Crisis Beneath the Sands: Groundwater Degradation and Health Risks in the Northeastern Algerian Sahara – The Case of Oued Souf Valley[1]

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Abstract:

The Oued Souf Valley in southern Algeria, part of the vast Sahara, is confronting a severe groundwater crisis driven by overexploitation, human-induced pollution, and climate variability. This study presents an extensive assessment of hydro chemical, bacteriological, and heavy metal contamination across three major aquifers: the shallow phreatic, complex terminal, and continental intercalary aquifers. Results from 58 monitoring wells and detailed sample analyses reveal alarming contamination levels in the phreatic aquifer, with electrical conductivity up to 7500 µS/cm, nitrate concentrations exceeding 150 mg/L, and high levels of aluminium, lead, and manganese. All phreatic samples showed very high pollution levels based on the Groundwater Pollution Index (GPI). Spatial analysis linked contamination patterns to intensive agriculture and urban expansion. Deeper aquifers displayed lower contamination but still frequently exceeded WHO standards for drinking water and irrigation due to high salinity and mineralization. Health risk assessments revealed hazard index (HI) values exceeding 1 for adults in 8 samples and for children in all samples, highlighting significant risks from long-term exposure to metals. Geostatistical modelling showed fluctuating groundwater levels between 2008 and 2021, driven by human activity and infrastructure failures. While ecological risk from heavy metals was generally low, localized samples showed considerable or high risk, especially due to lead contamination. The findings underscore the urgent need for integrated water management, stricter pollution controls, improved infrastructure, and targeted public health interventions to safeguard this vulnerable region's water resources and its population's health.

Keywords:

Northwest Sahara Aquifer System, groundwater pollution; Human Health Risk Assessment; Ecological Risk Assessment.

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1. Introduction

Water is a vital resource that shapes the distribution of human societies, the structure of economies, and the dynamics of political relations (Bechkit et al., 2024; Hamma et al., 2024; Rahal et al., 2024). Its uneven availability, driven by geographical and climatic factors, profoundly influences where and how communities develop, particularly in water-scarce regions (Barkat et al., 2022; Barkat et al., 2023a; Rahal et al., 2023; Barkat et al., 2023b). Access to water not only supports domestic and agricultural needs but also determines regional stability and power dynamics, as shared water sources often become points of tension or cooperation (Debabeche et al., 2022). In this context, the challenges of water scarcity extend beyond local concerns, highlighting the need for coordinated governance, sustainable management, and collaborative international efforts (Barkat et al., 2021).

Water scarcity presents significant challenges to achieving the Sustainable Development Goals (SDGs) (Sayed, 2015), particularly in arid and semi-arid regions where communities heavily depend on groundwater resources. Groundwater, accounting for approximately 98% of the Earth's liquid freshwater, plays a critical role in meeting domestic and agricultural water demands, especially in these regions (Panda et al., 2006; Táany et al., 2009; UNWWDR, 2015). It serves as the primary water source for nearly 2.5 billion people worldwide (Tatawat et al., 2008). However, its sustainable management faces numerous obstacles, including climate change, population growth, excessive abstraction, inadequate management practices, and poor coordination (Ravikumar et al., 2011). These issues have led to the depletion of aquifers, falling groundwater levels due to shifts in rainfall patterns and increased evapotranspiration, overextraction for agricultural and industrial use, and heightened contamination risks (Jha et al., 2007; Momodu et al., 2010; Luna et al., 2012). Such challenges have direct implications for several SDGs, notably Clean Water and Sanitation, Zero Hunger, Good Health and Well-being, and Climate Action (Velis et al., 2017). Addressing these challenges necessitates coordinated efforts from governments, communities, and international organizations to develop and implement sustainable groundwater management policies, particularly in arid regions (Srivastava et al., 2018; Zamani et al., 2022).

In southern Algeria, the Oued Souf Valley as a part of the vast Sahara relies almost entirely on groundwater to meet its drinking water and agricultural needs. This region is underlain by extensive groundwater reserves within geological formations of varying depth and thickness, which are part of the Northwestern Sahara Aquifer System. This system encompasses three major aquifers: the superficial phreatic aquifer, the complex terminal aquifer, and the continental intercalary aquifer, the latter two of which contain multiple, layered water-bearing formations. Together, these aquifers constitute one of the world's largest hydraulic reserves, with an estimated mobilizable potential of 5 billion cubic meters of water (ANRH, 1986; CDTN, 1992).

Despite the abundance of groundwater in the Oued Souf Valley, overexploitation since the 1980s followed by population growth, urban expansion, and economic development has created significant public health and environmental issues. Intensive pumping from deep aquifers, coupled with the discharge of untreated wastewater and the absence of a proper sewage system, has resulted in the contamination of shallow groundwater. This has disrupted the regional water system's equilibrium and threatens its long-term sustainability (Kadri et al., 2018).

These developments have triggered profound environmental and social changes in the region. The fragile ecological balance of the northern Sahara has been disturbed, infrastructure has been compromised, agriculture has suffered, and the traditional urban landscape including the historic Ghout system has been transformed. Public health challenges have worsened due to contamination of shallow aquifers with waste and nitrates, resulting in water stagnation and the proliferation of waterborne and parasitic diseases such as skin disorders, leishmaniasis, malaria, and typhoid (Côte, 1998).

In response to these crises, local authorities launched a major project in 2005 aimed at mitigating pollution and managing rising shallow groundwater levels. This project included sewerage networks, wastewater treatment initiatives, and water drainage systems. However, several obstacles prevented the project from fully achieving its objectives (Khezzani et al., 2018; Bouzegag et al., 2020). The failure of the vertical drainage system illustrates how human activities can exacerbate natural processes, affecting the fluctuations of the phreatic aquifer in the Oued Souf Valley. The contamination of shallow groundwater, its unauthorized use for irrigation and industrial purposes, and its connection to deeper aquifers pose significant threats to public health and the environment.

Given these challenges, a comprehensive assessment of the hydrochemical and bacteriological quality of groundwater in the Oued Souf Valley is essential to prevent further environmental and socioeconomic deterioration. This study aims to investigate the factors, particularly those driven by human activities that influence the stability of phreatic groundwater levels and the performance of the vertical drainage system in the region. It will also evaluate the hydrochemical and bacteriological quality of phreatic groundwater samples by measuring the concentrations of various physicochemical and microbiological indicators and comparing them to WHO guidelines to identify contamination sources and levels. Furthermore, the research will explore typical spatial patterns of these parameters across urban, peri-urban, and agricultural areas and assess the suitability of complex terminal and continental intercalary aquifers for drinking and irrigation purposes based on hydrochemical analysis.

2. Materials and methods

2.1. Environmental Setting of Oued Souf Valley

2.1.1. Hydrogeology

The phreatic aquifer (Guendouz et al., 2006), the shallowest groundwater reservoir in the area, consists of fine sands, sandy clays, and gypsum lenses that form the water table. Its thickness reaches about 100 meters, with water depths varying from 1 to 40 meters. Below it lies a clay layer that prevents further infiltration. By 2015, over 35,000 traditional wells were tapping into this aquifer. Its average permeability is approximately 10^{-4} m/s, with horizontal transmissivity and storage coefficient values around 10^{-2} m^2/s and 0.2, respectively. Recharge occurs naturally through rainfall infiltration and runoff from the southern boundary of the Great Oriental Erg, with episodic heavy rains, such as those in April 1947 and May 1967, also contributing (Castany, 1982; Dervierux, 1957; Ben Hamida, 2005; DRE, 2015; Kherici et al., 1996).

The complex terminal aquifer, a deeper system, is made up of multiple geological formations from the Cretaceous to Miocene periods. It lies 400–600 meters underground, has an average thickness of about 400 meters, and contains fossil water estimated to be 20,000–30,000 years old. In 2015, 182 deep wells accessed this aquifer, 28 used for irrigation and 154 for municipal and potable water supply (Abdous et al., 2005; Guendouz et al., 2003; Moulla et al., 2003).

Beneath this lies the continental intercalary aquifer, which includes deposits from the Middle Jurassic to Lower Cretaceous (Barremian and Albian stages). This formation, composed of sandstones and clayey sandstones, is situated between 1,800 and 2,200 meters depth, with a thickness of 200–400 meters. Its groundwater, also fossil water aged 20,000–30,000 years, is accessed by just four deep wells, all for drinking water due to its high temperature (above 70°C) (Cornet, 1964; Djennane, 1990). Figure 1 depicts the hydrogeological structure of the Northwest Sahara Aquifer System (NWSAS).

The Oued Souf region, in the northeastern Mesozoic basin of the Sahara, is dominated by fine-grained, compact, uniform sand dunes from the Quaternary period, reaching up to 100 meters in the south. It features plateaus (Sahans) covered in Quaternary gypsum, and saline depressions (Sebkha) located in the northern part of the Oued Souf Valley (Bel et al., 1966; Bel et al., 1970; Sebaa et al., 2009; Ballais et al., 2002). The geology of this Triassic basin (northeastern Sahara platform) consists of formations from the Lower Cretaceous to Quaternary, resting atop Paleozoic marine formations containing water, with total thicknesses exceeding 2,000 meters (BUSSON, 1972; Nesson, 1975; Giraud, 1978). Due to the region's arid climate and geomorphology, surface water resources are scarce (Dubief, 1965), making groundwater the principal water source for diverse uses in the Souf region (Drouiche et al., 2013).

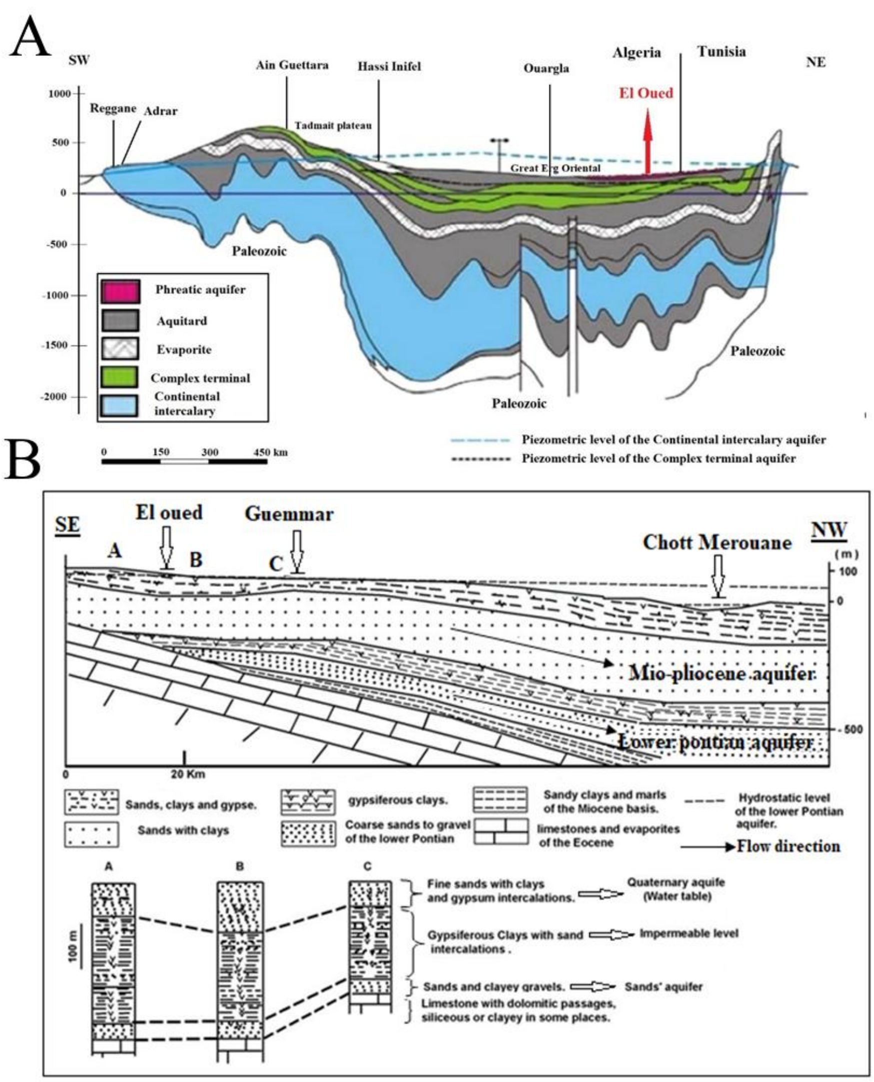

Figure 1. (A). Hydrogeological section of the North-West Sahara Aquifer System, (B). Geological cross-section of Oued souf valley, bottom: (A–C) are log correlation of Oued souf valley.

2.1.2. Topography

The Oued Souf Valley, located within the Great Eastern Erg in the Septentrional Sahara, represents a low-lying topographical area often referred to as the "lower Sahara" due to its modest elevation. The valley's altitude fluctuates between 64 and 100 meters (Cornet, 1964). Its slope is minimal, ranging from 0.03% to 0.16%, generally oriented from south to north, with notable depressions near the city center of El-Oued, as shown in figure 2.

Despite being named a "valley," the Oued Souf does not contain a flowing watercourse. Instead, it denotes a basin where sparse vegetation grows. According to (Najah, 1970), three primary landforms can be identified in the region: Sahanes, Ergs, and Sebkhas. The terrain reflects a combination of the Erg, characterized by dunes, and the Sahane, a sandy landscape interspersed with rocky plateaus extending southward, marked by alternating dunes and rocky ridges. The area features can be described as a depression zone with multiple chotts that slope eastward, and a Vast and prominent dunes, called Ghroudes, located south of Souf, which can rise as high as 200 meters.

A key distinction in Souf's topography lies between the Erg and Sahane regions. The Erg, making up roughly three-quarters of the area, comprises sand accumulations in the form of dunes. This sandy layer is substantial, typically several tens of meters thick. Recent well-drilling has revealed even greater thicknesses than previously estimated: 70–80 meters in southern Souf, 60 meters near El-Oued, gradually tapering to 30 meters in the northern areas, where it becomes a thin layer over Sebkhas (DUTIL, 1971).

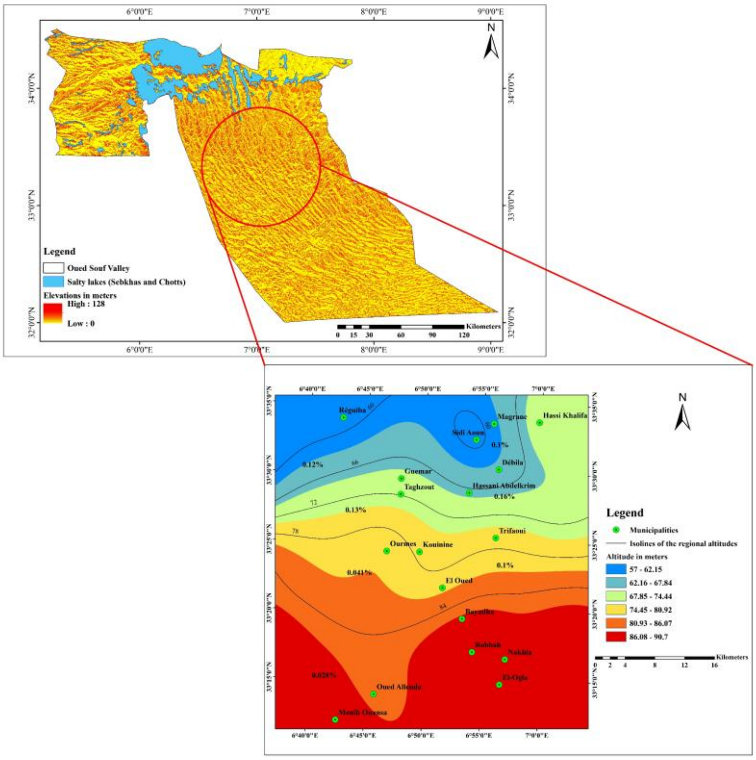

Figure 2. Integrated Topographic and Relief Map of Oued Souf region.

The Erg layer rests on an impermeable Pliocene clay bedrock. In contrast, the Sahane is a flat, often stony, depressed zone characterized by enclosed basins encircled by dunes. Sparse vegetation can grow in these basins, thriving on gypsum crusts. Sebkhas form when intense heat causes water to evaporate, leaving behind salt deposits. These salt pans arise from both phreatic and surface water sources, producing formations such as chotts and sebkhas (Briere, 2000). Additionally, from a broader geological perspective, sabkhas are saline basins typically found at the bottom of depressions in arid environments, often isolated from direct marine contact. However, they may still be linked to the sea through either narrow water channels (in deep basins) or by seepage (in shallow basins). These connections can result in sporadic water overflows, further increasing salinity. Over time, evaporation intensifies, leading to the formation of brine and precipitation of evaporites either across the entire basin or concentrated at one end, depending on the water depth (Medjber, 2014).

2.1.3. Economic Activities in Oued Souf Valley

The Oued Souf region has experienced a notable boom in agriculture over the past few decades, positioning it as one of Algeria's most productive agricultural areas. Farming activities are widespread across the region as presented in figure 3, with extensive areas dedicated to various agricultural uses, including pastures, herbaceous crops, fruit tree plantations, and fallow land. A key agricultural practice in the area is phoeniciculture (date palm cultivation), particularly within the Ghout system, a culturally significant and visually striking method that has shaped the Saharan landscape (Bataillon, 1955). This system involves hand-digging large craters where palm trees are planted, utilizing capillary action to draw water from the phreatic aquifer directly to the roots. This technique eliminates the need for traditional irrigation systems (Remini et al., 2011). Ghout systems take different forms such as circular, elongated, and rectangular depending on soil type and wind patterns (Bensaâd, 2011; Côte, 2006). The Ghout areas extend southward to the Libyan border, bordered by the Nemamchas Mountains, stretching east to Tunisia and west to the expansive Oued Righ oasis (Miloudi et al., 2019).

Since the 1990s, a significant shift has occurred in local farming practices with the adoption of mini-pivot irrigation systems. Supported by the State and driven by local farmers, this innovation has transformed Oued Souf into Algeria's leading potato-producing region. Today, the use of mini-pivot systems continues to expand alongside traditional Ghout farming methods (Remini et al., 2019). Fertilizer use in the region is tailored to local soil characteristics, crop types, and farmer preferences. Fertilizers commonly applied include nitrogen-based types such as ammonium nitrate and urea to encourage plant growth (Khouli et al., 2021), phosphorus-based fertilizers like superphosphate and rock phosphate to support root development and fruiting (Tsanakas et al., 2017), potassium-based fertilizers such as potassium chloride and sulfate for overall plant health and quality (Ouarekh et al., 2021), and organic fertilizers including compost and manure, which enhance soil structure and fertility (Abdallah et al., 2021).

Industrially, Oued Souf hosts a diverse range of activities spread across nine municipalities, covering sectors such as industrial chemistry, food and construction materials, metallurgy, textiles, leather, hydraulic binders, electrical appliances, mechanical and automotive industries (ANIREF, 2020). This industrial diversity makes Oued Souf a key industrial hub in Algeria. Additionally, the mining sector plays a significant role, with the region producing 78,500 tonnes of salt annually from the Chotts, along with 5,500 cubic meters of construction sand and 18,930 cubic meters of volcanic tuff each year.

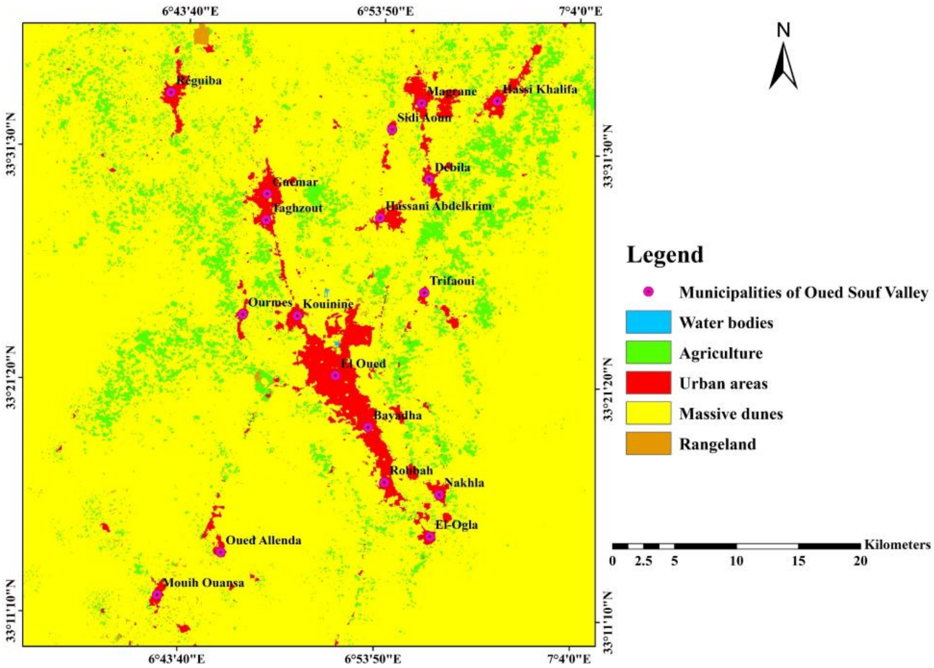

Figure 3. Land cover map of Oued Souf Valley.

2.2. Selection of Study Areas, Data Collection Procedures, and Methodological Applications

This research focused on assessing the groundwater systems in Oued Souf, selecting multiple study areas based on the targeted aquifers and available data. Specifically, it examined the phreatic, complex terminal, and continental intercalary aquifers. To analyze the spatial and temporal variation in the phreatic aquifer's groundwater levels, data were collected from 58 monitoring wells equipped with piezometers and level probes forming part of the vertical drainage network. Measurements were taken from the ground surface to the water table.

The physicochemical and bacteriological characteristics of the phreatic aquifer were evaluated using 28 samples: 22 from the vertical drainage system and six from surrounding agricultural and peri-urban locations. Parameters such as temperature (T), pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in the field with a Multi–350 i multiparameter instrument. Additional analyses followed established methods (Rodier, 1984). In a separate study in November 2022, the presence of heavy metals in the phreatic aquifer was analyzed using 14 samples and quantified with microwave plasma atomic emission spectrometry (MP-AES 4200, Agilent Technologies).

For the complex terminal aquifer, 49 groundwater samples were collected in March 2019 by ANRH- Agence Nationale des Ressources Hydrauliques and ADE- Algérienne des Eaux (El Oued Unit), covering the Mio-Pliocene and Pontian aquifers across El Oued, Debila, Guemar, Kouinine, Ourmas, Reguiba, and Taghzout. The continental intercalary aquifer was studied using three wells in El Oued. This dataset was provided by ANRH and ADE. Of these wells, eight represented the Mio-Pliocene layer, one the Pontian, and one the Lower Eocene. Figure 4 shows the study area with its administrative subdivisions.

The research applied a comprehensive methodology to address the research objectives. Geostatistical modeling with the ordinary kriging interpolation method was used to predict spatial patterns of groundwater levels and physicochemical elements in the phreatic and complex terminal aquifers (Webster et al., 2007). For mapping heavy metals, the inverse distance weighting (IDW) method was chosen due to the limited sample availability (Esri, 2012). For the environmental risk assessment of heavy metals in the phreatic aquifer, indices such as the contamination degree, geoaccumulation index (Igeo) (Singh et al., 2005), enrichment factor (EF) (Olivares-Rieumont et al., 2005), and potential ecological risk index (PER) (Fei et al., 2017) were calculated. A human health risk assessment was also conducted, evaluating long-term hazard levels through chronic daily intake (CDI), hazard quotient (HQ), and hazard index (HI) (USEPA, 2006; USEPA, 1999; Qiu et al., 2019; Murray et al., 1995).

The water quality index by (Brown et al., 1973) was applied to assess groundwater for drinking purposes across all hydrogeological units. Groundwater suitability for irrigation was determined using ionic parameters (meq/L) and indices including permeability index (PI) (Doneen, 1964), Kelly's ratio (KR) (Kelly, 1951), residual sodium carbonate (RSC) (El Bilali et al., 2021), residual base saturation coefficient (RBSC) (Amiri et al., 2023), exchangeable sodium percentage (ESP) (Zhou et al., 2021), sodium adsorption ratio (SAR) (Richards, 1947), total hardness (TH) (Todd, 1980), magnesium hazard (MH) (Ragunath, 1987), and others. Regarding the pollution assessment, groundwater pollution index (GPI) was applied to evaluate the contamination level (Subba et al., 2018).

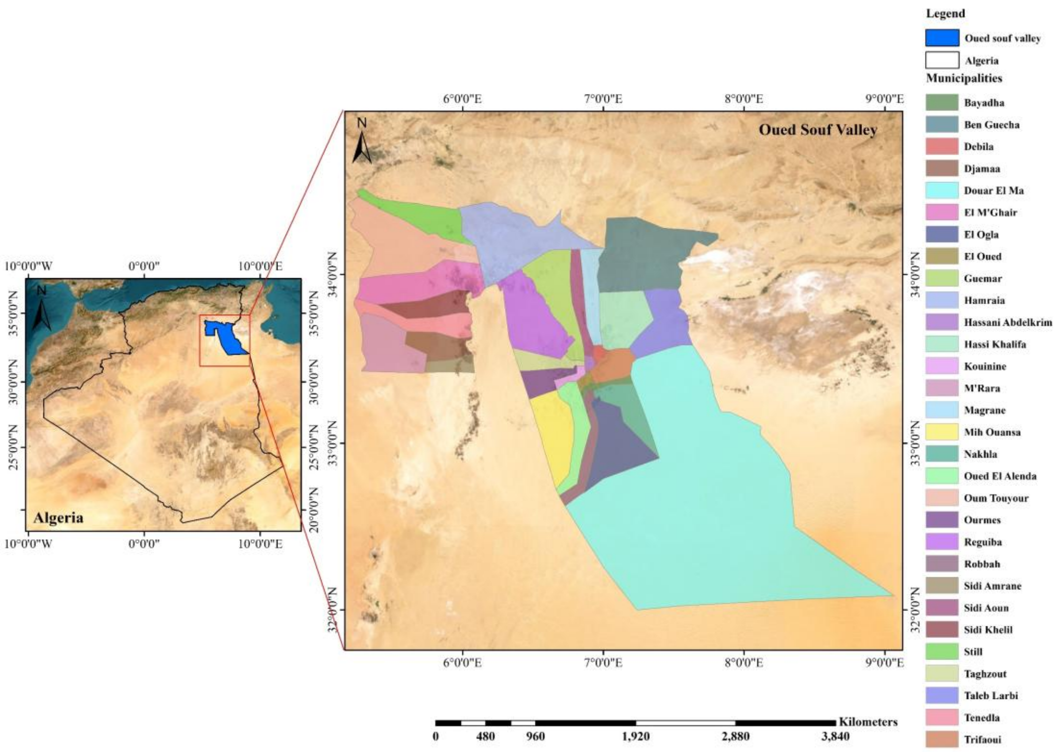

Figure 4. The administrative subdivisions of Oued Souf Valley.

3. Results and discussion

3.1. Analysis of Phreatic Groundwater Level Fluctuations and Influencing Anthropogenic Factors (2009-2018)

Through geostatistical modeling and map analysis, three distinct spatial patterns in the phreatic groundwater level were identified for the observation years 2008, 2009, 2014, 2016, and 2018. Initially, a noticeable rise in groundwater levels (upwelling) occurred from 2008 to 2009, followed by a decline from 2014 to 2018, and finally, a recovery from 2018 to 2021. The shallowest groundwater levels consistently appeared along a northwest-southeast axis in the study area, while the deepest levels were consistently found in the southwest during all observation years.

In 2008, the vertical drainage system began operating, resulting in shallow groundwater levels averaging 5.42 meters below ground level (mbgl). In 2009, this upwelling trend continued with similar patterns and an average depth of 5.06 mbgl, indicating a slight increase. However, from 2014 to 2016, groundwater levels began to decline, with shallowest depths gradually rising from the central northwest to the southeast. Depths ranged from 7.97 mbgl in 2014 to 7.81 mbgl in 2016. By 2018, the groundwater reached its deepest level at 12.74 mbgl, with a major spatial shift affecting nearly half the study area, extending from the south-southwest to the northwest. Although shallow areas maintained their general pattern, they experienced a significant drop compared to earlier years (as depicted in Figure 5).

A comparison with 2008 showed the following changes in groundwater levels: a decrease of 0.36 m in 2009, followed by more substantial declines of 2.56 m in 2014, 2.39 m in 2016, and 7.32 m in 2018 (as shown in figure 6). Despite these declines, by 2021 the groundwater level had risen to an average depth of 8.87 mbgl, representing a recovery of approximately 3.9 meters compared to 2018 levels (figure 6).

Fluctuations in the water table also resulted in areas with deep groundwater levels emerging in the northern part of the study area, extending westward and into the center. The reasons for these fluctuations can be divided into three key stages:

1. Water table rise (2008–2009):
   This phase was driven by several factors, including the region's natural topography and lack of natural drainage, poor coordination among water management sectors in Oued Souf Valley, excessive use of deep groundwater reservoirs, absence of sewage and drainage infrastructure, and leakages from the potable water system. Additionally, the vertical drainage system was in its early operational phase, requiring more time to effectively lower groundwater levels.
2. Water table decline (2009–2018):
   The decline was due to multiple causes:

- Independent exploitation of different parts of the aquifer system, reducing water recharge to the phreatic aquifer.

- Rapid agricultural expansion, especially around El Oued, which increased groundwater withdrawal and reduced infiltration.
- Replacement of septic tanks with vertical drainage systems in El Oued, which resulted in a steady water table decline and less contamination in the phreatic aquifer.
- Expansion of the sewage network in urban areas, reducing wastewater discharge into the environment and thus lowering the water table.

3. Water table rise (2021):
   The resurgence in 2021 was linked to factors such as:

- Drinking water supply inefficiencies, including high leakage rates, unauthorized withdrawals, and illegal connections.
- Poor integration with other water systems and unmetered withdrawals for firefighting, inspections, and maintenance.
- Legal and illegal industries, including gypsum production, which discharge large volumes of water into the environment.
- Issues in the drainage system, such as power outages and non-functional drains since 2018.
- Operational problems at the wastewater treatment plant, especially breakdowns in key equipment like the desander, causing reduced purification capacity and overburdening the system. Additionally, the complex structure of the phreatic aquifer, interspersed with shallow clay lenses, may also contribute to localized groundwater rises (Khechana et al., 2016).

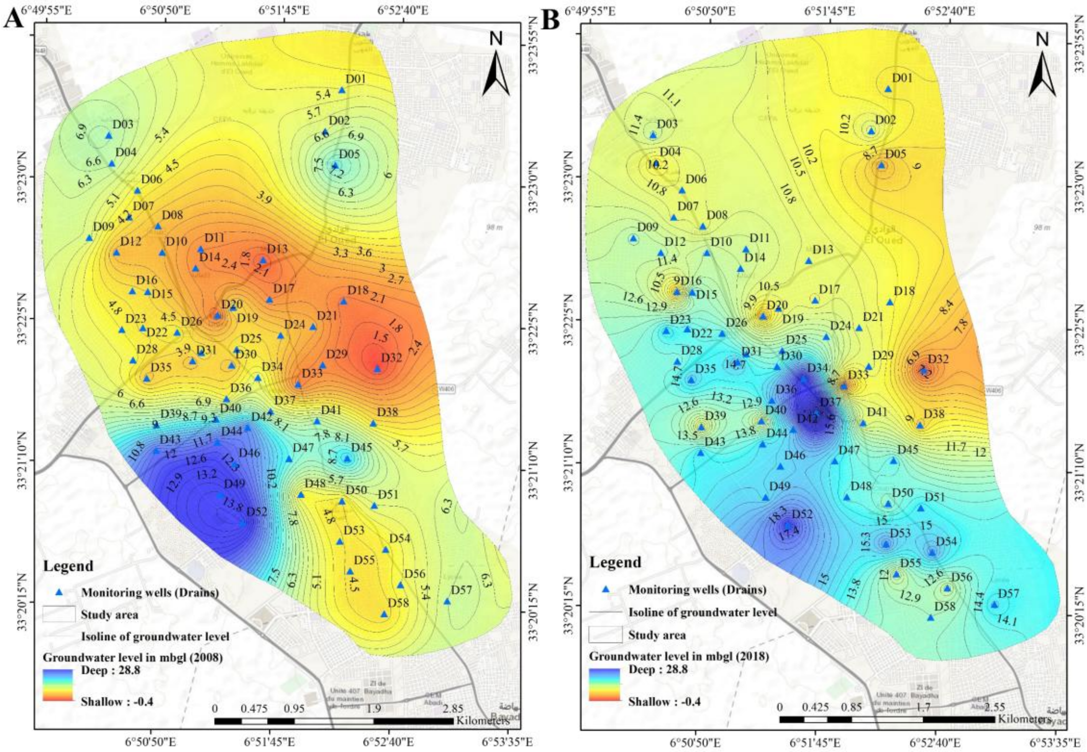

Figure 5. Evolution maps of groundwater level in the study area: (A). 2008, (B). 2018.

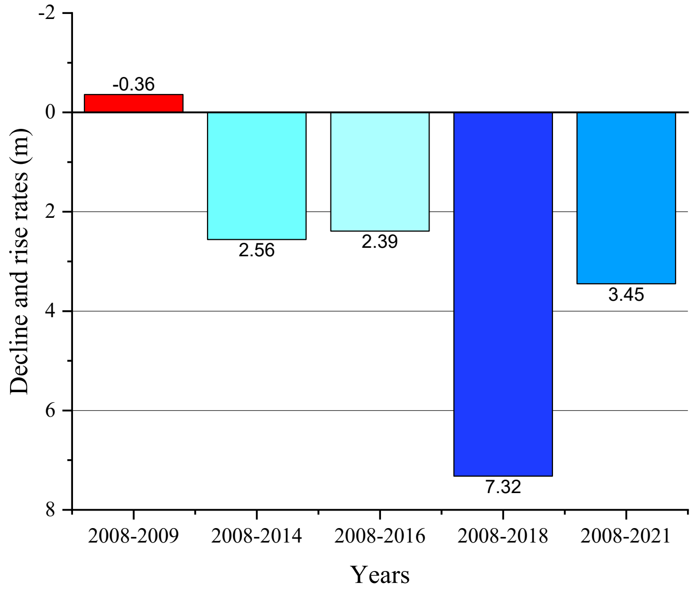

Figure 6. Decline and rise rates over the years of the observation period.

3.2. Assessment of the Physicochemical and Bacteriological Quality of Phreatic Groundwater

The physicochemical and bacteriological analyses of groundwater samples from the phreatic aquifer are summarized in table 1, presenting a statistical overview of the measured parameters. Groundwater temperatures ranged from 25°C to 31.4°C, which could influence quality by promoting microbial growth and reducing gas solubility. The pH values varied between 6.78 and 8.57, with most samples falling within the World Health Organization's (WHO) recommended limits. However, approximately 32% of the samples showed slightly acidic conditions. Electrical conductivity (EC) ranged from 3100 to 7500 µS/cm, exceeding WHO guidelines for potable water, indicating elevated levels of total dissolved solids (TDS), which were also above recommended thresholds in most cases. Turbidity levels were highly variable, affecting the aesthetic quality of the water and indicating the need for treatment before consumption. Some samples were found to be turbid or relatively turbid.

The concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), and chloride (Cl^{-}) were generally high, frequently surpassing WHO drinking water standards, though compliance varied across individual samples. Many samples also exceeded WHO limits for nitrate (NO_3^{-}), nitrite (NO_2^{-}), and ammonium (NH_4^{+}), suggesting possible contamination from agricultural runoff, sewage infiltration, or industrial discharges. Fluoride (F^{-}), sulfate (SO_4^{2-}), and phosphate (PO_4^{3-}) concentrations were above recommended levels in certain samples, though sulfate levels were generally within acceptable ranges.

Levels of dissolved oxygen (DO), chemical oxygen demand (COD), and biological oxygen demand (BOD) varied across samples, reflecting different levels of biodegradability and contamination. Fecal and total coliform counts were high in several samples, indicating significant bacterial contamination.

To assess water quality and pollution levels, the Groundwater Pollution Index (GPI) was applied on the Phreatic groundwater samples, and the results revealed the presence of a Very high pollution across all of the samples as shown in table 2.

Table 1. Statistical overview of the physicochemical and bacteriological parameters analyzed in the phreatic groundwater aquifer samples.

Parameters	Mean	SD	Skewness	Kurtosis	Min	Median	Max	WHO
T(°C)	27.8	1.61	0.47	-0.18	25	27.8	31.4	-
pH	7.25	0.45	1.63	2.32	6.78	7.09	8.57	6.5–8.5
EC (µs/cm)	4386	1310	1.28	0.42	3100	3850	7500	1000
Turbidity (NTU)	16.9	21	1.17	0.08	0.36	5.52	71.6	5
TDS (mg/l)	2350	1089	0.66	1.66	500	1925	5435	500
Ca^{2+} (mg/l)	714.4	148.4	0.23	0.1	440.9	705.4	1050.1	75
Mg^{2+} (mg/l)	381.3	177.1	-0.25	-0.89	36.4	429.1	705.1	50
Na^{+} (mg/l)	325.3	91.0	1.45	1.52	232.2	290.5	582.2	200
K^{+} (mg/l)	20.6	6.28	-0.03	-0.81	9.55	21.7	33.8	12
Cl^{-} (mg/l)	378.9	157.3	2.01	4.69	124.3	337.3	914.7	250
NO_3^{-} (mg/l)	27.7	38.1	2.17	5.11	0.1	12.8	159.4	50
HCO_3^{-} (mg/l)	162.2	94.6	0.96	0.82	36.6	142.1	429.4	120
F^{-} (mg/l)	1.47	0.65	1.66	3.13	0.69	1.3	3.31	1.5
SO_4^{2-} (mg/l)	199.3	44.3	-0.98	1.2	68.2	204.2	266.1	250
PO_4^{3-} (mg/l)	0.67	1.36	3.93	17.4	0	0.19	6.92	1
DO (mgO_2/l)	0.25	0.26	0.89	-0.48	0.02	0.13	0.83	-
NH_4^{+} (mg/l)	0.57	0.8	3.25	12.6	0.08	0.26	4	-
NO_2^{-} (mg/l)	0.88	1.88	2.12	3.03	0	0.05	6	-
COD (mg/l)	276.9	70.1	-0.35	-1.77	184	291.1	352	-
BOD_5 (mg/l)	121.4	19.8	0.06	-0.66	76.8	118.9	152.3	-
Total coliforms (UFC/100 ml)	2041	406.8	-0.51	-0.83	1290	2123	2580	-
Fecal coliforms (UFC/100 ml)	320.5	120.8	-0.02	-0.51	100	311	540	-

Table 2. The application results of the groundwater pollution index (GPI) on the Phreatic groundwater samples.

Range	Category	Number of samples

< 1.0	Insignificant pollution	-
1.0–1.5	Low pollution	-
1.5–2.0	Moderate pollution	-
2.0–2.5	High pollution	-
> 2.5	Very high pollution	All the samples

3.3. Spatial Analysis of the Phreatic Groundwater Quality

Based on the applied spatial analysis of hydrochemical parameters in the phreatic groundwater aquifer, I identified three distinct spatial patterns, as illustrated in Figures 7, 8, and 9:

1. Preurban and Agricultural Areas:
   High concentrations of electrical conductivity (EC), sodium (Na^+), potassium (K^+), chloride (Cl^-), bicarbonate (HCO_3^-), phosphate (PO_4^{3-}), and dissolved oxygen (DO) indicate both natural and human influences. Elevated EC suggests saline intrusion or fertilizer runoff, leading to increased mineral content in groundwater. High Na^+, K^+, and Cl^- levels are often linked to agricultural fertilizers and soil composition, pointing to agricultural activities. Increases in HCO_3^- may result from natural soil-water interactions or farming practices affecting chemical balance. PO_4^{3-} concentrations reflect agricultural runoff, particularly from fertilizers, suggesting nutrient-enriched contamination. High DO levels typically indicate good aeration and a healthy ecosystem, but they may fluctuate due to temperature changes, organic matter decomposition, or pollution.
2. Urban Areas:
   Elevated calcium (Ca^{2+}), magnesium (Mg^{2+}), fluoride (F^-), nitrite (NO_2^-), and ammonium (NH_4^+) levels are linked to urban influences. Ca^{2+} and Mg^{2+}, contributing to water hardness, may result from mineral dissolution, urban infrastructure decay, or mixed agricultural and urban runoff. Increased fluoride likely stems from industrial discharges or urban runoff, indicating human and industrial activity. NO_2^- and NH_4^+ levels suggest contamination from urban wastewater, sewage, and industrial sources.
3. Common to Both Agricultural and Urban Areas:
   High nitrate (NO_3^-), sulfate (SO_4^{2-}), biological oxygen demand (BOD), and chemical oxygen demand (COD) levels point to multiple pollution sources. NO_3^- concentrations are often caused by fertilizer runoff from agriculture and urban sewage. SO_4^{2-} may originate from industrial emissions or agricultural chemicals.

High BOD and COD reflect organic pollution from sources such as farming runoff, urban sewage, and industrial waste, signifying high oxygen demand to break down organic materials in the water.

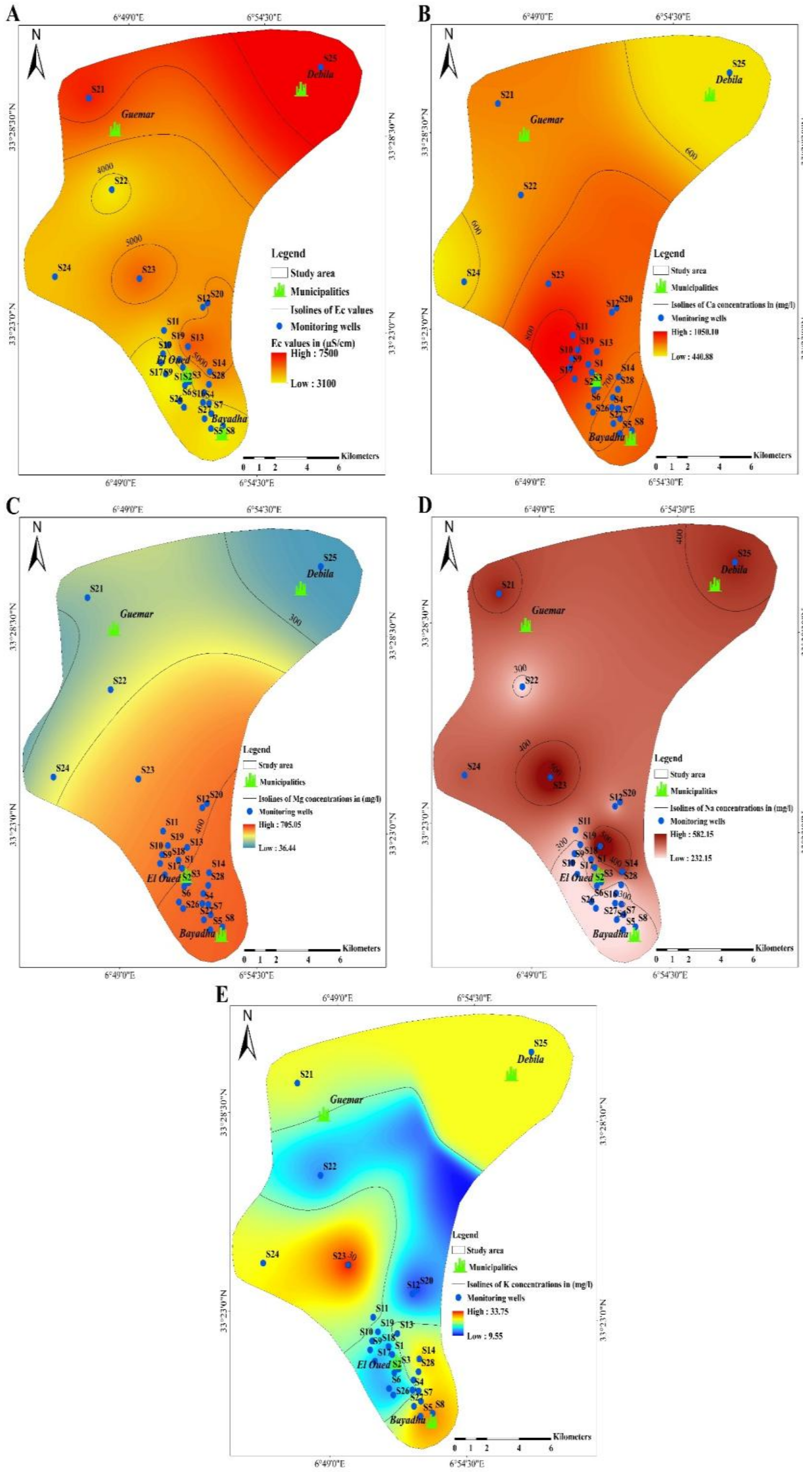

Figure 7. Spatial distribution of the chemical elements in the phreatic groundwater: (A). EC, (B). Ca^{2+}, (C). Mg^{2+}, (D). Na^{+}, (E). K^{+}.

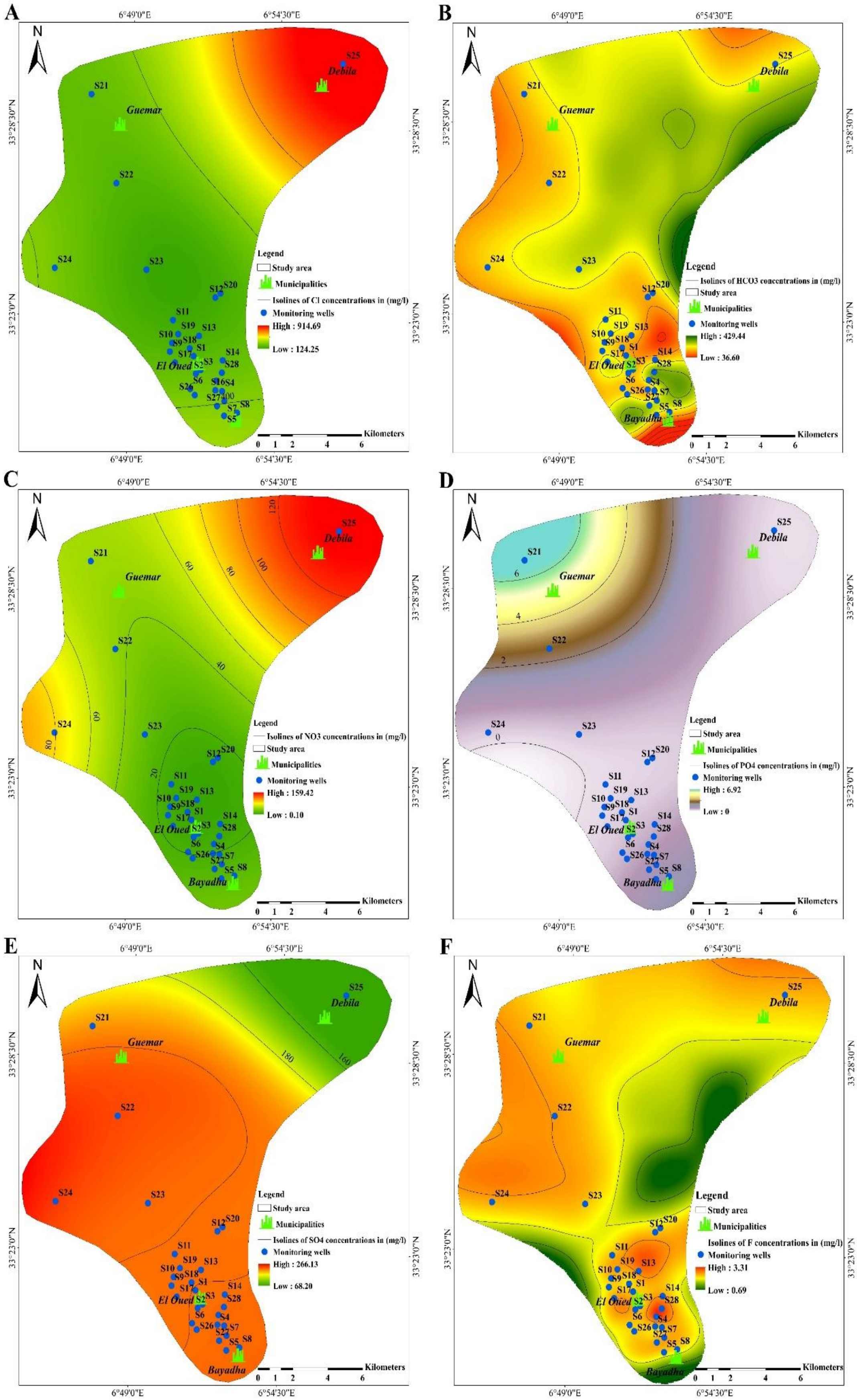

Figure 8. Spatial distribution of the chemical elements in the phreatic groundwater: (A). Cl^-, (B). HCO_3^-, (C). NO_3^-, (D). PO_4^{3-}, (E). SO_4^{2-}, (F). F^-.

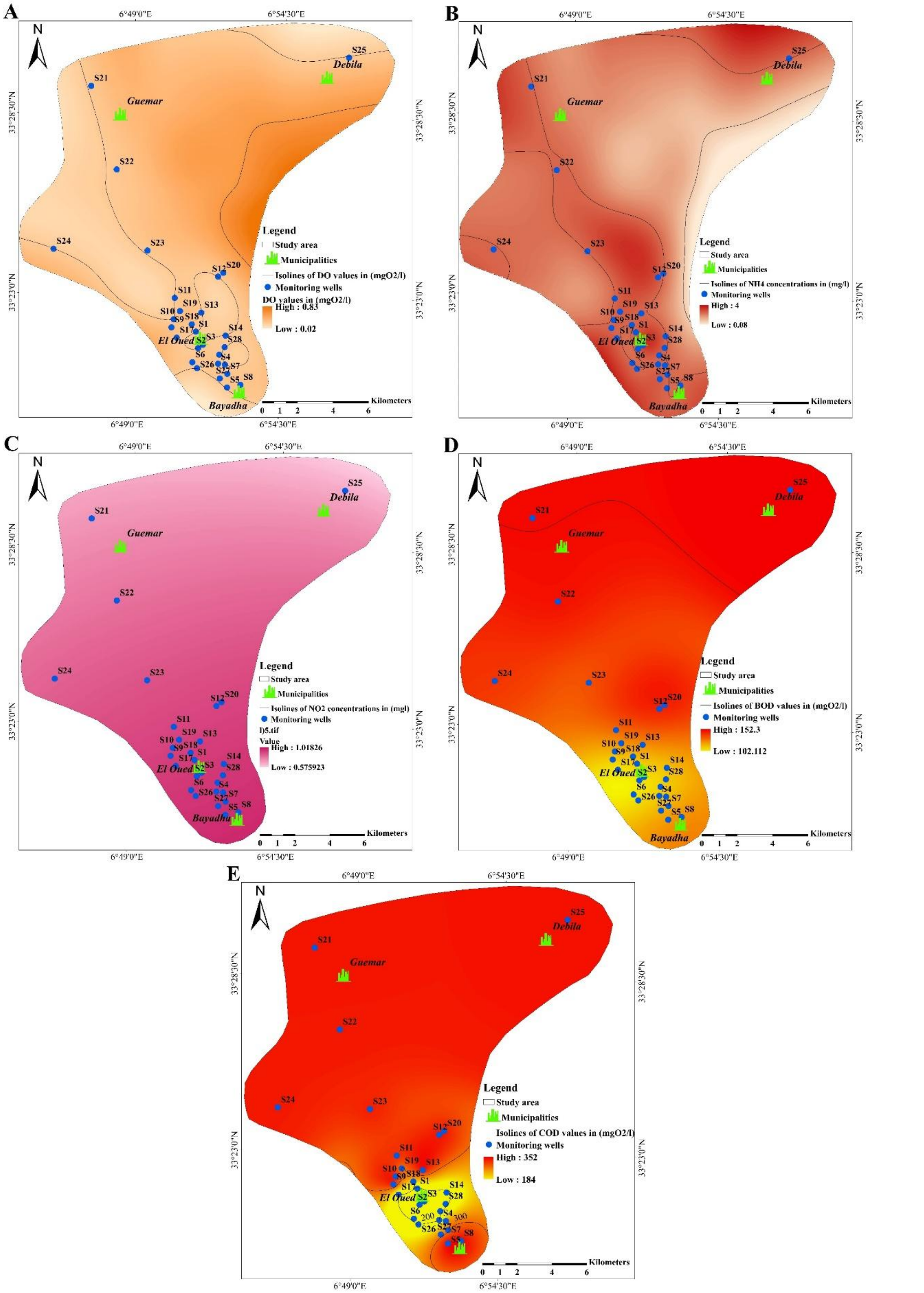

Figure 9. Spatial distribution of the chemical elements in the phreatic groundwater: (A). DO, (B). NH_4^+, (C). NO_2^-, (D). BOD, (E). COD.

The analysis revealed significant variations in the strength and structure of spatial dependencies for the hydrochemical parameters within the study area. Parameters like HCO_3^-, F^-, PO_4^{3-}, and COD demonstrated strong spatial dependency, indicating a pronounced correlation between data points. This led to clear separations in interpolated levels and the emergence of distinct patterns, resulting in a high degree of spatial autocorrelation. In contrast, parameters such as EC, Mg^{2+}, SO_4^{2-}, DO, and NO_2^- showed weak spatial dependency, suggesting low correlation across locations and minimal separation in interpolated levels. The remaining parameters exhibited moderate spatial dependency, reflecting localized clustering, trending, or spatial continuity. This variability likely arises from both local and regional factors, including the fluctuating phreatic groundwater level and its impacts on water quality.

3.4. Human Health Risk Assessment and the Presence of Heavy Metals

The analysis of metal concentrations in the phreatic groundwater aquifer of the Oued Souf Valley revealed that aluminum (Al^{3+}), iron (Fe^{2+}), manganese (Mn^{2+}), boron (B^{3+}), nickel (Ni^{2+}), and lead (Pb^{2+}) were present in varying concentrations, often exceeding WHO limits in different samples from both urban and agricultural zones, as summarized in table 3.

Table 3. Statistical summary of the analyzed heavy metals from the phreatic groundwater aquifer of the Oued Souf Valley and its comparison with WHO standards.

Variables	Mean	SD	CV	Min	Median	Max	WHO 2008
T (°C)	27.85	1.72	0.06	25	27.80	31.40	-
pH	7.31	0.52	0.07	6.78	7.11	8.57	6.5–8.5
EC (µS/cm)	4035.71	858.02	0.21	3100	3725	6200	1000
Al^{3+} (mg/l)	0.31	0.08	0.30	0.22	0.29	0.52	0.2
Fe^{2+} (mg/l)	0.21	0.09	0.43	0.11	0.19	0.40	0.3
Mn^{2+} (mg/l)	0.44	0.11	0.25	0.30	0.40	0.71	0.5
B^{3+} (mg/l)	0.63	0.43	0.68	0.19	0.45	1.41	0.5
Ba^{2+} (mg/l)	0.015	0.01	0.63	0.004	0.01	0.03	0.7
Bi^{3+} (mg/l)	0.14	0.11	0.75	0.00	0.15	0.28	-
Cd^{2+} (mg/l)	<Lod	<Lod	<Lod	<Lod	<Lod	<Lod	0.003
Co^{2+} (mg/l)	<Lod	<Lod	<Lod	<Lod	<Lod	<Lod	-
Cr^{3+} (mg/l)	0.01	0.01	1.23	0.00	0.00	0.02	0.05

Cu^{2+} (mg/l)	0.004	0.01	1.61	0.00	0.00	0.02	1
Li^{+} (mg/l)	<Lod	<Lod	<Lod	<Lod	<Lod	<Lod	-
Ni^{2+} (mg/l)	0.01	0.01	0.83	0.00	0.01	0.02	0.02
Pb^{2+} (mg/l)	0.01	0.01	2.71	0.00	0.00	0.05	0.01
Sr^{2+} (mg/l)	7.06	2.44	0.35	1.77	7.76	9.94	-
Zn^{2+} (mg/l)	0.01	0.01	1.61	0.00	0.00	0.04	3

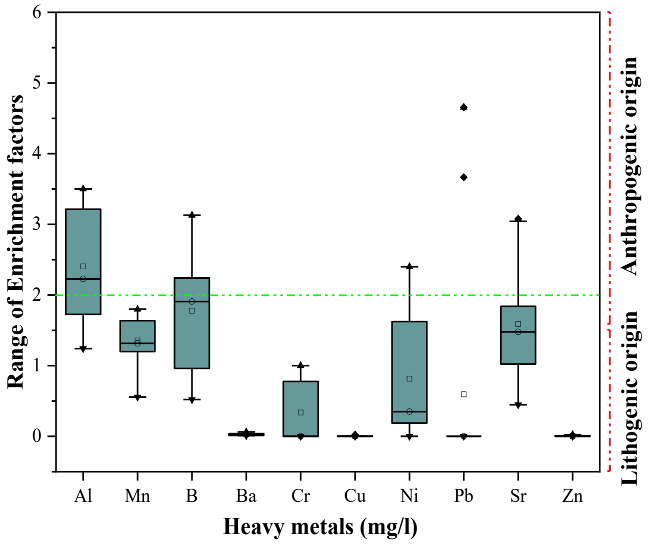

Figure 10. Box plot of enrichment factors of each analyzed metal in the phreatic groundwater aquifer.

Based on the conducted investigation into metal enrichment trends in the phreatic aquifer, presented in figure 10, the observed order of metal concentrations was Al^{3+}> B^{3+}> Sr^{2+}> Mn^{2+}> Ni^{2+}> Pb^{2+}> Cr^{3+}> Ba^{2+}> Cu^{2+}> Zn^{2+}. Minor enrichment of barium (Ba^{2+}), chromium (Cr^{3+}), copper (Cu^{2+}), and zinc (Zn^{2+}) were consistent across all samples, indicating a likely geogenic origin. Aluminium showed minor enrichment in nine samples and moderate enrichment in five, suggesting that anthropogenic activities contributed to elevated Al^{2+} levels in many parts of the study area. Manganese exhibited minor enrichment overall, but six samples showed higher levels, pointing to human-related sources such as wastewater discharge and farming. Boron was slightly elevated in eight samples and moderately enriched in others, with several cases indicating anthropogenic input. Nickel mostly displayed minor enrichment, with a few instances of moderate anthropogenic influence. Both lead and strontium showed variability, with some samples indicating moderate anthropogenic contributions. Overall, six samples were identified as influenced by human activities.

In terms of ecological risk, the analyzed metals generally posed a low threat, except in two samples. Sample S13 showed considerable ecological risk, while sample S14 indicated a high risk, specifically due to lead. However, overall ecological risk across all metals and samples was assessed as low.

Regarding potential human health risks from exposure to the detected metals in the phreatic aquifer, figure 11 presents the hazard quotient (HQ) and hazard index (HI) results for both adults and children. For adults, HI values exceeded 1 in eight samples, indicating a significant long-term health risk primarily from high concentrations of Al^{3+}, along with Fe^{2+}, Mn^{2+}, B^{3+}, Ni^{2+}, and Sr^{2+} in certain samples. For children, HQ values for Mn^{2+} surpassed 1 in nine samples, and Sr^{2+} levels were notably high in two samples, suggesting a potential non-carcinogenic health threat.

The levels of Fe^{2+}, Mn^{2+}, B^{3+}, Ni^{2+}, Pb^{2+}, Sr^{2+}, and Al^{3+} detected in the groundwater indicate a range of health impacts. Excess iron can contribute to chronic conditions such as cardiovascular disease and diabetes. Manganese exposure is linked to neurotoxic effects, while boron can cause gastrointestinal problems and kidney damage. Nickel exposure is associated with lung fibrosis, kidney disease, and respiratory cancers. Lead poses serious risks to children's development and cognitive function, and in adults, it can elevate blood pressure and impair fertility. High strontium levels can negatively affect bone density, and aluminum is linked to neurological conditions, including Alzheimer's disease.

Overall, the HI scores for children were alarmingly high, covering all wells in the study area. This suggests a significant, long-term health risk, particularly non-carcinogenic in nature. The high HI scores not only highlight immediate concerns but also point to potential future risks. Prolonged exposure to these contaminants could result in chronic health problems, especially affecting children's growth and development. Since children are inherently more vulnerable to environmental pollutants due to their developing bodies and higher intake relative to body weight, the elevated HI scores for this group are particularly concerning. Therefore, it is crucial for relevant authorities such as environmental and public health agencies to develop and implement strategies aimed at reducing these risks and protecting the health of children in the affected area. Community engagement and public awareness about potential hazards and protective measures are essential steps to safeguard the well-being of local residents, particularly children.

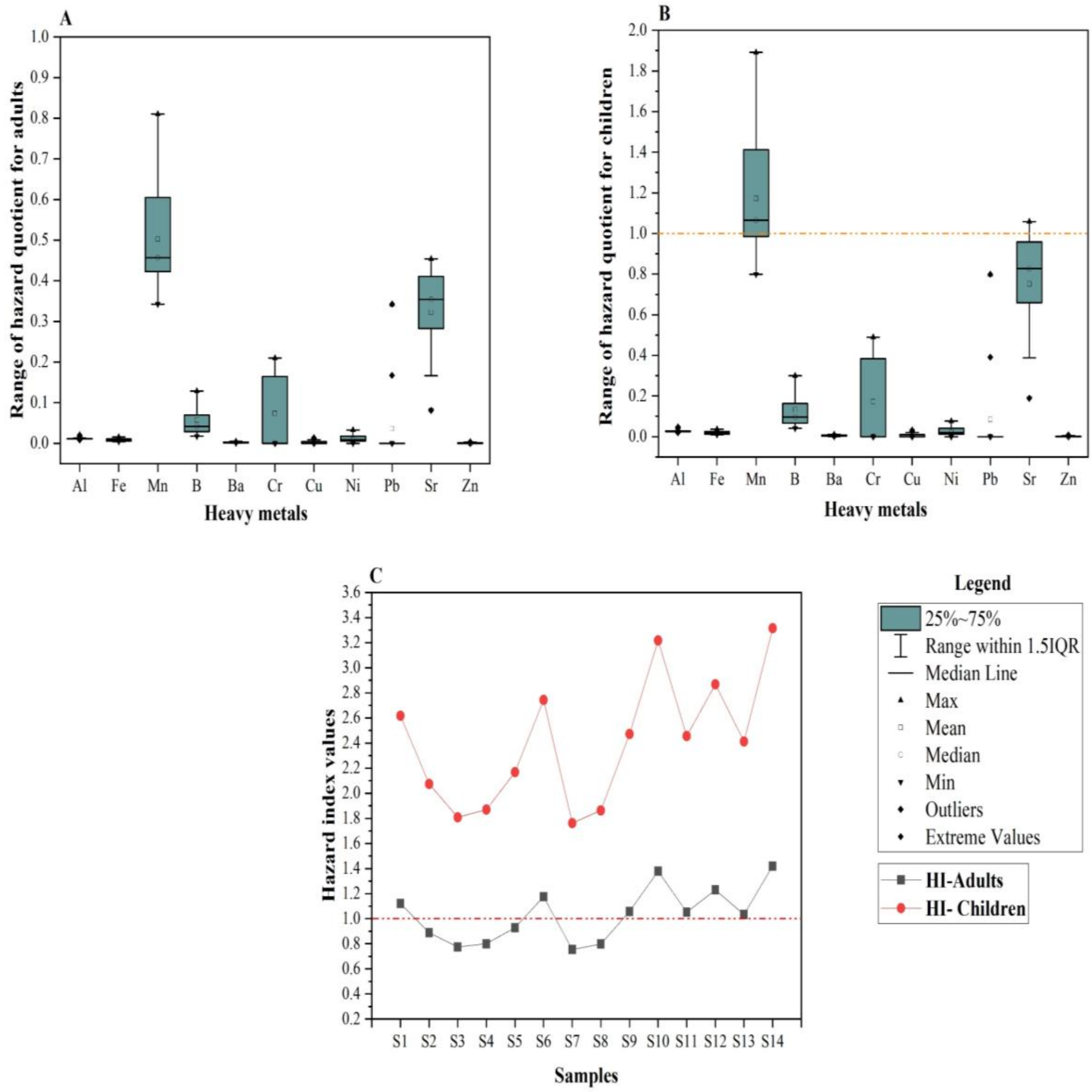

Figure 11. The results of health risk assessment: (A). Box plot of Hazard Quotients (HQ_s) of eleven heavy metals through ingestion exposure of adults, (B). Box plot of Hazard Quotients (HQ_s) of eleven heavy metals through ingestion exposure of children, (C). Hazard Index (HI) values eleven heavy metals for both cases.

3.5. Drinking and Irrigation Suitability of Deep Aquifers (Complex Terminal and Continental Intercalary)

The conducted hydrochemical assessment of the complex terminal groundwater, as detailed in table 4, revealed that both cation and anion concentrations in various wells of the complex terminal aquifer generally exceed the World Health Organization's (WHO) drinking water standards. This high mineralization likely contributes to poor water quality. However, nitrate levels were mostly within acceptable limits, which is likely due to natural purification processes, including denitrification occurring near discharge zones and nitrate fixation facilitated by clay layers.

The Water Quality Index (WQI) results show that a significant portion of the sampled wells (55.10%) exhibited poor to very poor water quality. Only a small number of samples reflected good water quality, and just two were deemed completely unfit for drinking purposes. Regarding irrigation suitability, various applied water quality indices indicated that the groundwater samples from this aquifer range from moderately suitable to unsuitable for irrigation use.

Table 4. List of the physicochemical parameters analyzed in the complex terminal groundwater aquifer samples.

Variables	Mean	S.D	Minimum	Maximum	WHO
T (°C)	23.12	5.05	11.80	35.10	-
pH	7.49	0.15	7.23	7.84	6.5–8.5
EC (µs/cm)	4131.48	382.97	2760.00	4730.00	1000
Salinity (%)	2.64	0.26	1.80	3.00	-
TDS (mg/l)	2650.92	246.36	1766.00	3027.00	500
Turbidity (Ntu)	0.43	0.52	0.07	3.23	5
Dry Residue (mg/l)	3075.10	478.89	1900	3980	-
Total Alkalinity (mg/l)	138.87	27.17	83.00	189.00	-
Ca^{2+} (mg/l)	274.96	36.85	200.40	360.72	75
Mg^{2+} (mg/l)	122.74	30.19	63.12	184.72	50
Na^{+} (mg/l)	379.41	57.93	137.00	600.00	200
K^{+} (mg/l)	33.35	7.01	15.00	50.00	12
Cl^{-} (mg/l)	888.59	144.18	457.34	1240.86	250
SO_4^{2-} (mg/l)	729.09	152.21	193.06	997.41	250
HCO_3^{-} (mg/l)	167.98	33.50	101.26	213.58	120
NO_3^{-} (mg/l)	22.39	6.62	1.91	34.90	50

The analysis of the continental intercalary groundwater aquifer revealed a range of conditions. Both electrical conductivity (EC) and total dissolved solids (TDS) were elevated, indicating significant mineralization and surpassing the World Health Organization's (WHO) recommended limits for safe drinking water. All major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}), with the exception of nitrate (NO_3^{-}), were found at concentrations above WHO standards, rendering the water unsuitable for direct human consumption. Phosphate (PO_4^{3-}) and ammonium (NH_4^{+}) levels were also high, and iron (Fe^{2+}) exceeded safe limits in one of the samples, as detailed in table 5. Despite these issues, the Water Quality Index (WQI) classified all samples from this aquifer as 'good' for drinking purposes. However, when evaluated for irrigation use, the same samples were rated from moderate to poor based on several indices, including EC, sodium percentage (%Na), total hardness (TH), permeability index (PI), potential salinity (Ps), and Kelly's ratio (Ka). This apparent contradiction—where the water is deemed suitable for drinking but less favorable for irrigation—can be explained by the different implications of water quality for human health versus soil and plant health. While the water may meet short-term drinking water criteria, its high salinity, sodium content, and other dissolved ions pose long-term risks to soil structure, permeability, and overall plant health when used for irrigation. This highlights how the varied effects on humans compared to crops and soil were central to the categorization of the continental intercalary groundwater samples for both drinking and irrigation purposes.

Table 5. Statistical summary of the continental intercalary groundwater samples.

Parameters	Mean	S.D	Minimum	Median	Maximum	WHO 2011
T (°C)	32.8	5.51	26.45	35.7	36.25	-
PH	7.19	0.09	7.10	7.21	7.27	6.5–8.5
EC (µS/cm)	2983.33	296.41	2795	2830	3325	1000
TDS (mg/l)	1909.33	189.69	1789	1811	2128	500
Turbidity (NTU)	2.81	2.22	0.88	2.3	5.24	5
Ca^{2+} (mg/l)	232.46	30.06	202.40	232.46	262.52	75
Mg^{2+} (mg/l)	100.87	21.29	80.21	99.65	122.74	50
Na^{+} (mg/l)	274.33	92.38	220	222	381	200
K^{+} (mg/l)	34.67	8.74	25	37	42	12
NH_4^{+} (mg/l)	0.31	0.08	0.22	0.35	0.36	-
Cl^{-} (mg/l)	652.34	30.91	631.06	638.15	687.79	250
SO_4^{2-}(mg/l)	604.49	108.90	541.21	542.02	730.24	250
HCO_3^{-}(mg/l)	153.72	14.99	142.74	147.62	170.8	120
NO_3^{-} (mg/l)	4.81	5.20	1.36	2.28	10.79	50
PO_4^{3-} (mg/l)	1.24	0.21	1.01	1.32	1.40	1
Fe^{2+} (mg/l)	0.54	0.61	0.17	0.20	1.25	0.3

4. Conclusion

This study provides a comprehensive evaluation of the hydrochemical, bacteriological, and heavy metal contamination in the groundwater systems of the Oued Souf Valley, a region critically reliant on these water resources for agriculture, domestic use, and industrial activities. The findings reveal alarming levels of contamination in the shallow phreatic aquifer, including excessive concentrations of salts, heavy metals (notably aluminum, lead, and manganese), and bacteriological pollutants, posing significant risks to public health—particularly for vulnerable populations such as children. Spatial analyses clearly indicate that both urban and agricultural activities are primary contributors to these pollution patterns. In contrast, while the complex terminal and continental intercalary aquifers exhibit comparatively lower levels of contamination, their water quality still frequently surpasses safe thresholds for drinking and irrigation, highlighting the widespread impact of anthropogenic pressures.

The importance of these results lies in their clear demonstration of the interconnectedness between human activity, environmental degradation, and public health risks. They underscore the urgent need for integrated water management strategies that include enhanced monitoring of groundwater quality, stricter regulations on waste disposal and agricultural practices, and the rehabilitation of essential water infrastructure. Moreover, this research emphasizes the critical need for public health interventions and awareness programs to mitigate the long-term health risks, particularly for children, who are disproportionately affected by contaminated water supplies. Ultimately, the insights gained from this study provide a vital foundation for designing sustainable water management policies aimed at preserving the fragile ecosystem of the Oued Souf Valley, ensuring water security, and advancing public health and socioeconomic stability in this arid and vulnerable region.

Notes on Contributors

Dr. Ayoub Barkat is a dedicated Water Resources Analyst and Sustainable Management Expert with over six years of experience addressing complex environmental challenges. Currently, he serves as an Assistant Professor at Mohamed Khider University of Biskra and as a Researcher at the Africa Research Institute. He recently earned his PhD in Natural Sciences/Earth Sciences with the
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Conflict of Interest

The author hereby declare that no competing financial interest exists for this manuscript.

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