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VULNERABILITY MAPPING TO POLLUTION OF SHALLOW AQUIFERS OF THE BANI TRANSBOUNDARY CATCHMENT (CÔTE D'IVOIRE, MALI) USING THE DRASTIC METHOD

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ABSTRACT

This study was conducted in the RIPIECSA (Interdisciplinary and Participatory Research on the Interactions between Ecosystems, Climate and Societies of West Africa) project led by Mali on climate variability, agricultural intensification and its impact on water resources of Bani River. The activities which could damage the water quality have been made on the Bani River.

Overall purpose of this study is to determine the degree of protection against pollution of shallow aquifers in the watershed borders of Bani River (Côte d'Ivoire, Mali), to ensure their sustainable exploitation. This knowledge requires the development of vulnerability map to aquifers pollution. The vulnerability map has been developed using DRASTIC method by exploiting the capabilities offered by GIS software ArcGIS 9.3.The analysis of this vulnerability map highlights four classes of vulnerabilities from "very low" vulnerability degree to "high" vulnerability. The class of "medium vulnerability" is the most dominant, expressed with 65.78% of the mapped areas. It covers an area of 62528 km². On the scale of hydrogeological vulnerability, this class belongs to category 2 which corresponds to an uncertain hydrogeological protection. The very high vulnerability class doesn't exist into the basin. Areas targeted with high sensitivity may be protected by prohibiting certain activities in these areas.

Keywords: Bani catchment, GIS, Hydrogeology, Vulnerability, Côte d'Ivoire, Mali.

INTRODUCTION

Water resources, particularly groundwater is increasingly called upon to cover the water needs in various fields (food, irrigation, industry, etc.). The increased exploitation of water resources in a current context of climate variability has raised awareness among users about the impacts of the deterioration of its quality Riser, 1992 in; Banton and Bangoy (1997). In the Bani catchment between Burkina Faso, Côte d'Ivoire, Guinea and Mali, several observations, being able to deteriorate eventually and irreversibly the quality of surface water and groundwater, were made. The most frequents are:

- the increasing of the cultivated surfaces and small developments of agro-forestry-grazing in the shallows and streams;
- the intensive use of fertilizers, pesticides and pesticides to improve crop yields;
- the throwing of industrial and craft pollutants into the big towns on high extension;
- the processes uses the cyanide in gold mining in the basin of Bani at Morila and Syama.

The RIPIECSA project was born to prevent the damage on the climate variability. The theme "climate variability, agricultural intensification: Impact on groundwater resources and surface of Bani in Côte d'Ivoire and Mali" led by Mali and the partnership with several institutions including the University Felix Houphouët Boigny-Cocody through the Faculty of Earth Sciences and Mineral Resources. It is within the framework of this project that this study was made. The objective aimed by this study is to determine the degree of protection against pollution of shallow aquifers of the Bani transboundary catchment (Côte d'Ivoire, Mali) to ensure their sustainable use.

Presentation of the study area

The study area, with 95,057 km^2, is situated between latitudes 9° and 13.5° N and longitudes 4.5° and 8° W (Figure 1). It is located in the Sudano-Sahelian with 78.95% on the South of Mali and 21.05% on the North of Côte d'Ivoire. Bani basin is characterized by a climate of Sudan in the north where annual rainfall varies between 858.74 mm and 1383.73 mm and a Sudano-Guinean climate in the south where annual rainfall reaches 1500 mm (Margat, 1968; Albergel *et al.*, 1993). On the geological plan, Bani basin is subdivided into two main geological units (Figure 2); the bedrock (60%) and the sedimentary (40%). The studied aquifer is the one alterite i.e. the superficial aquifer having the same characteristics into sedimentary and bedrock zones (Palausi, 1959). The rural people live mainly on the agriculture and the breeding. The agriculture is especially favored by an important hydrographic network with the intensive use of fertilizer and pesticides. The agro-industrial activities are based essentially on the production of the cotton which made its introduction in the basin since the year 1960. At this culture of pension intended to the export, it is necessary to add the peanut, the anacarde and the mango. Nowadays, we note an increasing use of fertilizer and pesticides necessary for the increase of the yields (Picouet, 1999; Adja, 2009). The breeding is the main pastoral activity. It is supported by the sheep and goat livestock. On the basin, there are sites of industrial and craft exploitation of gold. The industrial exploitation like Morila and Syama of Mali is based on the use of chemical processes such as the cyanurisation and other chemicals products. All these activities represent an enormous threat of the groundwater of Bani transboundary catchment.

MATERIAL AND METHOD

Data and Material

The data used for the mapping of the shallow aquifers vulnerability of Bani come from Côte d'Ivoire and Mali databases. These are constituted of:

- hydroclimatological data (temperature, rainfall) from multiple databases (SIGMA 2 of Mali, SODEXAM and LATASAH of Côte d'Ivoire). In Mali, five stations were selected (Beleko, Bougouni, Kolondieba, Sikasso, Ségou) and in Côte d'Ivoire, seven stations (Tengrela Boundiali, Odienné, Kouto, Madinani, Dembasso, Sanhala). Data cover the period from 1981 to 2000;
- boreholes data are extracted from the SIGMA 2 of Mali and DHH of Côte d'Ivoire. These data were collected over the period 1995-2002;
- data composed of topographic, geological and isopermeability maps
    - ✓ three (3) topographic maps with one (1) of Bani basin in Mali and two (2) from Côte d'Ivoire (Boundiali and Odienné) were used;
    - ✓ a geological map of Mali performed by Bassot (1981) and one of Côte d'Ivoire produced by Tagini (1971);
    - ✓ isopermeability map of the South of Mali established by Saad (1970);
- elevation data constituted by the SRTM images. These images are collected in 2008 by the U.S. space shuttle Endeavour and established by Jarvis *et al.* (2008).

For the processing and layers elaboration, the software of ArcGis 9.3 was used.

METHOD

Hypothesis, Parameters and Scoring System Used

The DRASTIC method was developed by "The Environmental Protection Agency" (EPA) in the United States in 1985 (Aller *et al.*, 1987). It is an empirical method to point rating assessment and mapping of groundwater vulnerability to pollution. It is based on specific assumptions:

- the area of application covers more than 0.4 km^2;
- the potential sources of contamination are found at the soil surface;
- potential contaminants reach the aquifer by the effectively infiltration process.

DRASTIC method is based on seven (7) criteria (Table 1). A numerical value (weight parametric) between 1 and 5 reflects the influence degree of each one.

At each of the parameters is associated a rating from 1 to 10, defined in terms of values ranges (Tables 2 to 8).

Calculation of the DRASTIC index

The DRASTIC vulnerability index (I_D), a measure of potential pollution, is determined from the formula of equation 1 :

$$I_D = D_r \times D_n + R_r \times R_n + A_r \times A_n + S_n \times S_r + T_n \times T_r + I_n \times I_r + C_n \times C_r \qquad (1)$$

Where r is the Weight and n corresponds the Rating of the parameter.

The degree of vulnerability (Table 9), following the DRASTIC index, is determined by the formula in the second equation (MAPAQ, 1998):

$$I\% = ((I - 23)/203) \times 100 \qquad (2)$$

The degree of protection can be also evaluated with the approach developed by the Ministry of Agriculture, Fisheries and Food of Quebec (1998) for judging the natural protection of groundwater. It is divided into three categories according to hydrogeological vulnerability (0-100%) based on DRASTIC indices percent calculated from the I_D (Table 10).

Validation of Groundwater Map Vulnerability to Pollution

The deteriorating quality of groundwater is assessed by physico-chemical and bacteriological measurements. Several authors who are Champagne and Chapuis (1993), Isabel *et al.* (1990), Mohamed (2001), Jourda *et al.* (2005), Jourda *et al.* (2006) and Savané *et al.* (2006) validated the assessment method of vulnerability to pollution based on chemical data of groundwater. To validate the vulnerability map produced in this study, chemical data were used to verify the reliability of the DRASTIC method. In the validation of vulnerability maps, areas actually contaminated should match with high vulnerability indices (Jourda *et al.*, 2005). However a vulnerable zone can have a low vulnerability index due to the fact that the vulnerability notion is not synonymic to a current pollution, but rather of a predisposition for these zones to a possible contamination, if nothing is undertaken to protect them. In this study, the validation of the vulnerability map established using the DRASTIC method focused on the analysis of the nitrate content rate in groundwater of the Bani basin.

RESULTS AND DISCUSSION

DRASTIC Index Map

The index map derived from this method is shown in Figure 3. DRASTIC vulnerability indices obtained oscillate between 52 and 171. The analysis of this map reveals growth indices from the South to the North.

Map of Vulnerability to Pollution of Bani

The reclassification of DRASTIC index gives the map of aquifer vulnerability to pollution on figure 4. The reclassified DRASTIC index of the table 11 reveals a distribution of pixels according to the various classes of vulnerability to pollution.

The analysis of the vulnerability map (Figure 3) obtained from the DRASTIC index allows to determine four (4) degrees of vulnerability (very low, low, medium and high). The medium class of vulnerability covers 65.78 % of the study area. It is followed by the low class of vulnerability which it is more observed in the North with 29.04%. The classes of very low and high degree of vulnerability are less important than the two first classes. Those classes occupy respectively 1.05% and 4.14% of the study area (Figure 5). The highest vulnerability class is more present in the bedrock zone.

Map of Hydrogeological protection

A hydrogeological classification according to the degree of vulnerability gives two categories 1 and 2 (Table 12). It resorts from this table that the category 1 is more observable in the North and in some places on the limit of sedimentary-bedrock and the category 2 on the rest of the study area (Figure 6).

Validation of the Vulnerability Map to Pollution

The validation of the vulnerability map to pollution of Bani catchment established by the DRASTIC method was done by measuring the concentrations of nitrates. We collected 238 nitrates values covering all the study area. Those values have been superposed on the vulnerability map. The various classes of nitrate concentration were established based on those of Madison and Brunett (1985) (Table 13). After the analysis of different values and their position in the vulnerability map, it comes out that the highest content of nitrate is seen in the South of Mali in Keniéba region. The medium contents are located in the West and South-west of the study area.

Concerning the lowest contents, they are concentrated in the East and the North-East (Figure 7). According to the spatial distribution of the different contents of nitrate (Table 14), it appears that:

- On 85 values of the first category, three are included in the "very low" class of vulnerability, 34 in the "low" class, 46 values in the "medium" class and 2 in the "high" class of vulnerability;
- On 142 values in category 2, none is included in the "very low" class of vulnerability. There are 48 in the "low" class, 85 in the "medium" class and 9 in the "high" class of vulnerability;
- On 11 values in category 3, none is included in the "very low" class of vulnerability and 6 values in the "low" class. The "medium" vulnerability class includes 5 values and no value for the "high" vulnerability class.

The best coincidence rates are in the Category "2" where there are 59.66% of the nitrate values in the medium class of vulnerability. That class is followed by the low class of vulnerability in the category "3" with 54.55% rate of coincidence and the medium vulnerability class for the category "1" with a coincidence rate of 54.12%. The global coincidence rate is 57.56% (137 values on 238). These results validate the vulnerability map to pollution of Bani obtained from DRASTIC method.

DISCUSSION

The realization of the vulnerability map to pollution requires a very long process from objectives identification to the presentation of results. The first problem that arose, was whether to consider separately the sedimentary area and the bedrock area since the Bani basin belongs to two different geological areas. The DRASTIC method does not provide a separated study in this case. Also, it was about the characterization of the intrinsic vulnerability of shallow aquifers of Bani basin.

Other difficulty met in this study resides in the elaboration of DRASTIC parameters. Nevertheless, the calculated infiltrations, which are included between 21 and 463 mm, are consistent with those obtained by Kouadio (2005) in Odienné (from 110 to 453.8 mm). These values of infiltration are closed to those obtained in Korhogo (from 75 to 226 mm) by Jourda (2005) and by Savané (1997) in Odienné (77 mm). The calculated running coefficient (5.75) is similar to that obtained by Bamba *et al.* (1996) on the basin of the Bani which is 5.3 by considering the period 1981-1995. This same value of running was obtained by Jourda (2005) in M'bengué in Côte d'Ivoire when considering the period 1986-1995. The permeability values found in the environment of bedrock were assigned to the alterite aquifers. But the drilling into the bedrock area are not intended primarily these types of aquifers. They are rather directed to bedrock aquifers where the flows are important. This did not prevent to take those values of conductivity found in the south of the basin situated in the bedrock zone. It reveals the difficulties of such a study and also a reliability of the obtained values. So the obtained DRASTIC index is included between 64 and 172. Compared to those obtained by some authors who are Jourda (2005) in Korhogo (from 77 to 158), Youan (2008) in Bondoukou (from 81 to 136), our values are acceptable. In that way, four classes of vulnerability have been obtained with the DRASTIC classification. A very low vulnerability class is located exclusively in the north of the study area, particularly in the Segou region. In this zone there are important depth to water, less recharge and an unsaturated zone predominantly by the clay. These 3 parameters caused this very low degree of vulnerability. In the north of this basin, the degree of vulnerability is low. A medium vulnerability class, which is the important class of this basin, is scattered on the entire basin. The high vulnerability is less important into this Bani basin.

The observation of the vulnerability map shows that the classes of medium and high vulnerability present in the south of the basin are an extension of the classes obtained by Jourda (2005) in M'bengué. A hydrogeologic classification from the DRASTIC index reveals two categories (1 and 2). The Category 1 is located in the north and the rest of the basin belongs to the category 2 with 96% of the study zone.

The overlapping of the nitrate values to the vulnerability map allowed validating the map of shallow aquifer vulnerability of Bani because the rate of coincidence of these two maps is 57.56%. This value is less than that obtained by Aké (2010) in Bonoua (77.35%) and higher than that obtained by Hamza *et al.* (2007) in the north-east of Tunisia (44%). The class of medium vulnerability and the category 2 of nitrate values gave a high rate of coincidence with 59.86%. It is thus necessary to take measures to protect the vulnerable zones targeted in this study.

CONCLUSION

The vulnerability map to pollution obtained was carried out by the DRASTIC method. The analysis of the groundwater vulnerability map obtained highlights four classes of vulnerability. Among these classes, the class of medium vulnerability is the most important with 65.78% of the study zone. The established vulnerability map is a help tool for decision. The targeted sensitive zones must be monitored because the Bani basin is an area with many agricultural and mining activities. It is thus desirable to regulate these activities on the basin with the use of the cyanide, the agricultural products farm.

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Table-1. DRASTIC weight parameters and their properties (Vrba and Zeporozec, 1994)

Symbol	Parameter	Weight
D	Depth to water	**5**
R	Recharge	**4**
A	Aquifer media	**3**
S	Soil media	**2**
T	Topography	**1**
I	Impact of the unsaturated zone	**5**
C	Conductivity	**3**

Table-2. Depth to water ranges and ratings (Aller *et al.*, 1987)

Range (m)	Rating
0 – 1.5	**10**
1.5 – 4.5	**9**
4.5 – 9	**7**
9 – 15	**5**
15 - 23	**3**
23 - 31	**2**
31 and more	**1**

Table-3. Net recharge ranges and ratings (Aller *et al.*, 1987)

Range (mm)	Rating
0 à 50	1
50 à 100	3
100 à 180	6
180 à 250	8
250 and more	9

Table-4. Aquifer media ranges and ratings (Aller *et al.*, 1987)

Aquifer media	Rating	Typical rating
Massive shale	1 - 3	2
Igneous or metamorphic weathered rocs	3 - 5	4
Igneous or metamorphic rocs	2 - 5	3
Till	4 - 6	5
Bedded sandstone, limestone and shale	5 - 9	6
Massive sandstone	4 - 9	6
Massive limestone	4 - 9	6
Sand and gravel	4 - 9	8
Basalt	2 - 10	9
Karst limestone	9 - 10	10

Table-5. Soil media ranges and ratings (Aller *et al.*, 1987)

Soil	Rating
Thin soil or roc	10
Gravel	10
Sand	9
Peat	8
Aggregated clay	7
Sandy loam	6
Loam	5

Silty loam	4
Clay loam	3
Black soil	2
Non aggregated clay	1

Table-6. Topography ranges and ratings (Aller *et al.*, 1987)

Range (%)	**Rating**
0 - 2	10
2 - 6	9
6 - 12	5
12 - 18	3
18 and more	1

Table-7. Vadose zone media ranges and ratings (Aller *et al.*, 1987)

Vadose zone media	**Rating**	**Typical rating**
Waterproof layer	1	1
Silt or clay	2 - 6	3
Shale	2 - 5	3
Limestone	2 - 7	6
Bedded limestone, sandstone and shale	4 - 8	6
Stone and gravel with silt and clay	4 - 8	6
Igneous or metamorphic	2 - 8	4
Sand and gravel	6 - 9	8
Basalt	2 - 10	9
Karst limestone	8 - 10	10

Table-8. Hydraulic conductivity ranges and ratings (Aller *et al.*, 1987)

Range (m/s)	**Rating**
$4{,}7.10^{-7}$ - $4{,}7.10^{-5}$	1
$4{,}7.10^{-5}$ -$14{,}7.10^{-5}$	2
$14{,}7.10^{-5}$ - $32{,}9.10^{-5}$	4
$32{,}9.10^{-5}$- $4{,}7.10^{-4}$	6
$4{,}7.10^{-4}$ - $9{,}4.10^{-4}$	8
$9{,}4.10^{-4}$ and more	10

Table-9. Degree of vulnerability following the DRASTIC index (Anonymous, 1987)

DRASTIC index (I_D)	**Degree of vulnerability**
23 to 84 (0 to 30%)	Very low
85 to 114 (31 to 45%)	Low
115 to 145 (46 to 60%)	Medium
146 to 175 (60 to 75%)	High
176 to 226 (76 to 100%)	Very high

Table-10. DRASTIC indices and percentage aquifer protection

	I_D %	**Conclusion**
Category **1**	0 to 35%	Aquifer certainly well protected
Category **2**	35 to 75%	Uncertain hydrogeological aquifer protection
Category **3**	75 to 100%	Certainly vulnerable aquifer

Table-11. Percent of different vulnerability classes

DRASTIC index	Number of pixels	Vulnerability	Percent (%)
23 à 84 (0 à 30%)	227	Very low	1.04
85 à 114 (31 à 45%)	6308	Low	29.04
115 à 145 (46 à 60%)	14290	Medium	65.78
146 à 175 (60 à 75%)	899	High	4.14
Total	**21724**		**100**

Table-12. Hydrogeologic classification

Index of vulnerability	Number of pixels	Vulnerability	Percent (%)
0 à 35%	828	Aquifer certainly well protected	3.90
35 à 75%	20419	Uncertain hydrogeological aquifer protection	96.10
Total	**21724**		**100**

Table-13. Categories depending on the concentration of nitrates (Madison and Brunett, 1985) modified

Categories	Range of nitrate ($mg.L^{-1}$)	Description	Number of values	Percent
Category 1	$[NO_3] < 0.9$	natural level, no human influence	85	35.71%
Category 2	$0.9 \leq [NO_3] < 13.5$	transition level, human influence as possible	142	59.66%
Category 3	$13.5 \leq [NO_3] < 50$	level showing a human influence but not harmful to health	11	4.62%
TOTAL			**238**	**100.00%**

Table-14. Coincidence between nitrate concentrations and vulnerability classes

Degrees of DRASTIC vulnerability	Number of Category 1 values	Number of the category 2 values	Number of the category 3 values	Total	Percent
Very low	03	00	00	**03**	**1.26%**
Low	34	48	06	**88**	**36.75%**
Medium	46	85	05	**136**	**57.14%**
High	2	09	00	**11**	**4.62%**
Total	**85**	**142**	**11**	**238**	**100%**
Percent	**35.72%**	**59.66%**	**4.62%**	**100%**	

Figure-1. Location of the study area

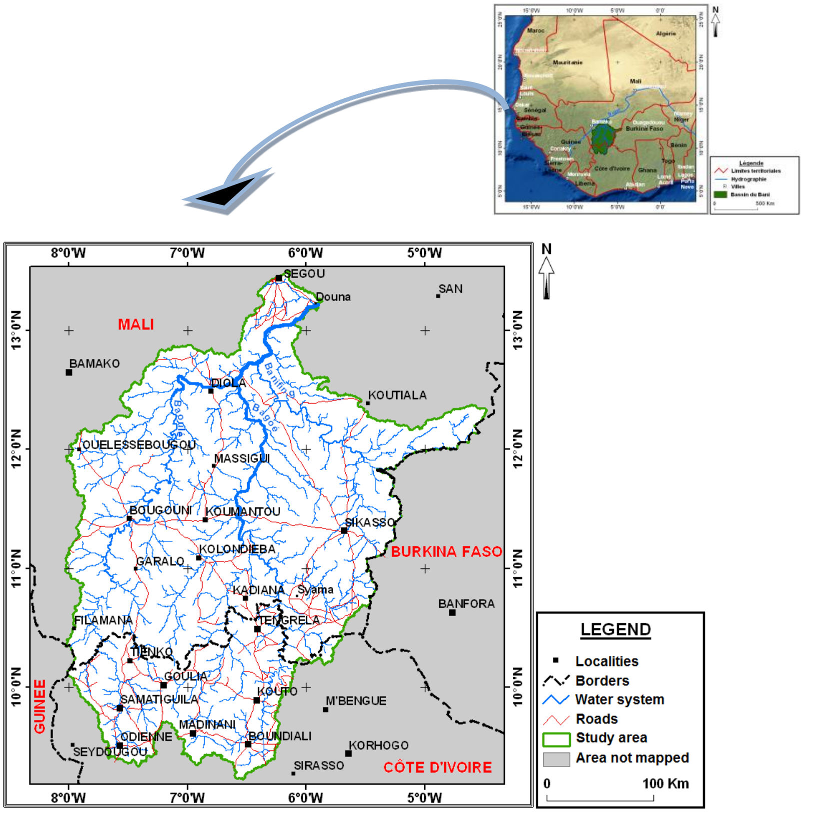

Figure-2. Geological map of the study area

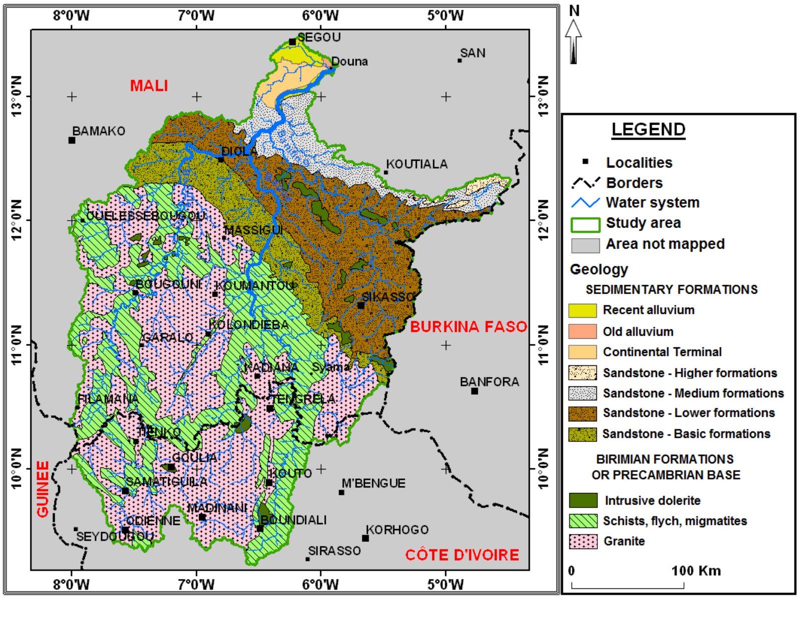

Figure-3. DRASTIC index map of the Bani catchment

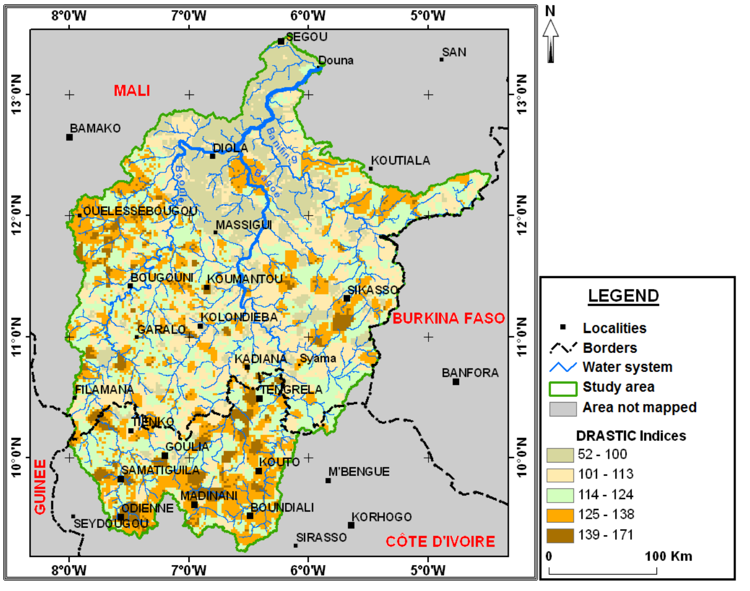

Figure-4. Map of groundwater vulnerability to pollution of Bani catchment

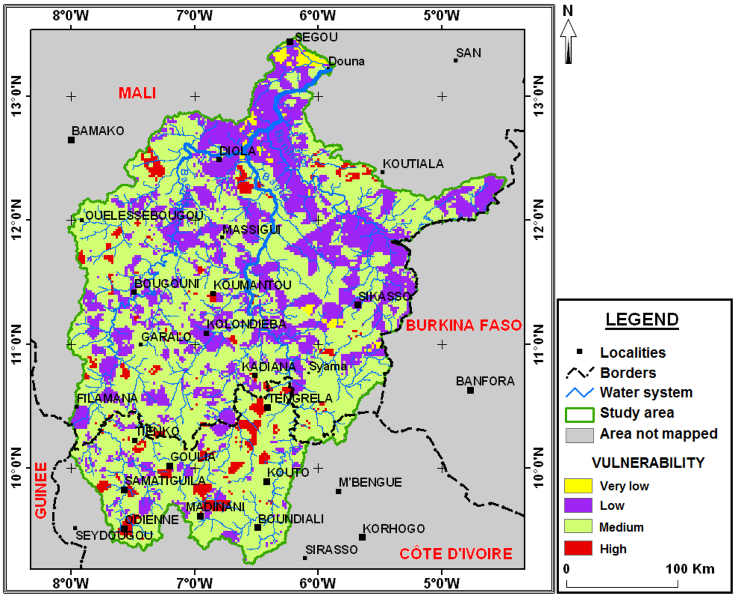

Figure-5. Spatial distribution of different classes of vulnerability

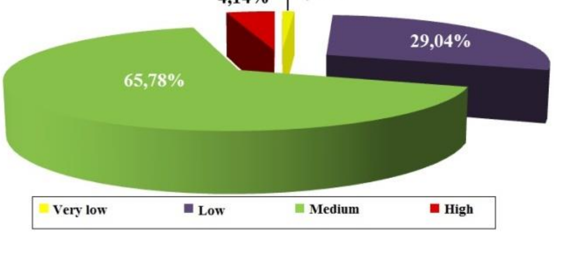

Figure-6. Map of hydrogeological protection of the Bani catchment

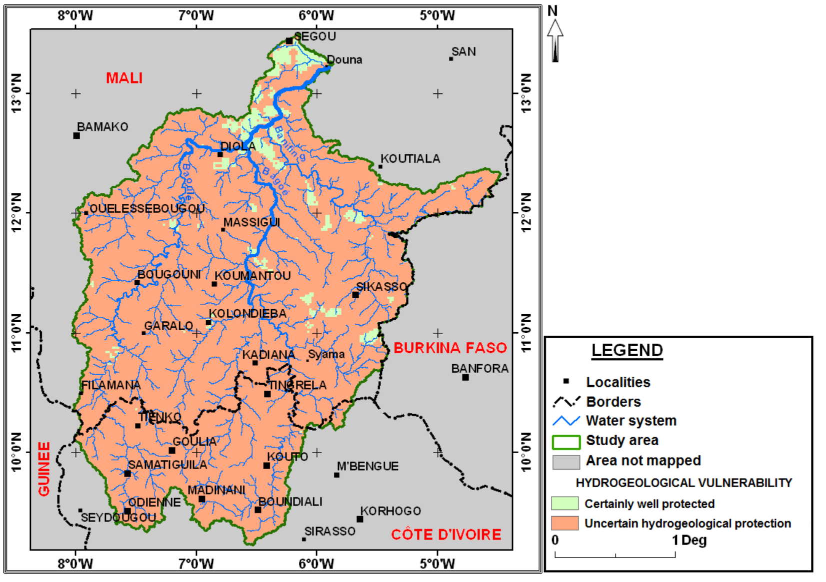

Figure-7. Spatial distribution map of nitrates values on vulnerability classes