Exploring groundwater quality in semi-arid areas of Algeria: Impacts on potable water supply and agricultural sustainability (Postprint)

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Date: 2024-02-07T00:00:00+00:00

Abstract

Groundwater quality assessment is important to assure safe and durable water use. In semi-arid areas of Algeria, groundwater represents the main water resource for drinking water supply of the rural population as well as for irrigation of agricultural lands. Groundwater samples from wells and springs were collected from the Gargaat Tarf and Annk Djemel sub-watersheds of the Oum El Bouaghi, Algeria, and were analyzed and compared with the World Health Organization (WHO) standards. Results showed that most of the measured physical and chemical parameters exceeded the quality limits according to the WHO standards. Groundwater had a slightly alkaline water pH (7.00–7.79), electrical conductivity>1500 µS/cm, chloride>500 mg/L, calcium>250 mg/L, and magnesium>155 mg/L. Water quality index (WQI) results showed that 68% of the area had excellent water quality, 24% of the samples fell into good category, and only 8% were of poor quality and unsuitable for human consumption. Six wells in the area showed bacterial contamination. Total coliforms (453.9 (\$±180.3)$CFU(colony - formingunits)/100mL), fecalcoliforms(243.2(\pm 99.2)CFU/100mL), andfecalstreptococci(77.9(\pm$\$32.0) CFU/100 mL) loads were above the standard limits set by the WHO. These results confirmed that water resources in the study area were strongly influenced by anthropogenic activities and were not recommended for consumption as drinking water.

Full Text

Preamble

Exploring Groundwater Quality in Semi-Arid Areas of Algeria: Impacts on Potable Water Supply and Agricultural Sustainability

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Abstract: Groundwater quality assessment is essential to ensure safe and sustainable water use. In semi-arid regions of Algeria, groundwater represents the primary water resource for drinking water supply to rural populations and for irrigation of agricultural lands. Groundwater samples from wells and springs were collected from the Gargaat Tarf and Annk Djemel sub-watersheds of Oum El Bouaghi, Algeria, and analyzed against World Health Organization (WHO) standards. Results showed that most measured physical and chemical parameters exceeded WHO quality limits. Groundwater exhibited slightly alkaline pH (7.00–7.79), electrical conductivity >1500 µS/cm, chloride >500 mg/L, calcium >250 mg/L, and magnesium >155 mg/L. Water Quality Index (WQI) results indicated that 68% of the area had excellent water quality, 24% fell into the good category, and only 8% were of poor quality and unsuitable for human consumption. Six wells in the area showed bacterial contamination, with total coliforms (453.9 ± 180.3 CFU/100 mL), fecal coliforms (243.2 ± 99.2 CFU/100 mL), and fecal streptococci (77.9 ± 32.0 CFU/100 mL) loads exceeding WHO standard limits. These results confirm that water resources in the study area are strongly influenced by anthropogenic activities and are not recommended for consumption as drinking water.

Keywords: bacteriological indicator; groundwater; watershed; physical-chemical parameter; water quality index

Citation: Noua ALLAOUA, Hinda HAFID, Haroun CHENCHOUNI. 2024. Exploring groundwater quality in semi-arid areas of Algeria: Impacts on potable water supply and agricultural sustainability. Journal of Arid Land, 16(2): 147-167. https://doi.org/10.1007/s40333-024-0004-4

1 Introduction

Groundwater plays a crucial role in ensuring human survival, fostering industrial development, supporting agriculture, and protecting ecosystems. Due to their importance, 97% of continental water exists in liquid form (Yapo, 2010), and these hydrosystems constitute a veritable continental ocean (Ntona et al., 2022). The availability and quality of groundwater—which supplies approximately half of the world' s drinking water and more than 40% of agricultural water use—are critical to industrial and agricultural development, urbanization, food and energy security, and environmental sustainability, while also affecting human health (Mukherjee et al., 2020; Misstear et al., 2023).

Groundwater establishes vital connections with surface environments and significantly influences aquatic ecosystem functioning (Chenchouni et al., 2022). Phreatic waters acquire various soluble chemical elements as they circulate underground and interact with different geological formations. Additionally, aquifers such as karst systems possess specific physical characteristics that can make them more susceptible to surface contamination or contaminant infiltration into the subsurface (Misstear et al., 2023). These elements, originating from geological or anthropogenic sources, can alter groundwater quality and consequently impact ecosystem characteristics (ElKashouty et al., 2022). Groundwater quality depends not only on the geological composition of the parent soil but also on reactive substances encountered during flow, ionic exchange, mineral alteration, and the dissolution of authigenic minerals (Etikala et al., 2019; Chenchouni et al., 2023).

Groundwater from both confined and surface aquifers serves as a vital resource utilized for multiple purposes (Prasad and Narayana, 2004). Conversely, the substantial volume of groundwater and its replenishment contribute to the remarkable stability and dynamics of subsurface ecosystems compared to surface systems (Tsujimura et al., 2007). Particularly in arid and semi-arid regions, communities heavily rely on groundwater as a potable water source (Li et al., 2018).

Among the most water-scarce areas globally, the semi-arid regions of Algeria face significant challenges regarding water availability. These areas experience reduced precipitation, often below 500 mm and frequently less than 300 mm annually, coupled with high evapotranspiration rates, resulting in scarce surface water resources (Allaoua et al., 2015). In semi-arid aquifers, groundwater quality can deteriorate rapidly due to various factors, including over-pumping, which poses additional threats (Lar and Gusikit, 2015; Heggy et al., 2022).

Intensive natural resource use and increased human activity have created serious groundwater quality problems (Lapworth et al., 2022). Groundwater is particularly sensitive to different pollution sources such as uncontrolled wastewater discharges, solid waste disposal, and fertilizer and pesticide applications. These natural hydrosystems are vulnerable to contamination from numerous pollutant sources (Lukubye et al., 2017), including extensive agro-industrial activities and urbanization that contaminate aquifers through agricultural fertilizers and pesticides, industrial and domestic wastes, landfill dumping, and pit latrines (Fida et al., 2023).

One of the most important pollution types in rural areas is animal or human fecal contamination (Barnes and Gordon, 2004). Microbial indicators of fecal contamination serve as markers to assess water quality because fecal matter may harbor pathogenic organisms that pose potential health risks. Given the significance of scientific research in achieving effective groundwater quality management, this study aims to review the current state of groundwater quality in the Annk Djemel and Gargaat Tarf sub-watersheds located in Oum El Bouaghi, Northeast Algeria, and understand its impact on drinking water supply and agriculture. Specific objectives include detailed evaluation of water physical-chemical characteristics, identification of contamination sources, and assessment of consequences for agriculture from a water resource sustainability perspective. The obtained results will be compared with WHO standards for drinking water using the Water Quality Index (WQI) as a means to report water quality measurements consistently to management authorities, decision-makers, and the public (Qasemi et al., 2023). This comprehensive analysis seeks to provide valuable insights into the water quality status of these areas, which are primarily influenced by agricultural activities. Furthermore, the results may inspire discussion about installation and the importance of installation. We will contribute to sustainable groundwater management by introducing a quality control system and establishing a monitoring network to evaluate aquifer degradation.

2.1 Study Area

The study area is located south of Oum El Bouaghi, Northeast Algeria, encompassing two sub-watersheds: Gargaat Tarf and Annk Djemel (35°38 -36°00 N, 06°35 -07°20 E; Fig. 1 [Figure 1: see original paper]). These sub-watersheds are separated by the Djebel Tarf massif, which consists exclusively of sub-horizontal limestone banks from the Cretaceous Age (upper Aptian Stage). The remaining surface area of the sub-watersheds comprises primarily recent geological formations from the Quaternary period, including massive limestone crusts, polygenic glacis coating the reliefs, ancient silts, arable land, and recent alluvium. Gargaat Tarf is characterized by the presence of dune formations. The hydrographic network is poorly developed and of endoreic type, with the main wadi, Wadi Boulefreis, originating in the Aures Area (Allaoua and Hafid, 2019).

The regional climate is continental and belongs to the semi-arid bioclimatic stage, with cold winters and hot, dry summers characterized by irregular precipitation. Prevailing winds originate from the southwest, west, and northwest. Minimum precipitation is 107.7 mm and maximum is 392.0 mm. Seasonal precipitation averages 122.0 mm in winter, 108.0 mm in spring, 50.0 mm in summer, and 132.0 mm in autumn. Monthly average temperatures range from 6.1°C in December to 38.3°C in August, with an average minimum of 2.1°C in December and the warmest month being August with an average of 22.1°C.

2.2 Water Sampling and Data Collection

The assessment involved determining and characterizing the physical-chemical and bacteriological properties of 25 groundwater samples collected from wells and springs (Fig. 1; Table 1) in 2023. Physical-chemical analyses were conducted on water from private wells and natural springs. Because water sample collection is delicate and conditions the analytical results and their interpretation, we followed a strict protocol to ensure sample homogeneity and representativeness. We used 500 mL polyethylene bottles, which were thoroughly washed with nitric acid and rinsed with distilled water before use. To further minimize potential contamination, we washed each bottle three times with the water to be analyzed before completely filling it with the sample. This meticulous procedure maintained sample integrity and ensured accurate, reliable analyses.

2.3 Water Physical-Chemical Analysis

After conducting in situ measurements of electrical conductivity (EC), temperature, pH, and dissolved oxygen (DO) using an oximeter CellOX 325 (Xylem Analytics Germany Sales GmbH & Co. KG WTW, Weilheim, Germany) with a WTW multi-parameter device Multiline P3 PH/LF SET (Wissenschaftlich-Technische-Werkstätten GmbH, Weilheim, Germany), we collected and pre-filtered water samples. The pre-filtered samples were placed in 1.5 L polyethylene bottles and stored at 4°C to preserve their integrity. Chemical analyses were subsequently performed at the Laboratory of Biology, Department of the Faculty of Exact and Nature Sciences at Oum El Bouaghi University, Algeria.

Calcium determination was carried out through complexometry using ethylenediaminetetraacetic acid (EDTA) titration in the presence of a colored indicator (Murexide, also known as ammonium purpurate) and a 2-N sodium hydroxide solution. Magnesium hardness was obtained by calculating the difference between total hardness and calcium hardness. This comprehensive analysis and accurate methodology ensure reliable, precise data for water quality assessment in the study area (Rodier, 2009).

Bicarbonates were determined by titrimetry, where a solution of known H_2SO_4 concentration was reacted with a precise sample volume (100 mL) in the presence of methyl orange indicator; the reaction occurs through neutralization of bicarbonate ions by H^+ ions from H_2SO_4. Chlorides were determined volumetrically by Mohr' s method, precipitating silver chloride through reaction of chloride ions with silver nitrate in the presence of 10% K_2CrO_4 indicator. Sulfate ($SO_4{}^{2-}$) was determined by nephelometry using a UV-visible spectrophotometer (WTW) set at 420 nm and calibrated prior to determination, with concentration related to the turbidity of the $BaSO_4$ suspension. Nitrates, nitrites, and ammonium were determined by colorimetry.

2.4 Water Bacteriological Analysis

Water samples from wells and springs were carefully collected in sterile bottles to maintain purity. After collection, samples were stored and transported to the laboratory in cooler boxes to preserve integrity and prevent water quality degradation during transport. Laboratory analysis was promptly conducted within 4 hours to ensure result freshness and reliability. This strict protocol minimized potential contamination and provided accurate data for the study. Analyses were performed at the laboratory.

Total Escherichia coli were counted using bromocresol purple lactose broth (BCP) tubes fitted with a Durham bell after 24–48 hours incubation at 37°C. For confirmatory testing on Schubert' s medium fitted with a Durham bell, aliquots from positive tubes (showing lactose fermentation and gas production) were incubated at 44°C for 24–48 hours. Addition of 2–3 drops of Kovacs reagent produced a red ring on the surface, indicating indole formation and thus confirming fecal coliforms. Fecal streptococci were detected on Rothe medium at 37°C for 24 hours, followed by subculture on Litsky medium for 24 hours at 37°C from positive Rothe tubes. Results were calculated as number of germs per 100 mL according to the Mac-Grady table.

2.6 WQI

The Water Quality Index (WQI) is a valuable and efficient tool for evaluating overall groundwater quality (Khan and Jhariya, 2017; Adimalla et al., 2018). Derived from comprehensive datasets, WQI presents information in a manner easily comprehensible to water resource managers and decision-makers (Rana and Ganguly, 2020), offering a consolidated, user-friendly approach that serves as a key component in informed decision-making and effective water resource management.

WQI is commonly utilized to assess groundwater suitability for drinking purposes worldwide (Khan and Jhariya, 2017; Wu et al., 2017; Adimalla and Venkatayogi, 2018; Verma et al., 2018). Five water classes are defined by WQI values: excellent (0–25), good (26–50), moderate (51–75), poor (76–100), and very poor (>100). To determine groundwater potability, we calculated WQI using the weighted arithmetic index method:

$$WQI = \sum_{n=1}^{n} q_n w_n$$

where q_n is the quality rating of the nth water quality parameter, w_n is the unit weight for the nth parameter, and n is the total number of parameters included in the calculation.

The quality index/sub-index (q_n^{th}) reflects the relative value of a parameter in polluted waters compared to its standard admissible value:

$$q_n = \frac{v_n - v_{io}}{s_n - v_{io}} \times 100$$

where v_n is the estimated value of the nth parameter, s_n is the standard permissible value, and v_{io} is the ideal value. The ideal value $v_{io} = 0.0$ except for pH and DO: for pH, $v_{io} = 7.0$ and $s_n = 8.5$; for DO, $v_{io} = 14.6$ and $s_n = 5.0$ mg/L.

Following Adimalla and Venkatayogi (2018), we used WQI to determine groundwater suitability for drinking. Initially, we considered maximum values for studied physical-chemical parameters based on Algerian standards for surface waters (Table 2) to establish each parameter’ s relative importance in overall water quality assessment. WQI calculation incorporates these weights and constants to provide a comprehensive, standardized evaluation aligned with Algerian surface water standards.

2.6 Statistical Analysis

To compare physical-chemical parameter values across sub-watersheds, we computed means ± standard deviations (SD) and ranges (minimum-maximum) based on observed data from wells and springs, treating them as replicates within each sub-watershed. To analyze variation between sub-watersheds, we conducted Welch’ s two-sample t-test after confirming normal distribution (Shapiro-Wilk test) and unequal variances (F-test).

Relationships between physical and chemical properties were examined using Pearson’ s correlation. The resulting correlation matrix was displayed in a single plot with corresponding P-values and correlation coefficients (r) using the Corrplot package (Wei and Simko, 2021). Since changes in water characteristics from growth of one bacterial group may impact other bacteria either positively or negatively (Loucif et al., 2020), linear regressions and correlation tests investigated interrelationships between bacterial group densities.

To explore relationships between water parameters and bacterial groups, we conducted redundancy analysis (RDA) using the Vegan package in R software (Oksanen et al., 2022). The RDA biplot was generated using correlative scaling. Pearson’ s correlation tests were performed between water parameter values at each sample site and RDA site scores (weighted sums of response variable scores), and between meteorological parameter values and RDA constraints (linear combinations of climate variables).

To assess the impact of measured physical-chemical parameters (represented by WQI values) on bacterial load variation for each bacterial group, we employed a generalized linear model (GLM). Bacterial load data were fitted to a Poisson distribution with a log link function. All statistical analyses were conducted using R software (R Core Team, 2023).

3.1 Water Physical-Chemical Properties

Well water parameters exhibited minimal seasonal variations throughout the year, making it appropriate to characterize each site by calculating average values across the entire study period. This averaging provides a representative, stable representation of water quality for each site, enabling comprehensive assessment without influence from short-term fluctuations or seasonal changes. Physical-chemical parameter values are presented in Table 3 .

The Annk Djemel sub-watershed was characterized by groundwater with a temperature of 16.8°C ($±0.3°C).WaterpHvariedbetween7.00and7.80withanaverageof7.30,whileelectricalcondu
averaged 383 mg/L (range: 109–835 mg/L), and Mg^{2+} averaged 147
($±19)mg/L.Sulfatesrangedfrom80to472mg/L(average : 252mg/L),chloridesaveraged591(±101)mg/L,nitr
0.01–68.22mg/L),phosphateaveraged0.18(±$0.06) mg/L (range: 0.02–0.70 mg/L), and ammonium values varied between 0.00 and 0.25 mg/L (average: 0.15 mg/L).

The Gargaat Tarf sub-watershed exhibited the following characteristics: temperature was 16.9°C ($±0.26°C),pHvariedbetween6.68and8.04(average :
7.38),ECwas3153(±608)μS/cm,andDOcontentwas6.79(±0.32)mg/L.Calciumcarbonatesaveraged508(±56)m
478mg/L),Ca^{2+}$ averaged 446 ($±87)mg/L,andMg^{2+}$ ranged from 32 to 481 mg/L (mean: 163 mg/L). Nitrates averaged 4.81 ($±1.12)mg/L,nitritesrangedfrom0.00to0.29mg/L(
0.25mg/L),phosphaterangedfrom0.01to0.14mg/L(average : 0.11mg/L),chloridesaveraged725(±$188)
mg/L, and sulfates ranged from 74 to 756 mg/L (average: 452 $±$76 mg/L). Despite spatial variations in physical-chemical parameters between sub-watersheds, differences were statistically insignificant (P>0.050) except for bicarbonates (P<0.003), sulfates (P=0.028), and nitrites (P=0.035) (Table 3).

3.2 Relationships Between Water Parameters

Correlation tests between groundwater physical-chemical parameters are summarized in Figure 2 [Figure 2: see original paper]. Analysis revealed significant correlations in 19 of 98 parameter pairs in the Annk Djemel and Gargaat Tarf sub-watersheds. In Annk Djemel, the strongest negative correlations were between DO and temperature (r = -0.94, P<0.001), HCO_3^- and temperature (r = -0.79, P=0.001), NH_4^+ and DO (r = -0.79, P=0.003), NO_2^- and temperature (r = -0.66, P=0.014), and NO_2^- and EC (r = -0.63, P=0.008). The strongest positive correlations were between Ca^{2+} and $CaCO_3$ (r = 0.97, P<0.001) and HCO_3^- and NO_2^- (r = 0.92, P<0.001). Other positive correlations included HCO_3^- and DO (r = 0.83, P=0.000), $CaCO_3$ and EC (r = 0.77, P=0.002), Ca^{2+} and EC (r = 0.77, P=0.004), Mg^{2+} and $CaCO_3$ (r = 0.77, P=0.002), Mg^{2+} and EC (r = 0.60, P=0.030), Cl^- and $CaCO_3$ (r = 0.78, P=0.002), Cl^- and Ca^{2+} (r = 0.77, P=0.002), and NH_4^+ and temperature (r = 0.69, P=0.009).

In the Gargaat Tarf sub-watershed, significant correlations occurred in 25 of 98 parameter pairs. Strong correlations were found between EC and $CaCO_3$ (r =

0.91, $P<0.001$), sulfates (r = 0.89, $P<0.001$), and Cl^- (r = 0.85, P=0.001). Other significant correlations included SO_4^{2-} and EC (r = 0.71, P=0.010), NO_2^- and HCO_3^- (r = 0.83, P=0.001), NO_3^- and HCO_3^- (r = 0.86, $P<0.001$), NO_3^- and Cl^- (r = 0.72, P=0.008), NO_3^- and HCO_3^- (r = 0.81, P=0.002), PO_4^{3-} and NO_3^- (r = 0.76, P=0.004), SO_4^{2-} and NO_2^- (r = 0.80, P=0.002), and SO_4^{2-} and NO_2^- (r = 0.60, P=0.041). Negative correlations included DO and temperature (r = -0.91, $P<0.001$), DO and NH_4^+ (r = -0.71, P=0.010), pH and PO_4^{3-} (r = -0.71, P=0.010), pH and HCO_3^- (r = -0.71, P=0.009), pH and NO_3^- (r = -0.61, P=0.035), and pH and Cl^- (r = -0.59, P=0.044).

3.3 Bacteriological Quality of Groundwater

Variations in bacterial load in the Annk Djemel sub-watershed are depicted in Figure 3 [Figure 3: see original paper]. Bacteriological examination revealed that out of 13 wells analyzed, 6 contained total heterotrophic bacterial loads. The average total coliform concentration across all wells was approximately 453.9 ($±180.3)$CFU/100mL, withamaximumof1900.0CFU/100mLobservedinwellP9.Fecalcoliformsaverag$ CFU/100 mL, with a maximum of 324.0 CFU/100 mL in well P3. Coefficient of variation (CV) results showed heterogeneous concentrations of bacterial load in examined surface waters (CV = 143% for total coliforms, CV = 147% for fecal coliforms, and CV = 151% for fecal streptococci).

3.4 Interrelationships Between Bacterial Groups

Interrelationships between bacterial groups are shown in Figure 4 [Figure 4: see original paper]. All bacterial densities were correlated with each other. Positive significant correlations ($P<0.001$) were revealed between fecal coliforms and fecal streptococci (r = 0.96), fecal coliforms and total coliforms (r = 0.92), and fecal streptococci and total coliforms (r = 0.89). Linear regression equation slopes ranged from 0.161 to 2.927, with the largest slope for fecal coliforms.

3.5 Effects of Water Characteristics on Bacterial Loads

RDA examined relationships between groundwater physical-chemical parameters and bacterial load. The first and second axes explained 96.9% and 2.9% of eigenvalues, respectively. According to the first axis, which represents the majority of information, most water parameters exhibited negative correlations with pH, DO, HCO_3^-, and NO_2^-. These parameters were positioned on the positive side of the axis, as was bacterial group distribution (Fig. 5 [Figure 5: see original paper]; Table 4), suggesting clear associations between groundwater physical-chemical parameters and bacterial presence.

On the second axis, which represents only 2.9% of variation, total coliform bacterial load was positively associated with nitrate concentrations and water temperature but negatively associated with pH. DO, Mg^{2+}, HCO_3^-, Cl^-, and EC were positively correlated with fecal coliforms and, to a lesser degree, with fecal streptococci. The RDA triplot indicated that all abiotic parameters and bacterial loads were negatively correlated on the first axis, showing that bacterial load increased with certain parameters such as NO_3^-, NH_4^+, SO_4^{2-}, and temperature, though these relationships were not statistically significant ($P>0.050$). Clear spatial separation based on water parameters and bacterial abundance allowed classification of sample sites into two groups: the first group comprised wells P9, P1, and P3, which showed significant mineralization, NH_4^+ pollution, and high bacterial load; the second group included remaining wells (P2, P4, P5, P6, P7, P10, S1, S2, S3) and three sources characterized by relatively average mineralization and near-zero pathogen contamination.

3.6 Effect of WQI on Bacterial Loads of Contamination Indicators

WQI values in Gargaat Tarf ranged from 17% to 50%, indicating water quality varying from excellent to very poor, while WQI in Annk Djemel showed 85% of samples with excellent quality and 15% with good quality. For the entire study area, 68% of samples fell into the excellent category, 24% into the good category, and only 8% into poor quality, rendering them unfit for human consumption (Fig. 6 [Figure 6: see original paper]).

A significant difference existed between average WQI values in the two subwatersheds ($P = 0.032$). Coefficient of variation results showed heterogeneous WQI values, with the Annk Djemel basin (CV = 139%) exhibiting more heterogeneous water quality than Gargaat Tarf (CV = 87%). GLM results showed negative effects of WQI on all three bacterial indicator groups: fecal coliforms ($t = -0.97$), fecal streptococci ($t = -0.93$), and total coliforms ($t = -1.00$). Although these relationships were negative (Fig. 7 [Figure 7: see original paper]), GLM analysis revealed no significant effects. Similarly, GLM showed no significant effects of water physical-chemical parameters on bacterial group load variations (Table 5), suggesting that bacterial load variations were not significantly influenced by water physical-chemical parameters.

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4 Discussion

Water quality assessment is generally based on monitoring microbial elements, particularly fecal coliform bacteria, and analyzing physical-chemical characteristics (Guemmaz et al., 2020; Loucif et al., 2020). Water parameters and quality are influenced by complex interactions between external and internal factors.

External factors include weather conditions, substrate characteristics (soil and sediment), and pollution sources, while internal factors result from biochemical reactions occurring within the water itself (Hacioglu and Dulger, 2009).

4.1 Water Physical-Chemical Properties

Physical and chemical parameters were compared with WHO standard guideline values (WHO, 2017). Temperature is a key parameter for drinking water quality assessment, influencing chemical reaction rates in water bodies, gas solubility, and water taste and color (Daghara et al., 2019; Calero Preciado et al., 2021; Moussaoui et al., 2024). Average water temperature across all seasons ranged from 15°C to 19°C, with thermal variation of about 0.2°C. Groundwater temperature varies with aquifer depth and season; the European Parliament has established an indicative limit of 25°C for human consumption water (Rodier, 2009).

In the study area, pH values ranged from 6.68 to 8.04 (average: 7.36), with most groundwater samples being weakly to moderately alkaline, attributed to water flow through surface and subsurface carbonate layers (Rao et al., 2012). Slightly alkaline water can inhibit heavy metal toxicity by precipitating carbonate or bicarbonate, rendering these metals unavailable (Ahipathy and Puttaiah, 2006). Water conductivity is essential as it evaluates an aqueous medium’ s capacity to conduct electric current (Sui et al., 2018). Groundwater EC ranged from 254 to 7160 S/cm, closely related to ion concentrations. Higher values indicate elevated total dissolved solids and increased salinity (Abboud, 2018). Large EC variations reflect significant differences in predominant geochemical processes.

DO concentration ranged from 3.99 to 9.53 mg/L (average: 6.77 mg/L), with WHO’ s maximum allowable limit being 8.00 mg/L (WHO, 2017). DO plays a pivotal role in groundwater quality by regulating trace metal valence states and restricting bacterial metabolism of dissolved organic species, making its measurement vital in most water quality studies (Bouaroudj et al., 2019; Cheng et al., 2019; Zhang et al., 2022).

Bicarbonates trigger groundwater alkalinity (Adams et al., 2001) and occur naturally from dissolution of carbonate formations like limestone and dolomite (Drever, 2001). As the most common anion in groundwater, bicarbonate originates primarily from soil CO_2 (Ahuja et al., 2008). Concentrations varied from 55 to 833 mg/L, attributable to leaching of carbonate formations. During irrigation, rainfall infiltration, and groundwater movement, carbonates in carbonate rocks may dissolve and supply groundwater with recharge water (Singh et al., 2012), accounting for low alkalinity levels in some wells that may reflect hydrochemical immaturity or shallow aquifers (Demetriades, 2011).

Chloride occurs naturally in all water types, but main sources include runoff, inorganic fertilizers, and wastewater discharges (Çadraku, 2021). In this study, Cl^- ranged from 64 to 2482 mg/L (average: 655 mg/L), exceeding the permissible limit of 250 mg/L. High Cl^- levels in groundwater can be hazardous to human health (Pius et al., 2012; Noori et al., 2014). Sulfate (SO_4^{2-}) originates from dissolution and leaching of rocks containing gypsum, iron sulfides, and other sulfur compounds (Arjum et al., 2021). In 75% of groundwater samples, SO_4^{2-} concentration exceeded the WHO recommended limit of 200 mg/L for direct drinking and domestic use.

Based on WHO guidelines (WHO, 2017), Ca^{2+} concentration in drinking water should not exceed 200 mg/L, though this limit is often exceeded globally. In this study, Ca^{2+} ranged from 109 to 1239 mg/L (average: 250 mg/L), originating from dissolution of carbonate and evaporitic minerals (calcite, dolomite, aragonite, gypsum, anhydrite) and carbonate cement in geological formations (Bozdağ and Göçmez, 2013). Mg^{2+} ranged from 32 to 481 mg/L (average: 155 mg/L), likely from leaching of carbonate minerals like calcite and dolomite (Magesh et al., 2013). Geospatial distribution showed higher cation concentrations in Gargaat Tarf than Annk Djemel, likely sourced from magnesium-containing minerals like dolomite and sulfate minerals present in the study area (Şener et al., 2017).

Nitrate (NO_3^-) presence in groundwater can be attributed to fertilizer application, human and animal sewage, plant deposits, and other nitrate-rich wastes (Chukwura et al., 2015; Vincy et al., 2015). Concentrations ranged from 0.01 to 68.22 mg/L, below WHO' s permissible limit of 50.00 mg/L. Ammonium (NH_4^+), nitrite (NO_2^-), and phosphate (PO_4^{3-}) concentrations were well below WHO maximum desirable limits, with mean values of 0.22, 0.16, and 0.13 mg/L, respectively. Low concentrations of these elements indicate minimal contamination from pollution sources.

Pearson' s correlation matrix analysis reveals links and associations between hydrogeochemical parameters, allowing identification of their origins and interrelationships (Guey-Shin et al., 2011; Mgbenu and Egbueri, 2019). Correlation coefficients (r) >0.70 indicate strong correlation, while r values between 0.50 and 0.70 suggest moderate correlation. Good correlations were observed between EC and HCO_3^- (r = 0.63), EC and $CaCO_3$ (r = 0.77), Ca^{2+} and $CaCO_3$ (r = 0.77), Mg^{2+} and $CaCO_3$ (r = 0.78), Ca^{2+} and SO_4^{2-} (r = 0.91), Ca^{2+} and Cl^- (r = 0.85), and SO_4^{2-} and NO_2^- (r = 0.80), indicating common origins. According to Singh and Mukherjee (2015), increased ion presence can be attributed to evaporitic mineral dissolution, which increases water' s ionic strength and promotes sulfate salt dissolution, leading to higher Mg^{2+} and Ca^{2+} concentrations (Alaya et al., 2014). Negative correlations between temperature and DO (r = -0.94) and between DO and ammonium (r = -0.71) illustrate negative interactions, as temperature influences oxygen solubility and biological activities like photosynthesis and respiration, impacting short-term oxygen balance (Butcher and Covington, 1995; Daghara et al., 2019; Calero Preciado et al., 2021).

4.2 Bacteriological Quality of Groundwater

Analyzing microbial abundance and diversity is useful for assessing drinking water quality (Favere et al., 2021). However, testing for all organisms is difficult due to complex isolation and identification procedures (Soni et al., 2023). A commonly used indirect method for assessing fecal contamination is analyzing coliform bacteria, considered reliable indicators (Kistemann et al., 2002; Nola et al., 2002; Barnes and Gordon, 2004). In wells P9, P1, and P3, coliform bacteria concentrations were 453.9 CFU/100 mL for total coliforms, 243.2 CFU/100 mL for fecal coliforms, and 77.9 CFU/100 mL for fecal streptococci, attributed to animal manure or dung application. Coliform concentrations were lower in deeper wells, confirming that artesian wells are safer than surface wells or outcropping springs. Global studies corroborate that runoff and short residence times in permeable soils facilitate direct manure infiltration into groundwater (Richardson et al., 2009; Masoud et al., 2016). Open defecation and private septic tank use lead to sewage entering groundwater sources in rural areas worldwide (Schijven et al., 2010; Masoud et al., 2016). Joseph et al. (2021) reported that livestock grazing elevates bacterial numbers, while Chadwick and Chen (2002) found the highest fecal coliform and fecal streptococci numbers in manure.

Lack of well protection also contributes to water enrichment with organic matter from windblown leaves and plant debris that decompose on site. All indicator bacteria were highly correlated (r = 0.89-0.96, $P<0.001$), indicating probable common contamination sources. Atherholt et al. (2003) suggested that many environmental total coliforms originate only from fecal sources. According to Francy et al. (2000), strong correlations between indicators may indicate identical or similar contamination sources. Atherholt et al. (2003) reported that combined fecal coliform and fecal streptococci indicators provide strong evidence of fecal contamination.

4.3 Effects of Water Characteristics on Bacterial Loads

Microorganism growth in water is closely influenced by environmental factors (Fister, 2016), establishing relationships between physical-chemical properties and bacterial abundance. In this study, bacteriological analysis revealed bacterial groups with similar tendencies. Guemmaz et al. (2020) reported similar results showing environmental factor influences on fecal bacterial loads in urban effluents discharged into Algerian arid wadis. Environmental factors such as pH, salinity, metal concentrations, and energy exert selective, direct effects on microbial community composition, abundance, and spatial distribution (Dell' Anno et al., 2003; Franklin et al., 2007; Guo et al., 2015; Jordaan et al., 2016; Liu et al., 2018). RDA analysis identified NO_3^-, NH_4^+, SO_4^{2-}, temperature, Ca^{2+}, EC, Cl^-, $CaCO_3$, and Mg^{2+} as the environmental variables that best explained bacterial distribution variations.

Total coliforms include fecal coliforms and all bacteria in this group share similar biochemical characteristics, occurring in soil or water (Rodier et al., 2009).

In this study, total coliforms responded positively to increased nitrate. Vandenberg et al. (2005) reported that coliform bacteria use ammonia and nitrate as nutrients. Fecal coliforms are specifically associated with feces (Rodier et al., 2009), and nitrate ions can be produced by ammonium ion oxidation in feces (Bou Saab et al., 2007), giving nitrate and fecal coliforms a common origin. Water temperature is one of the most significant environmental parameters influencing fecal indicator bacteria concentrations. While some studies report inverse relationships between fecal coliforms and water temperature, others find direct relationships (Loucif et al., 2020; Valenca et al., 2022). This study found that increasing temperature promotes development of total coliform, fecal coliform, and fecal streptococci bacterial loads, consistent with Chigbu et al. (2005) but differing from Tek et al. (2001), who observed no relationship.

Bacterial populations showed variable responses to other groundwater physical-chemical parameters. High EC, Mg^{2+}, Ca^{2+}, and $CaCO_3$ values were associated with increased bacterial abundance (Nola et al., 2002). In a Cameroon groundwater investigation, Nola et al. (2002) found that higher EC and concentrations of oxygen, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} promoted fecal coliform and fecal streptococci abundance. While Ondieki et al. (2021) reported total coliform increases at acidic pH, Loucif et al. (2020) found that alkaline pH impairs fecal coliform survival. Depending on available environmental parameters such as ideal pH, temperature, nutrient amount, and suspended particles, coliform bacteria survival can be prolonged or even expanded (Juhna et al., 2007).

4.4 WQI

During the research period, 68% of groundwater samples were classified as excellent, 24% as good, and 8% as poor quality. The poor-quality samples likely result from agricultural influence, effective ion leaching, excessive groundwater use, direct effluent discharge, and other factors (Sahu and Sikdar, 2008). WQI is an essential parameter for evaluating groundwater quality and determining consumption suitability (Mishra and Patel, 2001; Naik and Purohit, 2001; Avvannavar and Shrihari, 2008; Rana and Ganguly, 2020; Ram et al., 2021).

GLM testing of WQI with bacterial load indicators showed negative correlations. Low WQI values were closely related to high total coliform, fecal coliform, and fecal streptococci loads, indicating poor quality for some groundwater samples. However, GLM indicated non-significant effects. CV results showed heterogeneous WQI values, signifying spatial diversity and various pollutants threatening groundwater quality.

This study provides a robust assessment of groundwater quality in semi-arid Algerian areas, offering valuable insights into water suitability for drinking and agriculture. The comprehensive analysis of physical-chemical parameters and WQI application enhances finding clarity. However, limitations include a relatively small sample size potentially limiting generalizability, and the focus on specific parameters without seasonal variations may not fully capture groundwater quality dynamics. Future research with larger, more diverse datasets exploring temporal variations would strengthen result reliability and applicability.

4.5 Implementation and Perspective

This study prompts reevaluation of water management practices, advocating policies prioritizing groundwater quality preservation and enhancement. Results emphasize the urgency of collaborative efforts among stakeholders, policymakers, and local communities to ensure access to safe, potable water—a fundamental right for present and future generations. Facing bacterial contamination and water-related health risks, diverse solutions should be considered. Improving sanitation infrastructure is crucial to prevent contaminant spills into groundwater. Reinforcing water point protection through filters and physical barriers can mitigate direct contamination. Raising community awareness about proper hygiene practices and water source preservation is equally imperative. Regular water quality monitoring is essential for swift bacterial contamination response. Strict adherence to water quality standards and tailored regulation is necessary to oversee potentially contaminating activities. Fostering multi-stakeholder collaboration among local authorities, government organizations, communities, and water management experts is paramount to coordinate efforts for sustainably restoring and preserving water quality, ensuring safe potable water supply for local populations.

5 Conclusions

Groundwater quality assessment is crucial for ensuring safe, sustainable water use. In semi-arid Algerian regions where groundwater serves as the primary water source for rural communities and agriculture, its quality holds immense significance. This study extensively analyzed parameters in groundwater samples from the Gargaat Tarf and Annk Djemel sub-watersheds. Findings showed physical and chemical parameters surpassing WHO recommended limits, with slightly alkaline pH (7.00–7.79) and elevated EC, Cl^-, Ca^{2+}, Mg^{2+}, and other substances signaling compromised water quality. Despite these concerns, WQI offered a nuanced perspective: approximately 68% of the area exhibited excellent water quality, 24% good quality, but alarmingly, 8% showed poor quality, rendering it unsuitable for human consumption and emphasizing the need for remediation and management strategies.

Bacterial contamination in six wells further underscores human activity impacts on water resources. Elevated coliform and streptococci levels above WHO standards reflect anthropogenic influences, posing health risks and deeming certain water points unsuitable for drinking. These revelations demand immediate attention and strategic interventions. This research' s significance extends beyond observation, requiring actionable steps to rectify deteriorating groundwater quality. Efforts must focus on mitigating anthropogenic influences, implementing rigorous monitoring frameworks, and devising interventions to safeguard water resources.

Conflicts of Interest

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

Acknowledgements

Haroun CHENCHOUNI received funding from the European Union' s Horizon 2020 Research & Innovation Programme (2211) under the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) Project "SHARInG-MeD" and from the Directorate-General for Scientific Research and Technological Development (DGRSDT) under the Projets de Recherche Formation-Universitaire (PRFU) Projects (D00L02UN120120230002, D01N01UN120120230005). We express gratitude to Dr. Haythem DINAR (University of Oum El Bouaghi, Algeria) for invaluable assistance in plotting Figure 1.

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