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Water Quality Index-Based Assessment of Groundwater Quality in Laï City, Southern Chad

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Abstract

The Water Quality Index (WQI) is widely used as a reliable method for evaluating groundwater quality by integrating various physicochemical and bacteriological parameters into a single, comprehensive indicator. This study aims to evaluate groundwater quality in Laï City using the Water Quality Index (WQI). Specifically, it assesses the suitability of groundwater for drinking purposes across different locations within the study area. A total of 50 groundwater samples were collected and analyzed to determine the concentrations of major cations and anions. Next, the Water Quality Index (WQI) was calculated to assess the overall suitability of groundwater for human consumption. The findings indicate that groundwater in the study area is primarily characterized by a calcium-magnesium-chloride-sulfate hydrochemical facies. The Water Quality Index (WQI) assessment further revealed that 58% of the groundwater samples were classified as excellent in quality, whereas 22% were categorized as good. Conversely, 4% of the samples exhibited poor quality, and 6% fell within the very poor category. The remaining 10% were considered unsuitable for drinking purposes. In particular, groundwater from the areas surrounding Madjang and Sategui was identified as unsuitable for human consumption, indicating that its physicochemical characteristics do not meet the established drinking water quality standards. This observation points to possible anthropogenic contamination resulting from agricultural runoff and irrigation return flows associated with farming activities along the Logone River. Urgent implementation of effective groundwater management strategies and comprehensive planning measures is essential to safeguard groundwater resources and promote sustainable development in Laï City. Further studies should incorporate additional field investigations to evaluate the bacteriological quality of groundwater resources in Laï City.

Keywords

Groundwater Geochemistry, Water Quality Index, Laï City, Southern Chad

1. Introduction

Groundwater resources play a vital role worldwide by supporting economic development, safeguarding human health, and promoting social well-being [1]-[3]. In Chad, groundwater represents a major source of drinking water, with approximately 20% of total groundwater withdrawals allocated to human consumption, while the remaining 80% is primarily used for agricultural purposes [4]. Groundwater contamination resulting from both anthropogenic activities and natural processes is a global concern [5]-[7]. Among the various sources of contamination, anthropogenic activities, particularly agricultural practices, industrial discharges, and improper waste disposal, are major contributors to groundwater pollution [8]-[10]. However, the presence of these contaminants in groundwater poses a critical public health risk, as several studies have demonstrated [11]-[13]. Therefore, assessing pollution indices to control groundwater quality is crucial for effective water management and protection.

Over the past few decades, various methods have been developed to assess groundwater quality for drinking purposes. Among these, the Water Quality Index (WQI) has gained widespread acceptance as an effective tool for evaluating groundwater quality by integrating physicochemical and bacteriological parameters into a single index [14]. Consequently, it has been widely applied to evaluate groundwater quality status across many countries [15]-[18]. In addition, the WQI provides reliable and accessible information about water quality to various stakeholders, including policymakers and regulatory authorities [19]. For instance, Ram *et al.* (2021) [20] employed the Water Quality Index (WQI) to evaluate the suitability of groundwater for human consumption in Mahoba District, Uttar Pradesh, India; the WQI values obtained ranged from 4.75 to 115.93, indicating that groundwater was generally safe and potable, except in a few localized areas. In the same way, Kawo and Karuppannan (2018) [21] reported that WQI ranged between the good to excellent categories for the majority of the samples in Modjo River Basin, central Ethiopia. A study carried out by Safo-Adu (2022) [22] assessed groundwater quality at a waste treatment facility (WTF) in Shama Municipality in Ghana using the WQI model approach, and they reported that the WTF groundwater was unsuitable for use.

In Chad, several studies have assessed groundwater quality and its suitability for drinking and/or irrigation purposes [23]-[26]. However, the application of the Water Quality Index (WQI) to evaluate groundwater quality remains relatively limited. However, Kadjangaba *et al.* (2022) [24] used WQI to assess groundwater quality suitability for drinking and irrigation purposes in the City of Sarh, southern CHAD. Literature review revealed that there is no study using WQI to evalu-

ate Groundwater quality in Laï City, although its importance to describe groundwater quality. In addition, data on groundwater quality in Laï City is limited. The present study is carried out to fill the gap reported above. The goal of this work is to assess the groundwater quality status in Laï City via WQI application. Specifically, the study determined the suitability of groundwater for drinking purposes at different locations in the study area. A comprehensive assessment of the WQI is essential for establishing a baseline record to guide future water quality monitoring and remediation efforts in the study area.

2. Materials and Methods

2.1. Study Area

Laï, the capital of the Tandjilé Region, is located in southern Chad. The study area, encompassing Laï city, covers approximately 151.12 km^2 and is shown in **Figure 1**. Geographically, the study area lies between latitudes 8˚31'20"N and 9˚20'30"N and longitudes 16˚13'40"E and 16˚22'20"E. The area is characterized by the presence of three major rivers: The Logone, Tandjilé, and Kabia. Among these, the Logone River is the most prominent, originating in the central highlands of Cameroon and flowing northward toward Lake Chad. Meteorological data, including precipitation and temperature records for the period 1991-2023, were obtained from the National Agency of Meteorology. These data indicate that the region receives an average annual rainfall of approximately 1008 mm, with the rainy season extending over seven months, from April to October. The mean annual temperature ranges from 27.1˚C to 29.2˚C, while the elevation of the study area varies between 353 and 374 m above sea level. The geology of the Tandjilé Region, which encompasses the study area, is characterized by two major sedimentary formations: The Tertiary Continental Terminal formation and Quaternary fluvial-lacustrine deposits [27]. The hydrogeological setting is characterized by aquifers occurring in continuous sedimentary formations, which may be unconfined, semi-confined, or confined, as well as in discontinuous crystalline basement formations [28].

2.2. Sampling and Analysis

A total of 50 groundwater sampling points were selected across different districts of Laï city. The geographical coordinates of the boreholes and other water points for drinking purposes were recorded using a Garmin GPS device. The wells and boreholes identified within the study area (Laï City) and its surrounding localities are primarily used for domestic water supply. The depth to the groundwater table varies across the study area, ranging from 1.5 to 9.0 m below ground level. Relatively shallow groundwater levels (1.5 - 4.5 m) are observed in the southwestern and northwestern sectors, particularly around Lai, Sategui, and Gabri Mbassa. Conversely, the southeastern and northeastern sectors, including Djoun, Totalie, and Madjang, are characterized by deeper groundwater levels, with depths ranging from 4.5 to 9.0 m. Following standard sampling protocols, all boreholes were

continuously pumped for 20 minutes to eliminate the influence of stagnant water within the well and pipeline systems. Groundwater samples were then collected in pre-cleaned, 1-L polyethylene bottles, which were securely sealed immediately after collection. Field measurements of temperature, pH, turbidity, Total dissovel Solid (TDS) and electrical conductivity (EC) were performed on-site using a WTW™ Multi 3430 multiparameter meter. Subsequently, the samples were properly labelled, stored at 4˚C, and transported to the LHGR Laboratory at the University of N'Djamena for cation and anion analyses. The major cations, calcium (Ca^{2+}) and magnesium (Mg^{2+}), ammonium (NH_4^+), iron (Fe^{2+}), total dissolved solids, and total hardness (TH) were determined by the EDTA titration method, while sodium (Na^+) and potassium (K^+) concentrations were measured using a flame photometer (S-931). The major anions, including chloride (Cl^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-), were quantified by titration using a TitraLab AT1000 Series instrument. Sulfate (SO_4^{2-}) and nitrate (NO_3^-) concentrations were determined using a DR 6000 UV-visible spectrophotometer. The ionic balance error (IBE) method was applied in this study to assess the reliability and accuracy of the analytical results for the measured water quality parameters. The following equation was used to calculate the IBE.

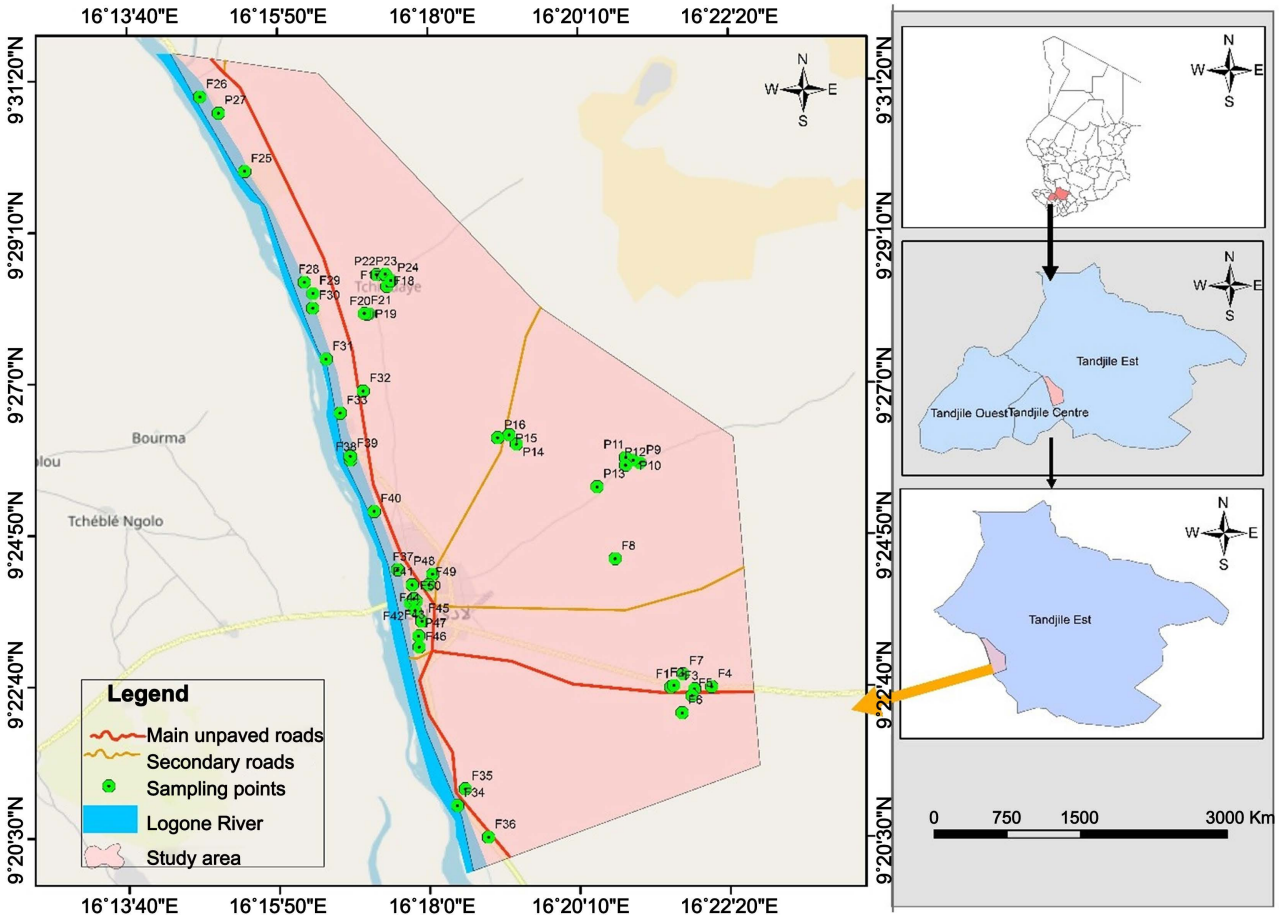

Figure 1. Study site and sampling locations.

$$\text{IBE} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100 \quad (1)$$

The IBE values calculated in this study were found to fall within the acceptable threshold of ±10%, indicating satisfactory analytical accuracy [29].

2.3. Water Quality Index Calculation

Water Quality Index (WQI) is a rating that reflects the composite influence of different water quality parameters [14] [30]. It provides a simplified means of synthesizing various physicochemical parameters into an overall measure of water quality [14]. In this study, the WQI of the groundwater was calculated using the model proposed by Dhakad *et al.* (2008) [31]. This model has been widely applied in previous studies to assess the physicochemical quality of groundwater [22] [32] [33]. Three steps are mandatory in order to calculate the WQI: (1) the quality rating (Qi) for each water quality parameter was calculated using Equation (1), (2) the relative weight (Wi) of each parameter was determined using Equation (2), (3) the WQI was computed by summing the products of the quality ratings and their corresponding relative weights, as expressed in Equation (3).

$$Q_i = \left(\frac{V_a}{V_s}\right) \times 100 \quad (2)$$

$$W_i = \frac{w_i}{\sum w_i} \quad (3)$$

$$\text{WQI} = \sum \left(Q_i W_i\right) \quad (4)$$

where Q_i represents the quality rating of each parameter, V_a denotes the mean concentration of each water quality parameter in groundwater, V_s refers to the corresponding standard value recommended by the WHO (2011) [34], w_i represents the assigned weight of each parameter, and W_i denotes its relative weight.

In this work, the WQI was calculated using 15 physicochemical parameters, as presented in **Table 1**. Each parameter was assigned a weight according to its potential health impacts and its relative importance in determining groundwater suitability for drinking purposes [15].

Table 1. Relative weighting of groundwater quality parameters.

Paramters	Weight (w_i)	Relative Weight (W_i)	WHO standard value [34]
T (˚C)	1	0.02	25.00
pH	3	0.06	8.50
EC (µS/cm)	3	0.06	1000.00
Ca^{2+} (mg/L)	3	0.06	75.00
Mg^{2+} (mg/l)	3	0.06	50.00
Na^{+} (mg/L)	3	0.06	250.00
K^{+} (mg/L)	3	0.06	55.00

Continued

Cl^- (mg/L)	5	0.09	250.00
SO_4^{2-} (mg/L)	5	0.09	500.00
NO_3^- (mg/L)	5	0.09	50.00
TDS (ppm)	5	0.09	500.00
TH (mg/L)	3	0.06	500.00
Turbidity (NTU)	5	0.09	5.00
NH_4^+ (mg/L)	5	0.09	1.50
Fe^{2+} (mg/L)	1	0.02	0.30
	$\sum 53$		

Following WQI calculation, groundwater quality in the study area was evaluated by comparing the resulting values with the classification criteria proposed by Chung *et al.* (2015) [35], as presented in Table 2.

Table 2. Water quality classification based on WQI according to Chung *et al.* (2015) [35].

WQI range	Type of water
<50	Excellent water quality
50 - 100	Good water quality
100 - 200	Poor water quality
200 - 300	Very Poor water quality
>300	Water unsuitable for drinking purposes

3. Result and Discussion

3.1. Physicochemical Properties of Groundwater

Table 3 presents the minimum, maximum, and mean values of the physicochemical parameters of groundwater samples measured both in situ and in the laboratory, alongside their comparison with the WHO (2011) [34] guidelines. The pH values ranged from 5.6 to 7.6, with a mean of 6.6. The electrical conductivity (EC) of groundwater samples in the study area ranged from 25 to 1031 µS/cm, with an average of 187.9 µS/cm. The maximum EC value exceeded the WHO (2011) [34] guideline value, indicating elevated concentrations of dissolved ions. The total dissolved solids (TDS) concentration in groundwater samples from the study area ranged from 11 to 518 ppm, with a mean value of 91.3 ppm (Table 2). The maximum TDS concentration exceeded the acceptable limit established by WHO (2011) [34]. Descriptive statistical analysis revealed that the concentrations of major cations in groundwater samples from Laï City (Table 2) ranged from 7.8 to 196 mg/L for Ca^{2+}, 0.9 to 80.7 mg/L for Mg^{2+}, 0.2 to 36.3 mg/L for Na^+, 0.0 to 0.8 mg/L for Fe^{2+}, and 0.1 to 6.2 mg/L for K^+. Regarding anions in groundwater, it is observed that bicarbonate (HCO_3^-) concentrations in groundwater ranged from 0.0 to 610 mg/L, with a mean value of 104.6 mg/L. Chloride (Cl^-) concentrations

varied between 23 and 241 mg/L, with an average of 80.4 mg/L. All groundwater samples had chloride concentrations below the WHO (2011) [34] guideline limit of 250 mg/L.

Table 3. Statistical summary of groundwater quality parameters.

Parameters	Unit	Min	Max	Mean	Standard deviation	Acceptable limit (AL)-WHO [34]
Calcium (Ca^{2+})	mg/L	7.8	196.0	45.0	22.5	25
Magnésium (Mg^{2+})	mg/L	0.9	80.7	28.8	12.1	50
Sodium (Na^{+})	mg/L	0.2	36.3	13.9	8.7	250
Potassium (K^{+})	mg/L	0.1	6.2	2.2	1.6	55
Bicarbonates (HCO_3^-)	mg/L	0.0	610.0	121.9	104.6	-
Chlorides (Cl^{-})	mg/L	23.0	241.7	80.4	26.2	250
Sulfates (SO_4^{2-})	mg/L	0.0	106.0	12.2	13.3	500
Nitrates (NO_3^{-})	mg/L	0.0	68.2	18.0	15.7	50
Total Hardness (TH)	mg/L	1.0	25.0	3.6	2.2	500
Ammonium (NH_4^+)	mg/L	0.0	3.9	0.8	1.0	1.5
Ferrous ions (Fe^{2+})	mg/L	0.0	5.8	0.8	0.9	0.3
PH	[H_3O^+]	5.6	7.6	6.6	0.4	6.5 - 8.5
Total dissolved solid (TDS)	ppm	11.0	518.0	91.3	93.9	500
Electrical conductivity (EC)	µS/cm	25.0	1031.0	183.0	187.9	1000

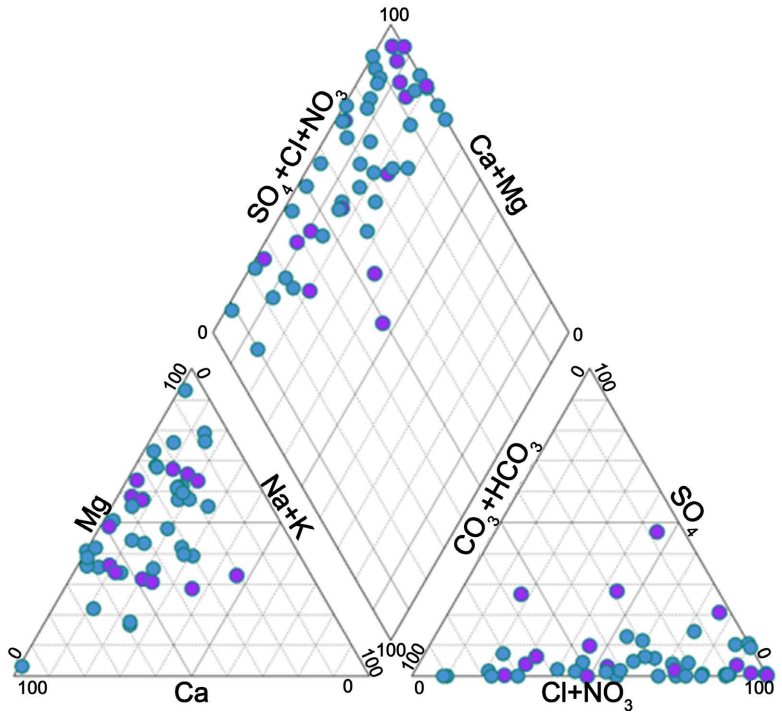

Figure 2. Piper diagram illustrating the hydrochemical facies of groundwater samples in the study area.

The results of the chemical analyses were represented on a Piper diagram (Figure 2) to identify and classify the different groundwater types. The Piper diagram is a valuable tool for assessing the geochemical evolution of groundwater types and identifying the factors influencing groundwater chemistry [36]. According to the Piper diagram (Figure 2), the groundwater in the study area is predominantly characterized by a calcium-magnesium-chloride-sulfate hydrochemical facies.

3.2. Assessment of Groundwater Quality for Drinking Purposes Using WQI Index

The calculated groundwater Water Quality Index (WQI) values for individual groundwater samples are presented in Table 4. The classification of groundwater quality based on the Water Quality Index (WQI) values (Table 5) revealed that 58% of the samples fall within the excellent water quality category. These samples were collected from Laï, Dray Mbassa, Djongo, and Tchindaî, as illustrated by the spatial distribution map of the WQI across the study area (Figure 3). This classification suggests that groundwater in these locations exhibits favorable physicochemical characteristics for drinking purposes. Furthermore, 22% of the samples were classified as good quality, while 4% were categorized as poor quality and 6% as very poor quality. The remaining 10% of the samples were classified as unsuitable for drinking purposes. In particular, the areas surrounding Madjang and Sategui exhibit groundwater quality unsuitable for drinking, indicating that the groundwater collected from these areas does not meet the required physicochemical standards for drinking water. The elevated turbidity and total dissolved solids (TDS) concentrations recorded in Madjang and Sategui may account for the poor groundwater quality in these areas. Notably, Sategui is situated close to the Logone River (Figure 1), where irrigated agricultural activities are widespread. Consequently, agricultural runoff and irrigation return flows may contribute to groundwater contamination through the infiltration of drainage water during aquifer recharge. The findings of the present study differ from those reported in previous investigations that employed the same method for calculating the Water Quality Index (WQI). For instance, Vasanthavigar *et al.* (2010) [15] found that only 4% of groundwater samples collected from wells were classified as having excellent physicochemical quality, whereas 60% were categorized as having poor water quality. Similarly, Kumar *et al.* (2015) [37] reported that only 20.8% of groundwater samples collected from boreholes fell within the excellent water quality category.

Table 4. Calculation of the Water Quality Index (WQI) for each Individual water sample.

Sample number	WQI	Type of water	Sample number	WQI	Type of water
1	22.74	Excellent water	26	26.64	Excellent water
2	84.28	Good water	27	358.73	Water unsuitable for drinking purposes

Continued

3	31.90	Excellent water	28	35.88	Excellent water
4	255.59	Very poor water	29	45.86	Excellent water
5	19.91	Excellent water	30	56.98	Good water
6	18.98	Excellent water	31	38.96	Excellent water
7	34.46	Excellent water	32	37.28	Excellent water
8	32.87	Excellent water	33	43.53	Excellent water
9	239.88	Very poor water	34	74.47	Good water
10	168.65	Poor water	35	48.86	Excellent water
11	47.17	Excellent water	36	56.68	Good water
12	33.63	Excellent water	37	52.90	Good water
13	145.75	Poor water	38	42.57	Excellent water
14	355.64	Water unsuitable for drinking purposes	39	42.16	Excellent water
15	40.96	Excellent water	40	69.74	Good water
16	2 294.41	Water unsuitable for drinking purposes	41	82.85	Good water
17	20.79	Excellent water	42	22.19	Excellent water
18	22.54	Excellent water	43	39.77	Excellent water
19	31.73	Excellent water	44	33.35	Excellent water
20	216.49	Very poor water	45	75.99	Good water
21	32.53	Excellent water	46	44.69	Excellent water
22	35.26	Excellent water	47	30.04	Excellent water
23	720.35	Water unsuitable for drinking purposes	48	54.33	Good water
24	318.53	Water unsuitable for drinking purposes	49	54.49	Good water
25	96.45	Good water	50	28.64	Excellent water

Table 5. Water quality classification based on WQI value.

WQI range	Water Quality Index (WQI) class	Number of samples	% of samples	Well locations
<50	Excellent quality	29	58%	Laï. Dray Mbassa. Djongo. Tchindaî
50 - 100	Good quality	11	22%	Gabri Mbassa
100 - 200	Poor quality	2	4%	Totalie
200 - 300	Very Poor quality	3	6%	Djoun
>300	Water unsuitable for drinking purposes	5	10%	Madjang. Sategui

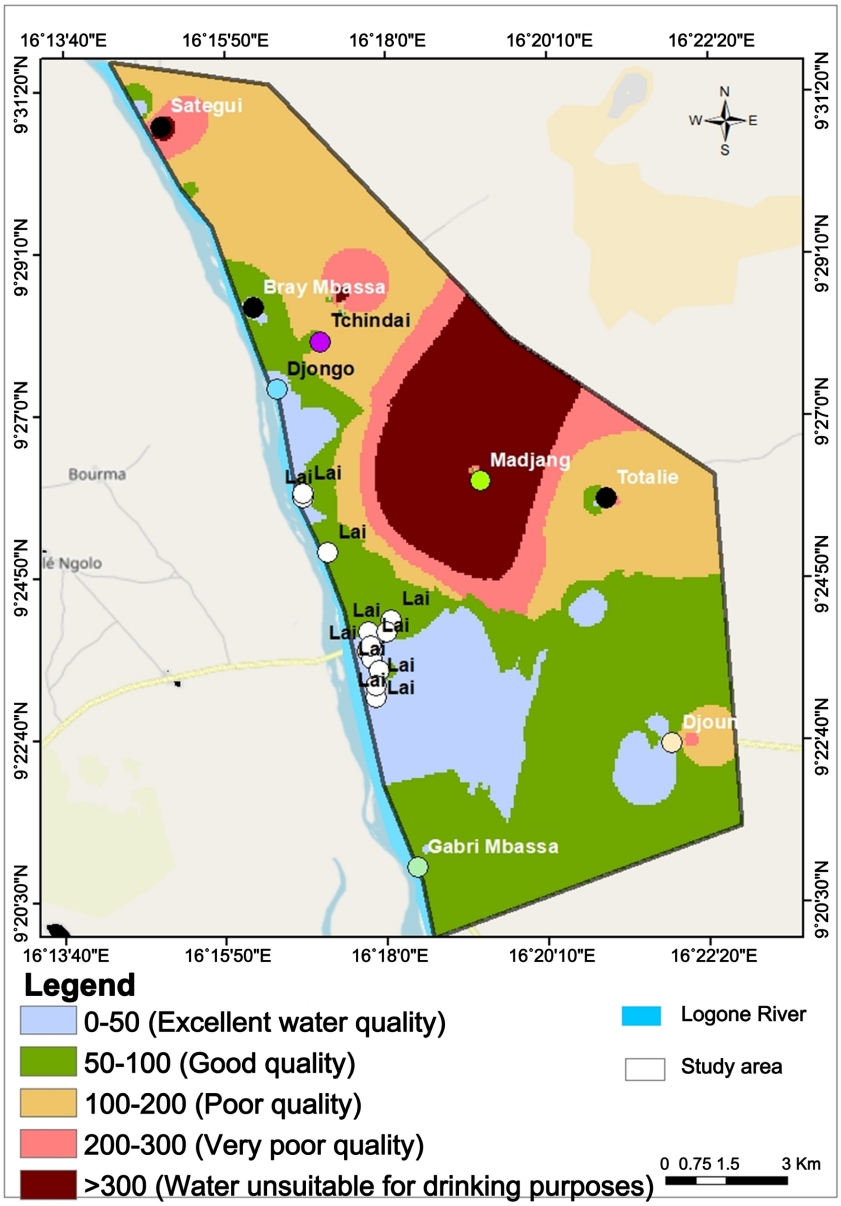

Figure 3. Spatial distribution of the water quality index (WQI) in Laï City, Southern Chad.

3.3. Correlation Matrix of Groundwater Quality Parameters

The Pearson correlation matrix illustrating the relationships among the physico-chemical parameters is presented in Table 6. Correlation matrix analysis is a useful tool for investigating the origin of groundwater mineralization by identifying and evaluating the relationships between pairs of physicochemical parameters. These relationships are assessed using Pearson's correlation coefficient (r), which quantifies the strength and direction of the association between two variables. A coefficient close to +1 indicates a strong positive correlation, whereas a value close to −1 indicates a strong negative correlation. The correlation matrix presented in Table 6 reveals negative to strong correlations among the following water quality parameters:

- Potassium and sodium (r = 0.96), indicating a very strong positive correlation.
- Sodium and electrical conductivity (r= 0.81), showing a strong positive correlation.
- Potassium and electrical conductivity (r = 0.77), also exhibiting a strong positive correlation.
- Bicarbonate and magnesium (r = 0.62), indicating a moderate positive correlation.
- Bicarbonate and calcium (r = 0.6), likewise showing a moderate positive correlation.

In contrast, chloride, sulfate, nitrate, ammonium, and iron exhibit no substantial correlation with the other parameters analyzed.

Table 6. Correlation matrix of groundwater quality parameters.

	T˚C	pH	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3^{-}	TDS	TH	Tubidity	NH_4^{+}	Fe^{2+}
T˚C	1.00														
pH	−0.09	1.00													
EC	0.20	−0.29	1.00												
Ca^{2+}	−0.07	−0.34	0.36	1.00											
Mg^{2+}	0.27	0.06	0.15	0.09	1.00										
Na^{+}	0.12	−0.04	0.81	0.03	0.17	1.00									
K^{+}	0.15	−0.04	0.77	0.00	0.14	0.96	1.00								
Cl^{-}	−0.11	0.00	0.17	−0.05	0.04	0.27	0.36	1.00							
SO_4^{2-}	−0.27	−0.07	0.09	0.14	0.14	0.07	0.01	−0.13	1.00						
NO_3^{-}	0.22	−0.23	0.21	0.13	−0.07	0.21	0.18	−0.23	0.15	1.00					
TDS	0.21	−0.30	1.00	0.36	0.15	0.81	0.77	0.17	0.09	0.21	1.00				
TH	0.16	−0.38	0.77	0.55	0.32	0.56	0.51	0.03	0.25	0.26	0.77	1.00			
Turbidity	−0.27	0.12	−0.10	0.10	0.10	0.03	−0.12	−0.11	0.32	−0.17	−0.10	−0.07	1.00		
NH_4^{+}	0.55	0.15	0.28	−0.04	0.11	0.17	0.13	−0.12	−0.04	0.28	0.28	0.31	−0.20	1.00	
Fe^{2+}	−0.01	−0.03	−0.21	0.04	0.42	−0.21	−0.29	−0.24	0.32	−0.08	−0.21	−0.10	0.53	−0.21	1.00

4. Conclusion

The Water Quality Index (WQI) is widely recognized as an effective tool for assessing groundwater quality by combining physicochemical and bacteriological parameters into a single composite index. The present study assessed the suitability of groundwater for drinking purposes across various locations within Laï City. The Piper diagram indicates that groundwater in the study area is predominantly dominated by the calcium-magnesium-chloride-sulfate hydrochemical facies. The classification of groundwater quality based on the Water Quality Index (WQI) revealed that 58% of the samples exhibited excellent water quality, while 22% were classified as good. In contrast, 4% and 6% of the samples fell into the poor and very poor water quality categories, respectively. The remaining 10% were deemed

unsuitable for drinking purposes. Notably, groundwater in the vicinity of Madjang and Sategui was found to be unsuitable for human consumption, suggesting that the water in these areas does not comply with the established physicochemical standards for drinking water. The WQI results indicate that Sategui and Madjang have a higher proportion of groundwater samples falling within the poor-quality category, exceeding the acceptable threshold reported by Chung *et al.* (2015) [35]. This finding suggests potential anthropogenic impacts associated with agricultural runoff and irrigation return flows from agricultural activities along the Logone River. Groundwater quality in Laï City is deteriorating to a concerning level, highlighting the urgent need for effective management and strategic planning to protect the fragile ecosystem and ensure sustainable development. Future research should include additional field investigations to assess the bacteriological quality of groundwater in Laï City and determine the microbiological safety of water intended for human consumption. Furthermore, long-term monitoring programs are recommended to ensure continuous assessment and effective management of groundwater quality over time in the study area.

Declaration of Generative AI and AI-Assisted Technologies in Manuscript Preparation

During manuscript preparation, the authors used Claude (Anthropics) solely for limited language editing of selected sentences in order to revise in order to improve clarity. No AI tool was used to generate research content, analyze data, interpret results, or prepare references; the ideas, argument, and intellectual contribution of the paper are entirely original. All AI-assisted suggestions were reviewed, revised where necessary, and approved by the authors, who take full responsibility for the final manuscript.

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Data Availability Statement

All relevant data are included in the paper or its Supplementary Information.

Author Contributions

Tidjani Bahar: conceptualization, investigation, methodology, resources, supervision, writing—original draft & editing. Mahamat Adoum Moussa: conceptualization, investigation, data curation, review draft and editing.

Conflicts of Interest

The authors declare there is no conflict of interest with respect to the research, authorship, and/or publication of this article.

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