	Unit	Malagasy Standards	WHO Standards	Excellent	Good	Medium	Poor	Very poor
Ph		6,5 - 9	6,5 - 8,5	6,5 - 8,5	6,5 - 8,5	6,5 - 9,2	<6,6 or >9,2	-
Color	**$mg.l^{-1}$ Pt-Co**	<15	<20	<20	20 - 50	50 - 100	100 - 200	>200
Turbidity	**NTU**	<5	<15	<15	15 - 35	35 -70	70 - 100	>100
Salinity	**$mg.l^{-1}$**	<1500	<1000	<375	375-650	650-1350	1350-1500	>1500
Conductivity	**$\mu S.cm^{-1}$**	< 3000	<2000	<750	750 - 1300	1300 - 2700	2700 - 3000	>3000
Nitrate	**$mg.l^{-1}$**	<50	<50	<5	5-25	25 - 50	50 - 100	>100
Nitrite	**$mg.l^{-1}$**	< 0,1	≤0,1	≤0,1	0,1 - 0,5	0,5 - 2	02-8	>8
Ammonium	**$mg.l^{-1}$**	< 0,5	≤0,5	≤0,03	0,03 - 0,3	0,3 - 0,5	0,5 - 1	>1

Sources: Proceedings of the water days 16-20 Nov 1992 Water quality for the WHO standard and Decree n°2004/635 of 15 June 2004 for the Malagasy standard.

The third part is the data processing, which consists of digitalizing data, processing data, and modeling using specific software. The latter is based on the simulation of the transport of nitrogen contaminants in an open aquifer. The software used for the modeling are **"Visual MODFLOW Flex 15.1"** and **"ArcGIS 10.8"**. In order to map the distribution of the nitrate and ammonium concentration level in the study area. The principle of correlating the concentrations obtained with the vulnerability indices of groundwater according to the SINTACS method was used. The model used to assess groundwater vulnerability in Mananara Avaratra is the SINTACS method, an intrinsic vertical vulnerability method developed by Civita (Civita, 1994). This model uses seven parameters, namely depth to water table, recharge, unsaturated zone, soil environment, aquifer environment, hydraulic conductivity, and topographic slope, which affect the movement of contaminants in the aquifer system (Civita, 1994, Civita et De Regibus, 1995). All these parameters are mandated with a constant relative weight, ranging from 1 to 5 (Arzika et Nacera, 2017). This model is unique in that it presents five different scenarios: Normal impact, Severe impact, Important drainage, Karst and Fissured terrain (Hamza et al., 2008). The weights assigned to the different parameters are presented in the table 2.

TABLE 2: WEIGHTS ASSIGNED TO THE SINTACS PARAMETERS IN THE DIFFERENT SCENARIOS OF THE METHOD (CIVITA, 1994)

Scenario	Normal impact	Severe Impact	Important drainage	Karst	Fissured terrain
S	5	5	4	2	3
I	4	5	4	5	3
N	5	4	4	1	3
T	4	5	2	3	4
A	3	3	5	5	4
C	3	2	5	5	5
S	2	2	2	5	4

A partial SINTACS index (I_i) is then obtained by multiplying the score of each parameter by its relative weight, with $I_i = P_i \times C_i$

Where P_i is the weight of each parameter; C_i is the SINTACS parameter score; and i is the number of each parameter according to the SINTACS model.

The total SINTACS index is the weighted sum of the partial indices for each parameter. The total SINTACS index is the weighted sum of the partial indices for each parameter.

$$SI = \sum_{i=1}^{n=7} I_i = \sum_{i=1}^{n=7} P_i \times C_i$$

The evaluation of the SINTACS index (SI) can only be done through a comparative analysis of the different regions. On this, a representation system must allow the user to directly visualize the degree of vulnerability. The principle of this representation is the classification of the vulnerability index into four categories of vulnerability: **Low (SI < 106), medium (SI ϵ [106 - 186]), high (SI ϵ [187 - 210]) et very high (SI > 210)** (Arzika et Nacera, 2017).

The maps obtained allow to place the relative degree of vulnerability of the studied area. In general, the pollution potential increases in the same direction as the index.

3 RESULTS AND INTERPRETATION

3.1 Contamination Risk Assessment Survey

The results of the land use survey (Fig. 2) show that 41% of the distributions present a medium risk of contamination, 35% very high risk, 18% a high risk, and 6% a low risk. These results show that the groundwater in Mananara Avaratra is probably polluted and should be analyzed in the field.

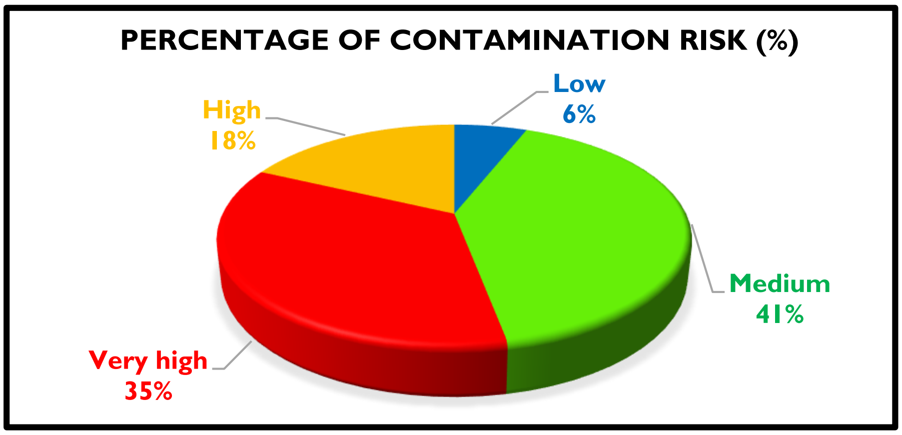

Fig. 2: Results of land use surveys

3.2 Physico-chemical a

According to the physico-chemical analysis of the samples, pH is slightly acid while nitrite, salinity, and conductivity are in conformity with WHO standards for potable water For turbidity, two of the seventeen samples do not meet the standard and, nine of the seventeen samples are above the color standard. Four samples show high concentrations of nitrate and ammonium. These results (table 4) prove the plausible presence of mineral or organic acids coming from plant debris buried in the soil and from fecal matter dispersed or buried in the sand.

TABLE 3 : RESULTS ON PHYSICO-CHEMICAL ANALYSIS

Samples	*X*	*Y*	*pH*	*Color mg.l^{-1} Pt-Co*	*Turb. NTU*	*TDS mg.l^{-1}*	*[NO$_3$] mg.l^{-1}*	*[NO$_2$] mg.l^{-1}*	*[NH$_4$] mg.l^{-1}*
ZI1	756807,67	1099849,437	**5,4**	**50**	**6,39**	0	4,241	DL	0,35
ZI2	757024,331	1099957,768	**5,7**	**40**	2,35	1	13,351	0,057	**0,68**
ZI3	757125,318	1099933,898	**5,6**	**75**	2,27	1	DL	0,061	0,14
ZII1	757222,632	1099533,626	**5,8**	**45**	1,84	0	DL	0,001	**0,89**
ZII2	755820,054	1099674,988	**6,1**	**50**	2,01	1	0,852	0,006	0,05
ZII3	756052,021	1099551,141	**5,2**	0	2,13	2	**136,987**	0,048	0,09
ZII4	756120,825	1099327,037	**4,7**	**20**	2,45	1	**105,365**	0,003	0,03
ZIII1	755904,584	1099220,882	**4,8**	0	2,38	1	**89,553**	0,024	0,08
ZIII2	755800,396	1099114,728	**5**	0	0,91	1,5	32,532	0,029	**0,73**
ZIII3	755668,686	1099085,241	**4,6**	0	1,35	1	39,118	0,061	0,04
ZIV1	755702,105	1098973,189	**4,6**	0	0,12	0	30,618	0,003	0,02
ZIV2	755765,011	1098874,897	**4,3**	**66**	**14,94**	0,5	**98,547**	0,006	0,48
ZIV3	755938,003	1098981,052	**5,7**	0	4,6	1	7,844	DL	0,12
ZV1	756651,597	1098234,039	**4,4**	**25**	2,13	0	11,349	0,003	0,01
ZV2	757013,309	1098912,248	**5,4**	**190**	1,77	1	0,208	0,03	0,07
ZV3	756899,291	1098924,043	**4,9**	0	2,55	1,5	0,905	DL	0,01
ZV4	756773,478	1098884,727	**5,5**	0	1,58	1,5	34,739	DL	**1,12**

DL: Detection limit

3.3 Pollution transport modeling

Pollution transport modeling in groundwater is an important tool for developing a proposal for protective measures based on the application of numerical modeling. It is used for the assessment of groundwater pollution and pollutant migration pathways to wells, as well as for the prediction of its fate and future impacts (Rapantova et al., 2017). The study was based on the consistent exploitation of existing data. An assembly of a large amount of material and information on the geological and hydrogeological conditions of the area concerned, including physico-chemical analyses carried out, was used before the numerical models were set up. The database also contains information on the results of the soil and groundwater sampling that were analyzed. The results of the nitrate and ammonium concentrations are consistent with each other. The location of the model domains is shown in the figures (Fig. 3 and 4).

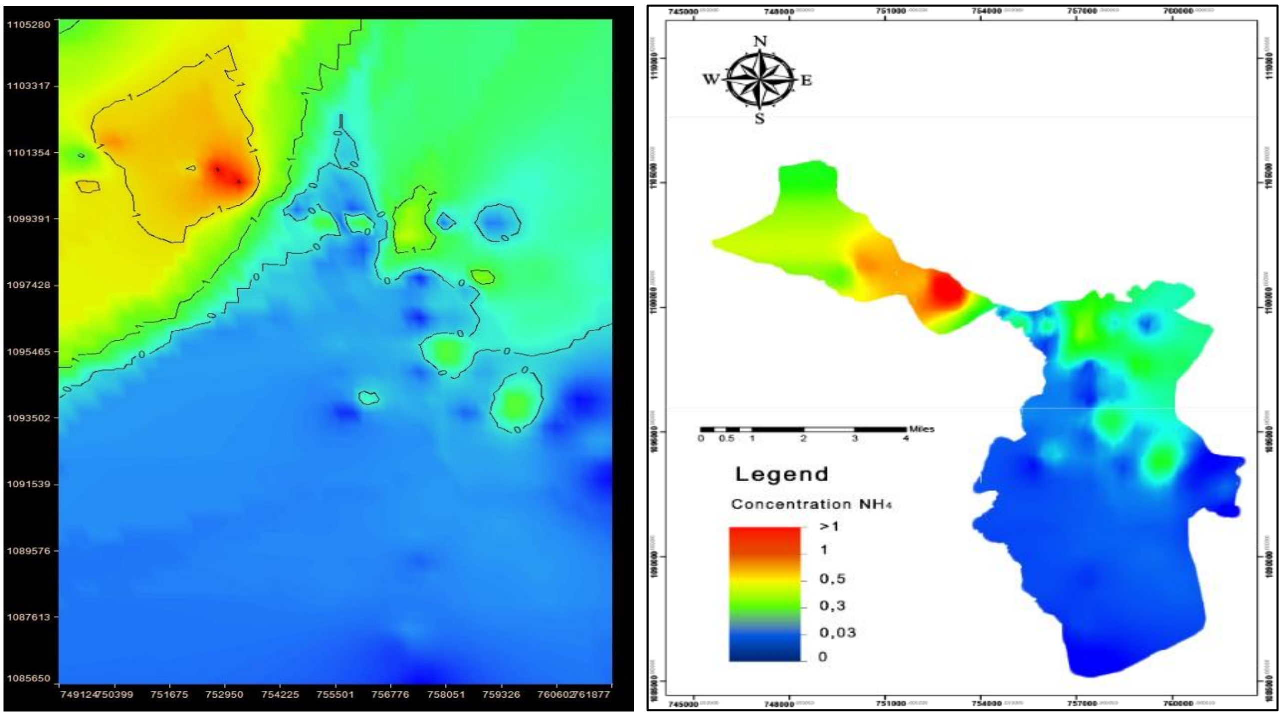

Fig. 3 : Ammonium content distribution map

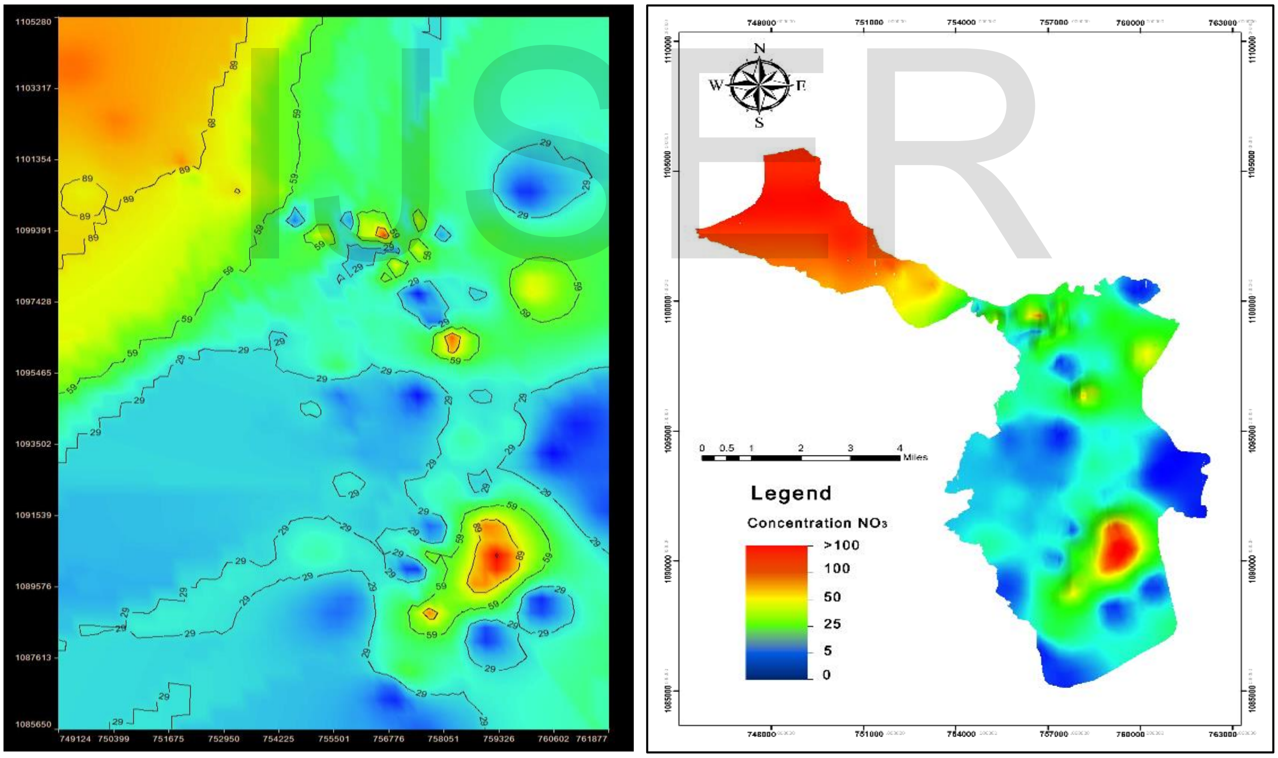

Fig. 4 : Nitrate content distribution map

3.4 Soil vulnerability assessment using the SINTACS method

The amalgamation of the seven maps (Fig. 5) created and the application of the SINTACS index equation for each parameter permitted to obtain the general index that allowed to have the final vulnerability map (Fig. 6). The study area is divided into two parts, one of which coincides with the normal impact scenario and the other with the severe impact scenario of the SINTACS method. The first scenario covers only 41.77% of the total area of the aquifer, while the second covers 58.23% of the total area. The obtained final vulnerability map (Fig. 6) shows the existence of three degrees of vulnerability: medium, high and very high. The areas of medium vulnerability cover 41.77% of the total area of the aquifer, those of high vulnerability 25.15% and those of very high vulnerability only 33.08%.

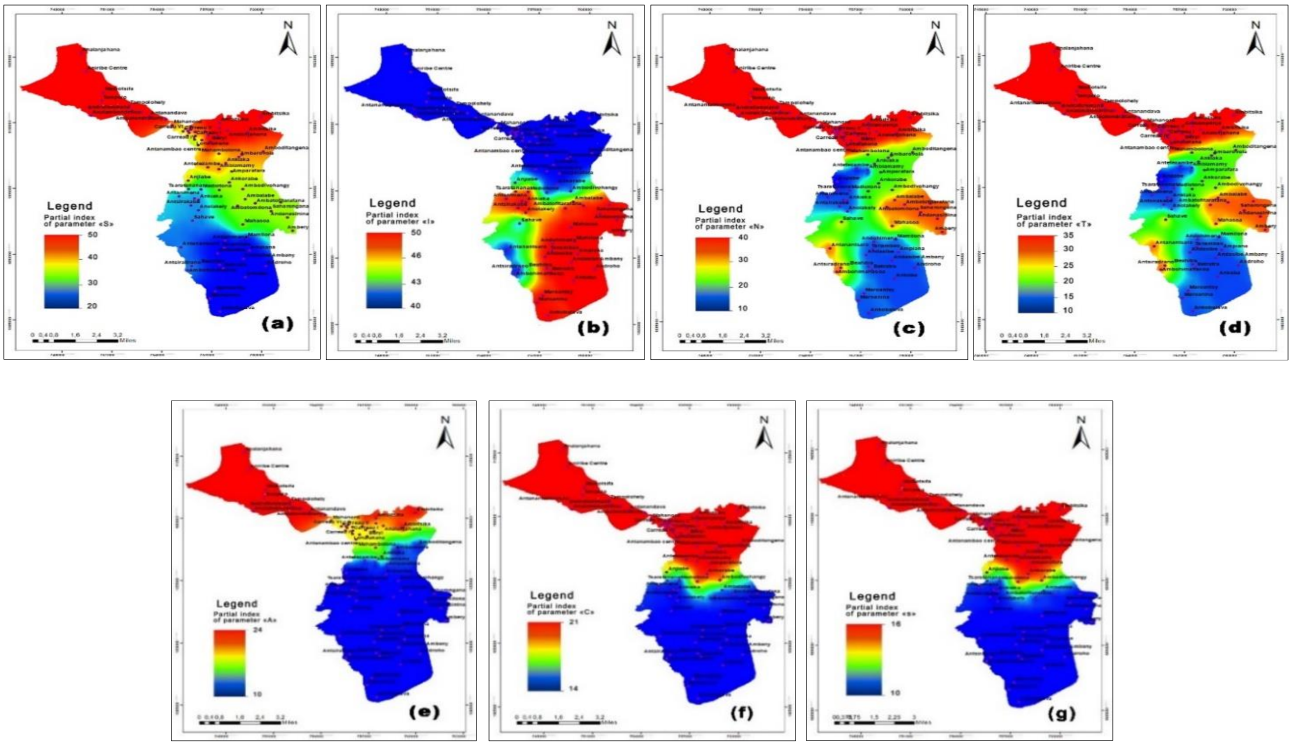

Fig. 5 : Maps of the seven parameters of the SINTACS index, of which (a) represents the depth of the water table, (b) recharge, (c) unsaturated zone, (d) soil environment, (e) aquifer environment, (f) hydraulic conductivity and (g) topographic slope.

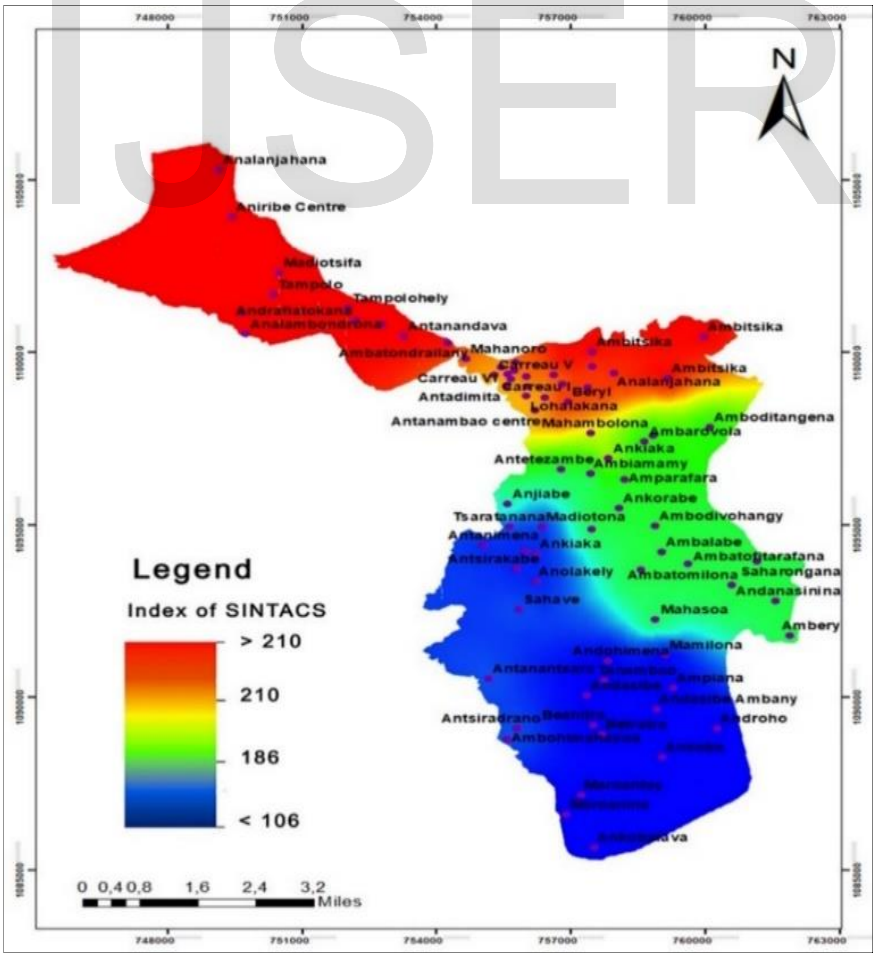

Fig. 6 : Map of vulnerability to pollution in the urban commune of Mananara Avaratra

4 DISCUSSIONS

The modeling of groundwater flows allows the production of distribution maps, leading to preventive measures by decreasing environmental degradation. The generalized increase of water pollution by nitrogen compounds reflects the imbalance of the nitrogen cycle generated by the intensification of agricultural activities and land use changes. The study of pollution by nitrogen compounds in the groundwater in question was tested and provided a comparison between the distribution of concentrations of Nitrate and Ammonium in groundwater and the distribution of different classes of vulnerability.

Nitrate and ammonium concentrations in groundwater presented in Fig. 3 and 4 show a clear anthropogenic footprint of groundwater. The concentrations are above the WHO standard limit for nitrate and ammonium. The highest concentrations are found almost in the nearshore and shallow area of the northern subwatershed. The nitrate results are in good agreement with the results of the Erostate paper in 2018(Erostate et al., 2018), which clearly highlighted the contamination of the aquifer by nitrate and ammonium, and showed also that the highest nitrate concentrations in the aquifer can be largely attributed to anthropogenic and agricultural activities in recent years which characterized the northern subwatershed. In contrast, these concentrations are relatively medium in the southern subwatershed. NO_3, NH_4, and NO_2 pollution in the aquifer in question was tested before conducting a comparison between the distribution of nitrates in the water of the aquifer and the distribution of the different classes of vulnerability that coincide with the distribution map of nitrate and ammonium.

As measure of protection, the use of the tool will help rise the population awareness to ensure a sustainable management of wellfields and their use in addition to the initiatives already undertaken by the government, communities, different institutions, and local authorities. It is urgent and a priority to carry out the following actions: the effective respect of the three protection perimeters around the wellfields by the riparian communities, in particular the immediate, close and remote protection perimeters; the effective respect of the standards for the construction of wells and sanitation works in the commune by the structures in charge of the design; to limit the diffuse agricultural and domestic pollution, to improve the rate of connection of the populations within the commune to the drinking water supply network managed by EGC3S (Entreprise Générale de Construction Sylvania-Sylverina-Sylvaincia), to promote monthly or biannually awareness campaigns on hygiene and basic sanitation, to treat periodically and cyclically the water reserves intended for the consumption of the surrounding population of the watersheds. With respect to wastewater management and urban sanitation, the population should be educated to avoid open discharge and to rehabilitate the sewerage systems.

5 CONCLUSIONS

The groundwater contamination highlights the impact of current environmental practices to reduce surface pollution by nitrates and ammoniums; these pollutants seep through the soil to the aquifer and progress into the "old" parts of the aquifer, indicating the low self-remediation capacity of the system. This geographical zoning agrees with the vulnerability maps by the SINTACS method. Indeed, the sampling sites with NO_3 and NH_4 concentrations, where the highest concentrations are located in the very high and high vulnerability classes, while the low concentrations coincide in the medium class. These indices are obtained from the superficial land use. These results are due to the geological nature, the nature of the soil (sandstone, sandy and alluvial), and the occupation of the soil at the surface. These are influenced by the geological nature, the nature of the soil, and the occupation of the soil at the surface.

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