



ISSN-1996-918X



Pak. J. Anal. Environ. Chem. Vol. 25, No. 2 (2024)

<http://doi.org/10.21743/pjaec/2024.12.11>

# Assessment of Industrial Impact on Groundwater Quality in N'Djamena, Chad

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Received 01 June 2023, Revised 29 July 2024, Accepted 01 August 2024

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## Abstract

This research study aims to quantify the physicochemical parameters of groundwater in the Farcha district of N'Djamena with a specific focus on evaluating contamination caused by chemical discharge and industrial residues. The methodology involved data collection, lithological borehole sections, and physicochemical analysis of electric conductivity (EC), pH, total dissolved solids (TDS), turbidity, iron concentration, alkalinity, hardness, phosphorus concentration, oil presence, concentrations of chlorine, silica, and hydrogen sulfide. Sample locations were deliberately selected proximately closest to potential sources of contamination. Twenty groundwater samples ( $n = 20$ ) were collected after flushing stagnant water from pipes. The resulting data indicated that the groundwater samples of studied areas were dominantly having neutral to slightly basic pH with modest mineralization ( $95.2 - 334 \mu\text{S}/\text{cm}$ ). The physicochemical quality parameters of the studied water samples were within the WHO permissible limits for drinking water. However, a noticeable increase in the amounts of iron and hydrogen sulfide was observed in sample E16 whilst sample E10 showed the elevated contents of silica and TDS. These contaminations are contributed by anthropogenic contamination from industrial wastewater infiltration and subsoil lithology. These concentrations are due to local geology or human activities, indicating vulnerability to pollution.

**Keywords:** Groundwater quality, N'Djamena, Industrial pollution, Aquifers Chad, Physicochemical parameters

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## Introduction

Groundwater is a significant source of drinking water in arid and semi-arid areas due to unpredictable weather conditions and a shortage of surface water [1]. Meanwhile, the long-term droughts and the lack of exploration for new water resources enhance the trend of water shortage in arid areas of the world. This might result from reduced precipitation followed by elevated evaporation [2]. The physicochemical qualities of groundwater have been contaminated

and degraded by agricultural, residential, and industrial toxic residues [2,3]. The scarcity of natural resources of water in N'Djamena can significantly be impacted due to rapid urbanization and pronounced industrial growth. The Chari River and its environs are the main sources of untreated wastewater that have a significant negative impact on the aquifers in the N'Djamena region. There are major risks to human health due to high levels of groundwater pollution. Likewise, expanding

installation and industrial activities may result in increase in the discharge of toxic waste to surrounding native surface water, changing their entire structure and integrity [4,5]. Recent investigations highlighted the effect of manufacturing processes of industries on the contamination of natural groundwater resources [4-6]. Similarly, industrial installations might potentially have a negative influence on groundwater quality [6]. When industrial residues like inorganic contaminants, hydrocarbons, and fertilizer residues seeped into the surrounding aquifer to contaminate the groundwater [5,7]. The statistical findings indicated the bed quality of groundwater which could directly affect residents in the N'Djamena area of Chad [8]. The groundwater of the study area is derived from the aquifers of the Quaternary strata and two Pliocene formations. These groundwater sources have a similar global pattern as reported in other regions [8]. The aquifers have limited availability of groundwater because of the high stress of wastewater arriving from industries and domestic activities. These facts may lead to the security of pure water supply for the local communities [5,7,8]. Furthermore, these groundwaters are unsafe for human consumption due to significant contamination. Consequently, this study is the first attempt to emphasize the current state of groundwater quality and how it could be impacted by industrial expansion in the N'djamena region. A critical knowledge gap was obvious to be addressed for the monitoring of groundwater contamination in the Farcha district within the industrial hub of N'Djamena.

In this context, the current study was designed to evaluate the physicochemical quality and the presence of iron in the groundwater linked with the industrial installations in the Farcha industrial zone in N'Djamena (Chad). In addition, the lithological profile of the targeted

industrial region was also thoroughly investigated. The proposed dual approach led to a comprehensive understanding of the Farcha district's geological structure and groundwater quality inside the N'Djamena region for both industrial growth and environmental control.

## **Materials and Methods**

### ***Chemicals and Reagents***

High-purity water was used during the experiment. The analytical grade reagent concentrated  $\text{HNO}_3$  for metal analysis, ascorbic acid 100g/L, silver nitrate ( $\text{AgNO}_3$ ), potassium chromate ( $\text{K}_2\text{CrO}_4$ ), methyl-orange and molybdate 3 reagent were obtained from the Laboratory of the National Society of Raffinate (SNR) at N'Djamena and purchased from Merck (Darmstadt, Germany) and Fluka (Buchs, Switzerland).

### ***Sampling Site***

N'Djamena is the administrative and political capital of Chad. It is situated in the west of the nation between  $12^\circ$ – $13^\circ$  N latitude and  $15^\circ$ – $16^\circ$  E longitude (Fig. 1). It was founded on April 22, 1900, and became a capital in 1919. It encompasses approximately 41,000 hectares with 3.1% of the total area of the country [9]. It is bordered to the west by Cameroon, to the north by Hadjer-Lamis, and to the south by Chari-Baguirmi. It is located near the meeting point of the Chari and Logone rivers. It is the largest municipality of Chad with a population of 1,390,309 and increased gradually with a 3.61% annual population growth rate [10]. The estimated population is expected to reach 2,541,000 by 2030. The city's main activities include trade, industry, livestock, agriculture, and fishing, with commerce employing 37.1% of the population. N'Djamena has a Sahelian climate with a short rainy season

from June to September and a dry season from April to November [11]. Between 1988 and 2018, rainfall ranged from 296 mm to 776 mm, with average annual temperatures reaching a maximum of 41.7°C and a minimum of 24°C. The city lies in the Lake Chad sedimentary basin, formed in the Early Cretaceous on a Precambrian basement, with geology mainly consisting of sedimentary series and Quaternary sand formations [12, 13]. The study region has distinguished hydrogeology with a complex groundwater system. The Pliocene deposits have a single water table, but the Quaternary horizons have two different water tables. In general, aquifers from the Quaternary layers are shallower. These may be more vulnerable to surface conditions and recent hydrological events. Meanwhile, those from the Pliocene framework primarily reflect a more ancient and deeper groundwater source. Thus, recognizing these different water levels is critical to managing groundwater efficiently, estimating water availability, and reducing pollution issues.

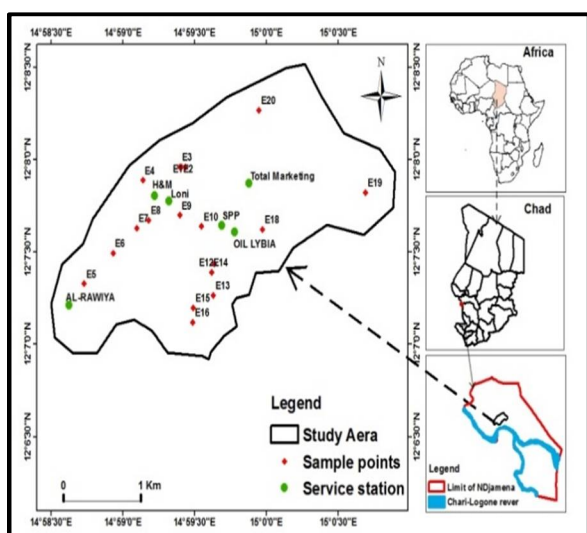


Figure 1. Geographic location of the study area

### Sample Collection

This study employed lithological log data from existing databases to develop a lithological profile using lithostratigraphic logs and borehole tests. Furthermore, a groundwater sample program was carried out in N'Djamena's industrial zone, with sampling locations chosen according to their accessibility and closeness to possible sources of contamination. Geographic coordinates were used to identify the sites from which a total of twenty groundwater samples ( $n = 20$ ) were collected. To ensure accuracy, the hand pumps and electric pumps were operated for three minutes to flush out any stagnant water in the pipes. The samples were collected in 1.5 L polyethylene bottles for physical and chemical analysis and preserved in a sampling box filled with ice to maintain a temperature of up to 4 °C. Similarly, separate 1.0 L polyethylene bottles were used to collect samples for cation analysis, which were treated on-site with 2.0 mL of concentrated  $\text{HNO}_3$ .

### Instrumentation

The detection of phosphorus and iron was conducted using a DR2800 spectrophotometer (Hach, USA). The pH was measured with a pH meter of Shanghai Beiyi Bioequip Information (Shanghai, China), and the electrical conductivity with a conductivity meter of Senseca Italy Srl (Caselle di Selvazzano, Italy).

### Physicochemical Parameters of Water: Instrumentation and Analytical Procedure

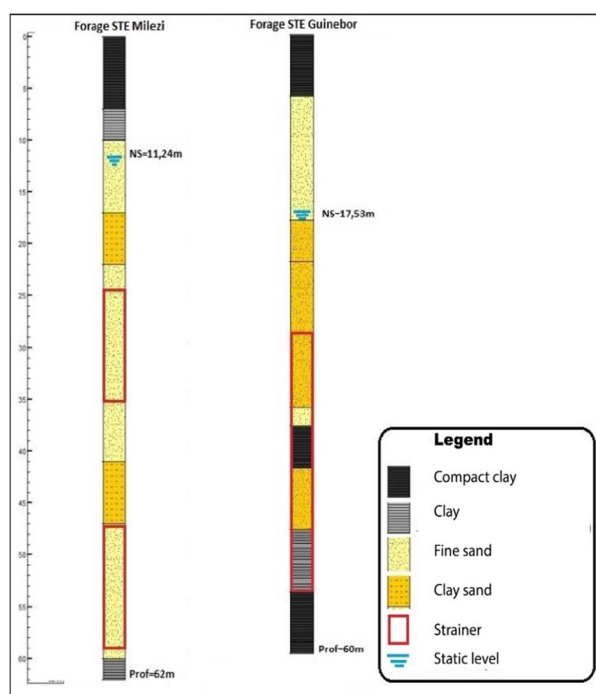
The qualitative chemical analyses were carried out at the analytical laboratory of the

National Society of Raffinate (SNR) at N'Djamena. The pH, total dissolved solids (TDS), temperature, electrical conductivity (EC), and appearance (turbidity) of the water samples were evaluated in situ using analytical methods [14]. The chloride was determined by the titrimetric method, while total hardness (TH) was determined by the ethylene diamine tetraacetic acid (EDTA) titrimetric method with Eriochrome black-T as an indicator [15]. Similarly, total suspended solids (TSS), total alkalinity (TA), chloride (Cl<sup>-</sup>), silica (Si), total phosphorus (TP), hydrogen sulfide (HS), oil, and iron (Fe) contents in collected water samples as reported elsewhere. The detection of phosphorus and iron was conducted using a DR2800 spectrophotometer with water samples collected in clean polyethylene containers, filtered, and mixed with specific reagents (PhosVer 3 for phosphorus and FerroVer for iron) before analysis. Analyses of Fe and TP were conducted in the Laboratory (SNR), N'Djamena. Calibration was performed with standard solutions and quality control measures included analyzing blank samples and standards, with results recorded in triplicate and compared to regulatory limits, ensuring accuracy and precision. Based on the measured parameters and the studied drillings, a statistical analysis is performed to evaluate the physicochemical quality of the water. This analysis involves identifying boreholes that exhibit high values or values that meet the World Health Organization (WHO) guidelines for drinking water for each specific parameter. Subsequently, the number of wells with elevated values for each parameter is calculated, as well as their frequencies, which represent the occurrence rate of wells with high values relative to the total number of wells for the given parameter.

## Results and Discussion

### *Litho-stratigraphic Characteristics*

The longitudinal profile-oriented northeast and southwest, derived from the drilling data, reveals distinct geological formations within the first 60 meters, comprising eight (8) different types of layers (Fig. 2). The lithology of the area exhibits vertical variations in facies, complicating the correlation between layers. Most localities feature compact clay formations at the surface. Superficial aquifer formations are found within some sandy layers beneath the clay. The litho-stratigraphic log of the Milezi borehole reveals eight types of layers, while the Guinebor borehole shows nine types. Generally, the water table aquifer is situated in the detrital levels of the Quaternary period, consisting mainly of alternating clay and sand layers, which overlay a thick clay formation [9]. It has been revealed that the soils in the area are of quaternary origin, comprising a mixture of sands, sandy clay alluvium, clays, clayey-sandy alluvium, and silts [8].



**Figure 2.** Representative hydrogeological profile of boreholes reaching the quaternary formations

This composition is not uniform, and changes based on the specific location being examined. Furthermore, the thickness of the surface clay layers varies across different areas. This variation in clay layer thickness is significant because it influences the existence of infiltration zones, which in turn affects the recharge of the surface water table. The presence or absence of these infiltration zones is crucial for determining the potential for groundwater recharge in different regions.

### *Physicochemical and Chemical Characteristics of Groundwater*

The quality of water can be affected by natural and anthropogenic sources that produce chemical components that might pollute groundwater directly or indirectly, followed by the lithological factor of the targeted location [16]. In fact, in the absence of anthropogenic influence, the chemical composition of water is governed by a variety of natural sources including geological,

biological, and hydrological processes. This combination leads to a diversity of physicochemical and microbiological qualities. The composition of water from the natural environment is highly variable depending on the geological layer from which it originates and the reactive chemicals it is likely to encounter during flow [17]. Thus, the quantitative and qualitative composition of groundwater in dissolved and suspended solids, either mineral or organic, determines its quality [18]. However, this quality can be altered when external substances come into contact with the groundwater [19]. This is the case with undesirable and toxic substances that make groundwater unfit for domestic consumption [20]. In the present work, the physicochemical analyses of groundwater in the study area focused on thirteen (13) parameters. The values of the physicochemical parameters of groundwater in the study area are summarized in Tables 1 and 2.

**Table 1.** Results of physicochemical parameters of groundwater in the study area.

Sample	Turbidity	pH	TSS	TDS	EC	Fe	TA	TH	TP	Oil	Cl	Si	HS
	NTU		mg/L	mg/L	$\mu\text{S/cm}$				mg/L				
E1	0.809	7.50	0	81.5	188.3	1.02	121.54	54.64	0.4	2.42	0.03	40.37	0.63
E2	0.415	7.49	4	47.5	193.4	0.13	126.60	54.64	0.2	1.05	0.03	46.63	0.32
E3	3.76	7.28	0	62.9	236.3	1.48	126.60	81.97	0.2	1.14	0.10	55.26	0.63
E4	0.102	7.50	0	61.2	160.4	0.02	106.35	114.75	0.2	2.01	0.09	38.56	0.32
E5	0.107	7.56	0	185.3	313.5	0.07	146.86	162.11	0.5	1.78	0.05	47.03	0.32
E6	0.141	7.55	0	73.4	168.7	0.06	146.86	63.75	0.1	1.26	0.07	38.86	0.63
E7	0.18	7.42	0	98.5	250.7	0.38	101.28	191.25	0.3	1.77	0.03	48.58	0.63
E8	0.125	7.40	0	68.1	170.7	0.04	101.28	63.75	0.4	1.45	0.05	26.85	0.32
E9	20.8	7.13	1	236.0	333.8	1.35	126.60	140.25	0.8	1.48	0.06	46.68	0.63
E10	0.798	7.23	0	315.0	276.8	0.02	126.60	127.50	0.2	1.36	0.04	115.7	0.63
E11	54.70	7.39	8	73.0	165.5	2.50	101.28	97.66	1.1	1.38	1.06	40.48	0.32
E12	6.36	7.43	0	113.2	175.4	3.24	101.28	97.66	0.5	1.26	0.07	48.41	0.32
E13	74.90	7.15	25	97.5	174.8	2.81	111.41	102.42	0.2	2.06	0.09	35.62	0.63
E14	34.90	7.30	4	96.6	168.2	1.20	106.35	100.04	0.1	1.78	0.06	108	0.63
E15	6.55	7.10	0	103.4	234.7	0.64	126.60	140.53	0.2	1.90	0.08	101.4	0.63
E16	0.178	7.35	0	73.1	166.7	4.86	96.22	102.42	0.4	1.11	1.18	55.75	0.63
E17	85.40	7.19	42	112.6	254.6	1.13	101.28	116.71	0.4	2.74	0.14	32.25	0.32
E18	4.94	7.42	0	47.0	95.2	0.04	55.20	50.02	0.3	1.01	0.03	31.71	0.63
E19	0.341	7.35	0	84.9	152.9	0.04	91.15	102.42	0.3	1.85	0.05	23.91	0.32
E20	0.372	7.51	0	91.2	132.8	0.07	81.02	64.31	0.2	1.04	0.07	84.91	0.63

Table 2. Statistic chemical parameters of groundwater.

Sample n=20	Parameters measured in (mg/L)								
	Fe	TA	TH	TP	Oil	Cl	Si	HS	TDS
Mean	1.06	110.12	101.44	0.35	1.59	0.17	53.35	0.51	106.10
Max	4.86	146.86	191.25	1.10	2.74	1.18	115.70	0.63	315.00
Min	0.02	55.2	50.02	0.10	1.01	0.03	23.91	0.32	47.00
Ecartype	1.34	21.8	38.06	0.24	0.48	0.33	27.07	0.16	66.45

The turbidity of groundwater in the study area ranges from 0.102 to 85.4 NTU, with an average of 14.79 NTU (Table 1). Turbidity is a measure of the cloudiness or haziness of water, typically caused by suspended solids that scatter light. High turbidity can reduce water quality and aesthetic value, interfere with disinfection, and indicate the presence of disease-causing organisms. Of the 20 water samples analyzed, 65% have turbidity less than 5 NTU, indicating that the maximum collected water samples are clear and within the WHO standard. However, fifteen percent of the samples have turbidity between 5 NTU and 30 NTU, categorized as slightly turbid, and another 15% have values greater than 50 NTU, classified as turbid. The WHO standard states that turbidity should be less than or equal to 5 NTU to ensure safe drinking water. Thus, 65% of the samples from the current study meet this standard, indicating that the majority of the groundwater is relatively clean and safe for consumption. However, the remaining samples exceed this threshold, with some reaching significantly higher turbidity levels. The elevated turbidity in these samples can be attributed to various factors, including the presence of colloidal compounds such as clays, rock debris, and microorganisms. Additionally, humic acids resulting from plant degradation or other forms of organic matter can contribute to turbidity.

The pH of the groundwater in the 20 boreholes studied is quite stable and close to neutral (pH = 7), with a few deviations. The

average pH of the studied areas was 7.36, with values ranging from 7.10 to 7.56. The neutrality of the groundwater indicated that these waters could be safe for the use of drinking and other domestic purposes. The pH levels were found to be consistent with those previously reported in the literature in identical regions [21 – 23]. For example, Abderamaneet al.[21] observed identical pH levels in the Chari Baguirmi region, while Ngaram[22] found comparable results in N'Djamena. These data showed a regional trend of neutral groundwater pH, implying that the groundwater in these regions is typically acceptable for drinking and other uses. The pH levels obtained in the studied region also comply with the national Chadian standard following the WHO standards for safe drinking water. Since the studied water with a neutral pH is less likely to have a negative impact on health or damage infrastructure, compliance with this regulation is essential for guaranteeing the health and safety of the local people. The characteristics of the rocks that groundwater passes through can account for the neutral pH values [23]. The minerals naturally present in aquifers may act as a buffer through hydrogeological reactions to keep the water neutral. This buffering capacity serves to stabilize the pH and prevent significant shifts while promoting overall groundwater quality.

Groundwater in the studied area has EC values ranging from 95.2 to 334  $\mu\text{S}/\text{cm}$ , with a mean of 201  $\mu\text{S}/\text{cm}$  (Tables 1 and 2). As EC values in the study area were within the

WHO (2006) threshold of 500  $\mu\text{S}/\text{cm}$ . This may indicate that the groundwater in the study area is safe. Whereas, an identical study carried out in an industrial area of Ogun State, Nigeria, reported a single site with a level of 684  $\mu\text{S}/\text{cm}$ , which exceeded the WHO recommendations limits for safe drinking water [24]. The influence of industrial activity on water quality is highlighted by this notable discrepancy. Industrial discharges, agricultural runoff, or other anthropogenic may enhance the EC in the groundwater samples of Ogun State, which indicates the presence of a higher concentration of dissolved ions. According to this comparison, it has been assumed that the ion balance of the Farcha groundwater has not been affected by anthropogenic activity in the studied area, keeping its quality within permissible limits for drinking water.

Fig. 3 depicts the geographical distribution of TDS content in the groundwater samples of the study area, demonstrating significant fluctuation in TDS levels. The results ranged between 47 mg/L at sample site E18 to 315 mg/L at sample location E10, with an average TDS value of 106 mg/L (Tables 1 and 2). The broad range revealed a diverse pattern of dissolved solids in the water samples. TDS levels are a significant indication of water quality, particularly for taste. Excellent-tasting water is often defined as having TDS levels less than 300 mg/L. Water quality can decline over 600 mg/L. However, it is still considered satisfactory when TDS levels are between 300 and 600 mg/L. The high concentration of dissolved chemicals causes the taste to get progressively worse as TDS levels rise beyond 1200 mg/L. Low TDS levels may give water a bland, undesirable taste. The results of this investigation show that most of the local water sources have outstanding taste quality, with TDS levels in 95% of the water samples being less than 300 mg/L. Sample E10 is the one significant exception, with a noticeably

elevated TDS content of 315 mg/L. This shows that the majority of water sources are not only safe but also delicious to drink. The high TDS value in sample E10 is due to a greater quantity of dissolved compounds. TDS mostly comprises inorganic salts and a minor quantity of organic materials. The major ingredients are cations (calcium, potassium, magnesium, and sodium) and anions (bicarbonates, carbonates, chlorides, nitrates, and sulphates). These minerals can originate from various natural sources and human activities. Natural sources contributing to TDS include geological formations and mineral springs. Human activities that increase TDS levels include sewage discharge, urban and agricultural runoff, and industrial wastewater. Additionally, salts used for road deicing can also contribute to the TDS load in water supplies.

The Fe content in the water samples ranges between 0.02 and 4.86 mg/L, with these values specifically observed at site samples E4-E10 and E16 (Tables 1 and 2). The average Fe content across all samples is 1.055 mg/L. Notably, 75% of the samples have an iron content within the 0-1.2 mg/L range, as illustrated in Fig. 3. However, 55% of the samples exceed the WHO standard of 0.3 mg/L for Fe content. This elevated Fe concentration in certain samples may be attributed to the preferential solubilization of minerals from specific geological formations in the reservoir or subsoil, as well as industrial sources. Research has indicated that within the typical pH range of groundwater (pH 5-8), dissolved Fe is present as  $\text{Fe}^{2+}$  [18,25, 26]. The primary sources of  $\text{Fe}^{2+}$  may be the dissolution of Fe (II) bearing minerals, or reduction of iron oxyhydroxides ( $\text{Fe-OOH}$ ) found in sediments, such as magnetite, ilmenite, pyrite, siderite, Fe (II) bearing silicates, and clay minerals like smectites. It may be the oxidation of arsenopyrites.

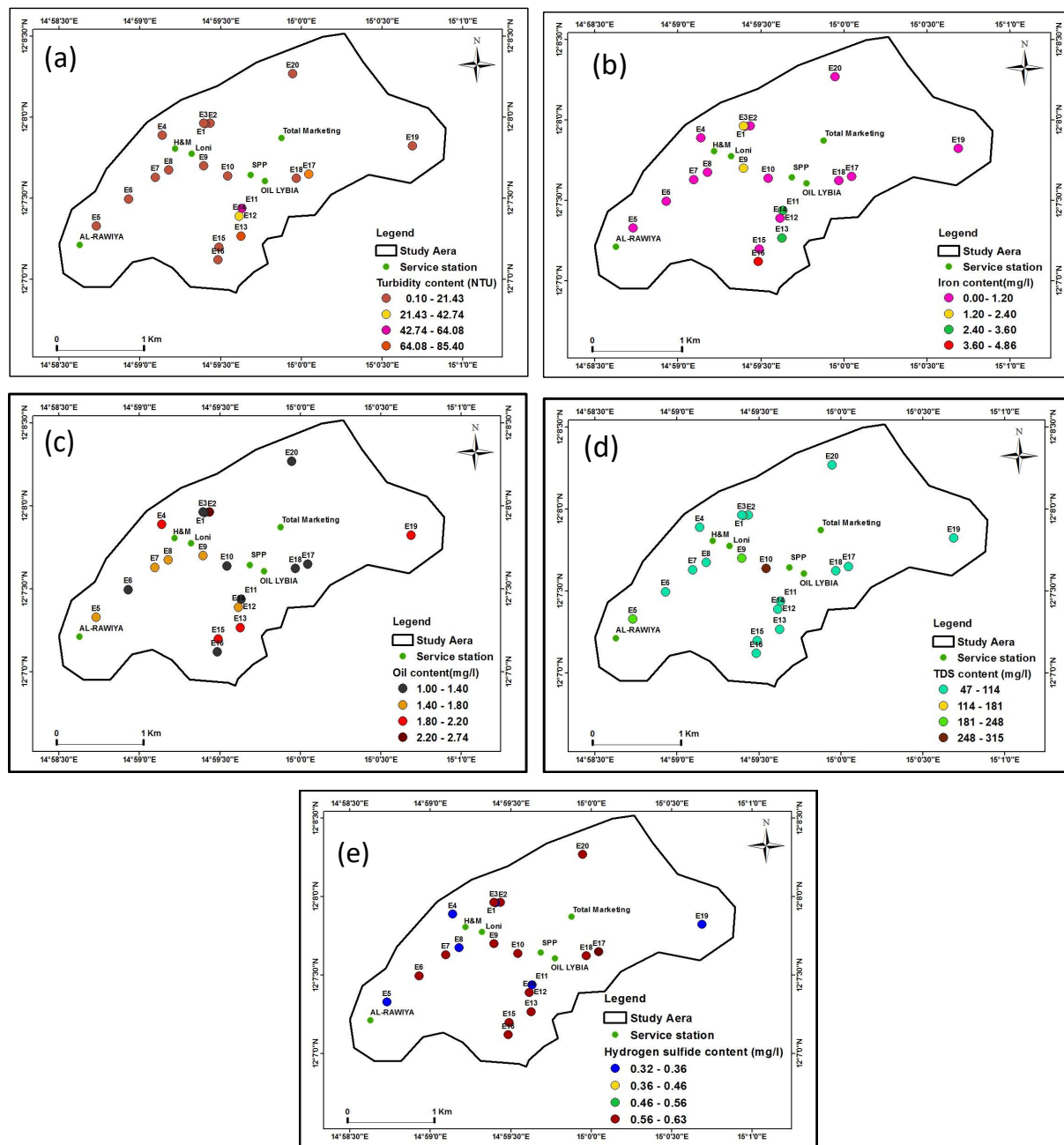


Figure 3. Map of spatial distribution of groundwater in the study area

Another study highlighted that the Fe content in water is more dependent on the aquifers or water table rather than the type of water sources [27]. If the aquifer contains Fe, then the tube-well water will also contain Fe, and vice versa. Additionally, Fe sulfate can be introduced into water from water treatment plants where it is used as a flocculant. In the

study area, the Fe content in groundwater appears to be derived from both natural sources (rocks and soils) and anthropogenic activities. High Fe levels in groundwater are associated with the weathering of rocks and the laterization of overburden materials [28]. Moreover, Fe is an essential trace element necessary for the proper functioning of living



organisms. However, excess Fe in water can increase the risk of cardiovascular diseases, cancers, and several neurodegenerative diseases [29, 30]. Fe plays a crucial role in the formation of haemoglobin, the protein responsible for transporting oxygen in the blood [25].

Regarding oil content in the analyzed samples, the values range from 1.01 to 2.74 mg/L (Table 1). Fig. 3 shows the distribution of oil content across boreholes: nine boreholes have values between 1.0 – 1.4 mg/L, five boreholes fall in the 1.40-1.80 mg/L range, four boreholes are within 1.80 – 2.20 mg/L, and one borehole has a value between 2.20 – 2.74 mg/L (Tables 1 and 2). Currently, there is no guideline for acceptable oil content in natural waters. The presence of oils can result from the decomposition of organic matter or pollution from wastewater containing lubricants, industrial oils, and related products.

Overall, the sampling points exhibit very low and consistent HS content in the analyzed waters, with concentrations varying between 0.32 and 0.63 mg/L (Tables 1 and 2). Among these, thirteen boreholes in the area present higher values, ranging from 0.56 to 0.63 mg/L (Fig. 3). The estimated taste and odor detection limits for hydrogen sulfide lie

between 0.05 and 0.1 mg/L. This indicates that the values obtained in the study area significantly exceeded these detection limits. The presence of HS in drinking water is concerning because it imparts an unpleasant taste and odor. Consequently, an organoleptic objective of  $\leq 0.05$  mg/L (expressed as HS) has been established to ensure water quality. HS is a colorless gas characterized by a distinctive rotten egg smell. It not only gives drinking water an unpleasant taste but also poses several practical issues. For instance, HS is corrosive to pipes, produces disagreeable odors, and can instantly blacken silverware. This gas can naturally occur in some groundwater sources, forming from underground deposits of decaying organic matter, such as rotting plants. It is frequently found in wells drilled through clay or sandstone, especially those near coal deposits, peat bogs, or oil fields. HS and sulfides of alkali and alkaline earth metals are soluble in water, contributing to its presence in various water sources.

Natural sources of HS include non-specific and anaerobic bacterial reduction of sulfates and sulfur-containing organic compounds. This gas is found naturally in crude petroleum, natural gas, volcanic gases, hot springs, and groundwater.

Table 3. Correlation coefficient between physicochemical parameters in water.

Parameters	Fe	pH	EC	TA	TH	TP	Oil	Cl	Si	PO <sub>4</sub>	HS
Fe	1.00										
pH	-0.28	1.00									
EC	-0.08	-0.38	1.00								
TA	-0.11	-0.03	0.66	1.00							
TH	0.03	-0.33	0.70	0.27	1.00						
TP	0.36	-0.06	0.24	-0.05	0.18	1.00					
Oil	-0.08	-0.27	0.26	0.15	0.34	-0.01	1.00				
Cl	0.70	-0.02	-0.18	-0.17	0.00	0.53	-0.22	1.00			
Si	-0.05	-0.30	0.20	0.17	0.22	-0.32	-0.15	-0.06	1.00		
PO <sub>4</sub>	0.35	-0.24	-0.20	-0.17	-0.01	0.45	0.19	0.48	-0.03	1.00	
HS	0.10	-0.30	0.03	0.02	0.01	-0.35	-0.17	-0.06	0.47	-0.16	1.00

It can also be released from stagnant or polluted waters and manure or coal pits. Commercially, HS is often produced as a by-product in several industrial processes. The principal source is during the purification of natural and refinery gases. Additionally, it is a by-product of Kraft pulp and paper manufacturing, as well as carbon disulfide production. HS is also generated by the reduction of sulfate and organosulfur compounds by the bacterium *Desulfovibrio desulfuricans* and is often associated with other sulfur-containing compounds like methane thiol ( $\text{CH}_3\text{SH}$ ), dimethyl disulfide ( $\text{CH}_3\text{S.S.CH}_3$ ), and carbonyl sulfide ( $\text{COS}$ ). The relative concentrations of HS and related species are influenced by the pH of the water, with higher HS concentrations occurring at lower pH levels. Therefore, in polluted waters where the pH can be neutral or acidic, the potential for HS formation is increased. Soil also acts as a significant reservoir for HS, contributing to its presence in groundwater. The study found that the HS content in the groundwater of the examined area arises from both natural sources and human activities. The above-listed processes are examples of natural sources of HS, whereas industrial discharges, agricultural practices, and other human activities that alter water chemistry and encourage the generation of HS are examples of anthropogenic activities that contribute to HS levels.

The data from evaluating the correlation between physicochemical characteristics revealed that the majority of these metrics are not substantially associated with one another (Table 3). Notable exceptions include a substantial association between Fe and  $\text{Cl}^-$  ( $R^2 = 0.70$ ), and between EC and TH ( $R^2 = 0.70$ ), with a modest correlation between TP and  $\text{Cl}^-$  ( $R^2 = 0.53$ ). As a result, the bulk of physicochemical characteristics do not correlate due to their various origins and unique geochemical behaviours. For example, Fe and

$\text{Cl}^-$  may show a significant association because of shared anthropogenic causes such as industrial discharges or the usage of de-icing salts, which can simultaneously increase both elemental concentrations in the environment. The relationship between EC and TH is also probably caused by dissolved minerals, especially calcium and magnesium ions, which affect both parameters in water chemistry.

However, as fertilisers carrying phosphorus compounds are frequently accompanied by molecules bearing chloride, agricultural runoff may have an impact on the mild connection between phosphorus and  $\text{Cl}^-$ . Other parameters showed no significant correlations, indicating that they could come from a range of sources, including different anthropogenic activities, natural geological formations, or atmospheric deposition, each of which would contribute independently to the chemical composition without being directly related to the others. These results underline the significance of taking into account a variety of factors and sources when examining the distribution and interaction of chemical components in a particular location, as well as the complexity of environmental systems.

## Conclusion

It is established that water levels in the Farcha district of N'Djamena range from 11.24 to 17.53 meters, with water-bearing buildings ranging in depth from 60 to 62 meters. The groundwater in this location has little mineral concentration and a pH near to neutral. The majority of the measured physicochemical parameters fall within or equivalent to the WHO-permitted limits for drinking water, suggesting that the water quality is appropriate for consumption. However, several areas have element concentrations that surpass the WHO's suggested maximum tolerable levels. For example, the groundwater sample designated

E16 included very high amounts of Fe and HS, whereas sample E10 had higher levels of Si and TDS. The local subsurface lithology is probably responsible for these high quantities, since it may naturally release these metals into the groundwater. Furthermore, anthropogenic activities lead to groundwater pollution, such as wastewater penetration. These results highlight the need for immediate action to prevent contamination of this vulnerable resource. Improving the quality of life for the populace and protecting the natural resources of the area under study in the medium and long term depend on the implementation of efficient pollution prevention measures. Coordinated efforts to monitor, control, and reduce pollution sources—both natural and anthropogenic will be necessary to ensure the sustainability of groundwater quality.

### Conflict of Interest

The authors declare no conflict of interest.

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