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HYDROCHEMICAL ASSESSMENT AND GROUNDWATER POLLUTION IN THE SOUTHERN HODNA CHOTT REGION (ALGERIA): CHARACTERISTICS, POLLUTION LEVELS, AND DRINKING WATER QUALITY IMPLICATIONS

Abstract: Groundwater pollution has become a major issue of concern to both researchers and policymakers. Many climatic and anthropogenic factors impact groundwater. Groundwater is the sole source of water for all needs in a semi-arid area south of the Chott Hodna. Recently, the quality of drinking water has declined due to overexploitation of the aquifer and the presence of contaminating factors. This study aims to describe the hydrochemical characteristics of the aquifer, assess the level of groundwater pollution, and geographically locate the polluted areas. In 2019, we analyzed samples from 45 boreholes south of the Chott Hodna for 13 physicochemical parameters. The level of water pollution was assessed using the Groundwater Pollution Index (GPI). This index has proven effective in communicating information about water pollution to citizens and policymakers. We also used geographical approaches such as inverse distance weighting (IDW) and conventional kriging to present the polluted areas. It was found that calcium concentrations were all above health standards, and more than 93% of the samples had SO_4^{2-} and TH concentrations above the drinking water threshold. In addition, 58% of the samples had nitrate levels above the drinking water standard of 50 mg/L. The Piper diagram classifies groundwater into sulfate-calcium-magnesium-chloride hydrochemical facies, and these waters tend to become salinized. The Gibbs diagram reveals that the groundwater is younger and that

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evaporation is the dominant process. According to the GPI results, 18% of the samples fell into the insignificant pollution category, and 40% into the low pollution category, while only 22% fell into the moderate pollution category, 7% into the high pollution category, and 13% into the very high pollution category. The geographical presentation of the GPI index revealed that the agricultural zone of Maadher is the one with poor water quality. The analysis showed that borehole water near Sebkha has higher mineral contents and is not potable, compared to borehole water in the northern and eastern study areas.

Keywords: groundwater quality, hydrochemistry, Groundwater Pollution Index (GPI), spatial distribution, drinking water standards

Introduction

Groundwater is a vital and often irreplaceable resource in semi-arid and arid environments, where surface water is scarce or non-existent for much of the year. In the Chott Sud-Hodna region, groundwater is the primary source of drinking water, water for agriculture, and other domestic uses. The harsh climate of this region is characterized by low and irregular rainfall, prolonged droughts, high temperatures, and intense evapotranspiration, which exacerbates this dependence on groundwater (Selmane et al., 2022). Consequently, the area's aquifers are essential for survival but are also highly vulnerable to overexploitation and degradation.

In recent decades, the sustainability of groundwater resources in the Chott Sud-Hodna basin has been increasingly threatened by both natural and human-induced factors. Human activities, including excessive water withdrawals for irrigation, uncontrolled wastewater discharge, and the intensive use of fertilizers and pesticides, have severely degraded groundwater quality. Areas near wadis and infiltration zones are particularly vulnerable to contamination, increasing the risks to aquifer systems. These combined pressures underscore the urgent need for systematic groundwater contamination assessments and the development of targeted management strategies.

Several studies conducted in North Africa and other arid regions have successfully applied groundwater quality indices combined with geospatial analysis to assess contamination profiles. For example, researchers Djebassi et al. (2021) applied the Groundwater Pollution Index (GPI) in the Tébessa Basin in northeastern Algeria, revealing pollution levels ranging from negligible to very high, attributable to both geogenic and anthropogenic sources. In Morocco, Sanad et al. (2024) combined the GPI with the Nitrate Pollution Index (NPI) and GIS techniques to map groundwater quality in the Mnasra region. The study's results demonstrated the significant influence of agricultural practices on contamination. Similarly, Boukich et al. (2025) reported seasonal variations in groundwater pollution in the Angads Plain, with higher pollution levels during dry periods, particularly in agricultural areas. In Tunisia, Abdelkarim et al. (2023) showed that nitrate contamination in the Sidi Bouzid Basin posed significant health risks, with more than half of the samples classified as slightly to moderately polluted. In Egypt, studies by Gad et al. also contributed to water quality research. In 2023, Megahed et al. used multi-criteria GIS modeling and PIG-type indices to delineate water quality zones and highlight anthropogenic pressures. Beyond North Africa, Iranian researchers, such as Najafpour and Soltaninia (2025), have integrated the PIG and GIS-based vulnerability mapping, and have demonstrated the effectiveness of combining spatial and statistical tools to assess groundwater contamination in arid environments.

Despite these advances, a major gap remains in research, as the integrated PIG + GIS methodology has not allowed for an adequate study of the Chott Sud-Hodna basin. Existing studies have either focused on other regions of Algeria or applied conventional indices without an explicit spatial approach. This explains the lack of comprehensive, high-resolution groundwater quality mapping for this area of major socio-economic and environmental importance. We must address this critical gap to support sustainable groundwater management in the face of pressures from climate variability and human activities.

In this context, the present study is guided by the following research hypothesis: integrating the Groundwater Pollution Index (PIG) with GIS-based spatial analysis can provide a more detailed and accurate assessment of groundwater contamination in the Chott Sud-Hodna basin. This work aims to make a threefold contribution:

(i) to apply and adapt the PIG methodology to the regional conditions of southern Algeria,
(ii) to produce a spatial assessment of groundwater quality using GIS techniques, and
(iii) to propose a methodological framework that can be replicated in other arid regions where data are scarce, for informed water resource management.

Finally, this study presents a comprehensive assessment of groundwater quality in the southern Chott Hodna basin, integrating PIG and GIS approaches. The PIG method provides a unique composite measure synthesizing multiple physicochemical parameters, while GIS facilitates the spatial visualization of pollution intensity and the identification of high-risk areas. This combined approach improves the understanding of contamination dynamics and supports evidence-based groundwater management strategies in semi-arid environments.

Description of the study area

The study site is located in the southern part of the Chott Hodna basin, specifically in northern Algeria (Fig. 1). The region is characterized by a semi-arid to arid climate with an average annual rainfall of approximately 150 to 200 mm. This minimal and irregular rainfall strongly influences local hydrological processes, particularly those regulating groundwater recharge. We explicitly note that climate variability has a significant impact on the availability and renewal of water resources in this fragile ecosystem.

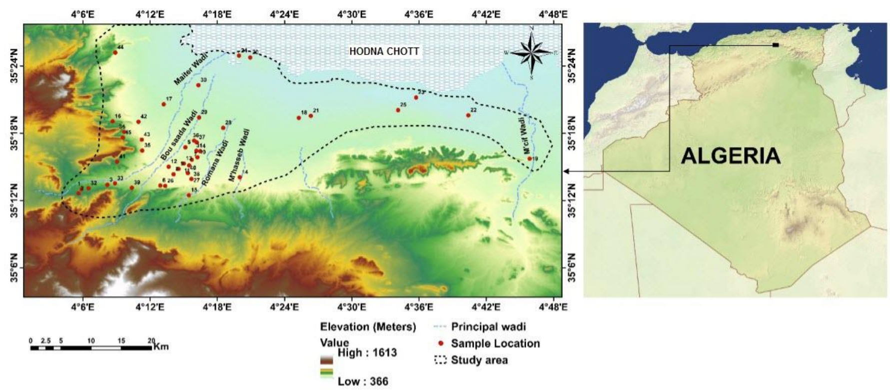

Fig. 1. Geographical location of the study area

In this area, intermittent rivers (wadis) such as Maîtrer, Bousaada, Roumana, and M'cif constitute the bulk of the hydrographic network. They play a vital role in both surface runoff and occasional groundwater recharge. The geology of the area is complex and exhibits considerable lithological variation (Fig. 2); Jurassic formations are particularly visible on the southern margins of the Hodna Basin mountains. Cretaceous limestones are visible to the north and south of the basin. Miocene sandstones crosscut the Cretaceous units. Quaternary sediments predominate in the central part of the basin over a marly substrate.

In the central plain, the Miocene-Plio-Quaternary aquifer system reaches a thickness of over 250 meters (Guiraud, 1973; Dougha, 2019). This aquifer is a heterogeneous and anisotropic reservoir composed of alternating layers of clays, sandy clays, sandstones, clayey sands, and conglomerates. It is fed primarily by three main pathways: direct infiltration by precipitation; percolating wadi water; and groundwater flow from the surrounding Cretaceous and Miocene rocks (Guiraud, 1973). Land use includes irrigated agriculture, which relies heavily on groundwater abstraction. This phenomenon, combined with demographic pressure and insufficient recharge, has led to a drop in groundwater levels of more than 15 meters since the 1970s (ANRH, 2006). The region is home to deeper Miocene and Pliocene aquifers, composed of intercalated marls and conglomerates, as well as a shallow Quaternary aquifer, often with high salinity. The latter is considered renewable, but, given excessive abstraction, it is becoming more sensitive.

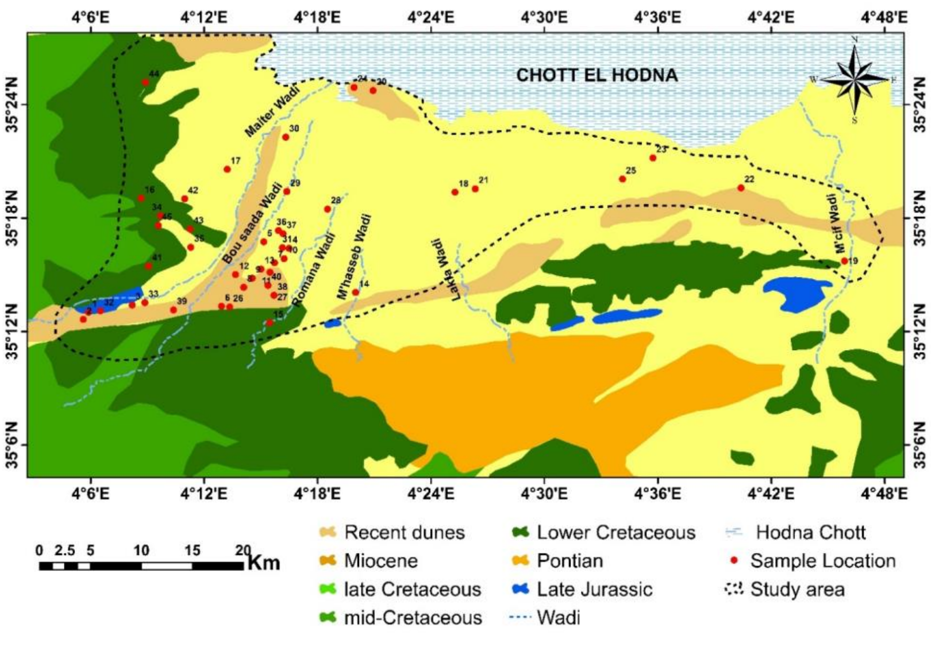

Fig. 2. Geological map of southern Chott Hodna

Materials and methods

Between March and April 2019, a field campaign was conducted to collect 45 groundwater samples from boreholes distributed throughout the study area. After pumping for 10 to 15 minutes, the samples were collected to ensure the stabilization of aquifer conditions and to avoid interference with stagnant water and contamination during sampling. Clean polyethylene bottles were used.

Using portable probes, in situ measurements of electrical conductivity (EC), pH, and temperature were performed in the field. Immediately after delivery of the samples to the Algerian Waters laboratory, analyses of the main ions (e.g., Ca^{2+}, Mg^{2+}, Na^{-}, Cl^{-}, $SO_4{}^{2-}$, $HCO_3{}^{-}$, and $NO_3{}^{-}$) were performed to ensure representative groundwater conditions. The ion balance (IB) method was performed to confirm the analytical accuracy of ion concentrations, and all samples remained within the permissible limit of ±6%.

Groundwater Pollution Index (GPI)

We used the Groundwater Pollution Index (GPI), developed by Subba Rao in 2012 and improved by subsequent studies (Bahrami et al., 2020; Verma and Singh, 2021; Ana et al., 2010), to assess water cleanliness and pollution levels.

The GPI index involves five calculation steps:

1. Determination of weight factor (R_w): Based on its importance to health, a weight (1 to 5) is assigned to each water quality parameter (see Table 1).
2. Calculation of the relative weighting factor (W_P): using equation (1).
3. Calculation of the concentration status (Sc): Equation 2 uses the measured concentration relative to the standard limits.
4. Using Equation 3, calculate the overall water quality (O_w) by multiplying W_P by Sc for each parameter.
5. Summation of O_w values: The GPI score for each sample is determined by summing all O_w values (Equation 4).

To classify pollution, this index reduces complex water quality data to a single number, helping to inform the public and decision-makers about risks (Reddy et al., 2022); (Miroslav et al., 2020; Adimalla et al., 2020). The World Health Organization (WHO) (2017) guidelines were used in this study to assess the GPI index.

$$W_P = \frac{R_W}{\sum R_W} \quad (1)$$

$$S_c = \frac{C}{D_c} \quad (2)$$

$$O_w = W_P \times S_i \quad (3)$$

$$GPI = \sum O_w \quad (4)$$

GPI classification: The impact of a water sample on human health is negligible if its quality is comparable to drinking water standards. A GPI index less than 1.0 means there is no pollution, while a value greater than 1.0 means that the concentrations of certain water parameters have increased (see Table 1).

In determining the weighting factors for the Groundwater Pollution Index (GPI), expert judgment considers how each water quality parameter affects both human health and environmental conditions. In this semi-arid setting, where groundwater quality is generally poor, ions such as SO_4^{2-}, NO_3^-, Cl^-, and Na^+ receive higher weights (4–5) because of their contribution to salinity and associated health risks. Parameters like pH, electrical conductivity, and HCO_3^- are assigned moderate weights (3) due to their buffering capacity and role in maintaining chemical stability. Meanwhile, Ca^{2+}, Mg^{2+}, and total hardness (TH), though less directly harmful, are crucial for understanding water hardness and are given intermediate weights (2–3). Low weighting is given to K^+ and NO_2^-, which are generally present in lower concentrations and have less effect on health (1) (see Table 1). As shown in studies such as Taloor et al. (2023) and Tiwari et al. (2022), where expert knowledge is combined with hydrochemical understanding to prioritize pollutants in vulnerable regions, this weighting approach is consistent with recent water quality indexing methodologies for arid and semi-arid environments.

Table 1. The GPI category, as well as the weight and relative weight of each parameter used for the GPI calculation

GPI **value**	**Category**	
GPI < 1.0	Insignificant pollution	
1.0 < GPI < 1.5	Low pollution	
1.5 < GPI < 2.0	Moderate pollution	
2.0 < GPI < 2.5	High pollution	
GPI > 2.5	Very High pollution	
Parameter	**GPI Index**	
	weight factor (R_w)	**Relative Weight (W_P)**
pH	3	0.083
EC	3	0.083
Ca^{2+}	2	0.056
Mg^{2+}	2	0.056
HCO_3^-	3	0.083
Cl^-	4	0.111
SO_4^{2-}	5	0.139
TH	3	0.083
NO_3^-	5	0.139
Na^+	4	0.111
K^+	1	0.028
NO^-_2	1	0.028
	$\sum \boldsymbol{R_w} = 36$	$\sum \boldsymbol{W_P} = 1.0$

Results and discussion

Hydrochemical processes in the aquifer

Compared to drinking water standards, hydrochemical characterization of groundwater samples revealed significant exceedances of important chemical parameters (Table 2).
In particular:

1. All boreholes had calcium (Ca^{2+}) concentrations above the permitted limits.

2. In 72% of the samples, sulfate (SO_4^{2-}) concentrations were above expected values.

3. Approximately half of the water points analyzed had excess magnesium (Mg^{2+}) and bicarbonate (HCO_3^-).

4. Furthermore, 58% of the samples had nitrate (NO_3^-) concentrations above 50 mg/L, indicating the presence of significant anthropogenic contamination, likely caused by domestic wastewater or agricultural runoff.

Table 2. Statistical data on physicochemical parameters

Variable	WHO Standards (2017)	Min	Max	Mean	Sample exceeding WHO standard (%)
T (°C)	-	12.50	30.50	20.81	0.00
PH	6.5 – 8.5	6.60	8.15	7.44	0.00
EC	1500.00	1033.00	5980.00	1937.91	73.33
Ca^{2+}	75.00	88.00	544.00	258.44	100.00
Mg^{2+}	50.00	34.00	214.00	99.30	88.88
HCO_3^-	300.00	102.00	488.00	284.93	53.33
Cl^-	250.00	67.00	902.00	242.09	35.55
SO_4^{2-}	500.00	200.00	850.00	577.67	71.11
TH	500.00	460.00	12200.00	1389.53	93.33
NO_3^-	50.00	2.00	262.00	73.86	57.77
Na^+	50.00	27.00	290.00	82.78	77.77
K^+	10.00	1.90	14.80	5.85	6.66
NO_2^-	0.20	0.02	0.02	0.02	0.00

All parameters in mg/l except, EC (25°C) in µs/cm, T in °C, and pH without unit.

To classify groundwater types and better understand their geochemical evolution, a Piper diagram was constructed (Fig. 3). The results indicate that most of the groundwater samples belong to the calcium-magnesium-chloride-sulfate hydrochemical facies, reflecting characteristics of hard, mineral-rich water. This composition corresponds to the dissolution of evaporite and carbonate rocks such as gypsum, anhydrite, and limestone, which are common formations in the region. Borehole F28 exhibits a distinct chemical signature with high concentrations of sodium-potassium nitrate and chloride, suggesting localized anthropogenic contamination, likely related to agricultural runoff or domestic wastewater (Selmane et al., 2022). Pronounced levels of Ca^{2+} and SO_4^{2-} further indicate persistent hardness, consistent with the weathering of gypsum strata (Dougha and Hasbaia, 2019).

We used graphical models and ion ratios to interpret the chemical processes governing groundwater chemistry. The main hydrogeochemical processes in this aquifer are: dissolution of evaporites (main source of Na^+ and Cl^-), the ionic composition is also influenced by the alteration of silicates, and dissolution of carbonates which adds Ca^{2+} and HCO_3^-, Deutsch (2020).

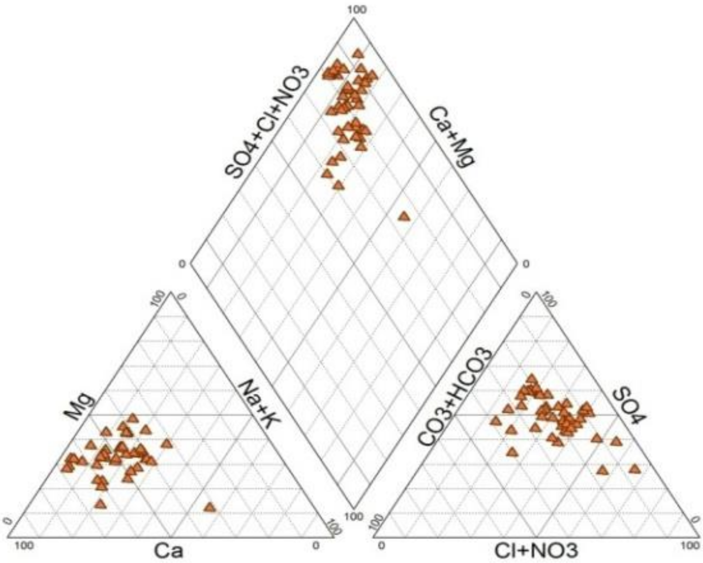

Fig. 3. Piper diagram illustrates the classification of groundwater

Additionally, we used the Gibbs diagram (Gibbs, 1970; Ehya & Saeedi, 2019) to assess the relationship between water chemistry and aquifer geology. The results show that evaporative concentration, rather than precipitation or rock-water interaction, is the primary cause of elevated salinity, placing all groundwater samples in the evaporation-dominated domain (Fig. 4). The lack of saturation and the Na^+/Cl^- ratios indicate that the aquifer contains relatively young water, which continues to be affected by active recharge and evaporation processes.

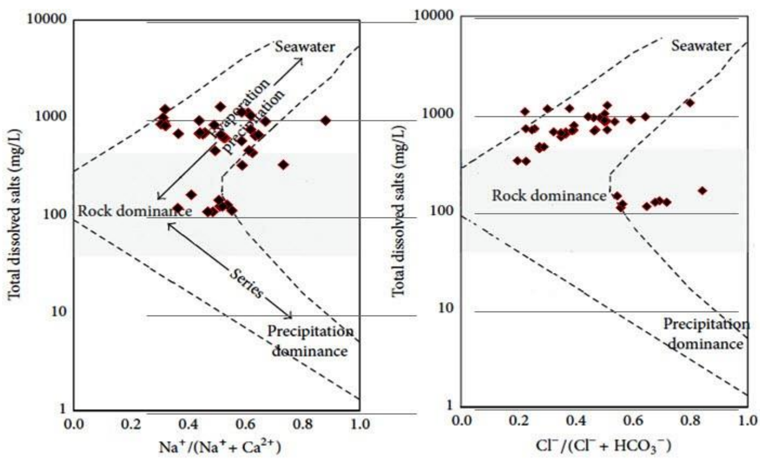

Fig. 4. Gibbs diagrams of groundwater samples

Spatial distribution of physicochemical parameters

Figure 5 illustrates the spatial variability of key hydrochemical parameters, including Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-}. There are clearly two main groundwater quality zones: concentrated near the Sebkha, areas of high mineralization show a predominance of evaporative concentration and mineral dissolution in arid environments, with ion concentrations often exceeding WHO drinking water standards (WHO, 2017). Perhaps reflecting more active recharge or lower anthropogenic input, lower concentrations are observed in boreholes in the western Maadher highlands and in the eastern part of the study area. Similar trends were observed for Mg^{2+}, Na^+, K^+ and electrical conductivity (EC), which peak in the northwest and highlight possible areas of saline intrusion or surface contamination (Stigter et al., 2006). ArcGIS (Darmawan et al., 2023) was used to assess and visualize spatial patterns by kriging interpolation, a geostatistical technique suitable for groundwater quality mapping.

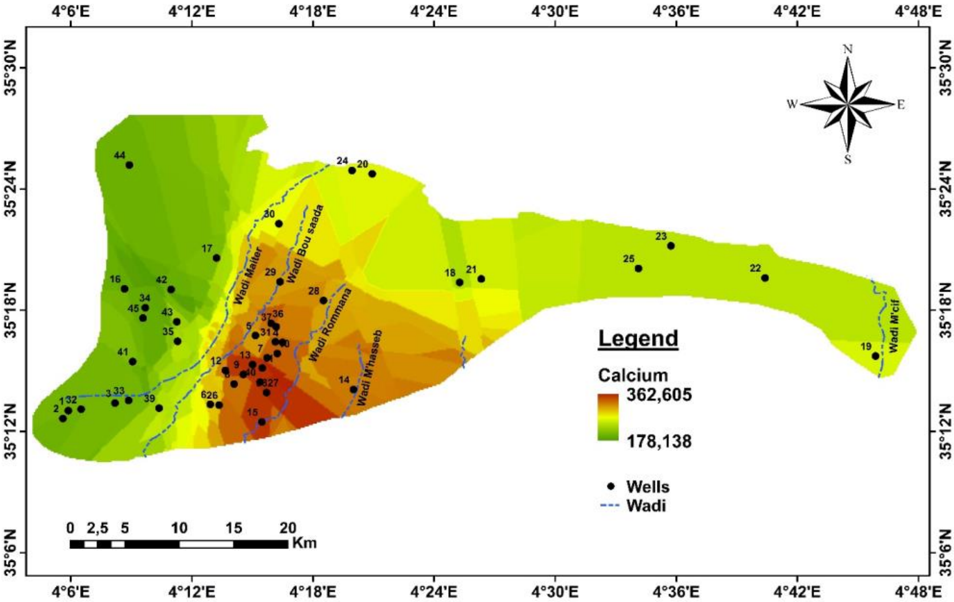

Fig. 5. (a) Spatial distribution map of calcium using the Kriging method

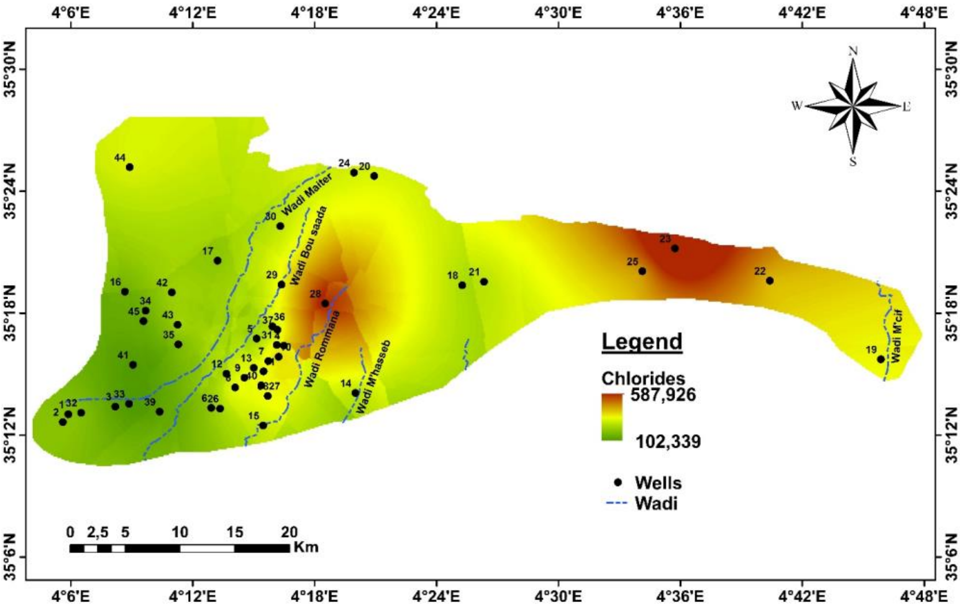

Fig. 5. (b) Spatial distribution map of chlorides using the Kriging method

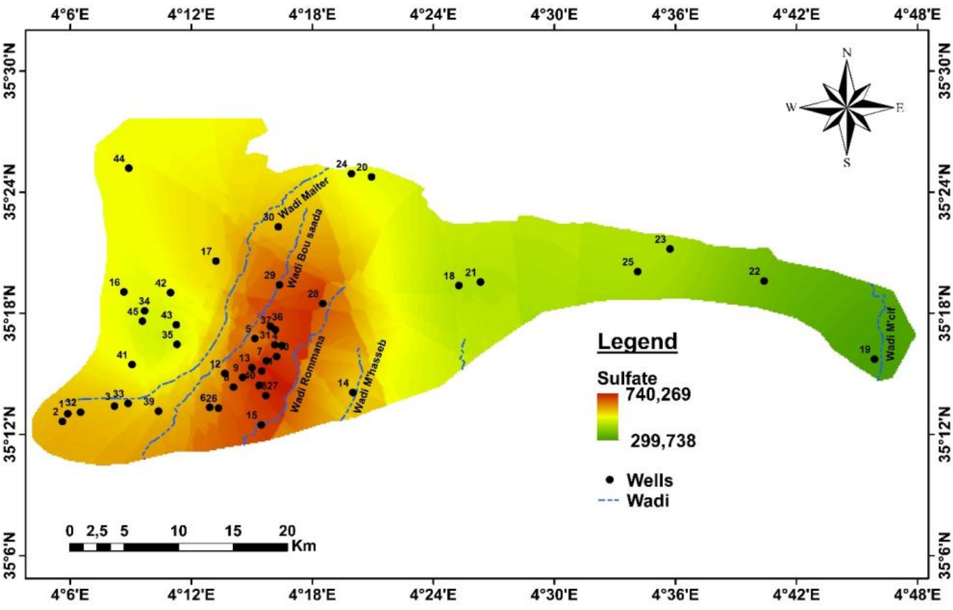

Fig. 5. (c) Spatial distribution map of sulfate using the Kriging method

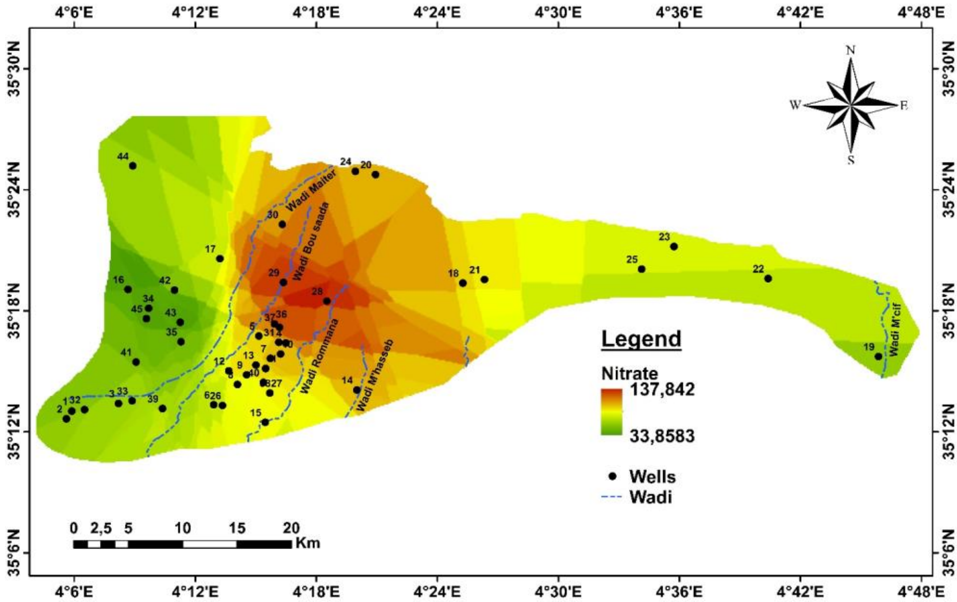

Fig. 5. (d) Spatial distribution map of nitrate using the Kriging method

Assessment of groundwater pollution

The Groundwater Pollution Index (GPI) approach assesses the degree of groundwater contamination. This index assigns pollution levels by combining several chemical criteria and comparing them to drinking water standards.

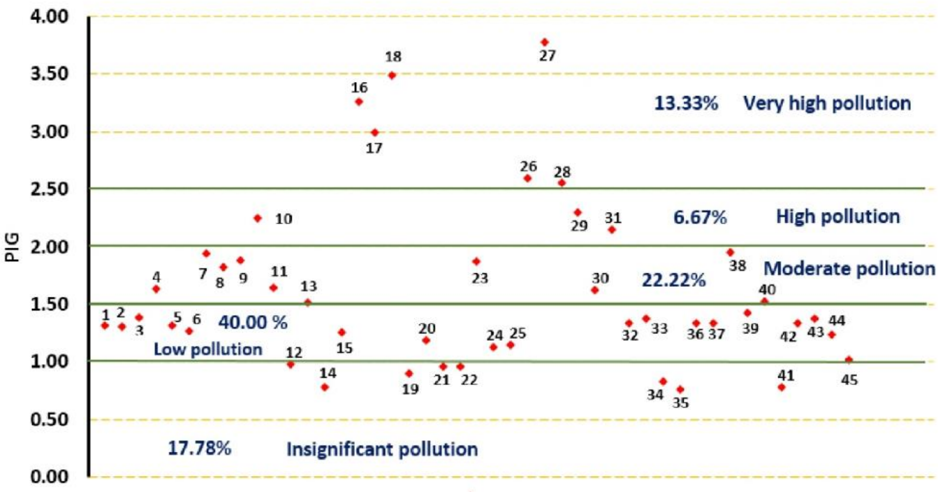

Fig. 6. Groundwater quality classifications based on the groundwater pollution index (GPI)

According to the results (Fig. 6), 18% of the samples were in the unpolluted category. 40% were somewhat polluted. 22% were moderately polluted and 20% were highly to very highly polluted.

These results are consistent with previous hydrogeological research conducted in arid areas, which revealed that insufficient wastewater discharge and agricultural return flows were the main sources of pollution. The most contaminated sites wells 16, 17, 18, 26, 27, and 28 are located in areas of high agricultural and human activity, according to the spatial distribution of GPI values determined using the kriging technique (Fig. 7). In contrast, the agricultural plain of Maadher and along the Maîter, Bousaada and Romana wadis areas likely affected by surface water-groundwater interaction show signs of moderate pollution.

The southern and southwestern regions have relatively clean water areas, implying either reduced anthropogenic pressure or improved aquifer self-purification systems.

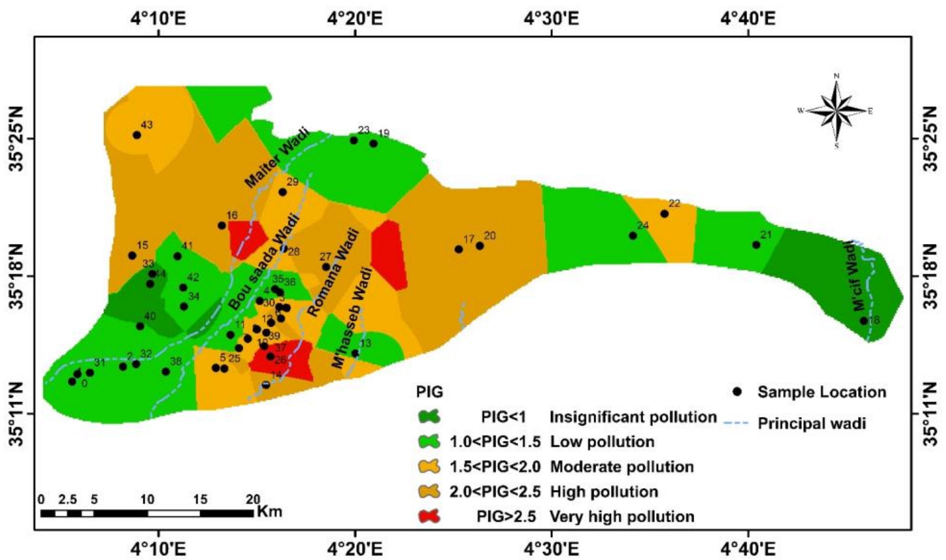

Fig. 7. Spatial distribution map of groundwater pollution index GPI using the Kriging method

Conclusion

This study demonstrates that groundwater in the southern Chott Hodna Basin is increasingly affected by a combination of natural geochemical processes—particularly evaporation-induced salinization—and human activities related to agriculture and wastewater disposal. The dominance of Ca–Mg–Cl–SO_4 facies and the frequent exceedance of WHO nitrate thresholds reveal a progressive decline in water quality, with only about 18% of samples meeting acceptable standards. The integration of the Groundwater Pollution Index (GPI) with GIS mapping has proven useful for identifying pollution hotspots and quantifying contamination intensity. Beyond its local significance, this work enriches the hydrogeological understanding of arid environments by showing how index-based evaluations like the GPI, when paired with spatial tools, can effectively trace anthropogenic pollution in regions with limited monitoring data. However, limitations such as sparse sampling, a lack of seasonal data, and potential interpolation errors can affect spatial accuracy. Future research should include multi-year monitoring, hydrogeochemical modeling, and the integration of socio-economic and climatic variables to better anticipate vulnerability trends. Overall, this study underscores the urgent need to protect groundwater through improved wastewater treatment, rational fertilizer management, and continuous monitoring based on the groundwater productivity index (GPI). It also establishes a methodological framework applicable to other arid and semi-arid ecosystems for the sustainable management of groundwater resources.

Conflicts of Interest: The authors declare no conflict of interest.

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