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Research Article

# Hydrogeochemical and Groundwater Quality Assessment of the Sarakhs Plain Using the Water Quality Index, Mineral Saturation Index, and GIS-Based Spatial Analysis

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## Abstract

This study evaluated the hydrogeochemical characteristics and drinking-water quality of the Sarakhs plain aquifer. Data from 292 wells were analyzed for physicochemical parameters (pH, EC, TDS, TH) and major ion concentrations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $CO_3^{2-}$, $HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$). Saturation indices were computed using PHREEQC, and a weighted-arithmetic water quality index (WQI) was applied to assess suitability. Results showed slightly alkaline conditions (pH: 6.4–8.6, mean 7.97). EC values ranged from 1020 to 37,500 µS $cm^{-1}$ (mean 3870 µS $cm^{-1}$), indicating high salinity. Sodium and chloride dominated the ionic composition, with the Piper diagram identifying mixed $Na^{+}$–$Cl^{-}$ and $Na^{+}$–$Mg^{2+}$–$Ca^{2+}$–$Cl^{-}$ facies. WQI analysis revealed that fewer than 12% of samples were good-to-excellent, while over 76% were poor-to-very poor. Spatial mapping showed better quality in the eastern plain near the Harirud River, highlighting its role in recharge and salinity dilution. Unlike previous studies that focused solely on quantitative aspects or individual water quality parameters, this study provides the comprehensive hydrogeochemical assessment of the Sarakhs plain aquifer integrating spatial analysis, saturation indices, and drinking water quality indexing across. Overall, groundwater quality in the Sarakhs plain is critically poor for drinking purposes, with serious constraints on its use. However, the Harirud River's recharge capacity offers a strategic opportunity for sustainable water management in the region. These findings underscore the urgent need for protective measures and informed resource planning.

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# 1- Introduction

Groundwater constitutes one of the most important sources of drinking, agricultural, and industrial water supply in arid and semi-arid regions and plays a fundamental role in the sustainable development of human communities [1,2,3]. In many parts of Iran, limited precipitation, intense evaporation, and the scarcity of surface-water resources have made reliance on aquifers as the principal water source unavoidable [4,5,6]. Nevertheless, the continuous and often unregulated exploitation of these resources, combined with the influence of natural and anthropogenic processes, has produced considerable changes in both the quantity and quality of groundwater, which can threaten ecosystem sustainability and water security [7,8].

The Sarakhs plain, located in northeastern Iran along the border with Turkmenistan, is one of the most important hydrological units of the Kashafrud basin. Owing to its distinctive geographical setting, diverse geological conditions, and the strong dependence of agricultural and industrial activities on groundwater, this plain occupies a special position in the water-resource management of Khorasan Razavi province [9,10]. The presence of evaporitic rocks, heterogeneous alluvial deposits, infiltration of agricultural return flows, and the possibility of water exchange with neighboring aquifers are among the factors that influence water quality in this region [11,12].

Hydrogeochemical investigation of aquifers, aimed at identifying the origin of major and minor ions, evaluating the dominant processes, and determining the effects of human activities, is one of the key tools for the optimal management of water resources [13,14]. Methods such as graphical-diagram analysis, water quality indices, and spatial analysis and zoning of the results obtained from hydrogeochemical studies allow for the precise interpretation of chemical data and the identification of processes such as mineral dissolution and precipitation, ion exchange, saline-water intrusion, and evaporation effects [15,16].

Recent international studies have demonstrated the effectiveness of integrated hydrogeochemical approaches for identifying groundwater salinization processes and controlling factors. In Iran, combined classical hydrochemical methods, multivariate statistical analyses, and geographical information system (GIS) were used to investigate groundwater quality in a coastal aquifer of northern Iran, finding that reverse cation–anion exchange dominated at approximately 76% of sampling sites [17]. In a methodologically advanced study, a multi-analytical framework combining deterministic and probabilistic water quality indices, geospatial analysis, fuzzy C-means clustering, and machine learning were combined to assess groundwater quality in southwest Iran [18]. In a study for the western Iran, both surface and groundwater resources were analyzed to reveal seasonal variations in water quality indicators [4]. Globally, in a research, ionic ratios, hydrochemical facies evolution diagrams, and saturation indices were employed to reveal that seawater intrusion, evaporation, and ion exchange are the primary processes governing groundwater salinity in coastal aquifers [19]. A research demonstrated the utility of GIS-integrated water quality indices for assessing groundwater suitability in arid regions of Algeria [1], while another one examined the combined effects of geology and agricultural activities on groundwater quality in Egypt [7]. In addition, a study further contributed to the field by employing a GIS-assisted hybrid approach combining multivariate statistics and inverse geochemical modeling to evaluate spatiotemporal groundwater quality changes [20]. These studies collectively highlight the value of integrated approaches for comprehensive groundwater quality assessment, yet their application to the Sarakhs plain remains unexplored.

Previous investigations in the Sarakhs Plain have primarily focused on the quantitative management of water resources, examining aspects such as the impact of dam construction and artificial recharge on groundwater levels [21,22]. Various technical reports have documented the declining groundwater levels and increasing salinity trends in the region over the past decades [23]. However, comprehensive hydrogeochemical studies have rarely been undertaken. A recent study provided a detailed hydrogeochemical assessment of the Sarakhs aquifer, analyzing 292 groundwater samples and revealing that electrical conductivity (EC) levels ranged from 1020 to 37500 $\mu S\ cm^{-1}$, rendering all samples unsuitable for drinking purposes [24]. The study identified that salinity is critically high in the western and central regions,

while the eastern parts benefit from fresher water due to natural dilution processes from the Harirud River [24]. Therefore, there is not a comprehensive investigation in which the role of geochemistry and geological formation exactly explains the water quality in the Sarakhs aquifer.

Accordingly, the objective of the present study is to investigate the hydrogeochemistry of the Sarakhs plain aquifer using groundwater quality data, to assess groundwater quality for drinking purposes, and to perform spatial analysis of the resulting data within a GIS environment to identify the spatial patterns of water-quality variation and clarify the processes governing its chemical composition. This study focuses on an integrated methodological framework, combining (1) comprehensive hydrogeochemical characterization using Piper diagram to identify dominant water types and hydrochemical facies, (2) application of water quality index along with saturation indices (SI) of different minerals to relate geological effects on water quality, and (3) GIS-based spatial interpolation and zoning to map GWQI distribution across the plain. This multi-tiered approach provides a more robust understanding of governing processes and their spatial distribution, building upon and extending the findings of recent international studies. The results can serve as a basis for decision-making in the sustainable management of groundwater resources and for reducing the adverse effects of over-exploitation and contamination.

### 1-1- Study area

This study was conducted in the Sarakhs plain, located in northeastern Iran, between longitudes 60°20′00″ and 61°35′25″ E and latitudes 35°59′00″ and 36°40′00″ N, covering a total area of 1930 km$^2$ (Figure 1). The regional climate is arid to semi-arid, with considerable variation in precipitation and temperature. The plain is predominantly flat as a result of fluvial sedimentation and is well suited to agriculture and settlement. Geologically, the Sarakhs plain forms part of the Kopet-Dagh sedimentary basin and consists mainly of Mesozoic and Cenozoic sedimentary rocks (Figure 1a) [9,10]. The geological formations include conglomerate, sandstone, claystone, shale, marl, limestone, and dolomite, deposited in marine and fluvial environments. The oldest units comprise the Kashafrud Formation (silty shale, sandstone) and the Mozduran Formation (limestone, dolomite, marl), both of Middle to Upper Jurassic age. The Cretaceous period, the longest geological era represented in the region, comprises nine major formations (Shurijeh, Tirgan, Sarcheshmeh, Sanganeh, Aitamir, Ab-e Deraz, Ab-e Talkh, Neyzar, and Kalat), each deposited in a different environment ranging from tidal flats to carbonate platforms and shallow-marine settings. During the Cenozoic (Tertiary), four lithological units were identified (Pestehligh, Chehelkaman, Khangiran, and Neogene red beds). The youngest deposits belong to the Quaternary and include aeolian (loess) sediments, saline marshes (sabkha), and fluvial-alluvial deposits. In terms of areal extent, Quaternary sediments cover 60%, loess 20%, saline marshes 6%, the Khangiran Formation 4%, Neogene red beds 3%, and the remaining formations approximately 1% each of the plain's surface [9,10,24].

The hydrological network of the plain is not self-contained and includes several rivers and watercourses (Figure 1c). The most important internal rivers are the Shurlogh and Chekowder, which flow from west to east. The Harirud River, the region's most important perennial river, enters the eastern part of the plain from Afghanistan and plays a major role in supplying surface water and recharging the groundwater system. The unconfined aquifer of the Sarakhs plain, covering an area of 710 km$^2$, is elongated in a north–south direction and is divided into northern and southern sections, the northern part being the larger [21,22]. Aquifer thickness decreases from 175 m in the east (near the Harirud River) to 20 m in the west. Its main lithological composition consists of gravel, sand, silt, and clay. Owing to its coarse-grained sediments and recharge from the Harirud River, the eastern part of the aquifer contains fresh water, whereas the western part, underlain by shallow Neogene bedrock and fine-grained sediments, contains brackish to saline water. The overall groundwater-flow direction is from south to north [10, 11, 12].

## 2- Materials and methods

Water-quality data for 292 wells drilled in the Sarakhs plain aquifer were obtained from the Khorasan Razavi Regional Water Company (Figure 1b). Groundwater sampling was conducted during 2022. The spatial distribution of sampling points is shown in Figure1b. The data comprise pH, total dissolved solids (TDS), EC, total hardness (TH), and the concentrations of calcium ($Ca^{2+}$),

magnesium ($Mg^{2+}$), sodium ($Na^{+}$), potassium ($K^{+}$), carbonate ($CO_3^{2-}$), bicarbonate ($HCO_3^{-}$), sulfate ($SO_4^{2-}$), and chloride ($Cl^{-}$). Prior to further calculations, the chemical balance of the water samples was verified using the ion-balance-error equation given below, in which ion concentrations are expressed in meq $L^{-1}$. A water sample is considered fully electroneutral and analyzed with acceptable accuracy when the value obtained from this equation falls within ±10%:

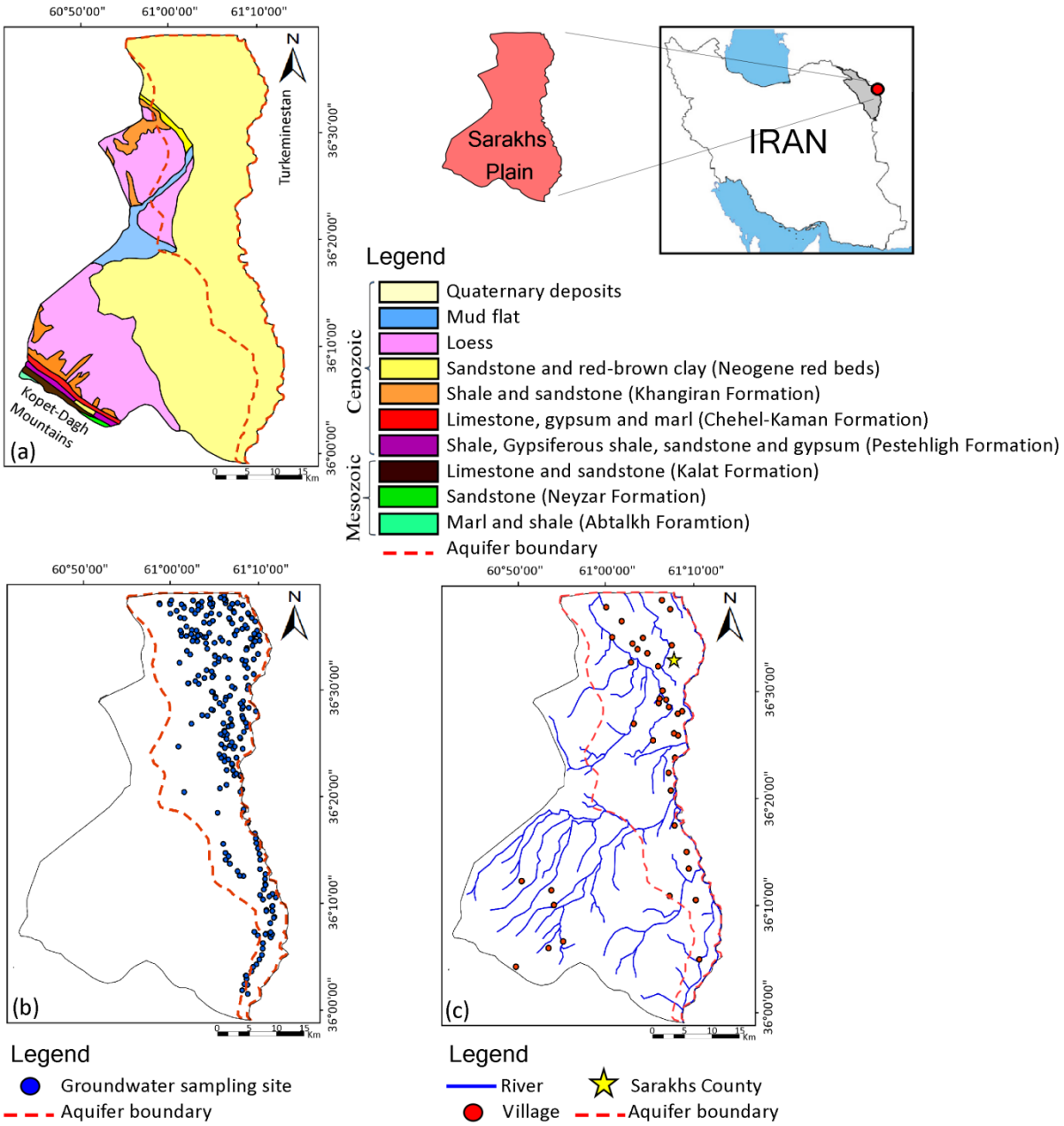



**Figure 1** (a) Geological map of the Sarakhs plain; (b) groundwater sampling points across the Sarakhs plain; (c) river network and surface-water bodies of the Sarakhs plain

$$E = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \times 100 \qquad \text{Eq. (1)}$$

The saturation index of a mineral in water indicates its degree of saturation. In general, three possible states can be considered for a given mineral in water: precipitation from solution, dissolution into solution, and equilibrium (simultaneous precipitation and dissolution). The saturation index is defined as the logarithmic ratio of the ion activity product of the mineral of interest ($I$) to its solubility-product constant at a given temperature ($Ksp$)

(Equation 2) [26,27]:

$$SI = \log \frac{I}{K_{sp}} \quad \text{Eq. (2)}$$

Depending on the numerical value of the saturation index for a given mineral, three conditions may arise:

(1) If SI > 0, the mineral is supersaturated in the water and is precipitating from solution.

(2) If SI = 0, the mineral is at equilibrium, i.e., simultaneously precipitating and dissolving.

(3) If SI < 0, the mineral is undersaturated in the water and is dissolving into solution.

In this study, the saturation indices of several minerals — gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), aragonite ($CaCO_3$), and halite (NaCl) — were computed using the hydrogeochemical software PHREEQC v.2.18.00.

To evaluate the suitability of the Sarakhs plain groundwater for drinking purposes, the weighted-arithmetic WQI method was employed [28,29]. This method simultaneously accounts for several physicochemical parameters and converts them into a single dimensionless index, enabling an overall assessment of water quality. First, for each parameter *i*, a quality rating (*qi*) was calculated as follows:

$$q_i = \frac{C_i - I_i}{S_i - I_i} \times 100 \quad \text{Eq. (3)}$$

$$q_i = \frac{C_i}{S_i} \times 100 \quad \text{Eq. (4)}$$

where *Ci* is the measured concentration of parameter *i*, *Si* is the permissible limit of parameter *i* according to the drinking-water standard, and *Ii* is the ideal value of parameter *i*, equal to 7 for pH and to zero for all other parameters. The unit weight of each parameter (*wi*) was then calculated as:

$$w_i = \frac{1}{S_i} \quad \text{Eq. (5)}$$

The normalized weight (*Wi*) of each parameter was subsequently obtained as:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad \text{Eq. (6)}$$

Finally, the water quality index was computed using the following relationship:

$$WQI = \sum_{i=1}^{n} W_i \times q_i \quad \text{Eq. (7)}$$

A WQI value below 50 indicates excellent quality, between 50 and 100 good quality, between 100 and 200 poor quality, between 200 and 300 very poor quality, and above 300 water unsuitable for drinking. Finally, zoning maps of the water-sample analysis results, the saturation indices, and the drinking-water quality index were produced using ArcMap 10.8.2 software.

# 3- Results and Discussion

## 3-1- Hydrogeochemical characteristics of the water samples

Analysis of the 292 groundwater samples from the Sarakhs plain aquifer showed that pH ranged from 6.4 to 8.6, with a mean of 7.97, reflecting the slightly alkaline nature of the water. EC, with a mean of 3870 μS $cm^{-1}$ and a range of 1020 to 37,500 μS $cm^{-1}$, indicates considerable variability in aquifer salinity. TDS ranged from 23.63 to 15,120 mg $L^{-1}$, with a mean of 2659.61 mg $L^{-1}$. TH, with a mean of 889.34 meq $L^{-1}$ as $CaCO_3$, falls within the very-hard classification. Examination of cation concentrations shows that magnesium (mean 11.57 meq $L^{-1}$) and calcium (mean 6.2 meq $L^{-1}$) contribute substantially to the ionic composition, while sodium, with a mean of 23.52 meq $L^{-1}$, accounts for the largest share among the cations, and potassium, with a mean of 1.07 meq $L^{-1}$, plays a comparatively minor role. Among the anions, chloride has the highest concentration (mean 20.34 meq $L^{-1}$), followed by sulfate (mean 18.67 meq $L^{-1}$) and bicarbonate (mean 4.71 meq $L^{-1}$), whereas carbonate, with a mean of 0.15 meq $L^{-1}$, contributes the least.

Ion-balance-error values ranged from 9.78% to −9.45%, with a mean of −0.21%, indicating high analytical accuracy and errors within the acceptable range (±10%). Based on the relative abundance of ions, the dominant cation sequence in the aquifer is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, and the dominant anion sequence is $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$.

To investigate the hydrogeochemical evolution process and to identify the dominant groundwater facies in the Sarakhs plain, the major cation and anion concentrations were plotted on a Piper trilinear diagram (Figure 2) [31].

**Table 1** Results of the analysis of the water samples examined in this study

| No. | Parameter | Maximum | Minimum | Mean | SD | Permissible limit [30] |
|---|---|---|---|---|---|---|
| 1 | pH | 8.6 | 6.4 | 7.97 | 0.34 | 7.5 |
| 2 | EC ($\mu S\ cm^{-1}$) | 37500 | 1020 | 3870 | 2630 | 1000 |
| 3 | TDS ($mg\ L^{-1}$) | 15120 | 23.63 | 2659.61 | 1754.28 | 500 |
| 4 | TH ($meq\ L^{-1}\ CaCO_3$) | 4100 | 170 | 889.34 | 538.15 | 300 |
| 5 | $Ca^{2+}$ ($meq\ L^{-1}$) | 45.2 | 0.9 | 6.20 | 5.17 | 5 |
| 6 | $Mg^{2+}$ ($meq\ L^{-1}$) | 40.5 | 0.6 | 11.57 | 6.17 | 4.1 |
| 7 | $Na^{+}$ ($meq\ L^{-1}$) | 88 | 1 | 23.52 | 13.29 | 8.7 |
| 8 | $K^{+}$ ($meq\ L^{-1}$) | 27 | 0 | 1.07 | 2.77 | 0.31 |
| 9 | $CO_3^{2-}$ ($meq\ L^{-1}$) | 1 | 0 | 0.15 | 0.28 | – |
| 10 | $HCO_3^{-}$ ($meq\ L^{-1}$) | 52.9 | 1.3 | 4.71 | 3.25 | – |
| 11 | $Cl^{-}$ ($meq\ L^{-1}$) | 190 | 2 | 20.34 | 20.61 | 7.05 |
| 12 | $SO_4^{2-}$ ($meq\ L^{-1}$) | 60 | 0 | 18.67 | 10.65 | 5.21 |
| 13 | E (%) | 9.78 | −9.45 | −0.21 | 1.03 | – |

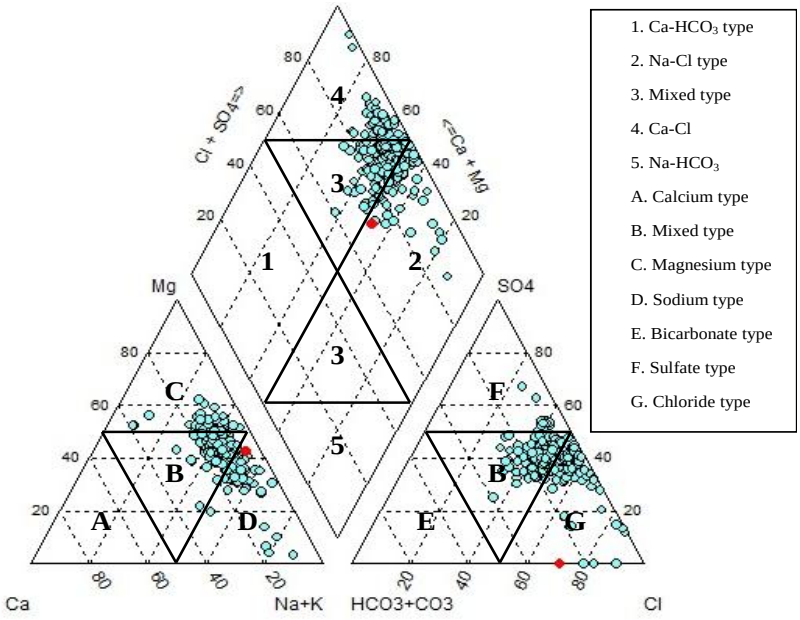



**Figure 2** Piper diagram of the water samples examined in this study

Analysis of the cation triangle shows that most of the collected samples plot within the Ca–Na–Mg field, indicating a mixed water composition, while the remaining samples are distributed mainly within the Na–Mg dominant field. In the anion triangle, most sampling points fall within field B, representing mixed SO–Cl–HCO waters. A portion of the samples fall within field G (chloride type) and a smaller number within field F (sulfate type). Examination of the central diamond field of the Piper diagram shows that the most prevalent hydrochemical facies is the mixed type (field 3), followed by the Na–Cl and Ca–Cl types, which are more frequent within fields 2 and 4, respectively.

## 3-2- Spatial distribution of the water-quality parameters

Based on the spatial-distribution maps of the main physicochemical properties of the groundwater (Figure 3), parameters such as pH and the carbonate and bicarbonate ions show no clear spatial pattern across the wells of the Sarakhs plain

aquifer. This suggests that variations in these parameters are more likely governed by local factors and intra-borehole chemical reactions (such as carbonate equilibrium and gas exchange with the atmosphere) than by regional or hydrodynamic controls. In contrast, parameters such as electrical conductivity, total dissolved solids, total hardness, and the concentrations of calcium, magnesium, sodium, and potassium cations and chloride and sulfate anions display a clear spatial trend, with the highest values observed in the western and central parts of the plain and the lowest values recorded mainly in the eastern part.

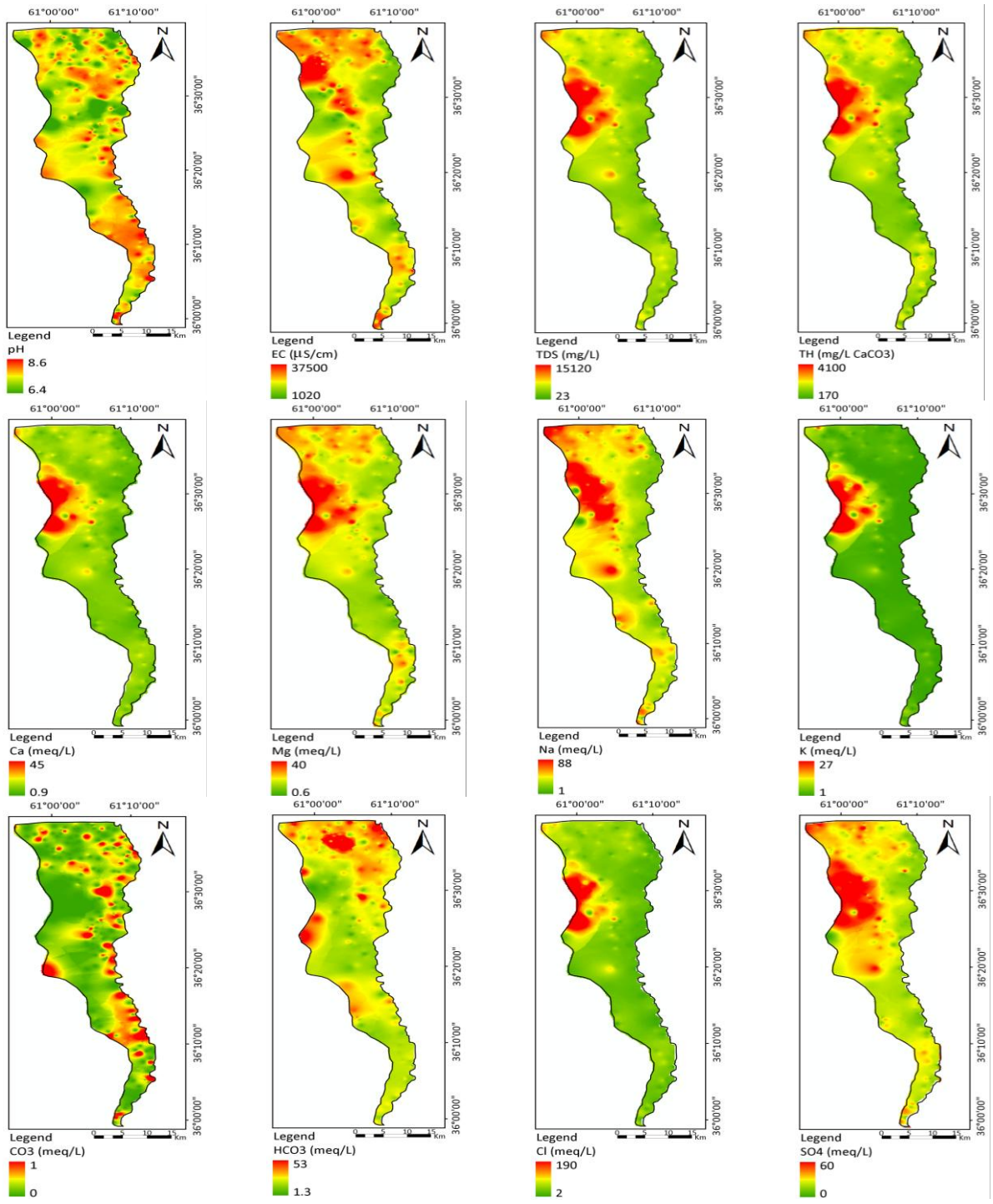



**Figure 3** Spatial distribution of the water-quality parameters of the groundwater in the Sarakhs plain aquifer

This pattern clearly reflects the roles of geological setting, groundwater flow, and differing recharge sources across the plain. One of the key factors controlling dissolved-solute concentrations in this region is the natural flow regime of the Harirud River. As one of the main sources of aquifer recharge, this river supplies fresh water to the eastern part of the plain while playing an effective role in reducing salinity and limiting saline-water intrusion. The river's flow pattern is such that the eastern part of the aquifer, owing to direct recharge from the Harirud River, exhibits higher water quality and lower salinity, whereas the western and central parts, being farther from the river, are more strongly influenced by saline geological conditions and by evaporation and seepage processes. The seasonal floods of the Harirud River not only recharge the aquifer but also dilute saline water and improve its chemical quality by raising the water table and infiltrating through the alluvial layers. In addition, the riparian vegetation strengthened by these floods removes part of the dissolved ions through natural filtration, further reducing solute concentrations.

Geologically, the western part of the plain consists mainly of fine clayey sands and coarse sands with high mineral content, containing considerable amounts of sodium, calcium, magnesium, chloride, and sulfate. This geological structure leads to extensive release of salts into the groundwater. In contrast, the eastern part consists mainly of loose alluvial deposits derived from the activity of the Harirud River and its tributaries (Quaternary deposits), which, owing to their higher permeability and more effective flushing, produce lower dissolved-solute concentrations in the aquifer. This lithological contrast results in a clear difference in groundwater quality, such that the western part of the plain, owing to the high leachability of salts from the formations, exhibits higher salinity and lower water quality, whereas the eastern part is characterized by lower salinity and higher water quality.

## 3-3- Spatial distribution of the mineral saturation indices

The saturation indices of the various minerals were calculated for each groundwater sample collected from the wells of the Sarakhs plain aquifer, and the results are presented in Figure 4. Based on these calculated indices, anhydrite, with maximum, minimum, and mean values of −0.35, −2.12, and −1.21, respectively, is undersaturated in all groundwater samples. Similarly, gypsum (with maximum, minimum, and mean saturation-index values of −0.14, −1.9, and −0.99) and halite (with maximum, minimum, and mean values of −3.97, −6.83, and −5.26) are also undersaturated, as indicated by their negative saturation-index values. The carbonate minerals (aragonite, calcite, and dolomite) show a different pattern, as their saturation indices display both positive and negative values. The aragonite saturation index, with a mean of 0.48, ranges from −0.5 to 1.73, while the calcite saturation index, with a mean of 0.62, ranges from a minimum of −0.48 to a maximum of 1.88. For dolomite, the saturation index has a mean of 1.67, ranging from a minimum of −0.24 to a maximum of 4.33. Thus, despite the presence of negative values in some samples, the overall status of the carbonate minerals can be regarded as supersaturated. Based on mean saturation-index values, the ascending order is: halite < anhydrite < gypsum < aragonite < calcite < dolomite.

As shown in Table 2, the dissolution of halite, anhydrite, and gypsum releases sodium, chloride, calcium, and sulfate ions into the water. In the Sarakhs plain, formations such as the Pestehligh, Chehelkaman, and Khangiran formations can act as natural sources of evaporitic minerals (halite, gypsum, and anhydrite) (Figure 1). Accordingly, the elevated concentrations of sodium, chloride, and sulfate ions (Table 1) can be attributed to water–rock interaction with the evaporitic minerals present in the region. Carbonate precipitation (Table 2) reduces the concentrations of calcium, magnesium, and bicarbonate ions in the water, which is why the concentrations of these ions in the groundwater samples are lower than those of sodium, sulfate, and chloride (Table 1). The Sarcheshmeh, Ab-e Talkh, and Ab-e Deraz formations belong to the carbonate formations, which have formed through the precipitation reactions presented in Table 2.

According to Figure 4, the spatial-distribution pattern of the saturation indices of the evaporitic minerals (anhydrite, gypsum, and halite) is similar, with maximum and minimum values observed in the western and eastern parts of the plain, respectively.

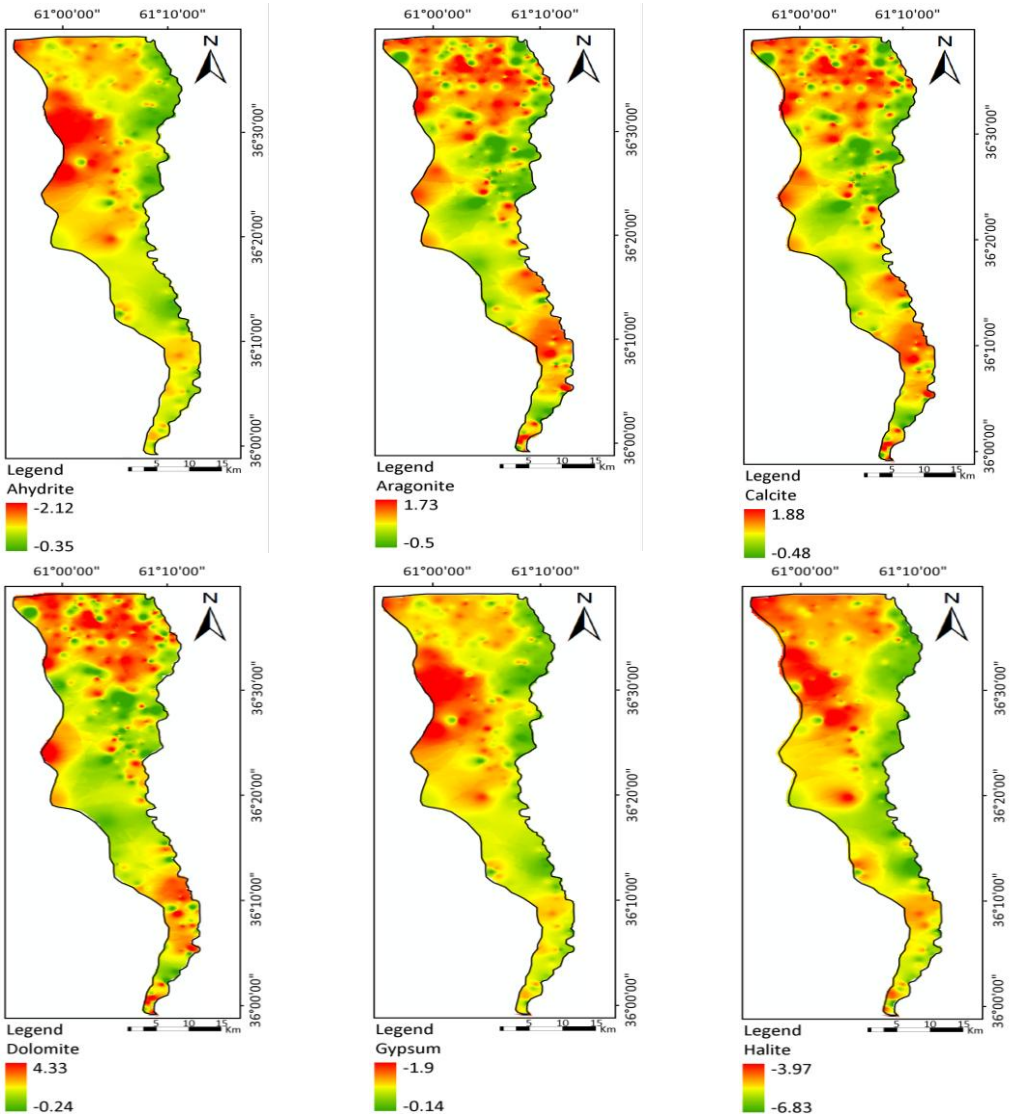



**Figure 4** Spatial distribution of the saturation indices of different minerals in the groundwater of the Sarakhs plain aquifer

**Table 2** Probable precipitation and dissolution reactions of the different minerals

| Reaction | Equation |
|---|---|
| Halite dissolution | $NaCl \rightarrow Na^{+} + Cl^{-}$ |
| Anhydrite dissolution | $CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-}$ |
| Gypsum dissolution | $CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O$ |
| Aragonite dissolution | $Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3 + CO_2 + H_2O$ |
| Calcite precipitation | $Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3 + CO_2 + H_2O$ |
| Dolomite precipitation | $Ca^{2+} + Mg^{2+} + 4HCO_3^{-} \rightarrow CaMg(CO_3)_2 + 2CO_2 + 2H_2O$ |

The carbonate minerals (aragonite, calcite, and dolomite) show their lowest saturation indices in the east and higher saturation indices in the northern, western, and southern parts relative to other areas. As with the spatial distribution of the physicochemical parameters (Figure 3), the role of the Harirud River in diluting dissolved solutes and reducing the saturation indices of the studied minerals is noteworthy. In addition, the lithological differences between the western and eastern parts of the Sarakhs plain, as described for the physicochemical parameters, also influence the mineral saturation indices.

### 3-4- Spatial distribution of the water quality index

Examination of the spatial-distribution map of the water quality index (Figure 5a) shows that groundwater quality in the Sarakhs plain is generally unfavorable. Large parts of the region, particularly the central and northern areas, fall within the poor, very poor, and unsuitable categories, reflecting the dominance of adverse geological and hydrogeochemical processes as well as the influence of human activities such as excessive groundwater withdrawal and the input of agricultural pollutants. In contrast, limited and scattered patches of better quality are observed in the southern areas and, more prominently, along the eastern margin of the plain.

The quantitative results obtained from the frequency-percentage chart of the quality categories (Figure 5b) likewise underscore the critical nature of the situation, with more than 42% of the groundwater falling into the very-poor category and about 34% into the poor category, while only 11% is of good quality and less than one percent is of excellent quality. This distribution clearly reflects the predominance of unsuitable water quality in this plain and the serious constraints on its use for drinking and even certain agricultural purposes.

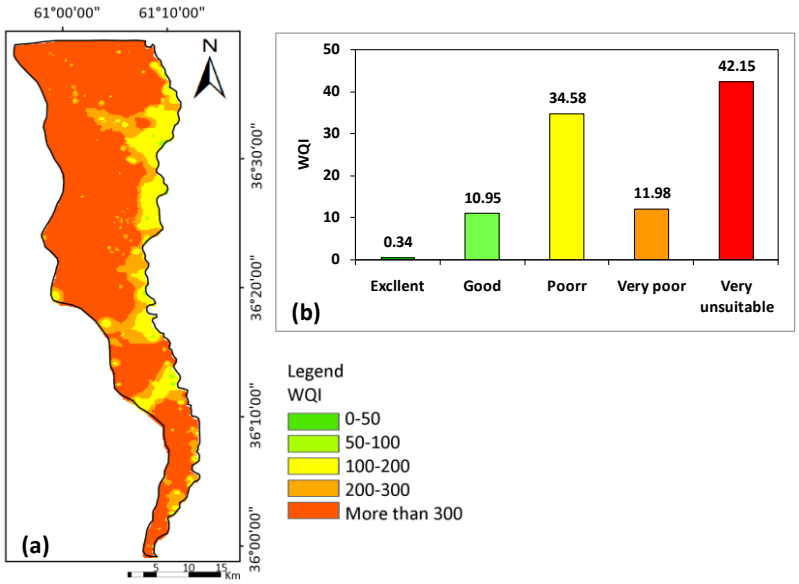



**Figure 5** (a) Spatial-distribution map of the water quality index; (b) percentage of water-quality categories among the groundwater samples of the Sarakhs plain

The beneficial role of the Harirud River in improving groundwater quality in the eastern parts of the plain is clearly evident. Comparison of the maps shows that the areas of better quality predominantly coincide with the course of this river. This indicates that aquifer recharge through the infiltration of Harirud River surface flows, which are relatively more favorable in chemical quality, has partially improved the hydrogeochemical conditions of the region and mitigated the adverse effects of salinity and high dissolved-solute concentrations.

## 4- Conclusions

The hydrogeochemical study of the Sarakhs plain showed that the quality of its groundwater is substantially affected by salinity, high concentrations of sodium and chloride ions, and elevated hardness. The dominant water types were the mixed $Na^+$–$Cl^-$ and $Na^+$–$Mg^{2+}$–$Ca^{2+}$–$Cl^-$ facies. The water quality index showed that more than 76% of the samples fall within the poor-to-very-poor categories for drinking-water use. These results indicate severe pressure on the groundwater resources of the plain and the need for their prudent management. Given the vital role of the Harirud River in aquifer recharge, it is recommended that groundwater abstraction be conducted within permissible limits and that well discharge rates be controlled to prevent further water-table decline and increasing salinity. In addition, the adoption of water-use optimization practices in agriculture, the use of desalination techniques in areas of high

salinity, and the establishment of continuous water-quality monitoring systems can contribute to the sustainable management of water resources. To mitigate the effects of contamination and salinity, appropriate drainage schemes, prevention of agricultural and industrial effluent discharge into the aquifer, and the adoption of low-water-consumption irrigation schemes in agricultural lands are recommended. Furthermore, enhancing artificial recharge and utilizing the capacity of the Harirud River as a supplementary source could improve groundwater quality over the long term.

Overall, this study demonstrates that, without the implementation of management and control measures, the Sarakhs plain will face an increasing risk of salinization and water-quality decline; however, with comprehensive planning and scientific water-resource management, sustainable exploitation and the fulfillment of drinking and agricultural water needs remain achievable.

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## Declaration of competing interest

*The authors declare that there is no conflict of interest to disclose regarding the submission of this paper to the journal. All authors have no financial or personal relationships that could potentially bias the content or findings of this research.*

## Authors contribution statement

*Maryam Tajbakhshian conceived of the presented idea and developed the methodology and performed the computations. Maryam Tajbakhshain and Abolfazl Mosaedi verified the analytical methods. All authors discussed the results and contributed to the final manuscript.*

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