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Research Article

Groundwater resources exploitation management in response to water scarcity challenges in Khuzestan Province, Iran

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Abstract: Water scarcity in Khuzestan Province, Iran, has attracted growing concerns despite the region's abundant water resources. The province predominantly relies on surface water, prompting an assessment of groundwater's potential to supplement water supplies during surface water shortages. This study assesses the province's groundwater availability and quality under increased exploitation conditions. Between 2008 and 2018, data on groundwater quantity and quality were collected from 204 exploration wells and 70 piezometric wells across 19 aquifers. The analysis revealed that 53% of aquifers in the eastern and northeastern regions experienced declining groundwater levels. Hydrochemical assessments indicated low concentrations of major ions in the northeastern, while high levels were observed from the central region towards the southeast. These variations were attributed to agricultural and industrial activities, seawater intrusion, and the influences of evaporation and geological factors. The dominant hydrochemical facies identified were of the Ca-Cl type. Water quality classification showed that 48% of groundwater samples fell within the C4S4-C4S1 category, primarily in the western, central, and southern regions, while 27% were classified as C3S2, C3S1, and 25% as C2S1, mainly in the northern and eastern regions. The Irrigation WWater Quality (IWQ) index indicated that many samples were suitable for irrigation. Additionally, the analysis potable groundwater was primarily found in the northern, northeastern, and eastern aquifers, with quality declining toward the south. The study highlights that certain aquifers in the northern and eastern regions offer greater potential for sustainable groundwater exploitation during water shortages. These findings provide valuable insights for on how to implement effective land and water management strategies to mitigate future water crises.

Keywords: Groundwater level; Groundwater quantity; Hydro-geochemistry; Irrigation water; Drinking water; Khuzestan province; GIS-based maps

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Introduction

Human activities and climate variability are placing increasing pressure on groundwater resources (World Water Quality Alliance, 2021), particularly in regions experiencing rising temperatures and population growth, such as in Khuzestan province (Suter et al. 2019; Yellapu and Bekkam, 2018). Surface water depletion due to rising temperatures has intensified competition for available resources (Famiglietti et al. 2011; Qin et al. 2019; Nazemi and Madani, 2018). In arid and semiarid regions, rapid agricultural and urban expansion has escalated demand for groundwater, while industrialization, population growth, overexploitation and regional droughts have led to declining groundwater levels and deteriorating water quality due to increased dissolved ion

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concentrations (Abbasnia et al. 2019; Chidambaram et al. 2022). Khuzestan Province (KHP), the largest province in southwestern Iran, is strategically significant due to its extensive water resources and economic contributions. Bordered by the Persian Gulf to the south and Iraq to the west, KHP serves as Iran's oil industry hub and is a pivotal trade gateway, playing a crucial role in the national economy (Sharifi, 2012). The province holds approximately 30% of Iran's total surface water and 3.0 billion cubic meters of groundwater storage, serving as the terminus of five second-order basins (Khuzestan Water and Power Authority, 2021). Additionally, Khuzestan is the primary agricultural center of Iran, with agriculture consuming approximately 90% of the province's total water usage, while industrial and domestic sectors account for the remaining 10%.

Despite being one of Iran's most water-rich region, Khuzestan faces severe water scarcity challenges. Mismanagement of water resources, including poorly planned dam construction and inefficient water allocation, has exacerbated the situation. The province's geographical proximity to the Gulf has further complicated water resource governance, particularly as freshwater resources are diverted for large-scale interbasin transfer projects, making water management a politically sensitive issues in Khuzestan. Climate change is another major contributor to water scarcity. According to the Iranian Meteorological Organization (2021), and the Standardized Precipitation Evapotranspiration Index (SPEI) (Mckee et al. 1993), it has been indicated that 98.7% of Khuzestan's area experienced drought between 2012–2021. Furthermore, the extensive cultivation of water-intensive crops like rice and sugarcane, which accounts for 8.5% of the province's agricultural water consumption, has further strained water supplies (IRAM, 2022). Other factors, including water contamination from industrial and oil-related activities, and rapid population growth, have led to reduced water availability resulting in economic, social, and environmental consequences.

High water demand in KHP, especially in the agricultural sector, continues to exert significant pressure on the province's water resources. National policies promoting self-sufficiency in strategic crops like wheat and rice have intensified agricultural water withdrawals, further exacerbated by inefficient irrigation systems, with an irrigation efficiency of just 46.9% (Abbasi et al. 2017). According to the Khuzestan Water and Power Authority (2021), surface water supplies approximately 79.8% of the province's water demand, while groundwater resources contribute 21.2%. However, river flow variability remains a critical challenge for water resource management in the province. The coefficient of variation in Khuzestan's annual river flow is 39%, significantly higher than the country's average of 29%, adding uncertainty in water availability. Moreover, these rivers originate from neighboring provinces, where declining rainfall has reduced total water flow and reservoir storage in major dams. Surface water quality has also been compromised by urbanization, industrialization, and agricultural expansion. Therefore, relying on average river flow as the basis for water supply planning presents a substantial risk, as these values may no longer provide a reliable foundation for future water resource management.

Consequently, decision-makers have determined that when surface water is insufficient to meet drinking and agricultural demands, groundwater can serve as a reliable resource to alleviate water scarcity. Considering all the aforementioned factors and given the relatively stable levels, groundwater resources in KHP may play a crucial role in compensating for the water shortage.

According to data from the Iran Water Resource Company, out of 43 aquifers in KHP, 23% exhibited rising groundwater levels, 50% experienced negligible declines, and 27% showed decreases ranging from 0.20 m/a to 0.80 m/a between 2003 and 2017. The relatively minor decline in groundwater levels has prompted provincial authorities to consider increasing groundwater exploitation to meet the province's growing water demands. These findings suggest that groundwater can play a key role in ensuring a stable water supply in KHP. However, this necessitates a comprehensive groundwater quality assessment for sustainable groundwater management.

Despite the importance of groundwater in the region, limited and scattered studies have evaluated the quality of groundwater only in some aquifers (Soltani et al. 2018; Ehya and Saeedi, 2019; Shakour et al. 2023). The study employs multiple methods to evaluate groundwater hydrogeochemical characteristics. Using AqQA software, a Piper diagram was generated to classify groundwater types and analyze hydrochemical processes. The Gibbs diagram, plotted with Origin software, identified major water chemistry mechanisms, while the Schoeller diagram assessed groundwater suitability for drinking. Agricultural suitability was assessed through parameters like electrical conductivity, sodium adsorption ratio, and permeability index, using standard reference diagrams. The Inverse Distance Weighting (IDW) method was applied to map the spatial distribution of groundwater quality for irrigation and domestic uses. Extensive studies have been conducted worldwide to evaluate groundwater quality using similar approaches (Valipour et al. 2014; Bhunia et al. 2018; Tarawneh et al. 2019; Abbasnia et al. 2019; Liang et al. 2019; Chidambaram et al. 2022; Hosseininia and Hassanzadeh, 2023; Techniques et al. 2023). Several studies have also applied GIS techniques, such as the IDW method, to analyze spatiotemporal variations in groundwater quality, providing valuable insight into future water resource quality trends (Alavi et al. 2016; Hosseininia and Hassanzadeh, 2023). The GIS-based mapping of key groundwater quality parameters plays a significant role in regional water management and informed decision-making (Mohammadi et al. 2017).

This study aims to comprehensively assess the quality of groundwater resources in KHP for domestic and agricultural use during periods of water scarcity. It uses reliable hydrogeochemical and GIS-based tools to analyze long-term trends. The research covers 19 aquifers in KHP, incorporating groundwater quantity data and water sampling from 204 groundwater wells over a ten-year period. The ultimate objective is to ensure that the resources meet quality standards for both domestic and agricultural uses.

1 Materials and methodology

1.1 Study area

Khuzestan Province (KHP) is the largest province in western Iran, covering an area of 6.42 million square kilometers, which constitutes approximately 4% of the country's total land area. The province is bordered by the Persian Gulf to the south and Iraq to the west and has a population of 4.71 million, with 33% residing in rural area (2016 census). Topographically, KHP is divided into two distinct regions: mountainous regions in the north and east, covering 35% of the province, and extensive plains which make up the remaining 65%. The province consists of 19 main plains (Fig. 1a).

The mountainous areas are part of the Zagros Mountains, mostly composed of limestone, sandstone, marl, conglomerate, and gypsum. The plains are characterized by low slope and the presence of salt domes from the Cambrian period. The prevail-

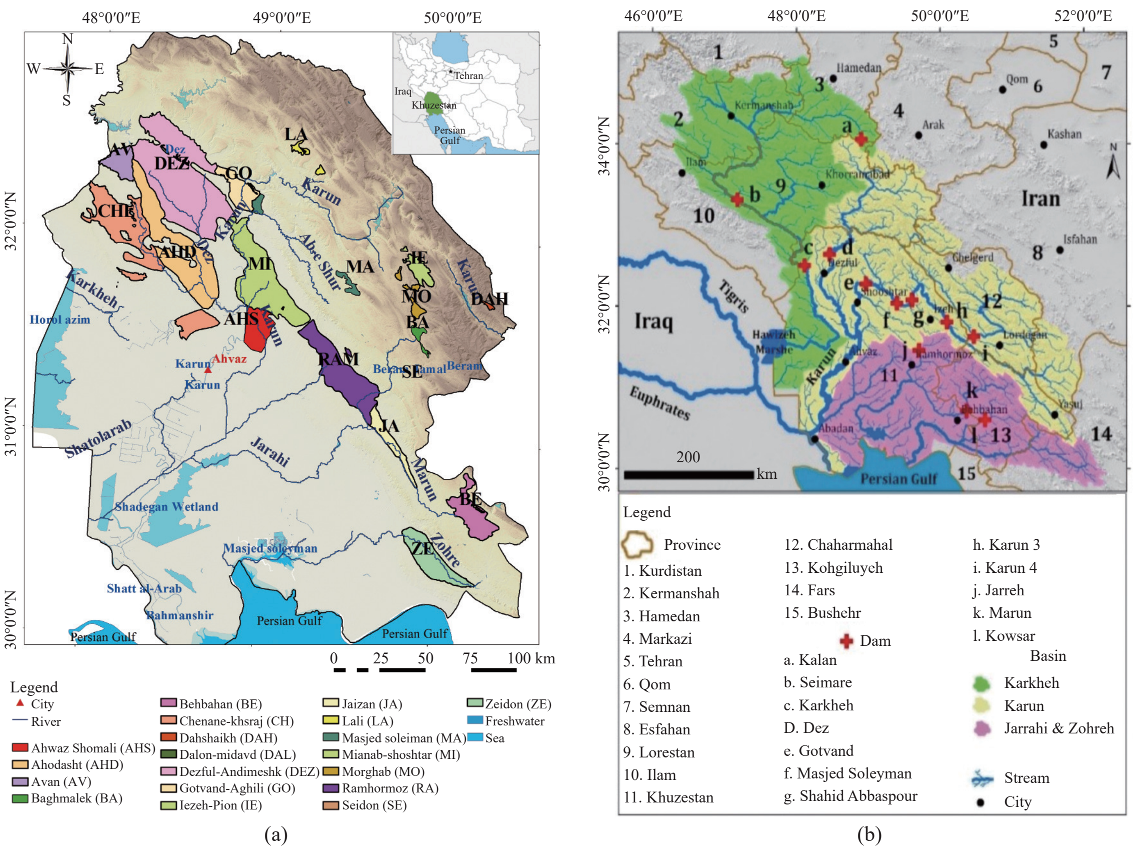

Fig. 1 a) The geographical location of the Khuzestan province (KHP) in southwestern Iran, Study area: Iran-Khuzestan province Khuzestan plains b) Basins, main rivers, and the location of dams in the study area

ing westerly winds originating from Mesopotamia and Saudi Arabia have caused the formation of dunes in the southern parts of the province. KHP has a predominantly arid and semi-arid climate, with an average annual rainfall of 284 mm and an average annual temperature of 25.3°C.

The KHP is Iran's key oil-producing region, accounting for 89% of the country's oil production, with all refining operations in Iran linked to this province. In addition, its strategic location as a cultural and economic gateway to Iraq make it an important hub for trade and commerce, contributing significantly to the country's export and import activities. KHP ranks second in the country's GDP, accounting for approximately (~14%) (Sharifi 2012). Agricultural is a dominant sector in KHP, making it the leading agricultural province in Iran. It ranks first in wheat production (1.5 million tons, approximately 12% of the country's total), first in corn (760,000 tons, about 40% of total country production), and third in rice production (2.7 million tons, around 11% of the country's total). The province consumes about 13% of the country's agricultural water and contributes about 14% of the country's agricultural output. Khuzestan is the terminal area of five second-order basins, receiving an annual surface flow of 26.74 Billion Cubic Meters (BCM) from upstream provinces (IRAM, 2022). The total volume of water flow is more than 32.49 BCM per year in KHP, representing a significant portion of Iran's total surface water resources (92 BCM/a) (Zekri, 2020). Additionally, KHP possesses 3.0 billion cubic meters of groundwater reserves, making it a privileged region in terms of water resources. Several major rivers flow through the province, including Karoun, Dez, Karkheh, Zohreh, Hendijan and Maroun, and Jarahi, with a combined annual of flow of 30.6 billion cubic meters. Water storage infrastructure in the province includes eight major reservoirs: Dez, Karkheh, Karun 1, Marun, Gotvand, Karun 3, Karun 4, and Jararhi. Additionally, KHP possesses several large dams, such as Dez, Shahid Abbaspour, Shohada, Karkheh, Khyrabad, Karun-3, Karun-4, and Masjed Soleyman (Khuzestan Water and Power Authority, 2021) (Fig. 1b).

Khuzestan's total annual water consumption is about 12,768 Million Cubic Meters (MCM). Of this, river flows and groundwater resources account for 79.8% (~10,188 MCM) and 21.2% (~2,058 MCM), respectively. The majority of the province's water is consumption occurs in the northern regions, where intensive agricultural activities dominate. As one of Iran's leading agricultural provinces, Khuzestan relies heavily on surface water supplies 93.5% of the agriculture sector's water demand, with the remaining 6.5% sourced from groundwater. Of the 10,188 MCM of surface water consumed in the province, 90.47% is allocated to agriculture, 5.26% to fisheries, 3.93% to domestic consumption, and 0.35% to industry and mining (Khuzestan Water and Power Authority, 2021). In most parts of the province, surface water remains the primary water source, while groundwater resources play a secondary role (Fig. 2) (Modernization studies of water comprehensive plan, Studies of the comprehensive plan of irrigation network under pressure in Khuzestan province). Groundwater usage is predominantly concentrated in agricultural sector, accounting for 74.79% of total groundwater consumption. Meanwhile, the industry and mining sectors use 13.68%, while 11.38% is allocated for domestic sector (Sharifi, 2012).

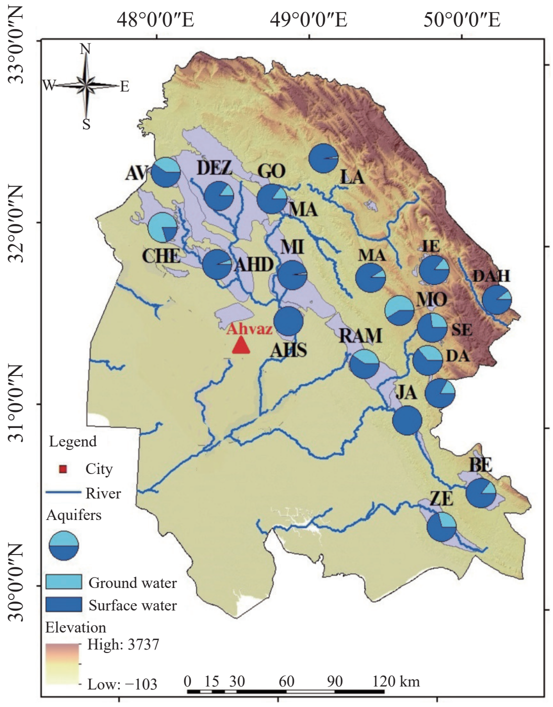

Fig. 2 The portion of surface and groundwater resources contribution in supplying the demands in the 19 plains of KHP

1.2 Data set

Groundwater quantity and quality data were obtained from Iran Water Resources Management Company, the Water Research Institute of the Ministry of Energy, and the Khuzestan province's regional water and sewage companies. The basin boundaries, as well as digital and base maps—including topographic, geological, and hydrographic maps—were prepared using GIS software. The study period spanned from 2008 to 2018, during which groundwater samples were collected from 204 pumping wells and 70 piezometric wells across 19 aquifers in Khuzestan. These samples were analyzed to assess groundwater suitability for drinking and agricultural purposes. The data processing and analysis were performed in Excel software. For groundwater quantity assessment, parameters such as reservoir storage coefficient and average change in groundwater level were examined to monitor fluctuations in groundwater wells. Data from piezometric, and observational wells were used to prepare drawdown maps and hydrographs delineating groundwater level fluctuations. Groundwater quality was evaluated in the study using multiple hydrochemical analysis methods. These included the Groundwater Quality Index (GQI) index and Wilcox, Piper, and Schoeller diagrams generated using AqQA software to classify water suitability for different uses. To map the distribution of groundwater quantity and quality, the Inverse Distance Weighting (IDW) method was utilized in ArcGIS 10.3. Additionally, the Gibbs diagram was used to identify the factors affecting groundwater chemistry. The conventional ionic components of collected groundwater samples included sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulphate (SO_4^{2-}), chloride (Cl^-), total dissolved solids (TDS), pH and, electrical conductivity (EC).

1.3 Analysis tools

The hydrogeochemical characteristics of groundwater were evaluated using the Piper diagram and the Piper groundwater quality indices, both generated using AqQA. The Piper diagram is one of the most effective graphic tools for analyzing groundwater hydrochemistry, as it helps classify groundwater types and identify the hydrochemical processes controlling groundwater composition (Piper, 1944; Yang et al. 2016). In this study, both the Piper diagram and Piper groundwater quality indices were used to classify groundwater types and analyze hydrochemical processes. The diamond-shaped field of the Piper diagram is divided into six distinct domains: I, II, III, IV, V, and VI, representing the following water types: $CaHCO_3$, NaCl, mixed $CaNaHCO_3$, mixed CaMgCl, CaCl, and $NaHCO_3$, respectively (Subramani et al. 2005; Sarath Prasanth et al. 2012). Freshwater generally falls within Domain I, whereas saline water, including seawater, is in Domain II. The mixing of freshwater and seawater is denoted by a horizontal transition across the diagram quantified using GQIPiper (mix) index, as expressed in Equation (1) in Table 1. The resulting index GQIPiper (mix) ranges from 0 (highly saline water, domain II) to 100 (highly fresh water, domain I). Additionally, the GQIPiper (dom) index, expressed in Eq (2), Table 1, provides further classification, ranging from 0 (CaCl water, domain V) to 100 ($NaHCO_3$ waters, domain VI). A Gibbs diagram was plotted using the Origin software.

The Gibbs diagram, generated using Origin software, was employed to identify the dominant mechanisms controlling groundwater chemistry (Gibbs, 1970; Tomaszkiewicz et al. 2014). This method has been widely used to examine the relationships between water chemical composition and geological/climatic influences (Ayisa et al. 2022). It represents TDS versus $Na^+/(Na^+ + Ca^{2+})$ and TDS versus $Cl^-/(Cl^- + HCO_3^-)$ to distinguish the

Table 1 Equation used to estimate groundwater quality indices

Index	Reference
$GQI_{piper(mix)} = \left[\frac{(Ca^{2+}+Mg^{2+})}{Totalcations} + \frac{(HCO_3^-)}{Totalanions}\right] \times 50$ (meq/l) (1)	(Subramani et al. 2005)
$GQI_{piper(dom)} = \left[\frac{(Na^{+}+K^{+})}{Totalcations} + \frac{(HCO_3^-)}{Totalanions}\right] \times 50$ (meq/l) (2)	
$SAR = \frac{Na^+}{\sqrt{Ca^{2+}+Mg^{2+}}}$ (3)	(Richards, 1954)
$KR = Na^+/(Ca^{2+}+Mg^{2+})$ (4)	(Kelly, 1957)
$Na\% = \left\{\frac{Na^+ + K^+}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}}\right\}$ (5)	(Willcox, 1955)
$MAR = (Mg^{2+} * 100)/(Ca^{2+}+Mg^{2+})$ (6)	(Paliwal,1972)
$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+}+Mg^{2+}+Na^+} * 100$ (7)	(Doneen, 1964)

primary hydrochemical processes: Evaporation, precipitation, and water-rock interaction.

The suitability of water for drinking purposes was determined by reference diagrams such as Schoeller (Schoeller, 1977). For agricultural suitability, various water quality parameters were assessed, including Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR) (Equation 3, Table 1), Kelly's Ratio (KR) in Equation (4), sodium percentage (Na%) in Equation (5), Magnesium Absorption Ratio (MAR) in Eq (6), and Permeability Index (PI) in Eq (7), and plotting the standard reference diagrams like US Salinity Laboratory (USSL) (1954) (Table 1). To visualize the spatial distribution of groundwater quality and quantity, the Inverse Distance Weighting (IDW) interpolation method in ArcGIS 10.3 was applied.

2 Result and discussion

2.1 Change of groundwater level in KHP's aquifers

The hydrograph in Fig. 3 represents ten years (2008–2018) of water level data collocated from piezometric wells across the study area. It shows the fluctuations in groundwater levels in Khuzestan province's aquifers, ranging from 5.33 meters above to 15.56 meters below the initial groundwater level.

During this period, approximately 53% of aquifers in the eastern and northeastern regions experienced groundwater level declines, while around 32% of aquifers in the central parts showed minimal decreases. Conversely, 15% of aquifers in the northern regions experienced an increase in groundwater levels (Fig. 4).

To analyze spatial groundwater changes, data from 70 piezometric wells were processed using GIS software to generate a groundwater drawdown map via the IDW method. The map shows that the most groundwater drawdown occurred in the northern part of Khuzestan province, particularly in Dezful and Andimeshk, groundwater level declined by up to 33 meters. Between 2008 and 2018, additional groundwater depletion was observed in aquifers located in the eastern and northeastern regions (such as Izeh and Baghmalek), as well as in the central and southern parts of the province. Overall, 48% of studied areas experienced groundwater level declines, while 52% of aquifers, primarily in the northwestern parts (including Avan, Ahodasht, and Chenanekhesraj), exhibited excess groundwater availability (Fig. 4).

2.2 Change of groundwater quality in KHP's aquifers

All groundwater sampled from the wells are alkaline, with a pH range of 6.8–8.3. Total dissolved solid (TDS) values varied between 190 mg/L and 7,800 mg/L, with an average of 1,548 mg/L. Calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) in the study area ranged between 1.87–33.98 mg/L, 0.05–39.31 mg/L, and 0.02–1 mg/L, respectively. Na, Cl, and HCO_3 concentrations varied between 0.18–64.1 mg/L, 0.35–53.35 mg/L and 0.64–10.1 mg/L, respectively. The presence of sodium in groundwater is largely influenced by saline intrusions, evaporites, and silicate minerals. However, sodium (Na^{+}), chloride (Cl^{-}), and bicarbonate (HCO_3^{-}) in the study area primarily originate from the weathering of the silicate hard rock. Sulfate (SO_4^{2-}) is the dominant anion, with an average concentration of 12.61 mg/L.

2.2.1 Hydrochemical features of the groundwater

The Piper trilinear diagram (Piper, 1944) is widely used to analyze groundwater chemistry by identifying relationships between dissolved constituents and to classifying hydrochemical facies. In the diamond-shaped central field of the Piper diagram,

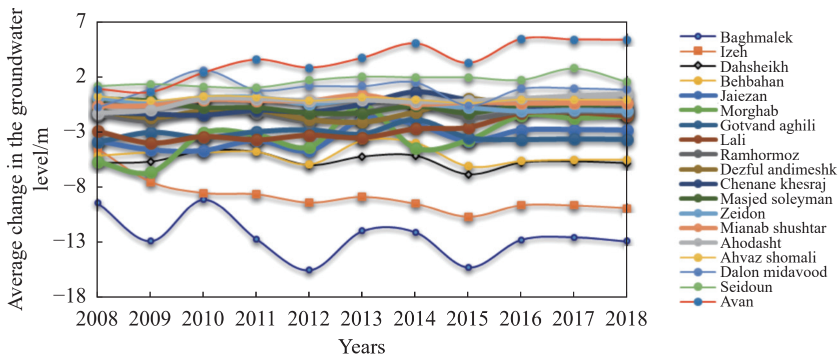

Fig. 3 The trend of variations in average groundwater level (m) (2008–2018)

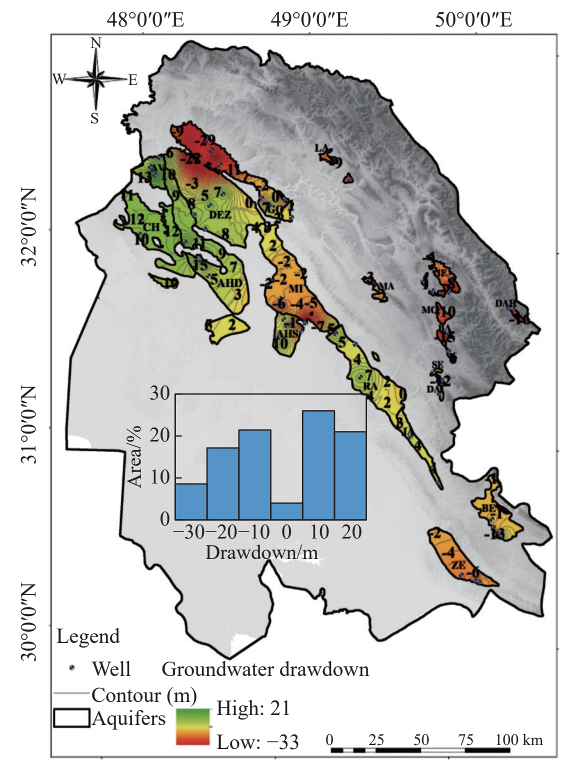

Fig. 4 Groundwater drawdown map in Khuzestan province with data of 2008–2018

groundwater samples collected over ten years are plotted in eight distinct fields (1, 2, 3, 4, 5, 6, 7, and 9). In field 1, approximately 95% of groundwater samples show higher alkaline earth metal concentrations (Ca^{2+} + Mg^{2+}) than alkaline metal cations (Na^{+} + K^{+}). Conversely, in field 2, about 5% of samples indicate higher levels of alkaline metal cations (Na^{+} + K^{+}) compared to alkaline earth metals (Ca^{2+} + Mg^{2+}). In field 3, approximately 38% of samples are dominated by weak acids (HCO_3^{-}) over strong acids (SO_4^{2-} + Cl^{-}). The remaining 62% of samples in field 4 exhibit dominance of strong acids over weak acids. In field 5, approximately 18% of the samples indicate that carbonate hardness (secondary alkalinity) exceeds 50%. In field 6, about 62% of the samples show that non-carbonate hardness (secondary salinity) exceeds 50%. Only 6% of the samples in field 7 indicate that non-carbonate alkalinity (primary salinity) exceeds 50%. About 14% of the samples in field 9 have an intermediate (mixed) chemical composition, where no cation-anion pair dominates.

In the cationic triangular field of the Piper diagram, approximately 30%, 40%, and 30% of the samples are plotted in the fields of magnesium, calcium, and sodium-potassium cationic types, respectively. In the anionic triangular fields, approximately 24%, 32%, and 44% of the samples are plotted in the fields of bicarbonate, chloride, and sulfate types, respectively.

In terms of hydrochemical facies, 33% of the samples, located in the center, west, and south of the province belong to the Ca-Cl facies. The remaining 25%, 14%, and 28%, situated in the east and the north, respectively, fall in Ca-Mg-HCO_3, Na-Cl, and mixed Ca-Mg-Cl facies (Table 2). The results suggest that 31% of the aquifers located in the highland regions (e.g. Izeh Pion, Baghmolek, Lali, and Marghab aquifers) predominantly exhibit bicarbonate-type water. These areas, being close to river headwaters, provide limited interaction between groundwater and geological formations. Conversely, aquifers in the lowland regions (lower reaches of basins) predominantly exhibit chloride and sulfate-type waters due to prolonged water-rock interaction during groundwater movement. The dominant facies of the groundwater in the study area are ranked as follows: Ca^{2+}, Na^{+}, and Mg^{2+}. These results provide insights into the geochemical evolution of groundwater and emphasize the influence of topography and geological formations on water chemistry (Fig. 5).

2.2.2 Processes influencing groundwater chemistry

In general, precipitation, evaporation, and rock weathering are the three major natural mechanisms affecting the water chemistry in the study area. To identify the dominant factors influencing groundwater hydrochemistry, a diagram was built to compare the concentration of TDS versus the weight ratios of Na^{+}/ (Na^{+} + Ca^{2+}) or TDS versus

Table 2 Ionic types and hydrochemical facies of groundwater samples collected during summer (n = 204) based on plots of hydrochemical data on Piper diagram

Groundwater chemical facies	Aquifer (No. and name)
Ca-Cl	12 Aquifers: Ahodasht, Ahwaz shomali, Avan, Behbahan, Jaiezan, Chenane khesraj, Daloon midavood, Ramhormoz, Seidon, Gotvand aghili, Mianab shishtar, Dahsheikh
Ca-Mg-HCO_3	5 Aquifers: Baghmalek, Dezful andimeshk, Lali, Iezih pion, Morghab
Na-Cl	2 Aquifers: Zeidon, Masjed soleiman

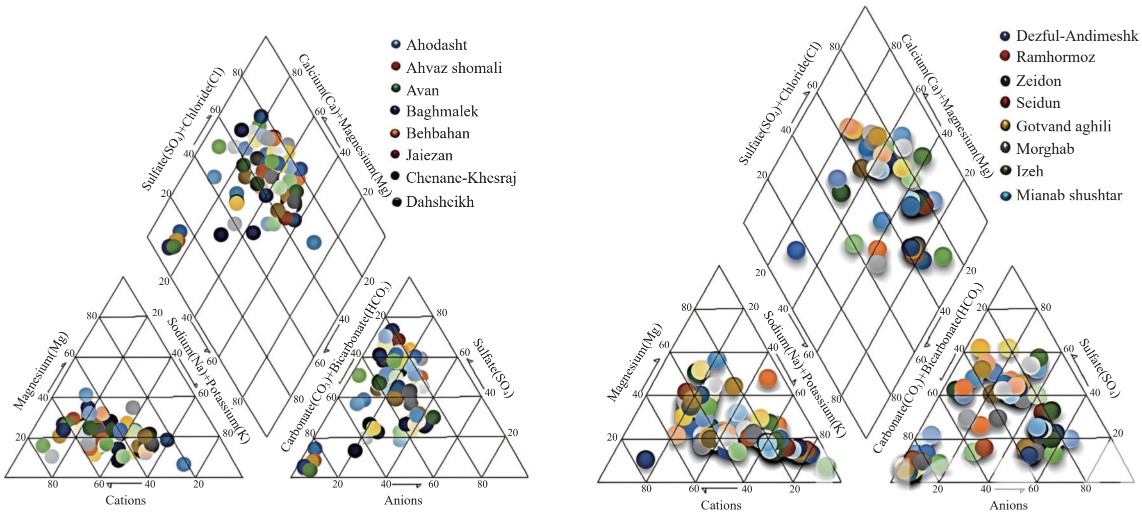

Fig. 5 Piper trilinear diagram showing the hydrochemical characteristics and hydrochemical facies of the groundwater based on the hydrochemical data of 204 groundwater samples

the weight ratios of Cl^-/ (Cl^-+ HCO_3^-) (Gibbs, 1970). Fig. 6 illustrates the influence of evaporation on groundwater chemistry, which is particularly evident in Khuzestan's arid and semi-arid conditions. The high levels of groundwater in some aquifers suggests that evaporation significantly affects the salinity of the groundwater in these regions. In addition, the diagram indicates that groundwater is also influenced by water-rock interactions. Half of the samples fall within the rock weathering interaction field, indicating that water-rock interactions are the prevailing natural mechanism influencing groundwater composition. The ratios of $Na^+/(Na^+ + Ca^{2+})$ varied from 0 to 0.98, with an average of 0.76, suggesting a strong cation exchange process in the groundwater system.

The effect of the evaporation process on the groundwater can be seen in Fig. 6. Samples positioned above the evaporation line show that evaporation is a key factor controlling the salinity of groundwater, though not the soler factor. The placement of samples above the 1:1 line suggests an excess sodium concentration in the groundwater. If the dominant anion of the groundwater is bicarbonate (Rogers, 1989), this excess sodium is

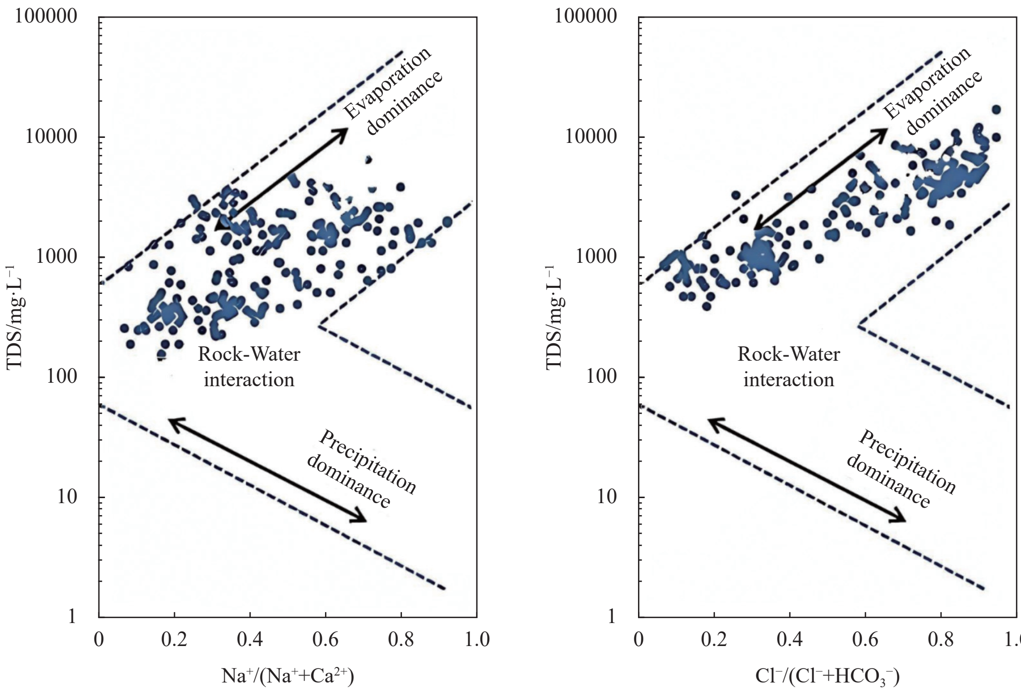

Fig. 6 Gibbs diagram for groundwater samples

mainly derived from the weathering of silicate rocks (Meybeck, 1987). The strong correlation between sodium and chloride ions (R^2=0.941) further indicates a shared origin for these two ions. The presence of some samples on the 1:1 line in the plot of sodium versus chloride confirms halite dissolution as another significant contributor to the high sodium and chloride concentrations in the groundwater. Therefore, in addition to evaporation, the weathering and dissolution of silicate and halite rocks also contribute to the concentration of sodium and chloride in the groundwater (Fig. 7).

Besides Gibbs diagram, an End-Member chart is employed to identify the rocks and minerals contributing to groundwater hydrochemical composition. By using the ratios of Mg^{2+}/Na^+ versus Ca^{2+}/Na^+ and HCO_3^-/Na^+ versus Ca^{2+}/Na^+, it is possible to assess the extent of water-rock interaction and its impact on groundwater geochemistry in the study area. Most of the samples are positioned between the fields representing silicates and carbonate (Fig. 7), suggesting that the dissolution of silicate and carbonates is the prevalent hydrogeochemical reactions in the groundwater system. Based on the chemistry of groundwater, the predominance of HCO_3^- and SO_4^{2-} over Ca^{2+} + Mg^{2+} points to silicate weathering, while the dominance of Ca^{2+} and Mg^{2+} suggests ion exchange processes (Elango and Kannan, 2007). In Khuzestan province, groundwater in the Baghmelek, Dezful andimeshk, Marghab, Izeh Pion, and Lali aquifers is primarily influenced by the weathering of silicate minerals. On the other hand, groundwater in Ahodasht, North Ahvaz, Avan, Behbahan, Chenane Khosraj, and Jaizan, Daloon, Midavood, Ramhormoz, Zidon, Sidon, and Mianab Shushtar reservoirs is more affected by the weathering of carbonate minerals. This indicates that silicate weathering is the main source of bicarbonate ions in some water bodies across Khuzestan province, as shown in Fig. 8.

The relationship between Ca^{2+}+Mg^{2+} and SO_4^{2-} + HCO_3^- is shown in Fig. 9. Nearly 90% of the sampling points have a (Ca^{2+}+Mg^{2+})/(SO_4^{2-} + HCO_3^-) ratio coefficient of less than 1, suggesting that groundwater needs to be kept in ionic balance through the dissolution of silicate minerals and evaporates. The remaining 10% of the sampling sites, with a (Ca^{2+}+Mg^{2+})/(SO_4^{2-}+HCO_3^-) ratio coefficient greater than 1, suggest that the Ca^{2+} and Mg^{2+} in groundwater mainly originated from the dissolution of carbonates (Fig. 9).

2.3 Assessment of water quality for domestic use

2.3.1 Piper diagram groundwater quality indices

The diamond field of the Piper diagram is divided into six distinct domains: I, II, III, IV, V, and VI, which correspond to $CaHCO_3$, NaCl, mixed $CaNaHCO_3$, mixed CaMgCl, CaCl, and $NaHCO_3$ type waters. These domains account for approximately 25%, 14%, 0%, 28% and 33% of the groundwater samples, respectively (Subramani et al. 2005). Domain I typically represents freshwater, while Domain II is associated with saline water, including seawater. The resulting index GQIpiper (mix) index ranges from 0, representing highly saline water (Domain II), to 100, representing highly fresh water (Domain I) (Equation 1). Table 3 further defines the other domains when the GQIpiper (mix) is used in conjunction with another index, GQIpiper (dom) (Equation 2). The GQIpiper (dom) index also ranges from 0, representing Ca-Cl water (Domain V), to 100, representing Na-

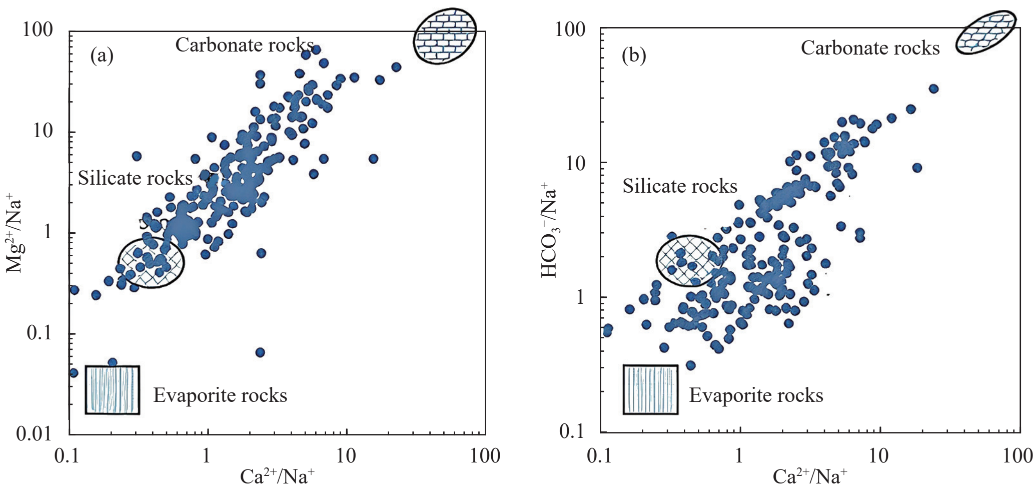

Fig. 7 End member diagram for groundwater samples

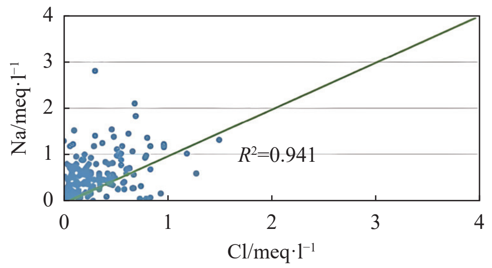

Fig. 8 Variation of Na/Cl diagram for groundwater samples

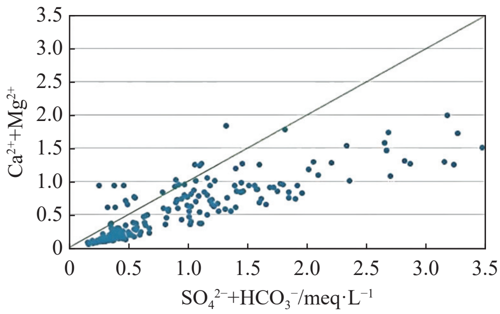

Fig. 9 Variation of $(Ca^{2+}+Mg^{2+})/(SO_4^{2-}+HCO_3^-)$ for groundwater samples

HCO_3 type waters (Domain VI). The ranges of GQIPiper (mix) and GQIPiper (dom) and their corresponding hydrogeochemical domains are presented in Table 3. To facilitate the classification of groundwater into these domains based on measured water quality data, an Excel-based algorithm was developed, which automatically assigns hydrogeochemical domains (Fig. 10).

2.3.2 Schoeller diagram

Schoeller diagram (Schoeller, 1977) is a widely used method for assessing the suitability of drinking water quality (Alavi et al. 2016; Almodaresi et al. 2019). This diagram classifies water based on the concentration of major cations (Ca^{2+}, Mg^{2+}, Na^{2+}), anions (Cl^-, HCO_3^-, SO_4^{2-}), Total Dissolved Solids (TDS), and Total Hardness (TH). According to this diagram, drinking water quality is classified into six categories: Good, acceptable, inappropriate, bad, temporarily drinkable in an emergency, and undrinkable. Fig. 11 shows that most water samples fall within the good acceptable, inappropriate, and bad zones. Water samples with good quality were located in the aquifers in the north, northeast, and east of the study area, with quality declining toward the south and southeast, as shown in Fig. 11. Among the 204 water samples analyzed, about 31%, 12%, 27%, 26%, and 4% were classified as good, acceptable, inappropriate, bad, and temporarily drinkable in emergency categories, respectively (Fig. 11).

2.4 Assessment of water quality for irrigation

The suitability of water for agricultural purposes has been investigated by various studies. The chemical water quality parameters and their changes have been analyzed using tools such as Schoeller, Wilcox, and Piper diagrams (Ayisa et al. 2022). Key parameters for evaluating the suitability of groundwater for irrigation include Electrical Conductivity (EC), Sodium Absorption ratio (SAR), sodium percentage (Na%), Magnesium Absorption Ratio (MAR), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Permeability Index (PI), and chloride (Cl^-) (Tiwari, 2011). Table 4 presents the classification of groundwater samples based on these parameters. Additionally, a graphical representation of the water sample suitability for irrigation was plotted using the US salinity and Wilcox diagrams.

2.4.1 Salinity hazard

Irrigation with saline water is identified as the primary factor reducing plant growth and crop production (Baghalian et al. 2008). EC is an important factor for assessing the salinity hazard and determining irrigation water suitability. The salinity of irrigation water was classified into five classes based on EC values, as shown in Table 4. Analyses of the water samples showed that 49 samples were in the good class, while 50 were

Table 3 GQI piper (mix) and GQI (Dom) to determine hydrogeochemical domains

Domain	$GQI_{piper(mix)}$	$GQI_{piper(dom)}$	Percentage of samples /%	Aquifers
I (Ca-HCO_3)	50–100	25–75	25%	Baghmalek, Dezful andimeshk, Morghab, Iezh pion, Lali
II (Na-Cl)	0–50	25–75	14%	Zeidon, Masjed soleyman
III (Ca-Na-HCO_3)	25–75	50–75	-	-
IV (Ca-Mg-Cl)	25–75	25–50	28%	Dezful andimeshk, Zeidon, Gotvand aghili, Baghmalek
V (Ca-Cl)	25–75	0–25	33%	Ahodasht, Ahvaz shomali, Avan, Behbahan, Jaiezan, Chenane khesraj, Daloon midavood, Ramhormoz, Seidon, Mianab shushtar
VI (Na-HCO_3)	25–75	75–100	-	-

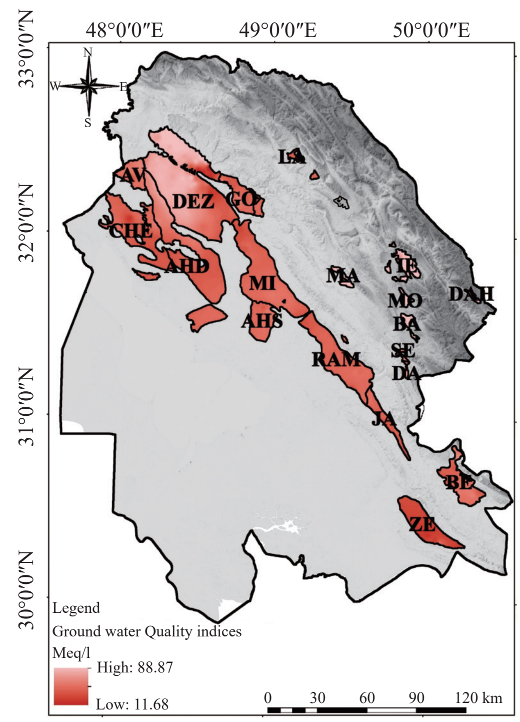

Fig. 10 Spatial distribution of groundwater quality indices (GQI) across the study's aquifers

classified as permissible and 35 samples as doubtful. Additionally, 34% (n = 70) of the groundwater samples were classified as unsuitable, covering some parts of the study area.

2.4.2 Sodium Absorption Ratio (SAR)

Table 4 defines the alkalinity hazard of irrigation water through the SAR parameter. Based on this classification, nearly all of groundwater samples fell into the excellent category for SAR, indicating that the water in the region is generally suitable for irrigation in terms of alkalinity hazard.

2.4.3 Sodium percentage (Na%)

High sodium content can destroy the soil structure, decreases soil permeability, and harms crop production. Therefore, it is as an essential parameter in assessing irrigation water quality (Singh et al. 2022). The sodium percentage (Na%) of collected samples was classified into five categories, according to the Willcox (1955) guidelines. Table 4 shows that most of the groundwater samples were in the good (42%) and excellent (38%) classes.

2.4.4 Magnesium adsorption ratio (MAR)

According to (Paliwal, 1972), MAR is classified

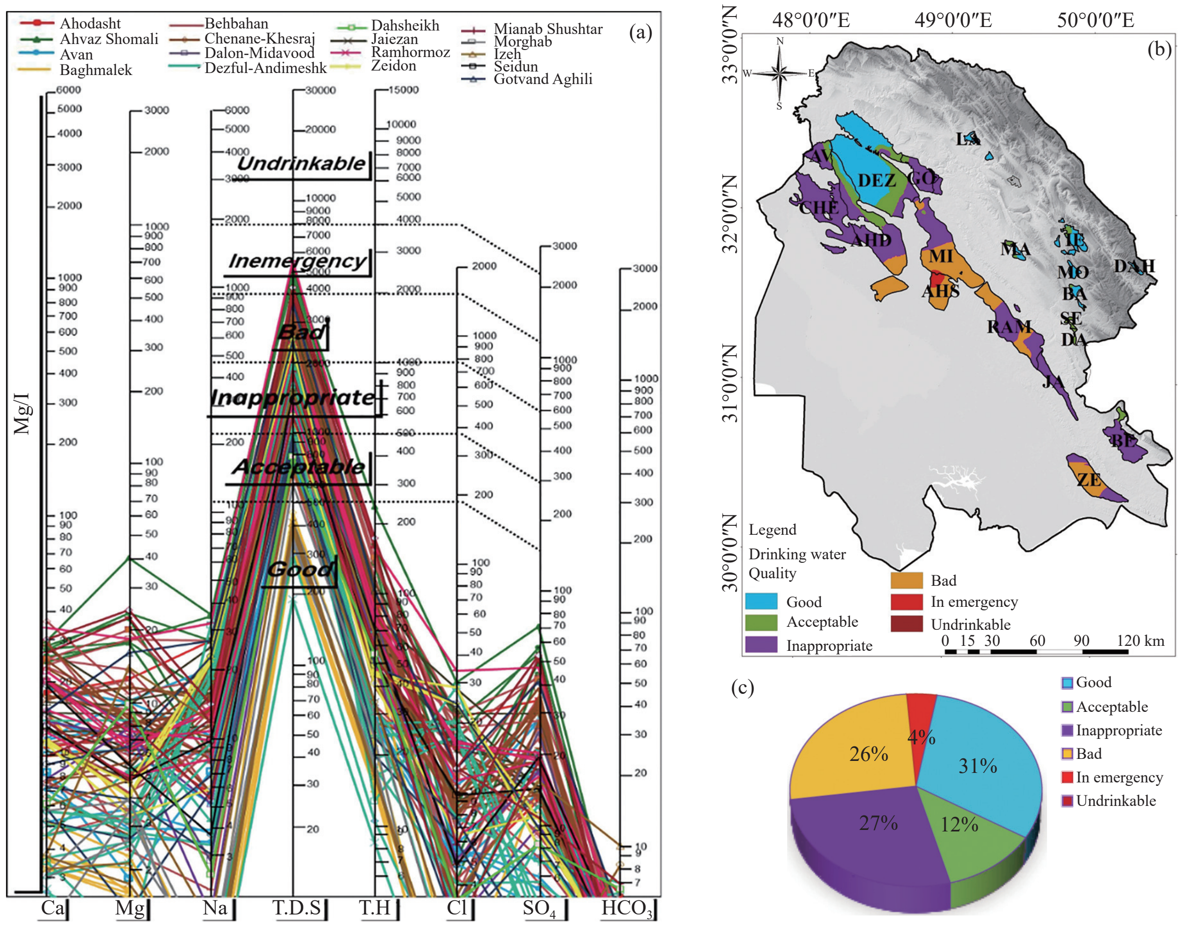

Fig. 11 (a) Schoeller diagram of 204 drinking water samples. (b) Spatial distribution of its categories; (c) Percentage of the sample in each category in the study area

Table 4 Classification of ground water samples based on irrigation water quality (IWQ) parameters

IWQ Parameters	Range	Class	Number of samples	Percentage /%
EC	<250	Excellent	0	0
	250–750	Good	49	24
	750–2000	Permissible	50	25
	2000–3000	Doubtful	35	17
	>3000	Unsuitable	70	34
SAR	<10	Excellent	204	100
	10–18	Good	0	0
	18–26	Permissible	0	0
	>26	Doubtful	0	0
Na%	<20	Excellent	78	38
	20–40	Good	82	42
	40–60	Permissible	33	15
	60–80	Doubtful	9	5
	>80	Unsuitable	2	0
MAR	>50%	Suitable	70	34
	<50%	Unsuitable	134	66
KR	<1	Suitable	182	89
	>1	Unsuitable	22	11
PI	>75%	Good	135	66
	25–75	Suitable	55	27
	<25%	Unsuitable	14	7
Na^+	<3	None	204	100
	3–9	Moderate	0	0
	>9	Severe	0	0
Cl^- (mg/L)	<140	None	204	100
	140–350	Moderate	0	0
	>350	Severe	0	0

into two classes: MAR>50% is suitable, and MAR<50% is unsuitable for agriculture purposes. Based on this classification, 34% (n = 70) of the samples are suitable and safe for irrigation, while 66% (n=135) are unsuitable, as shown in Table 4.

2.4.5 Kelly's Ratio (KR)

Kelly (1957) introduced a parameter known as Kelly's Ratio (KR), where a KR value < 1 indicates suitable irrigation water, while values greater than 1 are considered unsuitable. Among the 203 water samples in the study area, about 90% were deemed suitable for irrigation usage.

2.4.6 Permeability Index (PI)

The long-term effect of irrigation water with high levels of Na^+ and HCO_3^- on soil permeability was evaluated by Doneen (1964). In the study area, PI ranges from 13 to 373, with a mean value of 112. Table 4 shows that 66% and 27% of the samples are classified into the good and suitable categories for irrigation, respectively.

2.4.7 Sodium and chloride

Since sodium affects soil physical properties and plant survival, sodium hazard and chloride toxicity assessment are presented in Table 4. The groundwater values in the study area are generally suitable for irrigation purposes, with no significant risks related to sodium or chloride toxicity.

2.4.8 US salinity diagram

The US salinity diagram (USSL) is another hydrochemistry tool used to evaluate water suitability for irrigation purposes based on EC and SAR values (US Salinity Laboratory, USSL, 1954). According to the diagram, groundwater quality is classified into sixteen classes (Fig. 12).

Most of the water samples in the study area exhibit high EC and SAR values. According to Fig. 12, 14% of the groundwater samples fall into C4S1 type, indicating very high salinity and low sodium hazard, which is detrimental to agriculture. These samples are predominantly found in the

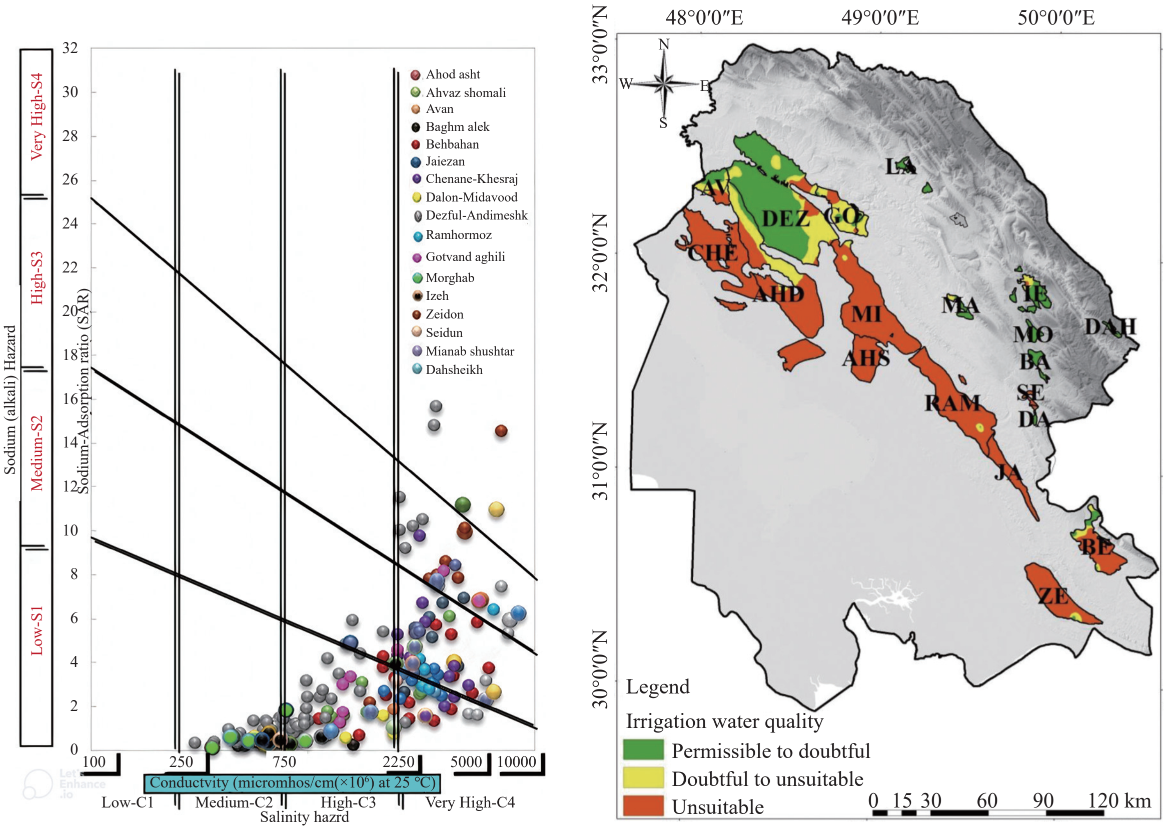

Fig. 12 Categorization of groundwater based on US salinity diagram for 204 water samples

west, center, and south of the study area. Additionally, 25% of the samples are classified as C3S1, which is suitable for agriculture and found in the north Another 25% are classified as C2S1, which indicates brackish water moderately suitable for agriculture, showing with medium salinity and low sodium hazards. This is primarily observed in the east of the province. The remaining samples are classified as C4S2 (20%), C4S3 (11%), C4S4 (3%), and C3S2 (2%).

2.5 Management plan for multi-purpose groundwater utilization

A management plan for the multi-purpose groundwater utilization is developed by integrating the mapping results of the regions with safe groundwater quality. Fig. 13 presents a map illustrating potential zones for multi-purpose groundwater utilization based on groundwater quality. This map is then compared with current land use data to evaluate the appropriateness of current land use practices. The land use information was obtained from Iran Water Resources Management Company, the Water Research Institute of the Ministry of Energy, and regional water and sewage companies of Khuzestan province. Based on groundwater quality classification for drinking and agriculture, and utilizing Arc GIS software for spatial and geographic analyses, areas with high potential for agricultural and drinking water uses

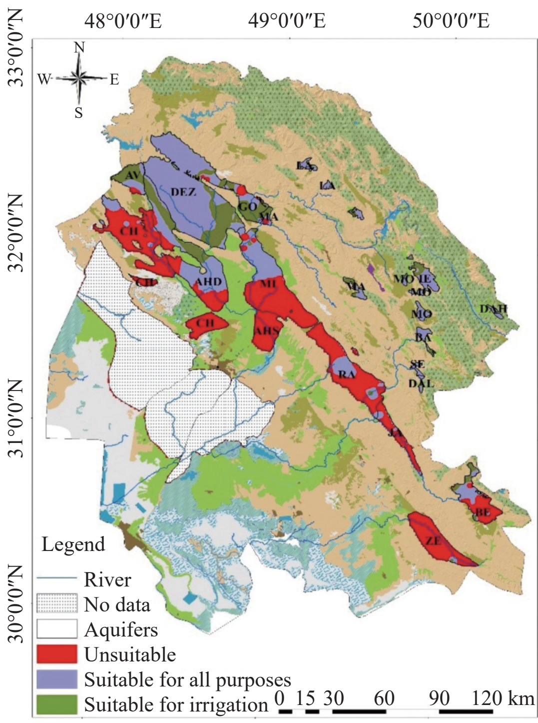

Fig. 13 Zonal management plan based on groundwater quality for various purposes

were identified from groundwater quality analyses in Khuzestan province. The groundwater sources in Khuzestan's aquifers are classified into three categories: unsuitable, suitable for all purposes and suitable for irrigation. Overall, 65% of the groundwater samples from the northern, northeast, and eastern parts of the province are of suitable quality for both agricultural and drinking purposes. Approximately 27% of groundwater has a high salinity and is of poor (bad) quality for both agriculture and drinking. The unsuitable regions are primarily located in the central and southern parts of the area. About 8% of the groundwater samples are classified as suitable solely for agricultural use.

This management plan can serve as a guide for governmental authorities in Khuzestan province to protect and manage groundwater resources for multiple purposes. In areas with unsafe groundwater quality, the priority is to identify the source of contamination and implement control measures. These measures may include implementing laws and regulations to control pollution, as well as raising public awareness and and encouraging reductions in anthropogenic activities that contribute to groundwater contamination.

Effective land use planning is crucial to controlling contamination. Ongoing, intensive monitoring of groundwater in vulnerable areas is necessary to pinpoint contamination sources and implement management strategies. The government should also work on developing safe water resources in areas where groundwater is unsafe. Regulations should be enforced to limit the exploitation of groundwater in areas with poor water quality. Land use practices need to be revised in areas where groundwater quality is unsuitable for irrigation or aquaculture. Currently, 38% of exploitation wells unsuitable for irrigation, and 15% of those suitable for agriculture, are located in the central and southern parts of the study area. Only 15% of exploitation wells meet standard quality requirements for irrigation. Research shows that 27% of exploitation wells with good and acceptable drinking water quality are used for drinking purposes, while only 5% of exploitation wells with poor quality are used for drinking (Fig. 14).

3 Conclusions and suggestions

The groundwater quality of Khuzestan province, Iran, was assessed using various analytical approaches, including the Piper diagram for hydrochemical analysis, the Schoeller diagram for domestic and Irrigation Water Quality (IWQ) parameters, and the US salinity diagram for irrigation purposes. The main findings were categorized

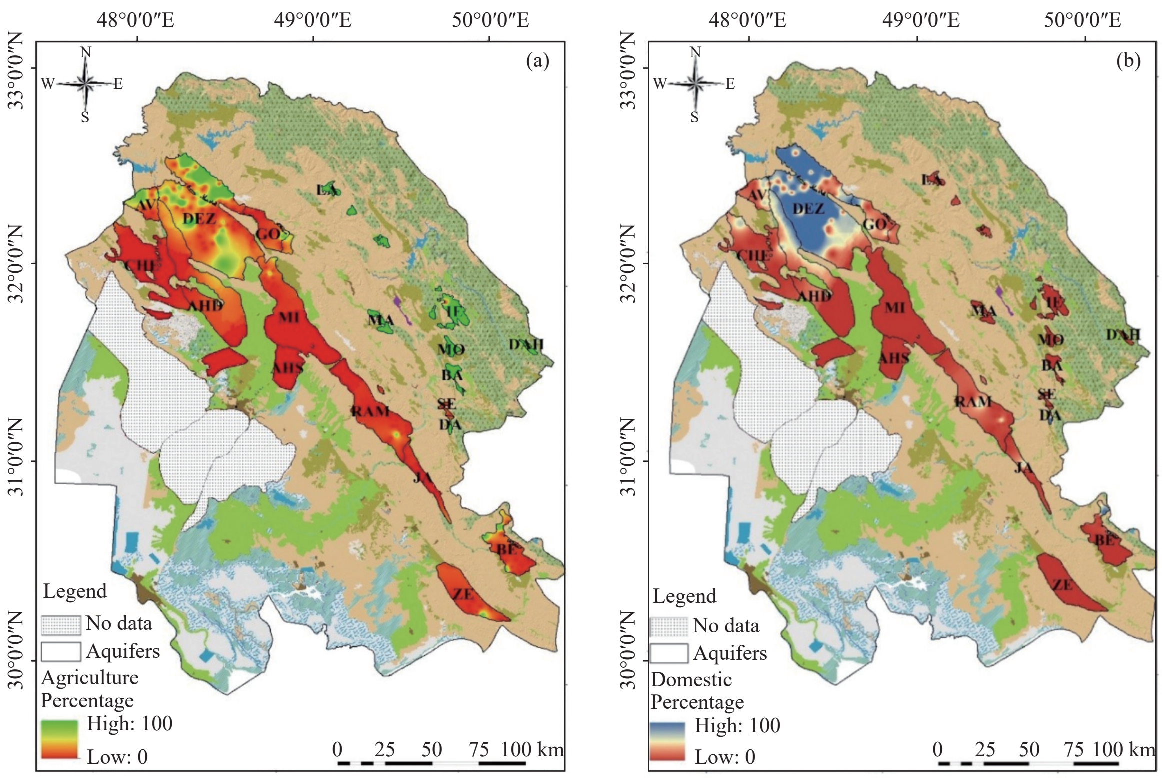

Fig. 14 Spatial distribution of the compliance percentage of groundwater pumping wells: (a) used for irrigation of cropland and (b) used for drinking water supply in relation to the corresponding water quality standards

below:

(1) The hydrograph shows groundwater level changes in Khuzestan province from 2008 to 2018, revealing a 53% decrease in the eastern and northeastern aquifers, a 32% decrease in central areas, and a 15% increase in the northern aquifers.

(2) Analysis of 70 piezometric wells revealed the largest drawdown in northern Khuzestan, with 48% of the areas experiencing declines, while 52% in the northwest had excess water. The groundwater types include CaCl (33%), $CaHCO_3$ (25%), NaCl (14%), and CaMgCl (28%), with Ca^{2+} and Mg^{2+} being the dominant cations.

(3) Gibbs and ion relationship analysis highlighted evaporation and water-rock interaction as key factors influencing groundwater composition, mainly through carbonate and silicate rocks' dissolution.

(4) The Schoeller diagram showed varying water quality, with good quality found mainly in northern and northeastern aquifers, and declining towards the south.

(5) Irrigation Water Quality (IWQ) assessments indicated that 34% of the samples had an EC >3,000, while 66% were suitable for long-term irrigation.

(6) The US salinity plots revealed that about 14% of groundwater samples were classified as C4S1, 25% as C3S1, and 25% as C2S1 types. The remaining samples were categorized as C4S2 (20%), C4S3 (11%), C4S4 (3%), and C3S2 (2%).

(7) 45% of groundwater samples were suitable for both agricultural and drinking purposes, while 27% of the samples in central and southern areas were unsuitable for agriculture. About 20% of the groundwater in Khuzestan is only suitable for drinking, and 8% is suitable for agricultural.

(8) Currently, 38% of wells are unsuitable for irrigation, with only 15% of wells meeting standard quality requirements for irrigation. Among wells with good drinking water quality, 27% are used for drinking, while 5% of poor-quality wells are still being used for drinking.

To address the issue of groundwater depletion and water scarcity in Khuzestan province, several recommendations are proposed, which are: Limiting the over-exploitation of groundwater resources, controlling agricultural development and practices to prevent further degradation of water quality, increasing the use of groundwater with suitable quality for both drinking and agricultural purposes, and reducing the reliance on inappropriate groundwater sources. This problem requires optimal and integrated management for the sustainability of water resources and a suitable plan for the allocation of water resources to reduce the risk. Furthermore, future research is also encouraged to explore the mutual transformations between surface water and groundwater, as such studies are essential for understanding the intricate relationships that underpin water resource management, especially in regions heavily dependent on surface water. Finally, it is recommended that the impact of climate change on groundwater be studied to better anticipate future challenges and opportunities for groundwater management in the region.

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