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

Authors: Noua ALLAOUA

Date: 2024-02-21T00:00:00+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)$CFU(colony-formingunits)/100mL), fecalcoliforms(243.2(\pm99.2)CFU/100mL), andfecalstreptococci(77.9(\pm$\$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

Noua ALLAOUA[1,2], Hinda HAFID[1,2], Haroun CHENCHOUNI[1,3]*

[1] Laboratory of Natural Resources and Management of Sensitive Environments, Larbi Ben M'hidi University, Oum-El-Bouaghi 04000, Algeria
[2] Department of Nature and Life Sciences, Faculty of Exact Sciences and Nature and Life Sciences, Larbi Ben M'hidi University, Oum-El-Bouaghi 04000, Algeria
[3] Laboratory of Algerian Forests and Climate Change, Higher National School of Forests, Khenchela 40000, Algeria

Abstract: Groundwater quality assessment is essential to ensure safe and sustainable water use. In semi-arid areas of Algeria, groundwater represents the main water resource for drinking water supply for rural populations 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 Oum El Bouaghi, Algeria, and were analyzed and compared with World Health Organization (WHO) standards. Results showed that most measured physical and chemical parameters exceeded quality limits according to WHO standards. Groundwater had 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 showed that 68% of the area had excellent water quality, 24% of samples 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 above 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

*Corresponding author: Haroun CHENCHOUNI (E-mail: chenchouni@gmail.com)

---

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 is in a liquid state (Yapo, 2010), and these hydrosystems form a real continental ocean (Ntona et al., 2022). The availability and quality of groundwater, which supplies about half of the world's drinking water and more than 40% of its agricultural use, is critical to industrial and agricultural development, urbanization, food and energy security, and environmental sustainability, and also affects human health (Mukherjee et al., 2020; Misstear et al., 2023).

Groundwater plays a crucial role in the water cycle, establishing vital connections with surface environments and significantly influencing the functioning of aquatic ecosystems (Chenchouni et al., 2022). Phreatic waters acquire various soluble chemical elements as they circulate underground and come into contact with different geological formations. Additionally, aquifers such as karst systems possess specific physical characteristics that can make them more susceptible to surface contamination or the infiltration of contaminants into the subsurface (Misstear et al., 2023). These elements, originating from geological or anthropogenic sources, have the potential to alter groundwater quality and consequently impact ecosystem characteristics (ElKashouty et al., 2022). The quality of groundwater relies not only on the geological composition of the originating soil but also on reactive substances encountered during its flow, ionic exchange, mineral alteration, and the dissolution of authigenic minerals (Etikala et al., 2019; Chenchouni et al., 2023).

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

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

Intensive use of natural resources and increased human activity have created serious problems with groundwater quality (Lapworth et al., 2022). Groundwater is particularly sensitive to different sources of pollution such as uncontrolled wastewater discharges, solid waste disposal, fertilizer, and pesticide applications. These natural hydrosystems are likely to be contaminated by many pollutant sources (Lukubye et al., 2017), such as the results of extensive agro-industrial activities and urbanization in contaminating aquifers including agricultural fertilizers and pesticides, industrial and domestic wastes, dumping in landfills, and pit latrines (Fida et al., 2023).

One of the most important types of pollution in rural areas is animal or human fecal contamination (Barnes and Gordon, 2004). Microbial indicators of fecal contamination are employed as markers to assess water quality because fecal matter may harbor pathogenic organisms that can pose potential health risks or adverse effects on human health. Given the significance of scientific research in achieving effective and efficient groundwater quality management, this study aims to review the current state of groundwater quality in the two sub-watersheds: Annk Djemel and Gargaat Tarf, located in Oum El Bouaghi in Northeast Algeria, and understand its impact on drinking water supply and agriculture. Specific objectives include the detailed evaluation of water physical-chemical characteristics, identification of sources of contamination, and study of the consequences on agriculture from a perspective of sustainability of water resources. The obtained results will be compared with World Health Organization (WHO) standards for drinking water, using the water quality index (WQI) as a means for reporting water quality measurement data and providing them in a consistent manner to authorities, decision-makers, and the public (Qasemi et al., 2023). This comprehensive analysis seeks to provide valuable insights into the water quality status of the mentioned areas, which are primarily influenced by agricultural activities. In addition, the results of this study 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, and two sub-watersheds (Gargaat Tarf and Annk Djemel) were selected (35°38 –36°00 N, 06°35 –07°20 E; Fig. 1 [Figure 1: see original paper]). They are separated by the massif of Djebel Tarf, which is exclusively constituted by sub-horizontal limestone banks of Cretaceous Age (upper Aptian Stage). The rest of the surface of the sub-watersheds is essentially made up of recent geological formations, i.e., Quaternary, formed by massive limestone crusts, polygenic glacis coating the reliefs, ancient silts, arable land, and recent alluvium. Gargaat Tarf is marked by the presence of dune formation or glass. The hydrographic network, represented by a poorly developed pattern, is of endoreic type. The main wadi, Wadi Boulefreis, originates in the Aures Area (Allaoua and Hafid, 2019).

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

2.2 Water Sampling and Data Collection

The assessment involved the determination and characterization of the physical-chemical and bacteriological properties of 25 groundwater samples, collected from wells and springs (Fig. 1; Table 1) in 2023. The physical-chemical analyses were carried out on water from private wells and natural springs (Table 1).

Because the collection of a water sample is quite delicate, the greatest care must be taken as it conditions the analytical results and the interpretation that will be given. To ensure sample homogeneity and representativeness, we collected and stored the water samples following a strict protocol. Polyethylene bottles with a capacity of 500 mL were used for this purpose. Before filling the bottles with water, we thoroughly washed them with nitric acid and then rinsed with distilled water. Additionally, to further minimize any potential contamination, we washed the bottles three times with the same water that was going to be analyzed. Once the cleaning process was completed, the bottles were completely filled with the water samples to be collected. This meticulous procedure aims to maintain the integrity of the water samples and ensure accurate and reliable analyses for the study.

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 then 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. By calculating the difference between total hardness and calcium hardness, we directly obtained the magnesium hardness of the analyzed water. This comprehensive analysis and accurate methodology ensure reliable and precise data for the assessment of water quality 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 volume of sample (100 mL) in the presence of methyl orange as an indicator. The reaction occurs due to the neutralization of bicarbonate ions by the H^+ ions of H_2SO_4. Chlorides were determined volumetrically by Mohr's method, precipitating silver chloride through the reaction of chloride ions with silver nitrate in the presence of 10% K_2CrO_4 as an indicator. SO_4^{2-} was determined by nephelometry using a UV-visible spectrophotometer (WTW) set at a wavelength of 420 nm and calibrated prior to any determination. SO_4^{2-} concentration is 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 their purity. After collection, we stored and transported these samples to the laboratory in cooler boxes to preserve their integrity and prevent any degradation of water quality during transportation. Laboratory analysis was promptly carried out within the next 4 h to ensure the freshness and reliability of the results. This strict protocol helps minimize any potential contamination and provides accurate data for the study. Analyses were performed at the laboratory.

Bromocresol purple lactose broth (BCP) tubes fitted with a Durham bell were used to count total Escherichia coli after a 24–48 h incubation period 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 h. Addition of 2–3 drops of Kovacs reagent results in the formation of a red ring on the surface, indicating indole formation and thus the presence of fecal coliforms. The search for fecal streptococci was carried out on Rothe medium at 37°C for 24 h. From the positive Rothe tubes, a subculture was performed on Litsky medium for 24 h at 37°C. We calculated the results as number of germs per 100 mL according to the Mac-Grady table.

2.5 Water Quality Index (WQI)

WQI is a valuable and efficient tool used to evaluate the overall quality of groundwater (Khan and Jhariya, 2017; Adimalla et al., 2018). It is derived from a comprehensive dataset and is presented in a manner that is easily comprehensible for water resource managers and decision-makers (Rana and Ganguly, 2020). WQI offers a consolidated and user-friendly approach to assess groundwater quality, making it a key component in informed decision-making and effective management of water resources.

WQI is commonly utilized to assess the suitability of groundwater for drinking purposes in various regions worldwide (Khan and Jhariya, 2017; Wu et al., 2017; Adimalla and Venkatayogi, 2018; Verma et al., 2018). Five water classes are listed by WQI value: excellent (WQI range: 0–25), good (WQI range: 26–50), moderate (WQI range: 51–75), poor (WQI range: 76–100), and very poor (WQI > 100). To determine if the groundwater is potable, 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 WQI calculation.

The quality index/sub-index (q_n) is a number that reflects the relative value of a certain parameter in polluted waters compared with 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 of the nth parameter in most cases; and v_{io} is the ideal value of the nth parameter. $v_{io} = 0.0$ 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.

According to Adimalla and Venkatayogi (2018), we used WQI to determine whether groundwater is suitable for drinking purposes. Initially, we considered the maximum values for the physical-chemical parameters studied based on Algerian standards for surface waters (Table 2). These values were utilized to establish the relative importance of each parameter in the overall assessment of water quality. WQI calculation takes into account these weights and constants to provide a comprehensive and standardized evaluation of water quality, aligning with established standards for surface waters in Algeria.

2.6 Statistical Analysis

To compare the values of different physical-chemical parameters in groundwater across the examined sub-watersheds, we computed means ± standard deviations (SD) and the range (minimum–maximum) based on observed data from wells and springs, considering them as replicates within each sub-watershed. To analyze variation of physical-chemical parameters between the two sub-watersheds, we conducted Welch's two-sample t-test after confirming normal distribution of data (using the Shapiro-Wilk test) and unequal variances (using the F-test).

Using Pearson's correlation, we examined connections between physical and chemical properties of water. The generated correlation matrix was displayed in a single plot together with corresponding P-values and correlation coefficients (r) using the Corrplot package (Wei and Simko, 2021). As changes in water characteristics resulting from the growth of one bacterial group may impact the growth of other bacteria either positively or negatively (Loucif et al., 2020), linear regressions and correlation tests were conducted to investigate 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 a correlative scaling method. Furthermore, Pearson's correlation tests were performed between water parameter values observed at each sample and RDA site scores (weighted sums of response variable scores) on one hand, and actual values of meteorological parameters and RDA constraints (linear combinations of climate variables) on the other.

To assess the impact of measured water physical-chemical parameters, represented by WQI value, on variation of bacterial loads for each of the three bacterial groups, we employed a generalized linear model (GLM). Bacterial load data were fitted to a Poisson distribution error with a log link function. All statistical analyses in this study 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 the average of measured values during the entire study period for each parameter. This approach provides a representative and stable representation of water quality for each site, enabling comprehensive assessment of well water conditions without being influenced by short-term fluctuations or seasonal changes. Values of physical-chemical parameters of sampled water are presented in Table 3 .

The Annk Djemel sub-watershed was characterized by groundwater with a temperature of 16.8°C (\$±0.3°$C).WaterpHvariedbetween7.00and7.80withanaverageof7.30.ECvariedbetween254$
mg/L. Average Ca^{2+} values were between 109 and 835 mg/L with an average of 383 mg/L, while Mg^{2+} had an average of 147 (\$±19$)mg/L.Sulfatesrangedfrom80to472mg/Landaveraged252$
mg/L.

Regarding nutrients, average NO_2^- was 0.18 (\$±\$0.06) mg/L with a range of 0.02–0.70 mg/L, NO_3^- averaged 10.49 (\$±\$5.13) mg/L, PO_4^{3-} averaged 0.15 (\$±\$0.02) mg/L, and NH_4^+ values varied between 0.00 and 0.25 mg/L with an average of 0.15 mg/L.

The Gargaat-Taref sub-watershed showed the following characteristics: temperature was 16.9°C (\$±0.26°$C)andpHvariedbetween6.68and8.04withanaverageof7.38.ECwas3153(\pm608)\mu S/cm$
mg/L and bicarbonates ranged from 210 to 833 mg/L with an average of 478 mg/L. Ca^{2+} averaged 446 (\$±\$87) mg/L. Mg^{2+} ranged from 32 to 481 mg/L with a mean of 163 mg/L. NO_2^- averaged 0.25 (\$±\$0.06) mg/L, NO_3^- ranged from 0.01 to 0.29 mg/L with an average of 0.25 mg/L, PO_4^{3-} ranged from 0.01 to 0.14 mg/L with an average of 0.11 mg/L, Cl^- averaged 725 (\$±\$188) mg/L, and SO_4^{2-} ranged from 74 to 756 mg/L with an average of 452 (\$±\$76) mg/L.

Despite spatial variations observed 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 of the two sub-watersheds are summarized in Figure 2 [Figure 2: see original paper]. Correlation analysis in the Annk Djemel and Garrat Taref sub-watersheds resulted in significant correlations in 19 of 98 pairs of water attributes.

For the Annk Djemel sub-watershed, the highest negative correlations were obtained between: DO and temperature ($r = -0.94$, $P < 0.001$), HCO_3^- and temperature ($r = -0.79$, $P = 0.001$), NO_2^- and DO ($r = -0.79$, $P = 0.003$), and NO_2^- and temperature ($r = -0.66$, $P = 0.014$). The highest positive correlations were obtained for 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 were recorded between: 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 $CaCO_3$ ($r = 0.78$, $P = 0.002$), NH_4^+ and EC ($r = -0.63$, $P = 0.031$), and NH_4^+ and temperature ($r = 0.69$, $P = 0.009$).

In the Gargaat Taref sub-watershed, significant correlation was found in 25 of 98 pairs of water attributes. There was strong correlation 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 were noted between SO_4^{2-} and EC and $CaCO_3$ ($r = 0.71$, $P = 0.010$). Significant correlation was also found between NO_2^- and HCO_3^- ($r = 0.83$, $P = 0.001$), NO_3^- and NO_2^- ($r = 0.86$, $P < 0.001$), NO_3^- and HCO_3^- ($r = 0.81$, $P = 0.002$), and PO_4^{3-} and NO_2^- ($r = 0.76$, $P = 0.004$), SO_4^{2-} and NO_2^- ($r = 0.80$, $P = 0.002$), SO_4^{2-} and NO_3^- ($r = 0.72$, $P = 0.008$), and PO_4^{3-} and HCO_3^- ($r = 0.60$, $P = 0.041$). Negative correlations included: DO and temperature ($r = -0.91$, $P < 0.001$), pH and NH_4^+ ($r = -0.71$, $P = 0.010$), pH and HCO_3^- ($r = -0.71$, $P = 0.009$), and pH and NO_3^- ($r = -0.61$, $P = 0.035$). Additional significant correlations were noted for pH and PO_4^{3-} ($r = 0.71$, $P = 0.010$) and pH and Cl^- ($r = 0.59$, $P = 0.044$).

3.3 Bacteriological Quality of Groundwater

Variations in bacterial load in the groundwater of 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 wells contained total heterotrophic bacterial load. The average concentration of total coliforms for all wells during the study period was approximately 453.9 ± 180.3 CFU/100 mL, with a maximum value of 1900.0 CFU/100 mL observed in well P9. For fecal coliforms, average concentration in all wells was approximately 243.2 ± 99.2 CFU/100 mL, with a maximum of 1000.0 CFU/100 mL found in well P3. For fecal streptococci, average concentration in well water was 77.9 ± 32.0 CFU/100 mL with a maximum of 324.0 CFU/100 mL in well P3. Regarding relative variation, the coefficient of variation (CV) showed that all concentrations of bacterial load in the examined surface waters were heterogeneous (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 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 ($r = 0.89$). The slopes of linear regression equations for these correlations ranged from 0.161 to 2.927, with the largest slope for fecal coliforms.

3.5 Effects of Water Characteristics on Bacterial Loads

RDA was employed to examine relationships between groundwater physical-chemical parameters and bacterial load. Results indicated that the first and second axes explained 96.9% and 2.9% of the eigenvalues, respectively. According to the first axis of RDA, 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 negative side of the axis. Moreover, bacterial group distribution was also plotted on the positive side of the axis (Fig. 5 [Figure 5: see original paper]; Table 4). This analysis suggests a clear association between physical-chemical parameters of groundwater and bacterial presence, indicating potential inter-relationships between these variables.

On the second axis of RDA, which presents only 2.9% of variation, bacterial load of total coliforms was positively associated with NO_3^- concentrations and water temperature, but negatively with water 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 load were negatively correlated on the first axis, showing that bacterial load increased with increases in a few parameters such as NO_3^-, temperature, and NH_4^+, but these were not statistically significant ($P > 0.050$). According to water parameters and bacterial abundance, there was clear spatial separation, allowing classification of sample sites into two groups based on physical-chemical quality and bacterial load: the first group comprised wells P9, P1, and P3. Water from these wells showed significant mineralization and pollution by NH_4^+ as well as high bacterial load. This group was opposed to the second group, which included the remaining wells (P2, P4, P5, P6, P7, P10, S1, S2, and S3) and three sources characterized by relatively average mineralization compared with other sites and almost zero pathogen contamination.

3.6 Effect of WQI on Bacterial Loads of Contamination Indicators

WQI of Gargaat Tarf varied from 17% to 50%, indicating water quality ranging from excellent to very poor, while WQI of Annk Djemel indicated that 85% of all samples analyzed were of excellent quality and 15% were good. For the entire study area, we found that 68% of samples fell into the excellent category, 24% fell into good categories, and only 8% were of poor quality and unfit for human consumption (Fig. 6 [Figure 6: see original paper]).

Throughout the study period, there was significant difference between average WQI values ($P = 0.032$) in the two sub-watersheds. Regarding relative variation, CV observed for the two sub-watersheds was largely higher, indicating that WQI was heterogeneous. In comparison, the Annk Djemel basin with CV of 139% had more heterogeneous water quality than Gargaat Tarf (CV = 87%). Regarding GLM results, the effect of WQI on bacterial load showed negative effects on the 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 observed for the bacterial groups. Similarly, when testing effects of water physical-chemical parameters on variation of bacterial group loads, GLM demonstrated no significant effects (Table 5). These results suggest that variations in bacterial loads were not significantly influenced by water physical-chemical parameters, indicating a lack of significant correlation between these factors.

---

4 Discussion

Water quality assessment is generally based on monitoring microbial elements, particularly the presence of fecal coliform bacteria, as well as analysis of 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 (such as soil and sediment), and pollution sources, while internal factors result from biochemical reactions occurring in the water itself (Hacioglu and Dulger, 2009).

4.1 Water Physical-Chemical Properties

The physical and chemical parameters of groundwater were compared with standard guideline values recommended by WHO (WHO, 2017). Temperature is one of the physical-chemical parameters used to assess drinking water quality, playing a role in many phenomena such as the speed of chemical reactions in the water body, decrease in gas solubility, and accentuation of water tastes and colors (Daghara et al., 2019; Calero Preciado et al., 2021; Moussaoui et al., 2024).

The average water temperature in all seasons was between 15°C and 19°C, with thermal variation of about 0.2°C. Groundwater temperature can vary depending on aquifer depth and seasons. For example, the European Parliament has established an indicative value for water temperature for human consumption at 25°C, considering this temperature as a limit not to be exceeded (Rodier, 2009).

In the study area, pH values ranged from 6.68 to 8.04, with an average of 7.36. Most groundwater samples were between weakly alkaline and moderately alkaline levels, a phenomenon 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 heavy metals unavailable (Ahipathy and Puttaiah, 2006). Water conductivity is an essential parameter because it evaluates the capacity of an aqueous medium to allow passage of an electric current (Sui et al., 2018). Groundwater EC generally ranged from 254 to 7160 S/cm, closely related to ion concentrations present in these waters. These higher values likely attributable to high ion concentrations indicate higher levels of total dissolved solids in groundwater, which contributes to increased salinity (Abboud, 2018). Furthermore, large variations in EC values reflect significant differences in predominant geochemical approaches in the study area.

DO concentration ranged from 3.99 to 9.53 mg/L, with an average of 6.77 mg/L. According to standards, the maximum allowable limit for DO in drinking water is 8.00 mg/L (WHO, 2017). DO concentration plays a pivotal role in groundwater quality as it regulates the valence state of trace metals and restricts bacterial metabolism of dissolved organic species. Due to these factors, measuring DO concentration is considered 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). These elements are found naturally in waters, and their presence is attributed to dissolution of carbonate formations such as limestone and dolomites (Drever, 2001). Bicarbonate is the most common anion in groundwater and comes mainly from CO_2 present in soil (Ahuja et al., 2008). Its concentration varied from 55 to

833 mg/L in water, and its origin can be attributed to leaching of carbonate formations. Singh et al. (2012) reported that during irrigation, rainfall infiltration, and groundwater movement, carbonates existing in carbonate rocks may be dissolved and supplied to the groundwater system along with recharge water. These processes could account for low alkalinity levels seen in some examined wells, possibly reflecting hydrochemical immaturity of the groundwater or shallowness of the aquifer (Demetriades, 2011).

Cl^- is found naturally in all types of water, but main contributing sources are runoff, inorganic fertilizers used in agricultural fields, and wastewater discharges (Çadraku, 2021). In the present study, Cl^- varied between 64 and 2482 mg/L, with an average of 655 mg/L, which exceeds the permissible limit (250 mg/L). The presence of high Cl^- levels in groundwater makes it potentially hazardous to human health (Pius et al., 2012; Noori et al., 2014). SO_4^{2-} comes from dissolution and leaching of rocks containing gypsum, iron sulphides, 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. However, this limit is often exceeded in groundwater in many parts of the world, including Europe, Asia, and Africa. Ca^{2+} concentrations varied between 109 and 1239 mg/L, with an average value of 250 mg/L. Ca^{2+} originates from dissolution of carbonate and evaporitic minerals such as calcite, dolomite, aragonite, gypsum, and anhydrite, as well as from carbonate cement present in geological formations (Bozdağ and Göçmez, 2013). Mg^{2+} varied between 32 and 481 mg/L, with an average of 155 mg/L. It is very likely that Ca^{2+} and Mg^{2+} presence in groundwater comes from leaching of carbonate minerals such as calcite and dolomite (Magesh et al., 2013). Geospatial distribution of cations showed higher concentrations in Gargaat Taref than Annk Djemel. It is very likely that the major source of Mg^{2+} in groundwater is from magnesium-containing minerals such as dolomite and sulfate minerals present in the study area (Şener et al., 2017).

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). NO_3^- concentration in analyzed water samples ranged from 0.01 to 68.22 mg/L, which was below WHO permissible consumption limits (50.00 mg/L). NH_4^+, NO_2^-, and PO_4^{3-} were well below maximum desirable WHO limits, with mean values of 0.22, 0.16, and 0.13 mg/L, respectively. Low concentrations of these three elements are attributed to low contamination of these waters with pollution sources.

Pearson's correlation matrix analysis is a valuable tool that reveals links and associations between hydrogeochemical parameters, allowing identification of their origins and interrelationships (Guey-Shin et al., 2011; Mgbenu and Egbueri, 2019). According to their report, when correlation coefficient (r) is greater than 0.70, it indicates strong correlation between two parameters, while r values between 0.50 and 0.70 suggest moderate correlation. Good correlation was 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 that all these elements could have the same origin. According to Singh and Mukherjee (2015), increased presence of these ions can be attributed to dissolution of evaporitic minerals. In addition, ionic strength of water increases due to dissolution of these evaporitic minerals, which promotes dissolution of sulphate salts, leading to increased Mg^{2+} and Ca^{2+} concentrations in groundwater (Alaya et al., 2014). Negative correlations were observed between temperature and DO ($r = -0.94$) as well as between DO and ammonium ($r = -0.71$), illustrating negative interactions between these parameters. Indeed, temperature influences both oxygen solubility in water and biological activities such as photosynthesis and respiration, which impact short-term oxygen concentration balance (Butcher and Covington, 1995; Daghara et al., 2019; Calero Preciado et al., 2021).

4.2 Bacteriological Quality of Groundwater

Analyzing abundance and diversity of microorganisms is a useful approach for assessing drinking water quality (Favere et al., 2021). However, it is difficult to test water for all organisms, as their isolation and identification is extremely complex (Soni et al., 2023). A commonly used indirect method to assess fecal contamination is analysis of coliform bacteria, which are widely considered reliable indicators of such contamination (Kistemann et al., 2002; Nola et al., 2002; Barnes and Gordon, 2004). 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 in wells P9, P1, and P3, respectively, due to application of animal manure or dung. Coliform bacteria concentrations were lower in deeper wells, confirming that artesian wells are safer than surface wells or outcropping springs. Several studies worldwide have corroborated these observations, confirming that runoff and short residence times in permeable soils play crucial roles in direct infiltration of manure into groundwater (Richardson et al., 2009; Masoud et al., 2016). Thus, the practice of open defecation and use of private septic tanks lead to sewage entering groundwater sources in rural areas worldwide (Schijven et al., 2010; Masoud et al., 2016). In the same context, Joseph et al. (2021) reported that livestock grazing activity elevated bacteria numbers, while Chadwick and Chen (2002) reported that the highest numbers of fecal coliforms and fecal streptococci were still present in manure.

Lack of protection of most wells also contributes to water enrichment in organic matter due to windblown inputs of leaves and other plant debris that decompose on site. All indicator bacteria were highly correlated with each other, with correlation coefficient r varying from 0.89 to 0.96 ($P < 0.001$). These positive correlations show that these indicators probably have the same contamination source. Atherholt et al. (2003) suggest that many total coliforms in the environment can only come from fecal sources. According to Francy et al. (2000), strong correlation between two indicators may indicate that they come from identical or similar contamination sources. Atherholt et al. (2003) reported that existence of both fecal coliforms and fecal streptococci indicators provides 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 a relationship between physical-chemical properties and bacterial abundance. In this study, bacteriological analysis revealed different bacterial groups with similar tendencies. Similar results were reported by Guemmaz et al. (2020), showing influence of environmental factors on fecal bacterial loads measured in urban effluents discharged into arid wadis of Algeria. Variations in environmental factors such as pH, salinity, metal concentrations, and energy exert selective and direct effects on composition, abundance, and spatial distribution of microbial communities (Dell'Anno et al., 2003; Franklin et al., 2007; Guo et al., 2015; Jordaan et al., 2016; Liu et al., 2018). RDA analysis shows that NO_3^-, NH_4^+, SO_4^{2-}, temperature, Ca^{2+}, EC, Cl^-, $CaCO_3$, and Mg^{2+} are the environmental variables that statistically best explain variations in bacterial distribution. Total coliforms include fecal coliforms, and all bacteria in this group have similar biochemical characteristics and are found in soil or water (Rodier et al., 2009).

In the present 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 oxidation of ammonium ions present in feces (Bou Saab et al., 2007). Nitrate ions and fecal coliforms therefore share a common origin. Water temperature is one of the most significant environmental parameters influencing concentrations of fecal indicator bacteria. Some studies have reported inverse relationships between fecal coliforms and water temperature, while others have found direct relationships (Loucif et al., 2020; Valenca et al., 2022). In our study, increasing temperature promoted development of bacterial load of total coliforms, fecal coliforms, and fecal streptococci. These results are consistent with Chigbu et al. (2005), who also found correlation between temperature and fecal coliforms. However, our results differ from Tek et al. (2001), who observed no relationship between temperature and these bacterial indicators.

Variable responses of bacterial populations were also observed in relation to other physical-chemical parameters. High values of EC, Mg^{2+}, Ca^{2+}, and $CaCO_3$ have been associated with increased abundance of these bacteria (Nola et al., 2002). In a bacteriological and chemical investigation of groundwater in Cameroon, Nola et al. (2002) discovered that higher EC and concentrations of oxygen, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} promoted abundance of fecal coliforms and fecal streptococci. Although Ondieki et al. (2021) claim that total coliforms rise at acidic pH, Loucif et al. (2020) assert that alkaline pH obviously impairs survival of fecal coliforms. Depending on available environmental parameters such as ideal pH, temperature, nutrient amount, and suspended particles, coliform bacteria survival can be prolonged and even expanded (Juhna et al., 2007).

4.4 Water Quality Index

A total of 68% of groundwater samples taken during the research period were classified as excellent water, with good water comprising about 24%, whereas poor water represented 8%. The latter, which exhibits poor quality, may 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 its suitability for consumption. In reality, WQI is a crucial indicator for determining groundwater quality and establishing whether it is fit for human use (Mishra and Patel, 2001; Naik and Purohit, 2001; Avvannavar and Shrihari, 2008; Rana and Ganguly, 2020; Ram et al., 2021).

WQI was tested with bacterial load values chosen as pollution indicators using GLM. The t-test shows negative correlations between WQI and bacterial load. Thus, low WQI values were closely related to high load values of total coliforms, fecal coliforms, and fecal streptococci, indicating poor quality for some groundwater samples in the study area. On the other hand, GLM indicated a non-significant effect of this correlation. Regarding relative variation, CV results showed that all WQI values were heterogeneous, signifying spatial diversity of the study area as well as various pollutants that threaten groundwater quality.

This study offers a robust assessment of groundwater quality in semi-arid areas of Algeria, providing valuable insights into water suitability for both drinking and agricultural purposes. The comprehensive analysis includes a range of physical-chemical parameters, and WQI application enhances clarity of findings. However, it is essential to acknowledge study limitations. The sample size is relatively small, potentially limiting generalizability of findings. Furthermore, focus on specific parameters and absence of consideration for seasonal variations might not fully encapsulate the dynamic nature of groundwater quality. Future research with larger and more diverse datasets, along with exploration of temporal variations, would strengthen overall reliability and applicability of results.

4.5 Implementation and Perspective

In the larger context, this study prompts reevaluation of water management practices, advocating for policies that prioritize preservation and enhancement of groundwater quality. Results emphasize urgency of collaborative efforts involving stakeholders, policymakers, and local communities to ensure access to safe and potable water—a fundamental right for the present and a necessity for future generations.

In the face of bacterial contamination and water-related health risks, diverse solutions can be considered. Firstly, improving sanitation infrastructure is crucial to prevent contaminant spills into groundwater sources. Additionally, reinforcing water point protection through filters and physical barriers can mitigate direct contamination. Raising community awareness about proper hygiene practices and preserving water sources is equally imperative. Implementing regular water quality monitoring is essential to swiftly respond to bacterial contamination. Simultaneously, strict adherence to water quality standards and tailored regulation is necessary to oversee potentially contaminating activities. Lastly, fostering multi-stakeholder collaboration among local authorities, government organizations, communities, and water management experts is paramount to coordinate efforts aimed at sustainably restoring and preserving water quality. This concerted action ensures a safe supply of potable water for local populations.

5 Conclusions

Assessment of groundwater quality emerges as a critical aspect in ensuring safety and sustainability of water usage. In semi-arid areas like Algeria, where groundwater serves as the primary water source for rural communities and agricultural activities, its quality holds immense significance. Our study extensively analyzed various parameters in groundwater samples from the Gargaat Tarf and Annk Djemel sub-watersheds of Algeria. Findings showed that physical and chemical parameters surpassed WHO recommended limits. Notably, pH ranged slightly alkaline (7.00–7.79), with elevated levels of EC, Cl^-, Ca^{2+}, Mg^{2+}, and other substances, signaling compromised water quality. Despite these concerns, WQI offered a nuanced perspective. A significant portion of the area, approximately 68%, exhibited excellent water quality, while 24% fell under the good category. However, alarmingly, 8% indicated poor quality, rendering them unsuitable for human consumption and emphasizing the imperative need for remediation and management strategies.

The presence of bacterial contamination, particularly in six wells, further underscores human influence on water resources. Elevated levels of coliforms and streptococci above WHO standards reflect anthropogenic impact on water quality, posing health risks and deeming certain water points unsuitable for drinking. These revelations call for immediate attention and strategic interventions. The significance of this research extends beyond mere observation; it demands actionable steps to rectify deteriorating groundwater quality. Efforts must focus on targeted measures to mitigate anthropogenic influences, implement rigorous monitoring frameworks, and devise interventions that safeguard water resources.

Conflicts of Interest

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

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 our gratitude to Dr. Haythem DINAR (University of Oum El Bouaghi, Algeria) for his invaluable assistance in plotting Figure 1.

Author Contributions

Conceptualization, methodology, investigation, data curation, resources, and writing—original draft preparation: Noua ALLAOUA; writing—original draft and writing—reviewing and editing: Hinda HAFID; formal analysis, visualization, writing—original draft, and writing—reviewing and editing: Haroun CHENCHOUNI. All authors approved the manuscript.

References

Abboud I A. 2018. Geochemistry and quality of groundwater of the Yarmouk Basin aquifer, North Jordan. *Environmental Geochemistry and Health*, 40(4): 1405–1435.

Adamou H, Ibrahim B, Salack S, et al. 2020. Physico-chemical and bacteriological quality of groundwater in a rural area of Western Niger: A case study of Bonkoukou. *Journal of Water and Health*, 18(1): 77–90.

Ahipathy M V, Puttaiah E T. 2006. Ecological characteristics of Vrishabhavathy River in Bangalore (India). *Environmental Geology*, 49(8): 1217–1222.

Ahuja R, Yammani R, Bauer J A, et al. 2008. Interactions of cubilin with megalin and the product of the amnionless gene (AMN): Effect on its stability. *Biochemical Journal*, 410(2): 301–308.

Alaya M B, Saidi S, Zemni T, et al. 2014. Suitability assessment of deep groundwater for drinking and irrigation use in the Djeffara aquifers (Northern Gabes, south-eastern Tunisia). *Environmental Earth Sciences*, 71: 3387–3421.

Alexakis D E. 2022. Applying factor analysis and the CCME water quality index for assessing groundwater quality of an Aegean Island (Rhodes, Greece).

Geosciences, 12(10): 384, doi: 10.3390/geosciences12100384.

Allaoua N, Hafid H, Merzoug D, et al. 2015. Evaluation of physic-chemical quality of well water in the area of OUM El-Bouaghi (High Plains of Eastern Algeria) characterization and analysis in principal component. *Advances in Environmental Biology*, 9(18): 63–72.

Allaoua N, Hafid H. 2019. *Biodiversity and ecology of aquatic fauna of eastern Algeria: Identification of the main groups and families of groundwater.* Sarrebruck, Germany: EUE. (in French)

Atherholt T, Feerst E, Hovendon B, et al. 2003. Evaluation of indicators of fecal contamination in groundwater. *Journal AWWA*, 95(10): 119–131.

Avvannavar S M, Shrihari S J E M. 2008. Evaluation of water quality index for drinking purposes for river Netravathi, Mangalore, South India. *Environmental Monitoring and Assessment*, 143: 279–290.

Barnes B, Gordon D M. 2004. Coliform dynamics and the implications for source tracking. *Environmental Microbiology*, 6(5): 499–509.

Bou Saab

Note: Figure translations are in progress. See original paper for figures.