Short thesis for the degree of Doctor of Philosophy (PhD)

Integrated Assessment of the groundwater resources of the Northwest Sahara Aquifer System – Case of Oued Souf Valley

Barkat Ayoub

Supervisor: Prof. Dr. György Szabó
Co-supervisor: Dr. Habil. Bouaicha Foued

UNIVERSITY OF DEBRECEN
Doctoral School of Earth Sciences

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1. *Introduction*

Worldwide, water supplies are under growing pressure due to a surge in demand fueled by population increase, the necessity for more agricultural output, industrial expansion from higher standards of living, pollution from human activities, and the effects of climate change [1–3]. It is forecasted that by 2050, at least a quarter of the global population will reside in nations facing freshwater shortages, owing to water scarcity and deteriorating water quality. As a response, the United Nations has included the goal of securing available and sustainable water management within its Sustainable Development Goals, as outlined in the 2030 Agenda for Sustainable Development, titled "Transforming Our World" [4].

Climate change acts as a factor that adds further stress to the hydrological cycle by altering precipitation patterns and exacerbating extreme weather events. This, in turn, worsens water scarcity and affects both the distribution and quality of water resources, as outlined in the IPCC's report of Climate Change in 2021: “The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change”[5]. These challenges underscore the urgent need for innovative and sustainable water management strategies to ensure the equitable distribution and efficient use of this precious resource. The World Resources Institute advocates for the integration of climate resilience into water resource planning to address these issues [6].

Water scarcity, particularly in arid regions, poses significant challenges to achieving the Sustainable Development Goals (SDGs), given the crucial role of groundwater. Groundwater is a key element of the hydrological cycle, found beneath the Earth's surface in a variety of landscapes, including hills, mountains, plains, deserts, and coastal areas, and even under seas and oceans. It accounts for 98% of the Earth's liquid freshwater, playing a vital role in meeting domestic and agricultural needs, especially in arid and semi-arid climates. Notably, it is the primary source of daily water for about 2.5 billion people worldwide [7–9]. As surface water supplies become increasingly strained, the importance of groundwater in meeting water demands is ever more highlighted [10]. Thus, effective groundwater management is essential for addressing both quality and quantity issues, as well as understanding its dynamics across different locations and over time [11]. However, the sustainable management of groundwater is complicated by factors such as climate change, population growth, inadequate management practices, and a lack of comprehensive understanding and coordination, leading to its gradual degradation [12].

This situation leads to numerous problems, including aquifer depletion, declining groundwater levels due to climate change-driven variations in rainfall patterns and increased evapotranspiration [13], over-extraction for agricultural, industrial, and domestic purposes [14], and increased vulnerability to contamination and pollution from various uses of groundwater [15]. These issues directly affect several sustainable development goals, such as Clean Water and Sanitation, Zero Hunger, Good Health and Well-being, and Climate Action [16]. Achieving these goals requires collaborative efforts from governments, communities, and international organizations to implement policies and practices that ensure the sustainable use and conservation of groundwater resources in arid regions [17,18].

Groundwater serves as the primary source of drinking and agricultural water for the Saharan communities in Southern Algeria, specifically within the Oued Souf Valley, which is part of the vast Algerian Sahara. Extensive groundwater reservoirs are found as aquifers within geological layers of varying depths and thickness beneath the Oued Souf valley. The groundwater system of the Oued Souf Valley is a component of the Northern Sahara aquifer system, which comprises three groundwater aquifers, layered from top to bottom. These are the phreatic aquifer (the superficial one), the complex terminal groundwater aquifer, and the continental intercalary groundwater aquifer, with the latter two consisting of multiple water layers stacked upon each other. Notably, they collectively represent one of the world's largest hydraulic reservoirs, with mobilizable potential estimated at 5 billion cubic meters of water [19,20].

Despite the abundance of groundwater in the Oued Souf region, this has led to several issues concerning public and environmental health. Whereas, since the 1980s, driven by population growth, urbanization, and the need for economic development, local authorities have chosen to extract deep groundwater from the complex terminal and continental intercalary aquifers, in addition to the phreatic aquifer, which was the primary source for drinking and irrigation. The intensive pumping from deep aquifers and the direct discharge of this water into the environment without adequate treatment, along with the lack of a sewage network and natural outlet, have resulted in polluted groundwater near the surface. This situation jeopardizes the equilibrium and viability of the production system in the El Oued Souf region [21].

Moreover, this phenomenon has instigated rapid and disruptive changes, profoundly altering the environment and living conditions, imperiling the delicate equilibrium of the northern Saharan region, and threatening various structures, as well as harming local agriculture and eroding the traditional urban character of the city, including the Ghout system, a traditional agricultural practice. Simultaneously, serious health problems related to the emergence of polluted phreatic groundwater, including the filling of septic tanks with black, foul-smelling water mixed with waste of all kinds, have facilitated the spread of bacteriological pollution in the superficial aquifer. Additionally, water quality has degraded due to nitrates from domestic and agricultural sources. High mineralization of water has been induced, in part, by evaporation from open water bodies and salt dissolution, with Ghouts being used as impromptu landfills contributing to this issue. Stagnant water has become a breeding ground for mosquitoes, leading to an increased prevalence of waterborne and parasitic diseases such as skin disorders, leishmaniasis, malaria, and typhoid [22].

To combat this pollution and the rising phreatic groundwater, local authorities initiated a mega-project in 2005. The project was structured around four main components: a sewerage plan, a purification plan, an evacuation plan, and a drainage plan. However, due to various challenges, the project did not fully achieve its primary objective [23,24]. The failure of the vertical drainage system underscores the impact of anthropogenic activities on natural factors, which in turn affect the spatial and temporal fluctuations of the phreatic groundwater table in the Oued Souf region. This failure continues to jeopardize the north-western Sahara aquifer system, passing through the Oued Souf Valley, in terms of water quality and suitability for drinking and irrigation, despite the natural separation of these systems. The contamination of the shallow aquifer, along with its unauthorized use for irrigation and industrial purposes, and its connection to the deep aquifer (complex terminal and continental intercalary), poses significant threats to public and environmental health in the region, necessitating an in-depth investigation into the hydrochemical and bacteriological quality of all the aquifer systems in the Oued Souf Valley to prevent adverse consequences that could impede socioeconomic activities in the region.

For these reasons, this dissertation aims to address the following scientific questions through a comprehensive investigation, employing a complex methodology for each of the aquifers comprising the Northwestern Sahara Aquifer System:

- What is the quality of the phreatic aquifer and its suitability for drinking and irrigation under the current functioning of the vertical drainage system?
- What are the physicochemical properties of the complex terminal and the continental intercalary groundwater aquifers, and are they suitable for drinking and irrigation purposes?
- How does the vertical drainage system perform, and what impact does it have on mitigating the upwelling of the phreatic groundwater table and its stability, in terms of spatial distribution and temporal variations of this aquifer, based on the data collected in the years 2008, 2009, 2014, 2016, 2018, and 2021?
- How can the shortcomings in water resource management in El Oued contribute to the persistence of groundwater upwelling?
- What is the spatial distribution of heavy metals and the extent of their contamination in the phreatic aquifer of the Oued Souf Valley?
- What are the human health and ecological risks associated with the presence of heavy metals in the phreatic aquifer?

These questions form the foundation of this thesis, which seeks to provide insights into the complex hydrogeological and environmental challenges facing the Oued Souf Valley and offer potential solutions to address them. Furthermore, the goal of this thesis is to investigate the hydrogeochemistry of the Northwest Sahara Aquifer System. This involves identifying pollutants within the aquifer to ensure the safety of its water for consumption and utilization. The research aims to comprehend the natural chemical behaviors of the aquifer to enable effective resource management. Furthermore, it seeks to develop sustainable management strategies for the aquifer, protect the environment from contamination risks, and support economic development. This is achieved by preserving groundwater as a reliable resource for agriculture, especially in water-scarce regions like the Oued Souf Valley.

2. Materials and methods

To achieve the core purpose of this thesis, several study areas have been selected including a wide variety of Oued Souf region municipalities based on the aquifer subject to analysis and the available data from the phreatic aquifer, the complex terminal aquifer, and the continental intercalary groundwater aquifers.

For evaluating the spatial distribution and temporal variations of the phreatic groundwater level in Oued Souf Valley, research has been conducted by involving 58 monitoring wells that form part of the vertical drainage system. The depth measurements of the groundwater were collected from the ground surface using level probes and piezometers installed in each drain throughout the entire system.

The physicochemical and bacteriological assessment of the phreatic groundwater aquifer in the Oued Souf Valley was conducted using twenty-eight samples (22 samples from the vertical drainage system, and six samples were collected from agricultural and peri-urban areas). Temperature (T), pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site using a Multi–350 i multi-parameter device, while the remaining analyses were conducted using the methods of [25].

The evaluation of the presence of heavy metals in the phreatic groundwater aquifer of Oued Souf Valley was conducted in a separate study in November 2022, where a total of 14 groundwater samples were gathered from this aquifer. The quantitative analysis of the elemental composition of the samples was carried out using microwave plasma atomic emission spectrometry (MP-AES 4200, Agilent Technologies).

To assess the complex terminal groundwater aquifer in the Oued Souf region, a total of forty-nine (49) groundwater samples were collected during March 2019 by the ANRH and Algerian of water company- Unity of El Oued (ADE- Algerriene des eaux- Unite d' El Oued). The sampling locations included El Oued, Debila, Guemar, Kouinine, Ourmas, Reguiba, and Taghzout, covering both Mio-Pliocene and Pontian aquifers. Furthermore, another assessment of the deepest aquifer (the continental intercalary) has been conducted using three wells located in El Oued municipality.

A comparative study of hydrochemical parameters in the complex terminal groundwater aquifer was conducted based on data from ten wells in El Oued municipality during the years 2012, 2014, 2015, 2016, 2017, 2018, 2019, and 2020. The data were obtained from the ANRH and the Algerian Water Company - Unity of El Oued (ADE - Algerienne des Eaux). Of the ten wells used for comparison, eight belong to the Mio Pliocene layer, one represents the Pontian, and another represents the Lower Eocene. Meanwhile, another comparative study was conducted to analyze the temporal variation of the continental intercalary groundwater aquifer using hydrochemical data from 2012, 2014, 2015, 2017, 2018, 2019, 2020, and 2021, also obtained from the ANRH and the Algerian Water Company - Unity of El Oued (ADE - Algerienne des Eaux).

The selected objectives of this thesis were achieved through the application of a comprehensive methodology aimed at providing answers to the research questions posed. Hierarchical Clustering Analysis was applied to each hydrochemical study of aquifers in the Northwest Sahara Aquifer System of Oued Souf Valley using Q-mode, Ward's linkage, and Euclidean distance to group groundwater samples and analyze differences based on similarity and spatial patterns. The software used were Origin Pro 2021 and IBM-SPSS Statistics version 26. The environmental hazards assessment of heavy metals in the phreatic groundwater aquifer, several indices were used, including the Contamination degree, the Geoaccumulation index (Igeo), Enrichment factor (EF), and Potential ecological risk index (PER). On the other hand, a human health risk assessment study was conducted to predict the probability and extent of hazards posed by certain activities to both human and ecosystem health over time, using the chronic risk level (Chronic daily intake- CDI), hazard quotient (HQ), and hazard index (HI) indices.

In all the studied hydrogeological horizons of this thesis, the water quality index proposed by [26] was applied to assess these waters for drinking use. While the assessment of groundwater systems in all the study areas for irrigation usage was performed using different ionic parameters in meq/L based on various indices, such as PI, KR, RSC, PS, RBSC, ESP, Ka, synthetic harmful coefficient (k), Na%, SAR, TH, and MH. Furthermore, for the pollution level assessment, several indices were used depending on their properties to assess the pollution in the groundwater. The indices used in this thesis are the National Sanitation Foundation Water Quality Index (NSFWQI), Groundwater Pollution Index (GPI), and Nitrate Pollution Index (NPI).

At the same time, Piper plot, Chadha plot, Stiff plots, Gibbs plots, and Chloro-alkaline index were used to study the hydrochemical facies and the controlling mechanism of all the groundwater systems, such as the phreatic aquifer, complex terminal, and the continental intercalary. Regarding the geochemical analysis of the aquifer systems, saturation indices, and mineral stability diagrams were used, as well as several molar ratios, such as the molar ratio in bivariate plots of Na^+-normalized Ca^{2+} and HCO_3^-, and (B) Na^+-normalized Ca^{2+} and Mg^{2+}.

For predicting the spatial propagation of the chemical element as well as groundwater level, geostatistical modeling was used through the ordinary kriging interpolation method for assessing the phreatic groundwater level and the physico-chemical elements in the phreatic groundwater aquifer complex terminal. Regarding the heavy metals, the IDW interpolation method has been used due to the limited obtained samples.

3. Scientific results

Thesis statement 1

I detected large fluctuations and a decline in the phreatic groundwater levels from 2009 to 2018, offset by another rising trend that might threaten the region in the near future. Furthermore, I found that several factors influence the stability of the phreatic groundwater level and the performance of the vertical drainage system, with the most important ones being of anthropogenic origin.

Based on my geostatistical modeling and generated maps, I identified three spatial patterns in the phreatic groundwater level during the observation years (2008, 2009, 2014, 2016, and 2018). The spatial pattern was characterized by an initial rise (upwelling) from 2008 to 2009, followed by a decline from 2014 to 2018, and then a resurgence from 2018 to 2021. The shallowest depth of the phreatic groundwater level consistently occurred in an area extending from the northwest to the southeast of the study area. Meanwhile, the southwest of the study area consistently exhibited the deepest groundwater levels in 2008, 2009, 2014, 2016, and 2018.

In 2008, with the commencement of the vertical drainage system, the groundwater levels were notably shallow, averaging 5.42 meters below ground level (mbgl). In 2009, the groundwater level continued its upwelling trend in the same areas, maintaining a similar pattern to 2008, with an average level of 5.06 mbgl, indicating a slight increase in upwelling. A significant decline in the phreatic groundwater level started in 2014 and continued in 2016. During these years, the shallowest levels were observed in a gradually rising state from the central northwest to the southeast, with fluctuation rates ranging from 7.97 mbgl in 2014 to 7.81 mbgl in 2016. In 2018, the data indicated the deepest groundwater level at 12.74 mbgl, with a notable spatial shift affecting approximately half of the study area (from the south-southwest to almost the northwest), while the shallowest levels were almost the same as in previous years but with a significant decline (for example of 2008 and 2018, as shown in *figure 1*). When comparing 2008 with subsequent years, the variations in groundwater decline and upwelling rates were -0.36 m in 2009, 2.56 m in 2014, 2.39 m in 2016, and 7.32 m in 2018, as shown in figure 2. Despite significant declines in previous years, the groundwater depth fluctuated around 8.87 mbgl in 2021, indicating a notable rise, especially compared to the 2018 levels, with an average increase of 3.9 meters, as shown in *figure 2*.

Furthermore, the instability of the water table level led to areas with deep groundwater levels emerging in the north of the study area, extending to the west and center. The reasons for these fluctuations in the phreatic groundwater level over the study period can be divided into three stages:

1. Rise of the water table from 2008 to 2009:

This was due to several contributing factors included natural topography, lack of natural drainage in the region, insufficient coordination among water management sectors in the Oued Souf Valley, intense exploitation of deep groundwater reservoirs, absence of sewage and drainage networks, and leakage from the drinking water supply system. Furthermore, in this period of observation, the vertical drainage system was in its initial functioning status which require much more time to start achieving its aim.

2. Decline of the water table from 2009 to 2018: This decline was caused by various factors:

    - Independent usage of the entire aquifer system for different purposes, which contributes to reducing water return to the phreatic aquifer.
    - Rapid agricultural expansion around El Oued Souf, particularly in areas surrounding the city, led to intensive groundwater use, reducing water infiltration back into the phreatic aquifer.
    - Transition from septic tanks to vertical drainage in El Oued, leading to a steady decline in water levels and reduced contamination in the phreatic groundwater aquifer.
    - Connecting most of urban areas to the sewage network and the reduction of wastewater disposal into the environment, which previously returned to the phreatic aquifer.

3. Re-rising of the water table in 2021: This rise was attributed to various factors:

    - Inefficiencies in the drinking water supply network, such as significant leakages, unaccounted withdrawals, and illegal connections.
    - Poor connections with other supply systems and unremunerated water withdrawals, including those for firefighting, inspections, and maintenance.
    - The presence of legal and illegal industries, like gypsum production, consuming significant water amounts and discharge these quantities into the environment.
    - Issues in the drainage system, such as power outages affecting the pumping process, and drains not functioning since 2018.
    - Problems at the wastewater purification plant, including equipment breakdowns, especially in the Desander, leading to excessive pressure on the plant and reduced purification efficiency.

Another factor, although not the focus of this research, is the non-homogeneity of the unconfined (phreatic) aquifer and its intercalation by clay lenses at shallow depths, which can cause groundwater to rise [27].

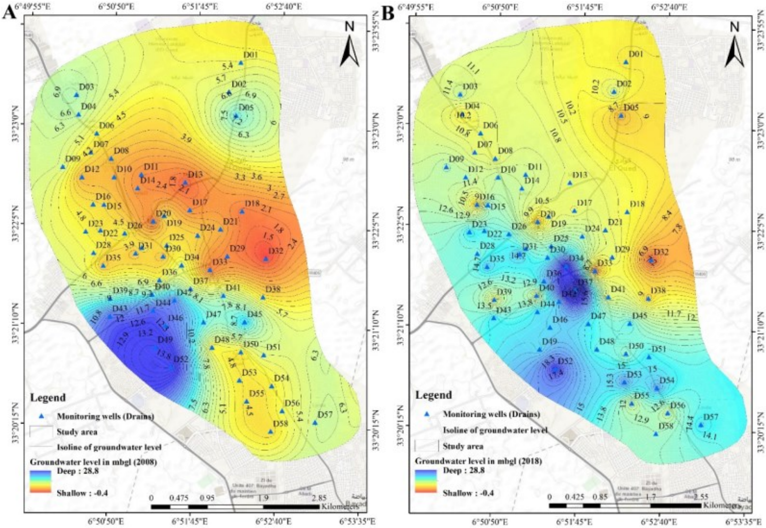

Figure 1. Evolution maps of groundwater level in the study area: (A) 2008, (B) 2018.

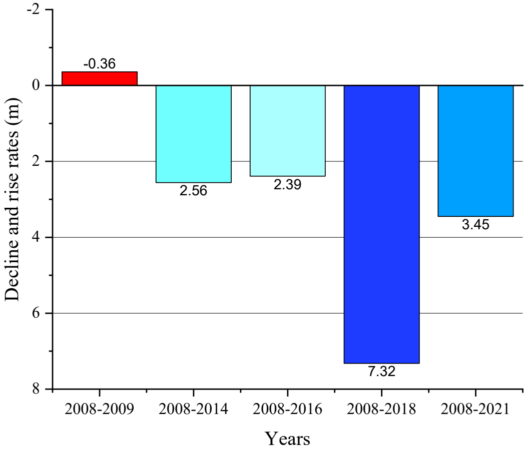

Figure 2. Decline and rise rates over the years of the observation period.

Thesis statement 2

Based on my comprehensive physicochemical and bacteriological analysis, I found that various water quality parameters, including Ca, Mg, Na, K, Cl, NO_3, NO_2, and NH_4 concentrations, often exceeded WHO guidelines, indicating the existence of contamination sources. Fecal coliform and total coliform levels indicated a high level of contamination in the analyzed groundwater samples.

According to my physicochemical and bacteriological analyses of the groundwater samples from the phreatic aquifer are presented in *table 1*, providing a statistical summary of the parameters examined. Groundwater temperatures ranged between 25 and 31.40°C, potentially influencing quality through microbial proliferation and reduced gas solubility. The pH values fluctuated between 6.78 and 8.57; while most samples fell within the World Health Organization's (WHO) recommended limits, approximately 32% exhibited slightly acidic conditions. EC values extended from 3100 to 7500 µs/cm, surpassing the WHO's guidelines for potable water. Elevated EC suggests a high concentration of total dissolved solids, which similarly exceeded WHO standards in most samples. Turbidity levels exhibited substantial variation, compromising aesthetic quality, and necessitating treatment prior to consumption. Some samples were identified as turbid or relatively turbid. The concentrations of Ca, Mg, Na, K, and Cl were predominantly high, frequently exceeding WHO's drinking water thresholds. Specific samples demonstrated varying compliance with these standards. Moreover, numerous samples surpassed WHO limits for NO_3, NO_2, and NH_4, suggesting potential contamination from agricultural runoff, sewage, or industrial effluents. Concentrations of F, SO_4, and PO_4 exceeded WHO guidelines in certain samples, whereas sulfate levels were generally within acceptable limits. DO, COD, and BOD varied among samples, reflecting differing degrees of biodegradability and pollution. Fecal and total coliform levels were elevated with some samples that indicated significant contamination.

Employing various indices such as the National Sanitation Foundation Water Quality Index, Groundwater Pollution Index, and Nitrate Pollution Index, the study revealed poor water quality, substantial groundwater pollution, and diverse levels of nitrate contamination.

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

Parameters	**N total**	**Mean**	**SD**	**Min**	**Max**	**WHO**
T(°C)	28	27.82	1.61	25.00	31.40	-
Ph	28	7.25	0.45	6.78	8.57	6.5–8.5
Ec (µs/cm)	28	4385.71	1309.83	3100.00	7500.00	1000
Turbidity (NTU)	28	16.88	21.02	0.36	71.60	5
TDS (mg/l)	28	2350.07	1088.98	500	5435.00	500
Ca (mg/l)	28	714.36	148.44	440.88	1050.10	75
Mg (mg/l)	28	381.32	177.05	36.44	705.05	50
Na (mg/l)	28	325.30	90.98	232.15	582.15	200
K (mg/l)	28	20.59	6.28	9.55	33.75	12
Cl (mg/l)	28	378.92	157.26	124.25	914.69	250
NO_3 (mg/l)	28	27.67	38.13	0.10	159.42	50
HCO_3 (mg/l)	28	162.22	94.59	36.60	429.44	120
F (mg/l)	28	1.47	0.65	0.69	3.31	1.5
SO_4 (mg/l)	28	199.31	44.34	68.20	266.13	250
PO_4 (mg/l)	28	0.67	1.36	0.00	6.92	1
DO (mgO_2/l)	28	0.25	0.26	0.02	0.83	-
NH_4 (mg/l)	28	0.57	0.80	0.08	4.00	-
NO_2 (mg/l)	28	0.88	1.88	0.00	6.00	-
COD (mg/l)	28	276.86	70.13	184.00	352.00	-
BOD (mg/l)	28	121.35	19.83	76.80	152.30	-
Total coliforms (UFC/100 ml)	28	2041.21	406.78	1290.00	2580.00	-
Fecal coliforms (UFC/100 ml)	28	320.46	120.79	100.00	540.00	-

Thesis statement 3

I have identified three typical spatial patterns within the parameters under study. Through applied spatial analysis, it was observed that peri-urban and agricultural areas are characterized by elevated levels of EC, Na, K, Cl, HCO_3, PO_4, and DO. In contrast, higher concentrations of Ca, Mg, F, NO_2, and NH_4 were discovered predominantly in urban areas. Additionally, NO_3, SO_4, BOD, and COD exhibited high levels in both agricultural and urban regions.

Based on my applied spatial analysis of the hydrochemical parameters analyzed in the phreatic groundwater aquifer, I found three distinct spatial patterns as shown *figure 3, figure 4 and figure 5*:

1. **Preurban and Agricultural Areas:**
   The presence of high levels of EC, Na, K, Cl, HCO_3, PO_4, and DO in the study area reflects various natural and anthropogenic influences. High EC often points to saline intrusion or the presence of fertilizer runoff, indicating increased mineral content. Elevated Na, K, and Cl are typically associated with agricultural fertilizers and the natural composition of the soil, suggesting agricultural impacts. HCO_3 increases may be natural, resulting from interactions between soil and water, or due to agricultural practices that alter the chemical balance. PO_4 is commonly linked to agricultural runoff, particularly from fertilizer use, indicating nutrient-rich pollution. High levels of DO are generally a positive sign, denoting good water aeration and a healthy aquatic environment; however, these levels can fluctuate due to temperature changes, organic matter decomposition, and other ecological or pollution-related factors.

2. **Urban Areas:**
   Elevated levels of Ca, Mg, F, NO_2, and NH_4 in the study area can be attributed to various environmental and anthropogenic factors. Ca and Mg, which contribute to water hardness, are commonly derived from the dissolution of minerals in water, urban infrastructure decay, or agricultural and urban runoff. Fluoride's increase may be linked to industrial discharges or urban runoff, reflecting human activity and industrial processes. NO_2 and NH_4 are often associated with urban wastewater, sewage, and industrial effluents, highlighting their origins in human waste and industrial activities

3. **Common to Both Agricultural and Urban Areas:**
   High concentrations of NO_3, SO_4, BOD, and COD in the phreatic aquifer suggest various pollution sources. Elevated NO_3 levels are often attributed to agricultural runoff containing fertilizers and possibly urban sewage. SO_4 can originate from multiple sources such as industrial emissions and agricultural chemicals. High BOD and COD are indicative of organic pollution, stemming from sources like agricultural runoff, urban sewage, and industrial waste, reflecting a high demand for oxygen needed to break down this organic material.

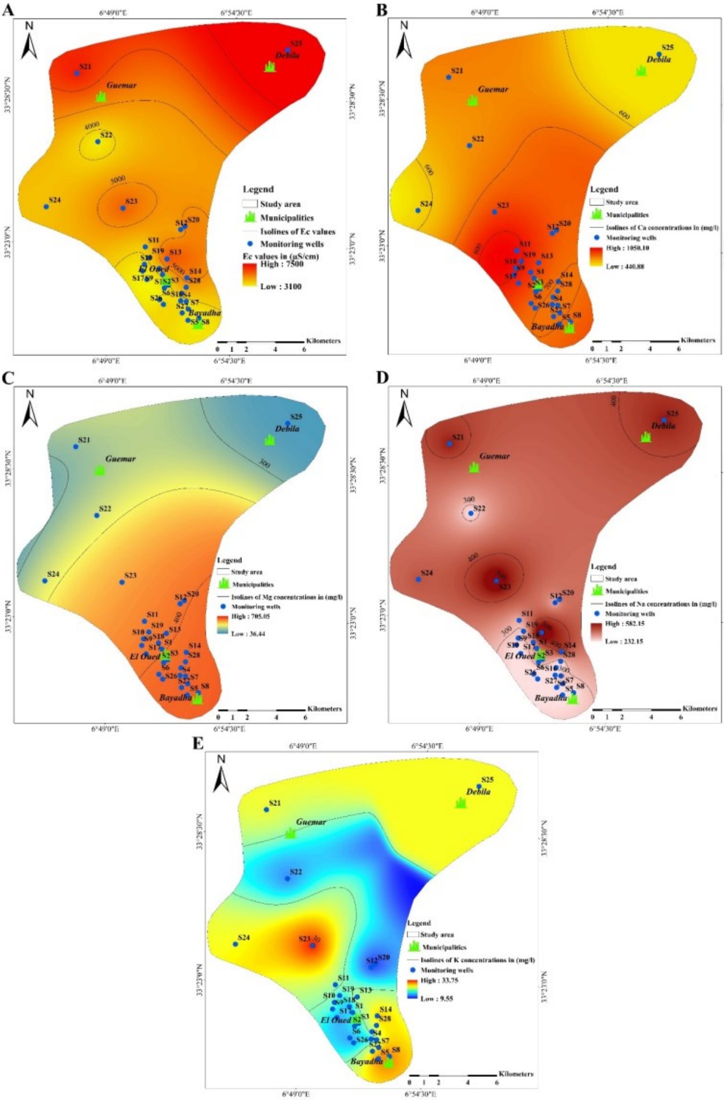

Figure 3. Spatial distribution of the chemical elements in the phreatic groundwater: (A) EC, (B) Ca, (C) Mg, (D) Na, (E) K.

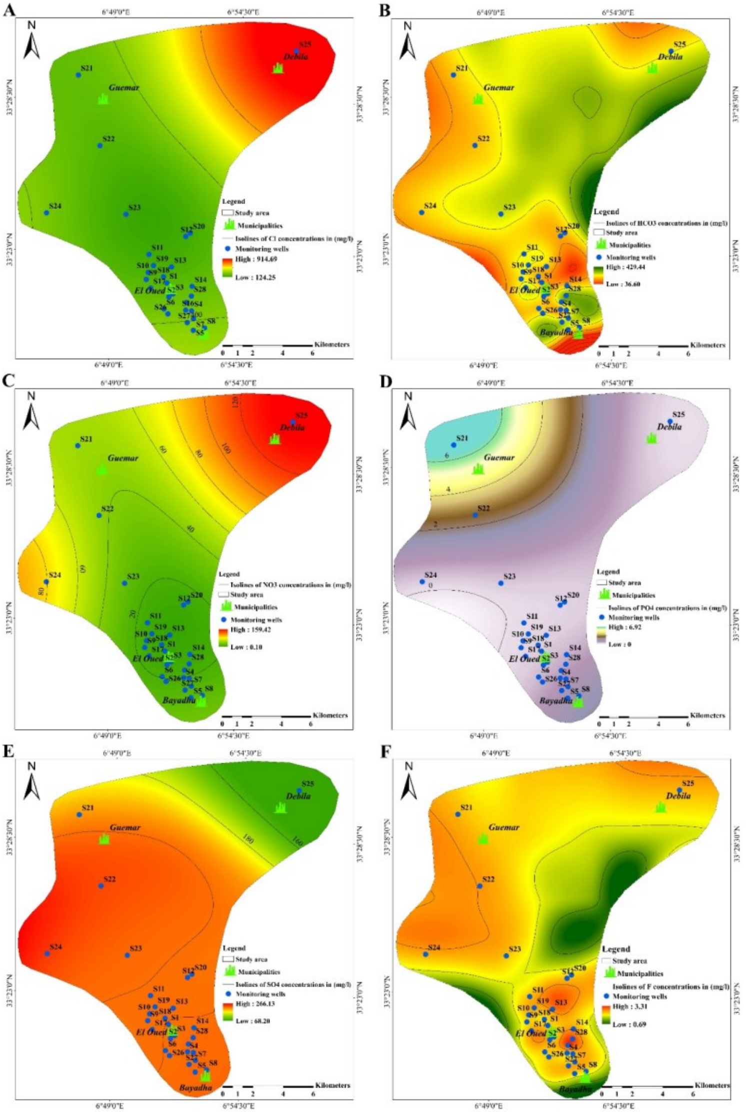

Figure 4. Spatial distribution of the chemical elements in the phreatic groundwater: (A) Cl, (B) HCO_3, (C) NO_3, (D) PO_4, (E) SO_4, (F). F.

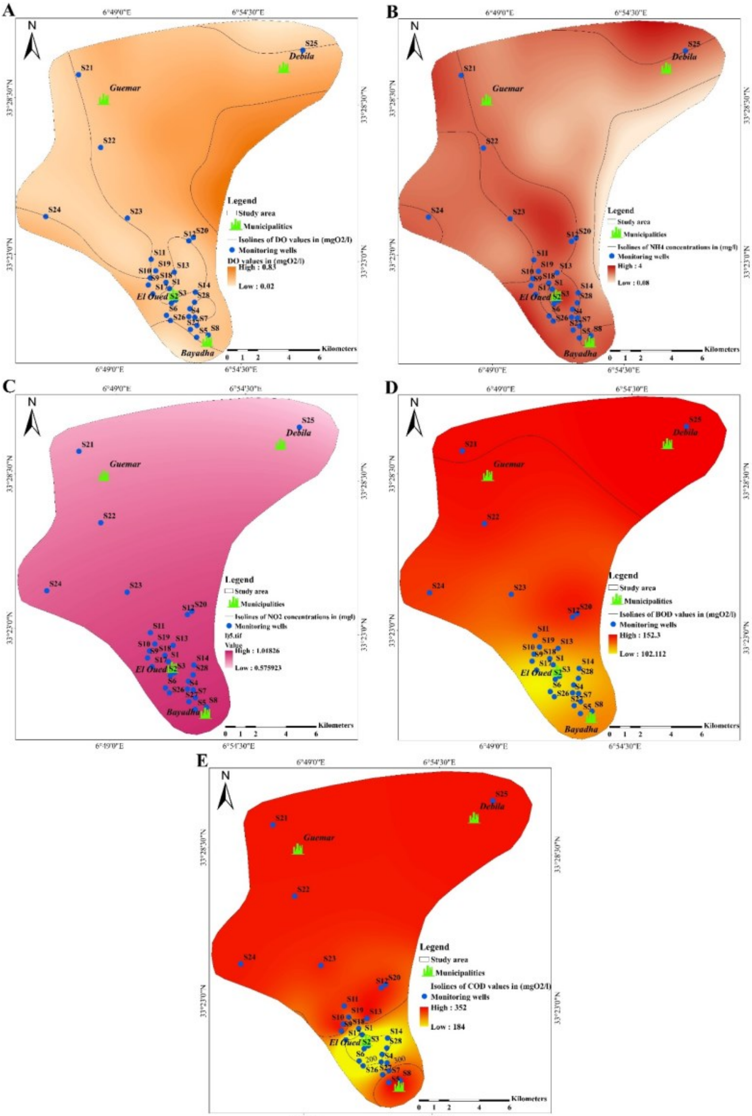

Figure 5. Spatial distribution of the chemical elements in the phreatic groundwater: (A) DO, (B) NH_4, (C) NO_2, (D) BOD, (E) COD.

Analysis of the results revealed significant variations in the strength and structure of spatial dependency for each hydrochemical parameter within the study area. Hydrochemical parameters such as HCO_3, F, PO_4, and COD demonstrated strong spatial dependency.

This indicates a pronounced correlation among data points for each parameter, leading to distinct separation between distributed interpolated levels and the emergence of noticeable patterns or similarities across the spatial data, culminating in a high degree of spatial autocorrelation. Conversely, parameters like EC, Mg, SO_4, DO, and NO_2 displayed weak spatial dependency, suggesting a lower correlation between data values for each parameter at varying locations relative to distance. This results in minimal separation between interpolated levels. The remaining hydrochemical parameters showed moderate spatial dependency, signifying a concentration of each element with a certain level of clustering, trending, or spatial continuity. The variability in data may stem from a mix of local and regional influences, imparting a moderate spatial dependence where data values not only relate to their immediate neighbors but also reflect variations due to wider-scale influences such as the problem of rising of phreatic groundwater level and its consequences on the water quality.

Thesis statement 4

According to my investigation of the analyzed metal levels in the phreatic groundwater aquifer, I found that Al, Fe, Mn, B, Ni, and Pb exceeded the permissible limits in both urban and agricultural areas. The varying concentrations pose significant long-term health risks, particularly for children. Furthermore, Al, Mn, B, Ni, Pb, and Sr exhibited high enrichment levels, suggesting an anthropogenic origin, while the rest of the metals were of lithological origin.

Based on my analysis of several metals in the phreatic groundwater aquifer of the Oued Souf Valley, I found that Al, Fe, Mn, B, Ni, and Pb had varied concentrations and were exceeding the WHO limits in different samples from both urban and agricultural areas, as shown in *table 2*.

Based on my investigation of metal enrichment in a phreatic aquifer, as presented in *figure 6*, I found a trend of Al > B > Sr > Mn > Ni > Pb > Cr > Ba > Cu > Zn. Ba, Cr, Cu, and Zn showed minor enrichment across all samples, suggesting a geogenic source. Aluminum had minor enrichment in nine samples and moderate in five, indicating an anthropogenic source for Al in most of the study area. Mn showed minor enrichment overall, but six samples had higher values, indicating anthropogenic sources, especially in urban and agricultural areas linked to activities like wastewater discharge and farming. Boron enrichment was minor in eight samples and moderate in others, with several suggesting anthropogenic sources. Nickel mostly showed minor enrichment, with a few samples indicating moderate anthropogenic influence. Lead and strontium also varied, with some samples indicating moderate anthropogenic sources. Overall, six samples were deemed of anthropogenic origin.

Table 2. 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 (mg/l)	0.31	0.08	0.30	0.22	0.29	0.52	0.2
Fe (mg/l)	0.21	0.09	0.43	0.11	0.19	0.40	0.3
Mn (mg/l)	0.44	0.11	0.25	0.30	0.40	0.71	0.5
B (mg/l)	0.63	0.43	0.68	0.19	0.45	1.41	0.5
Ba (mg/l)	0.015	0.01	0.63	0.004	0.01	0.03	0.7
Bi (mg/l)	0.14	0.11	0.75	0.00	0.15	0.28	-
Cd (mg/l)	<Lod	<Lod	<Lod	<Lod	<Lod	<Lod	0.003
Co (mg/l)	<Lod	<Lod	<Lod	<Lod	<Lod	<Lod	-
Cr (mg/l)	0.01	0.01	1.23	0.00	0.00	0.02	0.05
Cu (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 (mg/l)	0.01	0.01	0.83	0.00	0.01	0.02	0.02
Pb (mg/l)	0.01	0.01	2.71	0.00	0.00	0.05	0.01
Sr (mg/l)	7.06	2.44	0.35	1.77	7.76	9.94	-
Zn (mg/l)	0.01	0.01	1.61	0.00	0.00	0.04	3

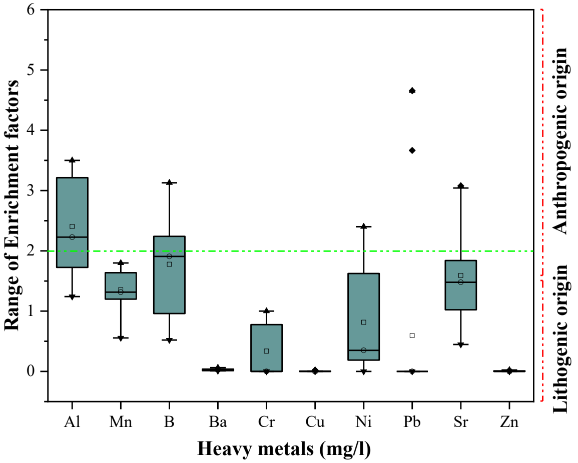

Figure 6. Box plot of enrichment factors of each analyzed metal in the phreatic groundwater aquifer.

On the other hand, the detected levels of the analyzed metals posed no significant ecological risk, except for two samples. S13 showed considerable ecological risk, and S14 a high risk, specifically concerning lead. Overall, the potential ecological risk for all metals was considered low across the samples. Regarding the human risk that may be generated from exposure to the detected metals in the phreatic aquifer. *Figure 7* presents the hazard quotient (HQ) and hazard index (HI) outcomes for adults and children. In the case of adults, HI values exceeded 1 in eight samples, suggesting significant long-term health risks primarily due to high levels of Al and other metals like Fe, Mn, B, Ni, and Sr in certain samples. For children, HQ values for Mn exceeded 1 in nine samples, and Sr was notably high in two samples, indicating potential non-carcinogenic health risks for children in these cases.

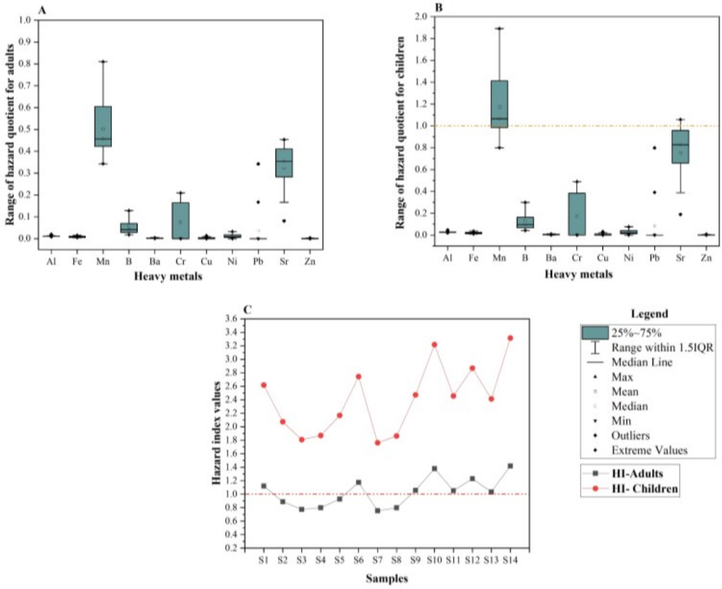

Figure 7. The results of health risk assessment: (A) Box plot of Hazard Quotients (HQs) of eleven heavy metals through ingestion exposure of adults. (B) Box plot of Hazard Quotients (HQs) of eleven heavy metals through ingestion exposure of children. (C) Hazard Index (HI) values of eleven heavy metals for both cases.

The current level of Fe, Mn, B, Ni, Pb, Sr, and Al penetrating the digestive tract or causing skin contamination through the phreatic groundwater can have diverse effects on human health, since an excessive amount of iron in the body can cause chronic illnesses like heart disease and diabetes. Manganese exposure leads to neurotoxic effects, while boron can cause gastrointestinal issues and kidney damage. Nickel exposure is linked to lung fibrosis, kidney problems, and respiratory tract cancer. Lead can result in developmental and cognitive issues in children, as well as high blood pressure and fertility problems in adults. Excessive strontium affects bone density, and aluminum is associated with neurological disorders like Alzheimer's disease. Consequently, the Hazard Index (HI) scores registered exceedingly elevated levels concerning children, encompassing all the wells within the research area. This indicates a substantial and enduring health hazard, along with a noteworthy non-cancer-related adverse impact. Elevated HI scores not only imply immediate dangers but also project into the foreseeable future. Prolonged exposure to these contaminants may result in persistent health issues, with the potential to impede the growth and development of children. Furthermore, children are inherently more susceptible to environmental pollutants than adults, given their ongoing physical development and their tendency to consume or breathe in a higher proportion of pollutants relative to their body weight.

Consequently, the elevated HI scores for children warrant special concern. Hence, it is imperative to involve pertinent authorities, including environmental agencies and public health departments, in formulating and executing strategies aimed at mitigating these risks and safeguarding the well-being of children in the affected region. Additionally, active community engagement and the dissemination of information about potential hazards and protective measures are essential steps to ensure the welfare of residents, particularly children.

Thesis statement 5

Based on my applied hydrochemical analysis of the complex terminal and the continental intercalary groundwater aquifers, I found that the majority of the complex terminal groundwater aquifers have poor water quality for drinking but acceptable quality for irrigation. Conversely, the continental intercalary groundwater aquifer is suitable for both drinking and irrigation despite its high mineralization and hardness.

Based on my hydrochemical assessment of the complex terminal groundwater data presented in *table 3*, I have found that the cationic and anionic contents in various wells of the complex terminal aquifer typically exceed the World Health Organization's (WHO) guidelines for drinking water due to high mineralization. However, nitrate levels generally remain within safe limits, likely attributed to natural purification processes such as denitrification near discharge points and nitrate fixation by clay layers. Additionally, the applied Water Quality Index (WQI) results indicate that many of the wells have poor to very poor water quality (55.10%), with only a small fraction exhibiting good quality. Only two samples were deemed unfit for drinking. On the other hand, based on several applied water quality indices for irrigation assessment, it was revealed that these groundwater samples have moderate to unsuitable quality for irrigation purposes.

Table 3. 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 (mg/l)	274.96	36.85	200.40	360.72	75
Mg (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 (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 showed varied conditions. EC and TDS were high, suggesting heavy mineralization and surpassing World Health Organization (WHO) safe drinking water limits. All cations (Ca, Mg, Na, K) and anions (Cl, SO_4, HCO_3) except for NO_3 exceeded WHO standards, deeming the water unsuitable for direct consumption. Elevated levels of PO_4 and NH_4 were observed, and Fe levels in one sample exceeded WHO guidelines as detailed in *table 4*.

Despite these concerns, the Water Quality Index (WQI) rated all samples as 'good' water for drinking use. However, the same water is considered moderate to bad for irrigation according to EC, %Na, TH, PI, Ps, and Ka. This discrepancy between the suitability of the continental intercalary groundwater aquifer of Oued Souf Valley for drinking and irrigation purposes is because the water quality of the analyzed aquifer has the potential for long-term adverse effects on soil structure, permeability, and overall plant health. This poses risks to soil health and plant growth when used for irrigation due to high salinity, sodium content, or other harmful dissolved ions. Which indicates that the varied impacts on human versus plant health played a major role in the categorization of the continental intercalary groundwater samples for drinking and irrigation utilization.

Table 4. 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 (mg/l)	232.46	30.06	202.40	232.46	262.52	75
Mg (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(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 (mg/l)	1.24	0.21	1.01	1.32	1.40	1
Fe (mg/l)	0.54	0.61	0.17	0.20	1.25	0.3

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List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Barkat, A.**, Bouaicha, F., Rahal, Z., Mester, T., Szabó, G.: Evaluation of climatic conditions from 1978 to 2020 of Oued Souf Valley (Southern East of Algeria).
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