

Analysis and Monitoring of Groundwater Vulnerability and Quality in the Sudano-Sahelian Zone: Case of the Yagoua Rice-Growing Basin, Cameroon

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Abstract

The main aim of this study is to determine whether the groundwater in the Yagoua rice-growing basin is of satisfactory quality for human consumption. A pollution vulnerability map of the study area was first produced using the modified DRASTIC method. The area was then subdivided according to the vulnerability map results to guide sampling, and finally, the groundwater of the basin was classified. Intrinsic vulnerability mapping showed that the study area is dominated by very low to low vulnerability classes, covering 97% of the total area. The basin was divided into three zones based on vulnerability: zone 1 corresponds to the very low vulnerability class, zone 2 to the low vulnerability class, and zone 3 to the medium vulnerability class. Physicochemical analysis results indicated that iron is the major element, with concentrations well above the maximum allowable limit. The Piper diagram showed that 60% of the analyzed water has a calcium-magnesium bicarbonate facies. The Water Quality Index (WQI) reveals that 53% of the study area has non-potable groundwater, linked to high iron content. Groundwater in the Yagoua rice-growing basin is unfit for human consumption and requires prior treatment. Modelling shows that, higher permeability and deeper wells or water table generally have older groundwater and less vulnerability to pollution.

Keywords: Modified DRASTIC method; Groundwater vulnerability; Yagoua rice-growing basin; Far North Cameroon.

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Introduction

Water resources in Sahelian zones, including the Yagoua rice-growing basin, consist largely of groundwater. Except for the Logone River, watercourses in this basin are seasonal and dry up completely during the dry season. The local population relies mainly on groundwater, accessed through boreholes or constructed and unconstructed wells.

Irrigated double-cropping has been practiced on over 5,300 hectares in Yagoua since the establishment of the Society for the Expansion and Modernization of Rice Cultivation in Yagoua (SEMRY) in 1971 (Mamoudou, 2019). This intensive farming, like many other agricultural activities, involves substantial use of pesticides and phytosanitary products, in addition to other anthropogenic activities that can readily pollute groundwater (Yao et al., 2020; Konan et al., 2023).

Furthermore, the Yagoua rice-growing basin is situated in a flood-prone sedimentary zone, which facilitates pollutant infiltration into the aquifer (Konan et al., 2023; Neh et al., 2023). The key issue is whether groundwater in the Yagoua rice-growing basin is safe for human consumption—in other words, assessing the impact of rice cultivation on groundwater quality (Kone et al., 2009). In general, intensive rice and vegetable farming threaten local water resources due to the uncontrolled use of agricultural inputs following market liberalization, while certain practices promote the direct infiltration and migration of pollutants into groundwater (Barber et al., 1993; Sinan et al., 2000; Touati et al., 2018; Amrani et al., 2019). The main objective of this research is to assess groundwater vulnerability in the Yagoua rice-growing basin using the modified DRASTIC method.

Materials and Methods

Presentation of the Study Area

The study area is located in the Mayo-Danay Division, Far North Region. It covers part of the districts of Yagoua and Kaï-Kaï and the entire district of Vélé, situated between approximately 10°10'N, 14°30'E and 10°40'N, 15°20'E, covering an area of about 889.55 km² (Fig. 1). The climate is Sahelo-Sudanian, characterized by a long dry season from October to early May and a short rainy season from June to September. The morphology is dominated by a floodplain (Ngounou et al., 2007). The soils of the area are poorly evolved, including vertisols, tropical ferruginous soils, hydromorphic soils, and halomorphous soils (Barbery et al., 1980; Seignobos et al., 2000). Agriculture in the area is dominated by rice cultivation, irrigated using water from an artificial lake.

Modified DRASTIC Method for Groundwater Vulnerability

The modified DRASTIC method (Sinan and Razack, 2006) is based on parameters relating only to the vadose (unsaturated) zone and does not consider the permeability and lithology of the substrate, as these two parameters are not directly involved in the vertical transfer of pollution from the soil surface. Several researchers have shown that groundwater vulnerability can be assessed without using all the standard DRASTIC parameters (Sinan and Razack, 2006; Nkounkou et al., 2016). According to Rosen (1994), the hydraulic conductivity of the aquifer does not significantly influence vulnerability, as it is not directly involved in adsorption, cation exchange, or

redox reaction processes. The modified DRASTIC method is used to assess and map intrinsic vertical vulnerability to groundwater pollution using a parametric rating system. This is a numerical rating method based on five parameters: D: Depth to groundwater; R: Recharge; S: Soil media; T: Topography; I: Impact of the vadose zone. The data used to calculate the DRSTI parameters are presented in Table 1.

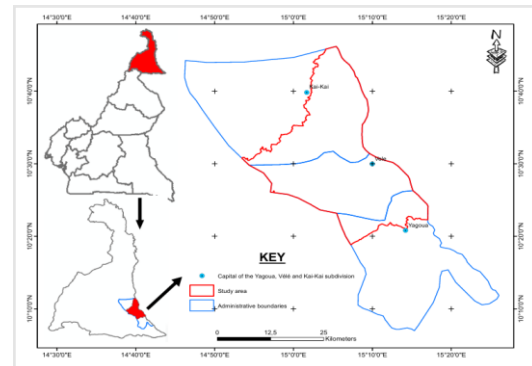


Fig. 1 Location of the Study Area

Table 1 Origin and acquisition method of data used to create the DRASIC parameter layers.

Types of data	Origin	Method of acquisition	Output map
Well data	Field inventory	Interpolation	Water depth (D)
Rainfall data	Annual recharge map of the Far North	Digitisation	Efficient recharge (R)
Soil type	Soil map of the Logone and Chari alluvial basin	Digitisation	Soil (S)
Topography	Satellite image	Extraction	Slope (T)
Surface geology	Geological sketch of the Logone and Chari alluvial basin	Digitalisation	Unsaturated zone (I)

The method assigns a weight ranging from 1 to 5 and a score from 1 to 10 to each parameter (Table 2) to reflect their relative importance in terms of vulnerability. The final vulnerability index (I_v) is the sum of the products

of each parameter's rating multiplied by its weight, according to the following formula:

$$I_v = D_r D_w + R_r R_w + S_r S_w + T_r T_w + I_r I_w \quad \dots(1)$$

where,

D, R, S, T and I are parameters used by the modified DRASTIC method and r, w are weights and scores assigned to each parameter used.

According to Aller et al. (1987), the index values obtained are grouped into five classes (Table 3), each of which corresponds to a degree of vulnerability.

Table 2 Parameter weights and rating for the modified DRASTIC method.

Parameter	Class	Rating	Weight
D (m)	0 – 1,5	10	5
	1,5 – 4,5	9	
	4,5 – 9,0	7	
	9,0 – 15,0	5	
	15,0 – 23,0	3	
	23,0 – 30,0	2	
	> 30	1	
R (mm)	0 – 50	1	4
	50 – 100	3	
	100 – 175	6	
	175 – 225	8	
	> 225	9	
S	Thin or absent	10	2
	Gravel	10	
	Sand	9	
	Sandy silt	6	
	Silt	4	
	Silty silt	3	
	Clay	1	
T	0-2	10	1
	2-6	9	
	6-12	5	
	12-18	3	
	> 18	1	
I	Silt and Clay	2 – 6	5
	Shale	2 – 6	
	Limestone	2 – 5	
	Sandstone	2 – 7	
	Sand and gravel with silt and clay	4 – 8	
	Sand and gravel	4 – 8	
	Basalt	2 – 10	
	Karst limestone	8 – 10	

Table 3 Index values for each level of vulnerability.

Degree of vulnerability	Vulnerability index
Very low	< 80
Low	80 – 120
Medium	121 – 160
High	161 – 200
Very high	> 200

Development of Vulnerability Map

The cartographic approach was implemented using ArcGIS software, which enabled the compilation of spatial data, calculation of indices based on the geographical distribution of weighted ratings assigned to the five parameters, and production of a vulnerability map representing the variation in vulnerability indices. Classification of these indices according to the modified DRASTIC criteria allows the relative vulnerability of each studied sector to be spatialized. Figure 2 illustrates the various stages involved in producing the vulnerability map.

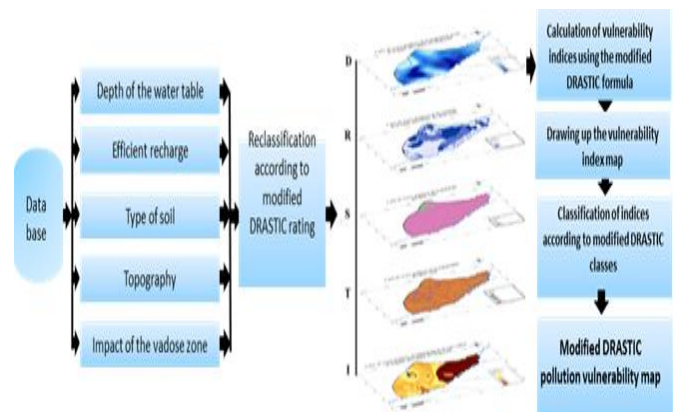


Fig. 2 Steps in producing the final pollution vulnerability map

Depth of Water Table

Water Depth refers to the depth of the water surface in an unconfined aquifer. It represents the total thickness of the horizons a pollutant must traverse to reach the water table (Chandoul and Trabelsi, 2008). The depth map of the water table in the study area is based on measurements from 53 wells. Following data interpolation, each pixel was classified according to the DRASTIC method (Fig. 3). The ratings (scores) for this parameter (D) range from 1 to 10.

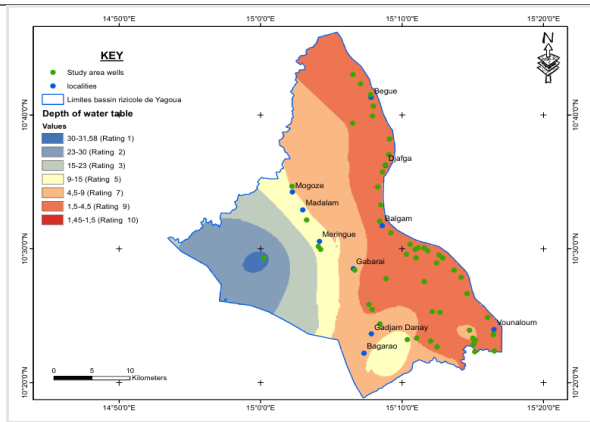


Fig. 3 Water table depths in the study area

Efficient Recharge

Effective recharge is the volume of water per unit area that infiltrates and reaches the aquifer. This water transports pollutants from the land surface through the vadose zone to the saturated zone. Generally, the greater the recharge volume, the higher the potential for aquifer contamination (Chandoul and Trabelsi, 2008). The groundwater recharge map of the Yagoua rice basin (Fig. 4) was generated using the Groundwater Recharge and Water Balance method (Wendland et al., 2003).

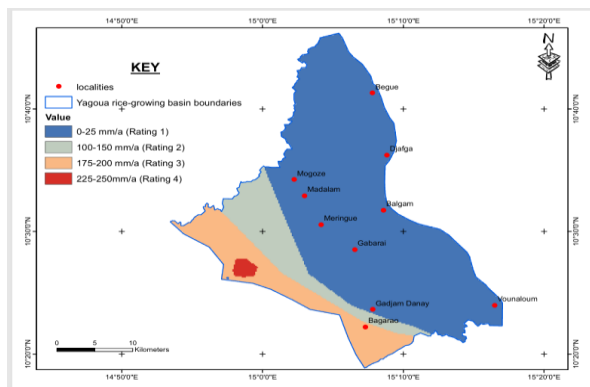


Fig.4 Average groundwater recharge in the Yagoua rice-growing basin.

Type of Soil

The nature of the soil significantly influences groundwater contamination by surface pollutants. It can reduce, delay, or accelerate the propagation of pollutants toward the aquifer. Soils richer in clay have a greater capacity to absorb pollutants, thereby providing better protection for groundwater (Chandoul and Trabelsi, 2008). The soil type map of the Yagoua rice-growing basin (Fig. 5) was derived from the 1/200,000-scale soil map of the Logone and Chari alluvial basin.

Topography

The topography parameter in the modified DRASTIC method is represented by slope values in percent. This parameter reflects the capacity of surface water to either runoff or infiltrate into groundwater, thereby influencing the potential introduction of pollutants into the aquifer. Steeper slopes promote greater runoff and consequently reduce groundwater contamination (Chandoul and Trabelsi, 2008). Conversely, areas with gentle slopes tend to retain water longer, favoring the infiltration of contaminants. The slope map (Fig. 6) was generated through interpolation using ArcGIS software.

Impact of the Vadose Zone

The vadose zone lies between the soil layer and the water table. The nature of this zone is an important parameter in vulnerability assessment, as it influences the rate at which pollutants propagate toward the aquifer (Chandoul and Trabelsi, 2008). For this study, a 1/1000000-scale geological sketch of the Logone alluvial basin, together with lithological sections from four boreholes drilled in the area, were processed in ArcGIS software to produce the vadose zone map (Fig. 7).

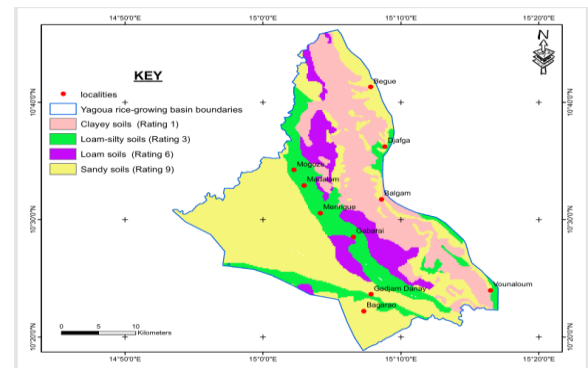


Fig. 5 Soil types in the Yagoua rice-growing basin.

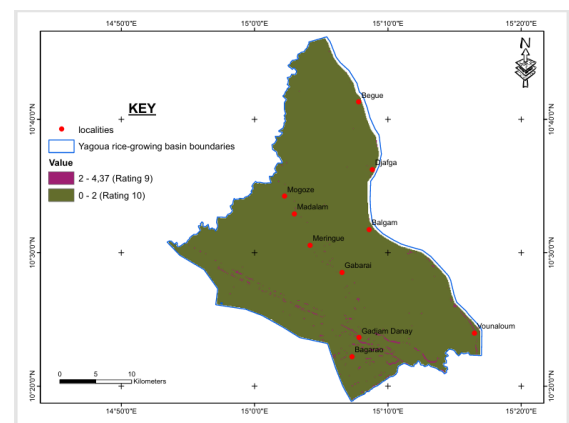


Fig.6 Topographical slopes in the Yagoua rice-growing basin.

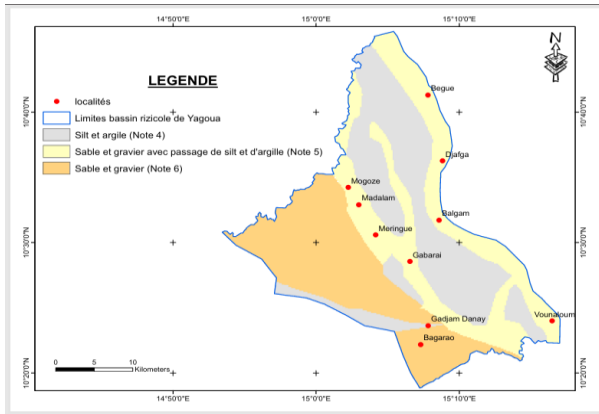


Fig.7 Map of notes associated with the unsaturated zone in the study area.

Determination of WQI

Water samples were collected from 10 boreholes in the study area during august 2024, and the Water Quality Index (WQI) was calculated using 14 parameters: Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Ammonium (NH₄), iron (Fe), chloride (Cl), sulfate (SO₄), bicarbonate (HCO₃), nitrate (NO₃), Nitrite (NO₂), Phosphate (PO₄), and Fluoride (F). This index classifies water quality by comparing measured parameters with international (WHO) or Cameroon national standards. The importance of each parameter depends on the intended water use. The overall water quality index is calculated using the following equation (Talhoui et al., 2020).

$$WQI = \frac{\sum_{i=1}^n Q_i * W_i}{\sum_{i=1}^n W_i} \quad \dots(2)$$

where,

W_i = Numerical value called relative weight, specific to each physicochemical parameter;

Q_i = Quality assessment scale;

n = Number of physicochemical parameters.

Estimation of Relative Weight (W_i)

The weight of each parameter (W_i) is the ratio of the relative weight (R_w) of each parameter by the total of the relative weights which is given by:

$$W_i = \frac{K}{S_i} \quad \dots(3)$$

where,

W_i = Relative weight, specific to each parameter;

S_i = Standard value of the water standard;

K = Proportionality constant calculated using the following equation:

$$K = \frac{1}{\sum_{i=1}^n (\frac{1}{S_i})} \quad \dots (4)$$

Calculation of the Quality Assessment Scale (Q_i)

$$Q_i = \frac{C_i}{S_i} \quad \dots (5)$$

where,

Q_i = Quality assessment scale for each parameter;

C_i = The concentration of each parameter in mg/L.

Authors such as Brown et al. (1972), Chatterjee and Raziuddin (2002), Tyagi et al. (2013), Aher et al. (2016), and Talhoui et al. (2020) have developed classifications and guidelines for water use based on the Water Quality Index (WQI). This resulted in five water quality classes, ranging from excellent to non-potable water (Table 4).

Table 4 Classification and potential use of water according to the WQI

WQI class	Type of water	Potential use
0 - 25	Excellent quality	Drinking water, irrigation and industry
> 25 - 50	Good quality	Drinking water, irrigation and industry
>50 - 75	Poor quality	Irrigation and industry
>75 - 100	Very poor quality	Irrigation
> 100	Non-drinking water	Appropriate treatment required before use

Results and Discussion

Vulnerability Map of Groundwater

The groundwater vulnerability map for the Yagoua rice-growing basin, produced using the modified DRASTIC method (Fig. 8), shows vulnerability index values ranging from 65 to 125. These indices distinguish three vulnerability classes: very low, low, and medium. According to the scale established by Aller et al. (1987), Barber et al. (1993), Merchant (1994), and Chandoul and Trabelsi (2008), very low vulnerability corresponds to values of 65–80, low vulnerability to 80–120, and medium vulnerability to 121–125. The very low vulnerability class is located in the central part of the basin, where clay-sandy soils hinder pollutant migration to the water table, covering 25% of the groundwater area. The more extensive low vulnerability zones flank the very low vulnerability areas, accounting for 72% of the groundwater. In the eastern part, low vulnerability is attributed to the clayey soil despite shallow water table depths. In the west, low vulnerability is linked to relatively greater water table depths despite sandy soils. The medium vulnerability zone in the southern part of the basin,



where both soil and vadose zone are sandy, represents only 3% of the groundwater area. Therefore, the Yagoua rice-growing basin is largely sheltered from pollution, as 97% of its groundwater exhibits very low to low vulnerability.

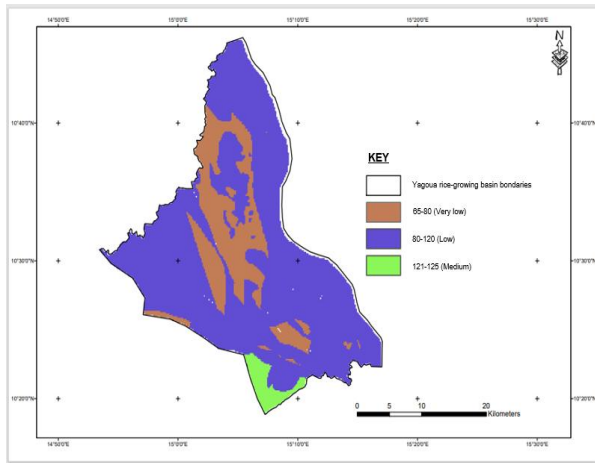


Fig. 8 Vulnerability map of the study area using the modified DRASTIC method

Physicochemical Analysis

Figure 9 shows three zones. We have assigned numbers 1, 2 and 3 to zones with very low vulnerability, low vulnerability, and medium vulnerability, respectively. The ten sampling points were selected taking into account these different zones as well as the land use in the study area.

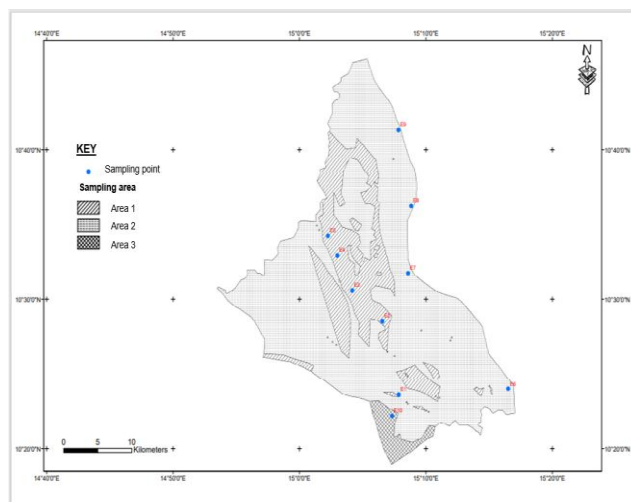


Fig. 9 Locations of sampling points.

Table 5 Distribution of pollutants by sampling zone.

Point	Sampling		Pollutant Element
	Location	Area	
F1	Gadjam Danay	Low vulnerability	Iron
F2	Gabarai	Very low vulnerability	Iron
F3	Meringue	Very low vulnerability	Fluor
F4	Madalam	Very low vulnerability	Iron, Fluor
F5	Mogoze	Very low vulnerability	Iron
F6	Vounaloum	Low vulnerability	Iron
F7	Balgam	Low vulnerability	Iron
F8	Djafga	Low vulnerability	/
F9	Begue	Low vulnerability	/
F10	Bagarai	Medium vulnerability	Iron

Groundwater Quality

Hydrogeochemical facies

The hydrogeochemical characteristics of groundwater were assessed. The water quality has been assessed for drinking purposes. The detailed observations show that pH value ranges from 6.28 to 7.53 with an average of 6.96. Electrical conductivity ranges from 88 to 358 $\mu\text{S}/\text{cm}$ with an average value of 216.2 $\mu\text{S}/\text{cm}$ and TDS concentration is 44 to 179 mg/L having an average value of 108 mg/L. Ca concentration is 6.02 to 41.08 mg/L with an average of 18.57 mg/L whereas, the Mg concentration ranges from 1.87 to 6.77 mg/L with an average of 3,93 mg/L. Na concentration ranges from 4.05 mg/l to 50.43 mg/L have an average value of is 14.10 mg/L. Whereas, K concentration ranges from 1.62 to 5.77 mg/l and the average value is 2.81 mg/L. HCO_3 having a range 54.9 to 201.3 mg/L with an average value of 123.53 mg/L. The concentration of SO_4 shows a minimum value of 0.31 up to 2.43 mg/L with an average of 0.79 mg/L. Cl is having 0.42 to 1.48 mg/L with an average value of 0.77 mg/L. Among anions, the average abundance trend found was in the order of $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ (Table 7), on the other hand, the dominant cations were in the order of $\text{Ca} > \text{Na} > \text{Mg} > \text{K}$ (Table 8).



Table 6 Physico-chemical parameters of groundwater of the study area.

Sample Code	Sampling Area	Sampling Location	Parameters concentration			
			T°C	pH	E.C. ($\mu\text{S}/\text{cm}$)	TDS (mg/L)
F1	2	Gadjam Danay	27.8	6.40	342	171
F2	1	Gabarai	29.1	6.92	189	95
F3	1	Meringue	27.9	7.51	358	179
F4	1	Madalam	29.1	7.18	247	123
F5	1	Mogoze	29.6	6.62	325	162
F6	2	Vounaloum	29.3	6.65	99	49
F7	2	Balgam	28.8	7.22	88	44
F8	2	Djafga	28.1	7.25	89	44
F9	2	Begue	29.3	7.53	111	55
F10	3	Bagarai	29.4	6.28	314	158
		Mean	28.8	6.96	216	108

Table 7 cations physico-chemical parameters of groundwater of the study area.

Sample Code	Sampling Area	Sampling Location	Parameters concentration (mg/L)					
			Ca	Na	K	Mg	NH ₄	Fe ²⁺
F1	2	Gadjam Danay	27.30	4.05	5.77	5.91	0.05	2.88
F2	1	Gabarai	15.29	13.64	2.20	2.52	0.05	0.56
F3	1	Meringue	20.45	50.43	2.69	3.96	0.05	0.003
F4	1	Madalam	20.67	19.45	2.19	4.28	0.05	0.24
F5	1	Mogoze	41.08	12.65	1.90	6.74	0.05	0.43
F6	2	Vounaloum	6.88	5.35	1.62	2.49	0.05	1.05
F7	2	Balgam	7.01	5.18	2.21	1.87	0.05	0.23
F8	2	Djafga	6.02	7.61	2.44	2.19	0.05	0.07
F9	2	Begue	9.35	7.13	1.99	2.58	0.05	0.081
F10	3	Bagarai	31.66	15.49	5.03	6.77	0.05	2.75
		Mean	18.57	14.10	2.80	3.93	0.05	0.83

Table 8 Anions physico-chemical parameters of groundwater of the study area.

Sample Code	Sampling Area	Sampling Location	Parameters concentration (mg/L)						
			HCO ₃	CO ₃	NO ₂	NO ₃	PO ₄	Cl ⁻	SO ₄
F1	2	Gadjam Danay	158.60	3.00	0.05	0.05	0.05	0.62	0.45
F2	1	Gabarai	103.70	3.00	0.05	0.05	0.05	0.42	0.70
F3	1	Meringue	192.20	3.00	0.05	0.05	0.05	0.79	2.43
F4	1	Madalam	140.30	3.00	0.05	0.60	0.05	0.98	1.07
F5	1	Mogoze	201.30	3.00	0.05	0.05	0.05	1.24	0.46
F6	2	Vounaloum	67.10	3.00	0.05	0.05	0.05	1.48	0.89
F7	2	Balgam	54.90	3.00	0.05	0.05	0.05	0.46	0.47
F8	2	Djafga	54.90	3.00	0.05	0.37	0.05	0.46	0.47
F9	2	Begue	73.20	3.00	0.05	0.05	0.05	0.57	0.65
F10	3	Bagarai	189.10	3.00	0.05	0.05	0.05	0.63	0.31
		Mean	123.53	3.00	0.05	0.14	0.05	0.77	0.79

Classification of Waters According to PIPER

Figure 10 shows the results of groundwater analyses on the Piper diagram according to different types of water. Three hydrogeochemical facies can be distinguished from this diagram: the calcium and magnesium bicarbonate facies, which is the most dominant with 60% of the water from the boreholes studied. This facies results from the dissolution of calcium carbonate minerals in particular, but also magnesium-containing silicates; the calcium bicarbonate facies, which comes in second place and accounts for 30% of water samples from the study area; and finally, the sodium and potassium carbonate facies, which accounts for 10% of water points.

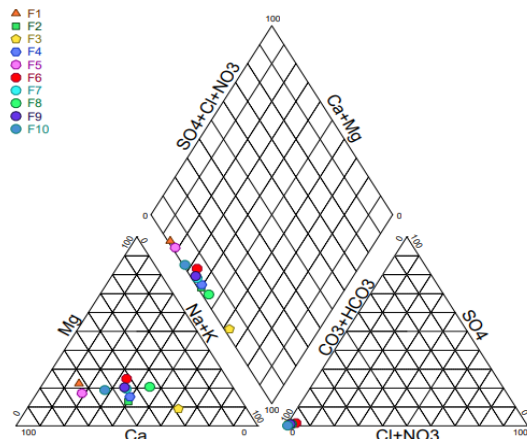


Fig. 10 Distribution of groundwater samples in the Study Area Using the Piper Diagram.

Classification of Water in the Yagoua Rice-Growing Basin by Calculation of the WQI

Using the WHO standard and formulas 4 and 5, the relative weight of each physicochemical parameter was calculated (Table 9).

Table 9 Values of the relative weights of physicochemical parameters.

Parameter	Si	1/Si	K	Wi
Calcium	100	0.010	0.049	0.0005
Magnésium	50	0.020	0.049	0.0010
Sodium	150	0.007	0.049	0.0003
Potassium	12	0.083	0.049	0.0040
Ammonium	0.5	2.000	0.049	0.0970
Chlore	200	0.005	0.049	0.0002
Sulfate	250	0.004	0.049	0.0002
Carbonate	30	0.033	0.049	0.0016
Bicarbonate	305	0.003	0.049	0.0002
Nitrate	50	0.020	0.049	0.0010
Nitrite	0.1	10.000	0.049	0.4851
Fluorure	0.7	1.429	0.049	0.0693
Phosphate	0.5	2.000	0.049	0.0970
Fer	0.2	5.000	0.049	0.2426

Quality Assessment Scale (Qi)

The quality assessment scale was calculated for all analyzed samples using formula 6. The results obtained are summarized in Table 10.

Table 10 Values of (Qi) calculated for the analyzed samples.

Parameter	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Calcium	27.30	15.29	20.50	20.67	41.08	6.88	7.01	6.02	9.35	31.66
Magnésium	11.82	5.04	7.92	8.56	13.48	4.98	3.74	4.38	5.16	13.54
Sodium	2.700	9.093	33.600	12.970	8.433	3.567	3.453	5.073	4.753	10.327
Potassium	48.08	18.33	22.4	18.25	15.83	13.5	18.42	20.333	16.583	41.917
Ammonium	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Chlore	0.310	0.210	0.400	0.490	0.620	0.740	0.230	0.230	0.285	0.315
Sulfate	0.180	0.280	0.970	0.428	0.184	0.356	0.188	0.188	0.260	0.124
Carbonate	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Bicarbonate	52.00	34.00	63.00	46.00	66.00	22.00	18.00	18.00	24.00	62.00
Nitrate	0.10	0.10	0.10	1.20	0.10	0.10	0.10	0.74	0.10	0.10
Nitrite	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Fluorure	25.710	62.860	183.000	101.400	30.000	34.290	42.860	42.857	48.571	24.286
Phosphate	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Fer	1440.0	280.0	1.3	120.0	215.0	525.0	115.0	35.0	40.5	1375.0



Water Quality Index (WQI) and Classification

Groundwater samples and their WQI values are presented in Table 11. Therefore, the groundwater quality status can be categorized into five types based on WQI values, namely excellent water (<50), good water (50–100), poor water (100–200), very poor water (200–300) and water unsuitable for drinking (>300) (Table 4). The computed WQI values for the groundwater samples in the study area ranged from 39.32 to 39.48 (Table 11), among these, 30% (03 wells) of the samples fall under the Good quality category, 20% of samples (02 wells) fell under Poor and Very poor-quality water category and 30% (03 wells) of the

samples showed Non-drinking water category. According to research by Aher (2012); Deshpande et al. (2014) and Aher and Deshpande (2015), the boreholes having poor and very poor water, indicating effective leaching, dissolution process and the rock–water interaction process is the main source for degrading the groundwater quality. This result is similar to that obtained by Tyagi et al. (2013) and then Das and Chaudhary (2021), working respectively on water quality assessment in terms of water quality index and in the application of water quality index for groundwater quality assessment of Biratnagar in Nepal.

Table 11 WQI water classification.

Sample	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
WQI	377.50	98.58	39.32	62.45	80.55	155.99	57.16	37.77	39.48	361.61
Water quality	Non-drinking water	Very poor quality	Good quality	Poor quality	Very poor quality	Non-drinking water	Poor quality	Good quality	Good quality	Non-drinking water

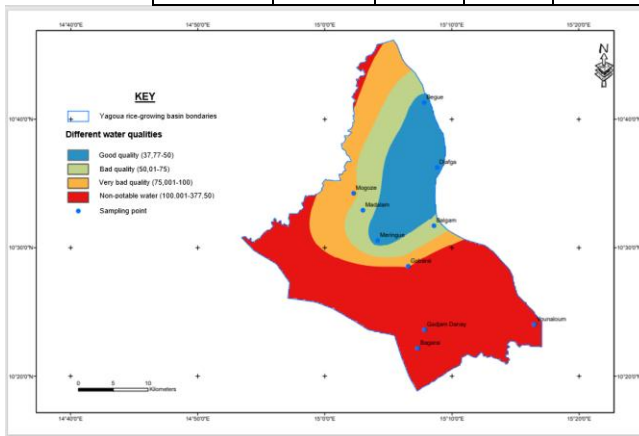


Fig. 11 Water quality index map of the study area

Conclusions

Protection of groundwater resources is essential to ensure quality and sustainable use. However, predicting vulnerability to anthropogenic pollution can be difficult where data are limited. This is particularly true in the Sahel region of Africa, which has a rapidly growing population and increasing water demands. The aim of this study was to assess the vulnerability and physicochemical quality of

groundwater in the Yagoua rice-growing basin. Specifically, the work involved: first, producing a pollution vulnerability map of the area using the modified DRASTIC method; second, subdividing the study area according to the vulnerability results to guide sampling; and third, classifying the basin's water using the Piper diagram and the Water Quality Index (WQI). Intrinsic vulnerability mapping divided the Yagoua rice-growing basin into three zones: zone 1 (very low vulnerability), zone 2 (low vulnerability), and zone 3 (medium vulnerability). Sampling was conducted across all zones. The physicochemical analysis results showed that pollutant concentrations exceed admissible standard limits and that the contamination does not originate from the land surface; even zones of very low vulnerability are affected. Regarding groundwater classification, the Piper diagram indicated that 60% of the analysed water has a calcium-magnesium bicarbonate facies, suggesting that the groundwater originates from limestone aquifers. Mapping of the WQI reveals that 53% of the study area has non-potable groundwater, primarily due to high iron content, rendering it unfit for consumption. The current study suggests that the groundwater of the area under deteriorated water

quality needs treatment before consumption and also to be protected from the perils of geogenic/anthropogenic contamination. According, Rusydi et al. (2021), iron toxicity in rice is a significant challenge, especially under prolonged flooding conditions. Symptoms include appearance of small brown spots on leaf lamina, bronzing of leaf tips and root decay. Affected roots often exhibit a dark brown to black coating, stunted growth and reduced tillering. Finally, this research demonstrated the effectiveness of assessing aquifer vulnerability and the value of monitoring groundwater contamination, particularly in terms toward improving spatial and temporal resolution.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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