Hydrochemical Characterization and Spatial Analysis of Groundwater Salinization in the Ghiss–Nekor Coastal Aquifer (Northern Morocco)

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Abstract. Groundwater salinization has become one of the most critical environmental challenges threatening coastal aquifers in Mediterranean semi-arid regions. This study investigates the physicochemical characteristics and salinization mechanisms of the Ghiss-Nekor Aquifer through a hydrochemical survey conducted during January 2026. A total of 57 groundwater samples were collected and analyzed in situ for pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity, combined with GIS-based spatial analysis to identify hydrochemical gradients and vulnerable zones.

The results reveal strong spatial variability in groundwater quality across the aquifer. Elevated EC, TDS, and salinity values are predominantly concentrated in the northeastern coastal sector near Trougout, indicating advanced groundwater mineralization and progressive seawater intrusion. Salinity values reached more than 5.30 g/L, while EC exceeded 9,283 µS/cm in highly affected areas. Conversely, southern and southwestern sectors exhibited lower mineralization levels due to stronger freshwater recharge conditions. The spatial coincidence of high salinity indicators confirms the dominant influence of marine intrusion, intensified by groundwater overexploitation, recurrent droughts, tectonic structures, and anthropogenic pressures.

The study further demonstrates that lithological conditions and water–rock interactions contribute significantly to groundwater mineralization through evaporite and carbonate dissolution processes. Neutral to slightly alkaline pH conditions indicate stable hydrochemical environments dominated by carbonate buffering mechanisms. The integration of hydrochemical interpretation and spatial analysis provides new insights into the functioning of the Ghiss–Nekor coastal aquifer and highlights the urgent need for sustainable groundwater management strategies in northern Morocco.

Keywords. Groundwater salinization, Coastal aquifer, Seawater intrusion, Hydrochemistry, GIS spatial analysis.

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1 Introduction

Groundwater constitutes one of the most strategic freshwater resources worldwide, particularly in arid and semi-arid regions where surface water availability is limited and highly vulnerable to climate variability. Coastal aquifers are increasingly subjected to multiple anthropogenic and natural pressures including agricultural intensification, urban expansion, industrial activities, excessive groundwater abstraction, and climate change-induced droughts [1–4]. These pressures often result in groundwater quality deterioration through salinization, nitrate contamination, and hydrochemical imbalance, threatening both human consumption and agricultural sustainability [5–8]. In Mediterranean environments, where water scarcity is becoming more severe, the preservation of groundwater quality has emerged as a major environmental and socio-economic challenge [9–12].

Salinity is considered one of the most critical issues affecting coastal aquifers worldwide. Elevated salinity levels may originate from seawater intrusion, evaporite dissolution, water–rock interaction, irrigation return flows, or the concentration of dissolved salts under arid climatic conditions [2,13–15]. Several studies conducted in Mediterranean coastal aquifers have highlighted the increasing vulnerability of groundwater systems to salinization processes, particularly in regions characterized by overexploitation and limited recharge [16–18]. In many coastal plains, hydrochemical investigations based on physicochemical parameters such as electrical conductivity, total dissolved solids, chloride, sulphate, sodium, and magnesium concentrations have proven effective for identifying the origin and evolution of salinity [19–22]. Hydrochemical facies analysis and statistical approaches are commonly used to distinguish marine intrusion from geogenic mineralization processes [23,24].

At the international scale, numerous hydrochemical studies have focused on the characterization of coastal aquifers in Mediterranean and semi-arid regions. Investigations conducted in Italy, Tunisia, Spain, Egypt, Algeria, and Greece demonstrated that seawater intrusion remains one of the principal drivers of groundwater degradation in coastal zones [25–27]. Giambastiani et al. [25] reported unstable hydrodynamic conditions and significant groundwater salinization in the Emilia-Romagna coastal aquifer in Italy due to marine influence and groundwater overexploitation. Noureddine G. et al. [26] highlighted the hydrochemical evolution and salinity increase in southeastern Tunisian aquifers under combined geological and anthropogenic effects. Similar findings were reported in other Mediterranean basins where chloride and sulphate enrichment were associated with both evaporitic formations and seawater mixing [18,28,29]. These studies underline the necessity of hydrochemical monitoring as an essential tool for sustainable groundwater management.

In Morocco, groundwater resources play a central role in drinking water supply, irrigation, tourism, and industrial development. However, increasing water demand combined with recurrent drought periods has intensified pressure on aquifer systems across the country [30]. Moroccan coastal and inland aquifers have experienced progressive degradation characterized by high mineralization, nitrate pollution, and salinity increase [30–33]. Previous studies conducted in the Saïss, Souss-Massa, Moulouya, Martil-Alila, Loukkos, and Chaouia aquifers revealed significant spatial variability in groundwater quality controlled by lithology, agricultural practices, and marine intrusion [34–36]. Hydrochemical investigations carried out in several Moroccan aquifers demonstrated that salinity is frequently associated with evaporite dissolution, carbonate weathering, and excessive pumping near coastal zones [37,38]. In semi-arid areas, climatic conditions further enhance evapotranspiration processes and salt accumulation within groundwater systems [33].

The Ghiss–Nekor coastal aquifer, located in the Rif region of northern Morocco near Al Hoceima city, constitutes one of the main groundwater reservoirs supporting domestic water supply and agricultural activities in the area. This aquifer is characterized by a Mediterranean semi-arid climate, irregular precipitation, and increasing anthropogenic pressures related to agricultural expansion and urban growth. The hydrogeological structure of the basin is influenced by alluvial deposits, carbonate formations, and evaporitic materials that may significantly affect groundwater mineralization. Due to its coastal position, the aquifer is also potentially exposed to seawater intrusion, especially under intensive groundwater abstraction conditions.

Several hydrochemical studies have already investigated groundwater quality within the Ghiss–Nekor plain and surrounding Rifian aquifers [38–40]. Bouhout et al. [39] reported that groundwater samples from the downstream part of the Ghiss–Nekor aquifer were chemically dominated by chloride and sulphate ions, suggesting the influence of seawater intrusion and evaporite dissolution. Other investigations in the Rif region highlighted elevated electrical conductivity and salinity values associated with geological formations rich in evaporitic minerals as well as agricultural contamination [40,41]. Nevertheless, despite the increasing concern regarding groundwater salinization in the region, recent seasonal investigations remain limited, particularly after the recurrent drought episodes observed during the last decade.

The present study aims to characterize the physicochemical quality of groundwater in the Ghiss–Nekor aquifer during the March 2026 campaign in order to evaluate the extent and origin of salinization processes. The study focuses on the spatial distribution of major physicochemical parameters and their relationship with hydrogeological conditions. Particular attention is given to salinity indicators such as electrical conductivity, chloride, sodium, sulphate, and total dissolved solids.

This work is based on two main scientific hypotheses. The first hypothesis assumes that groundwater salinization within the Ghiss–Nekor aquifer is primarily induced by seawater intrusion resulting from the proximity of the Mediterranean Sea and excessive groundwater abstraction. The second hypothesis assumes that groundwater mineralization is mainly controlled by geological and lithological processes, especially the dissolution of evaporitic and carbonate formations naturally present within the aquifer system. Through hydrochemical characterization and comparative analysis, this study seeks to identify the dominant processes responsible for groundwater salinity and to provide scientific evidence supporting sustainable groundwater management strategies in the Ghiss–Nekor coastal plain.

2 Materials and Methods

2.1. Study Area

The present study was conducted in the Ghiss–Nekkour coastal aquifer (Cf. Fig. 1), located in the Al Hoceima Province in northern Morocco along the Mediterranean coast. This aquifer constitutes a strategic groundwater resource for the region and is mainly exploited for drinking water supply, agricultural irrigation, and various socio-economic activities.

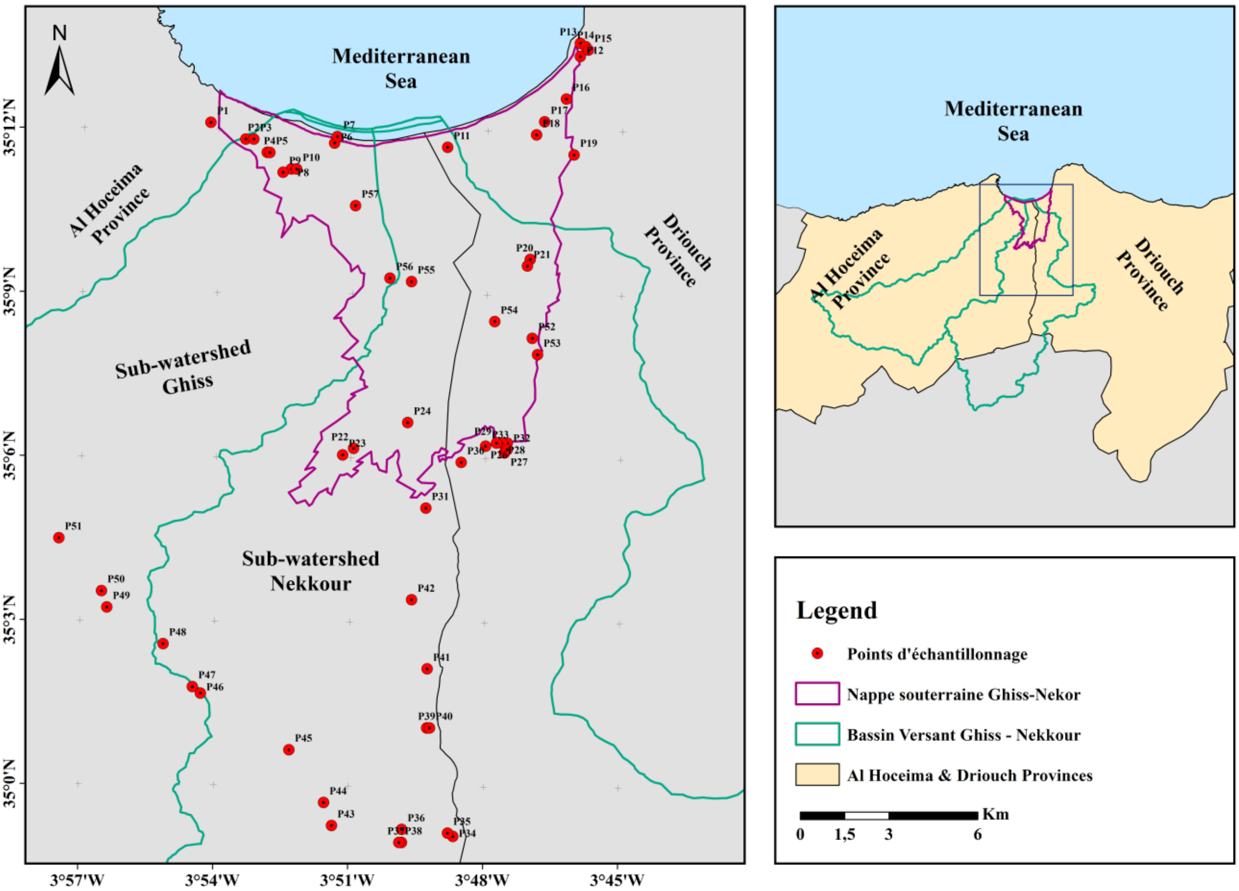

Fig. 1 Location of the Ghiss-Nekor Basin showing the Ghiss and Nekor sub-watersheds, groundwater sampling points, and the administrative boundaries of Al Hoceima Province and Driouch Province along the Mediterranean Sea coast in northern Morocco.

The Ghiss–Nekkour basin is characterized by a semi-arid Mediterranean climate marked by irregular rainfall patterns and increasing pressure on groundwater resources [42]. The proximity to the Mediterranean Sea, combined with groundwater overexploitation and recurrent drought conditions, makes this aquifer particularly vulnerable to salinization and seawater intrusion processes[3] .

From a geological perspective, the study area belongs to the Rif domain and is composed of Quaternary alluvial formations, detrital deposits, and complex tectonic structures. The presence of tectonic faults, particularly in the Trougout area, may influence groundwater circulation and promote hydrological exchanges as well as saline water migration within the aquifer system [43].

2.2. Sampling Strategy

A groundwater sampling campaign was carried out on January 27, 28, and 31, 2026, within the Ghiss–Nekkour aquifer. The campaign was conducted prior to the precipitation events recorded in the following weeks in order to obtain representative hydrochemical data under relatively stable hydrological conditions.

The sampling strategy was designed based on previous investigations conducted in the study area, particularly hydrochemical studies previously performed in the Ghiss–Nekkour aquifer [44]. While earlier studies relied on a limited number of sampling points, the present investigation expanded the observation network to 57 sampling sites distributed both inside and outside the hydrogeological boundaries of the aquifer.

This spatial extension aimed to improve the representativeness of the dataset and to better characterize the spatial variability of hydrochemical parameters. The sampling points included traditional wells, boreholes, and different groundwater abstraction points used for agricultural and domestic purposes.

2.3. In Situ Physicochemical Measurements

Physicochemical parameters of groundwater were measured in situ using a portable multiparameter device (Hanna Instruments HI9829), previously calibrated before each measurement campaign [45].

The analyzed parameters included pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and water temperature.

Electrical conductivity is widely used as an indicator of groundwater mineralization and constitutes a key parameter for assessing salinization and seawater intrusion processes [46]. TDS and salinity values also provide essential information regarding dissolved salt concentrations and the degree of groundwater quality degradation [47].

The pH parameter provides valuable information on geochemical interactions between groundwater and geological formations, particularly dissolution and mineralization processes occurring within the aquifer [48].

2.4. Data Processing and Spatial Analysis

The geographic coordinates of the sampling points were recorded in the field using a portable GPS device with an accuracy of approximately ±3 m and subsequently integrated into a Geographic Information System (GIS) in order to generate thematic maps showing the spatial distribution of hydrochemical parameters.

Spatial interpolation techniques were applied to produce maps of electrical conductivity, TDS, salinity, and pH, allowing the identification of hydrochemical gradients and areas affected by mineralization anomalies. This approach enables the visualization of the spatial distribution of the investigated parameters and the identification of sectors potentially impacted by salinization processes [49].

The spatial analysis also facilitated the examination of the relationships between groundwater quality, coastal proximity, geological formations, and tectonic structures within the study area.

2.5. Methodological Approach

The methodology adopted in this study is based on an integrated approach combining: 1. field investigations, 2. in situ physicochemical measurements, 3. hydrochemical analysis, 4. GIS-based spatial processing and 5. hydrogeological interpretation of the results.

This methodological framework is widely applied in studies dealing with groundwater quality assessment and salinization processes in coastal aquifers [50,51]. It allows the identification of mineralization gradients, seawater intrusion vulnerable zones, and the influence of geological formations and tectonic structures on groundwater quality.

The combined analysis of electrical conductivity, TDS, salinity, and pH constitutes an effective tool for characterizing the hydrochemical status of the Ghiss–Nekkour aquifer and identifying the processes responsible for groundwater quality degradation.

The integration of spatial data within a Geographic Information System (GIS) enabled the production of thematic maps facilitating the visualization of hydrochemical anomalies and the interpretation of salinization mechanisms occurring within the study area.

This approach also aims to establish a solid scientific basis for improving the understanding of the hydrogeological functioning of the Ghiss–Nekkour aquifer and to contribute to sustainable groundwater management strategies in the context of Mediterranean coastal aquifers.

3 Results and discussions

3.1. Spatial Distribution of Electrical Conductivity (EC)

The spatial distribution of electrical conductivity (EC) in the Ghiss–Nekkour aquifer reveals significant spatial heterogeneity, reflecting important variations in groundwater mineralization (Cf. Fig. 2). EC values range from approximately 1,782 µS/cm to more than 9,283 µS/cm, indicating the coexistence of low to highly mineralized groundwater within the aquifer system. The lowest EC values are mainly observed in the southern and southwestern sectors, whereas the highest values are concentrated along the northern coastal fringe and particularly in the northeastern part of the aquifer near the Trougout area.

This spatial pattern suggests a progressive increase in groundwater salinity toward the Mediterranean coastline. Similar hydrochemical behavior has been widely documented in Mediterranean coastal aquifers affected by seawater intrusion processes [52]. The increase in EC values toward coastal sectors reflects the mixing between freshwater and saline marine water, which leads to higher concentrations of dissolved ions in groundwater.

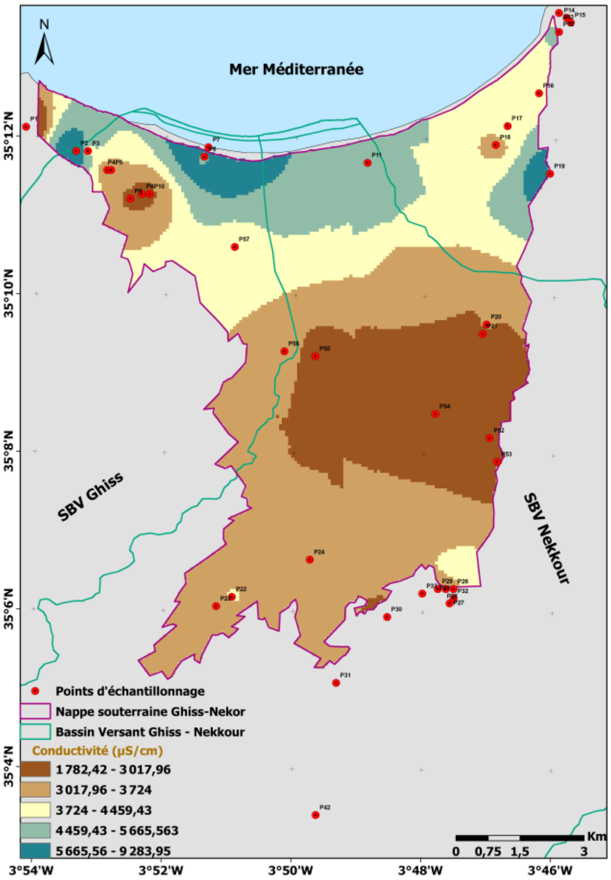

Fig. 2. Spatial distribution of electrical conductivity (EC, µS/cm) in the Ghiss-Nekor Aquifer.

The northeastern sector near Trougout constitutes the most mineralized zone of the aquifer. This anomaly may be related not only to marine intrusion but also to tectonic controls. The Trougout fault likely acts as a preferential pathway facilitating the inland migration of saline water through fractured geological formations. Previous hydrogeological studies conducted in the Ghiss–Nekkour aquifer demonstrated that structural discontinuities strongly influence groundwater circulation and salinization processes [44,53]. Bourjila [53] reported that nearly 20% of the aquifer is currently affected by seawater intrusion, especially within 2 km from the shoreline.

The central sector exhibits intermediate EC values, probably resulting from mixing processes between freshwater recharge and saline groundwater. Recharge from the Ghiss and Nekkour rivers, rainfall infiltration, and lateral groundwater flow from mountainous areas may contribute to groundwater dilution in these sectors [54]. Furthermore, lithological conditions may also influence groundwater mineralization through water–rock interaction processes and dissolution of soluble minerals.

The relatively low EC values recorded in southern sectors indicate better groundwater quality conditions and weaker marine influence. These areas likely correspond to preferential recharge zones connected to the Ghiss and Nekkour watersheds. Similar spatial distributions of EC were reported in Moroccan coastal aquifers such as Moulouya, Souss-Massa, and Bou-Areg, where groundwater mineralization increases progressively toward coastal discharge zones [50,55].

Overall, the EC distribution confirms that groundwater quality in the Ghiss–Nekkour aquifer is strongly controlled by seawater intrusion, geological structures, climatic conditions, and anthropogenic pressures.

3.2. Spatial Distribution of Total Dissolved Solids (TDS)

The spatial distribution of Total Dissolved Solids (TDS) closely follows the pattern observed for electrical conductivity, confirming the strong relationship between dissolved ion concentrations and groundwater mineralization. TDS concentrations vary from approximately 892 mg/L to more than 4,655 mg/L (Cf. Fig. 3). The highest values are mainly concentrated in the northern coastal sector and northeastern part of the aquifer, whereas lower concentrations dominate the southern and southwestern sectors.

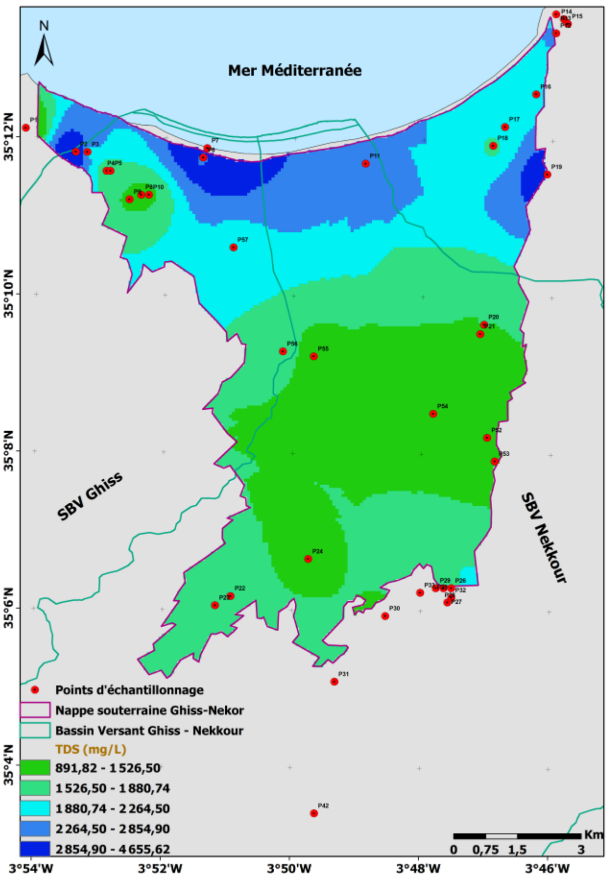

Fig. 3. Spatial distribution of total dissolved solids (TDS, mg/L) in the Ghiss-Nekor Aquifer.

The increase in TDS values toward the Mediterranean coastline clearly indicates saline enrichment of groundwater. According to hydrochemical classifications, groundwater with TDS concentrations exceeding 1,000 mg/L is generally considered mineralized, while concentrations above 3,000 mg/L reflect strong salinization processes [56]. Several groundwater samples collected in coastal sectors exceed these thresholds, confirming advanced groundwater quality degradation.

The spatial coincidence between high EC and high TDS values demonstrates that dissolved salts constitute the main factor controlling groundwater conductivity. Similar relationships between EC and TDS were reported in coastal aquifers worldwide [57]. Elevated TDS concentrations are commonly associated with seawater intrusion, evaporite dissolution, evaporation processes, and anthropogenic contamination [46].

In the Ghiss–Nekkour aquifer, salinity increase may additionally result from agricultural return flow, excessive irrigation, and infiltration of domestic wastewater. Agricultural intensification in the plain contributes to the accumulation of dissolved ions such as sodium, chloride, sulfate, and nitrate within groundwater [58]. Previous investigations also highlighted the role of groundwater overexploitation in promoting saline water intrusion and concentration of dissolved salts [44].

The southern sector exhibits comparatively lower TDS concentrations, indicating stronger freshwater recharge and lower marine influence. According to Mazzourh et al. [54], recharge areas within the Ghiss and Nekkour watershed are mainly located in upstream mountainous regions characterized by favorable infiltration conditions.

The TDS distribution therefore confirms that the Ghiss–Nekkour aquifer is subjected to progressive salinization processes driven by both natural and anthropogenic mechanisms.

3.3. Spatial Distribution of Salinity

The salinity map (Cf. Fig. 4) highlights strong spatial variability across the Ghiss–Nekkour aquifer. Salinity values range from approximately 0.95 g/L to more than 5.30 g/L. The highest salinity levels are concentrated mainly in the northeastern coastal sector near Trougout and locally in northwestern coastal areas, whereas lower salinity values dominate the southern and southwestern sectors.

This distribution strongly supports the influence of seawater intrusion as the principal mechanism responsible for groundwater salinization. Coastal aquifers are particularly vulnerable to marine intrusion due to hydraulic imbalance between freshwater and seawater caused by excessive groundwater abstraction and reduced recharge [59].

The northeastern sector appears to be the most vulnerable zone within the aquifer. The presence of the Trougout tectonic fault likely facilitates seawater migration inland by increasing aquifer permeability locally. Geological discontinuities and fractured formations often constitute preferential pathways for saline water intrusion in coastal aquifers [50,53].

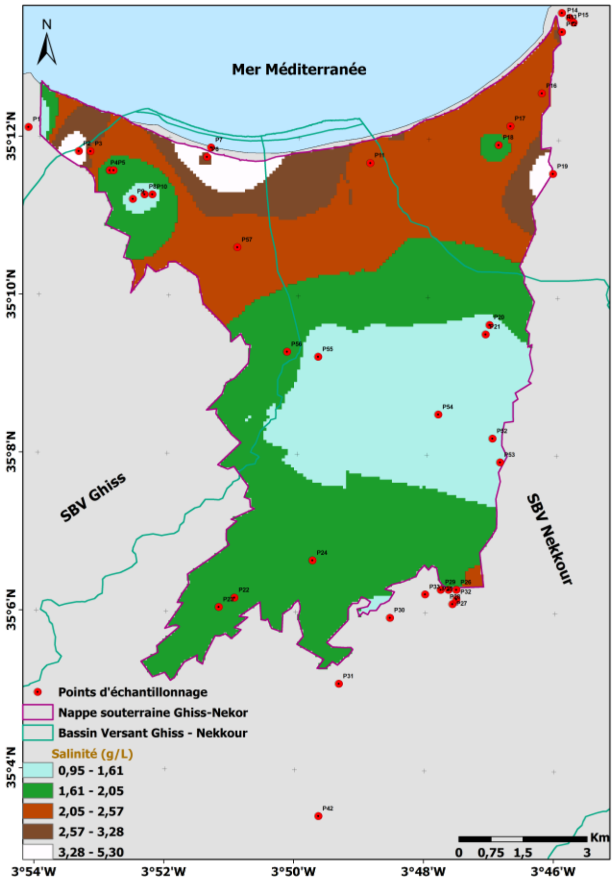

Fig. 4. Spatial distribution of salinity (g/L) in the Ghiss-Nekor Aquifer.

According to Bourjila [53], seawater intrusion in the Ghiss–Nekkour aquifer increased significantly between 2015 and 2022 due to prolonged drought periods and overexploitation of groundwater resources. Similar salinization dynamics have been reported in several Mediterranean aquifers exposed to climatic stress and intensive pumping [60].

In addition to marine intrusion, groundwater salinity may also be influenced by water–rock interactions involving dissolution of evaporitic and carbonate minerals. The geological formations surrounding the aquifer contain lithological units capable of releasing dissolved ions into groundwater [61].

Anthropogenic factors further aggravate groundwater salinity. Agricultural practices, irrigation return flow, fertilizer application, and urban wastewater infiltration contribute to increasing dissolved salt concentrations in groundwater [47]. The cumulative effects of climatic variability and human activities therefore accelerate groundwater quality degradation.

The southern sectors remain comparatively less affected due to stronger freshwater recharge and greater distance from marine influence. These areas may constitute strategic zones for groundwater protection and sustainable management.

Overall, the salinity distribution demonstrates that the Ghiss–Nekkour aquifer is undergoing active salinization controlled by marine intrusion, tectonic structures, lithological conditions, climatic stress, and anthropogenic pressure.

3.4. Spatial Distribution of pH

The pH values measured in groundwater samples as shown in the Fig. 5 indicate generally neutral to slightly alkaline conditions throughout the aquifer. The recorded pH values range from approximately 7.22 to 8.57, with most groundwater samples showing values between 7.4 and 7.8.

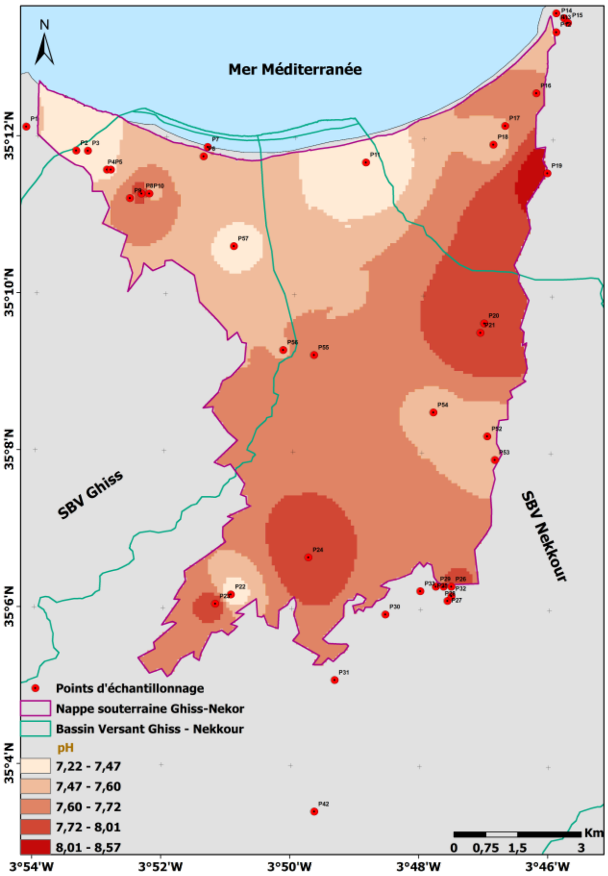

Fig. 5. Spatial distribution of pH values in the Ghiss-Nekor Aquifer.

These hydrochemical conditions are characteristic of groundwater circulating through carbonate-rich geological formations. The dissolution of carbonate minerals such as calcite and dolomite contributes to buffering groundwater acidity and maintaining relatively stable pH conditions [62].

The slightly alkaline character of groundwater reflects important water–rock interaction processes occurring within the aquifer system. Similar pH conditions have been reported in many Mediterranean coastal aquifers dominated by carbonate lithologies [63].

Higher pH values observed locally in northeastern coastal areas may indicate longer groundwater residence times, enhanced mineral dissolution, and saline water mixing processes. Hydrochemical investigations conducted in the Ghiss–Nekkour aquifer showed that groundwater chemistry is strongly controlled by rock weathering, evaporation, and marine intrusion mechanisms [44].

The relatively stable pH values suggest that groundwater salinization is mainly associated with dissolved salts and seawater mixing rather than acidic contamination. This hydrochemical stability is common in aquifers influenced by carbonate geology and semi-arid climatic conditions [64].

Moreover, alkaline groundwater conditions may influence ion mobility and geochemical equilibrium within the aquifer system. The pH distribution therefore confirms the combined influence of geological formations, hydrogeochemical reactions, and groundwater circulation dynamics.

3.5. Hydrochemical Processes and Groundwater Salinization Mechanisms

The combined interpretation of EC, TDS, salinity, and pH distributions reveals complex hydrochemical processes controlling groundwater quality within the Ghiss–Nekkour aquifer.

The spatial coincidence between high EC, TDS, and salinity values in coastal sectors confirms that seawater intrusion constitutes the dominant salinization mechanism affecting the aquifer. Coastal areas near Trougout are particularly vulnerable due to the combined effects of marine intrusion and tectonic controls.

Previous hydrochemical studies identified sodium-chloride facies dominance in coastal groundwater samples, indicating advanced seawater influence [44,53]. Hydrochemical facies evolution diagrams, ionic ratios, and seawater intrusion indices confirmed the progressive transformation of freshwater into mixed and saline groundwater types [53].

Groundwater overexploitation plays a major role in accelerating saline intrusion processes. Intensive pumping for domestic and agricultural purposes lowers groundwater levels and reduces the hydraulic pressure of freshwater against seawater intrusion [59]. Climate change and recurrent drought conditions further aggravate the situation by decreasing natural recharge rates [65].

Geological structures also significantly influence groundwater salinity dynamics. The Trougout fault enhances hydraulic connectivity between marine water and aquifer formations, facilitating inland migration of saline water [53]. Lithological heterogeneity additionally contributes to spatial variations in groundwater chemistry through dissolution and ion exchange processes.

Anthropogenic contamination further contributes to groundwater mineralization. Agricultural intensification, excessive fertilizer use, wastewater infiltration, and irrigation return flow increase dissolved ion concentrations within the aquifer [47].

Conversely, southern and southwestern sectors remain less affected by salinization due to stronger recharge conditions associated with upstream watershed infiltration. These zones therefore represent strategic areas requiring protection to ensure sustainable groundwater management.

Overall, groundwater salinization in the Ghiss–Nekkour aquifer results from the interaction of several natural and anthropogenic factors, including seawater intrusion, tectonic structures, groundwater overexploitation, climatic variability, water–rock interaction, agricultural activities, and urban pressure. These findings are fully consistent with previous hydrochemical and hydrogeological investigations conducted in the Ghiss–Nekkour coastal aquifer and other Mediterranean coastal environments.

4 Conclusion

This study provides a comprehensive hydrochemical assessment of groundwater quality within the Ghiss-Nekor Aquifer and highlights the growing vulnerability of this Mediterranean coastal aquifer to salinization processes. The spatial analysis of electrical conductivity, total dissolved solids, salinity, and pH revealed significant heterogeneity in groundwater mineralization across the aquifer system.

The results clearly demonstrate that the northeastern coastal sector, particularly near the Trougout area, is the most affected by groundwater salinization. Elevated EC, TDS, and salinity values confirm the progressive intrusion of seawater into the aquifer, facilitated by excessive groundwater abstraction, recurrent drought conditions, and tectonic discontinuities that enhance saline water migration inland. At the same time, geological formations rich in evaporitic and carbonate minerals contribute to groundwater mineralization through dissolution and water–rock interaction processes.

The study also highlights the influence of anthropogenic activities, especially agricultural intensification, irrigation return flows, and urban pressure, which further aggravate groundwater quality degradation. In contrast, the southern and southwestern sectors remain relatively less affected due to stronger recharge conditions and reduced marine influence, making these areas strategic zones for future groundwater protection and sustainable resource management.

Overall, the findings confirm that groundwater salinization in the Ghiss–Nekor aquifer results from the combined interaction of marine intrusion, geological controls, climatic stress, and human activities. The integrated methodological approach adopted in this work demonstrates the effectiveness of combining hydrochemical indicators with GIS-based spatial analysis for understanding salinization dynamics in coastal aquifers. These results provide an important scientific basis for the development of monitoring programs, groundwater protection measures, and sustainable water management policies adapted to Mediterranean semi-arid environments.

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