

Impact of climate change on hydrochemical properties and quality of groundwater for domestic and irrigation purposes in arid environment: A case study of Al-Baha region, Saudi Arabia

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Research Article

Keywords: Groundwater resources, Water quality, Salinity, Water quality index (WQI), Al-Baha region

Posted Date: March 23rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1354587/v1>

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Version of Record: A version of this preprint was published at Environmental Earth Sciences on January 2nd, 2023. See the published version at <https://doi.org/10.1007/s12665-022-10731-z>.

Abstract

Over-exploitation of groundwater, rising temperature, and declined precipitation have resulted in groundwater quality deterioration, subsequently affecting human health and agricultural productivity. Therefore, to evaluate the suitability of groundwater for domestic and irrigation purposes, groundwater samples were collected from 88 locations in Sarat Al-Baha region, Saudi Arabia. The hydrochemical characteristics were assessed to evaluate the suitability of groundwater for drinking and irrigation purposes. The results revealed that most groundwater samples were medium to highly salinity hazards; nevertheless, no sodicity hazards were expected. By using the water quality indices, 70.5% of studied waters were class II. Nevertheless, 91% of collected samples were in acceptable concentrations of heavy metals and nitrate. The saturation index showed that the groundwater was largely under-saturated with most minerals, indicating a possibility of salinity increase due to increasing the concentration of iron, calcium, magnesium, sodium, chloride and sulfate due to the dissolution of under-saturated minerals. Due to the increased salinity levels, more than 90% of the collected groundwater samples showed low quality for irrigation due to higher potential for salinity problems. Furthermore, the development of salinity of groundwater in Sarat Al-Baha could be the result of the increased temperatures and decreased rainfall. Therefore, it is recommended to implement appropriate management practices to optimize groundwater usage and decrease the potential of further deterioration in its quality. The discharge of groundwater need to be controlled, strictly preventing the drilling of new wells. It is also important to assess the suitability of planted crops, and implement proper water management practices to sustain groundwater resources in Sarat Al-Baha region. The approach used in this study can be used to alike environment worldwide.

Introduction

Elevated temperature and declined precipitation rate ultimately reduce the recharge rates of groundwater, subsequently deteriorating the quality of groundwater particularly in arid regions. Consequently, the groundwater quality and vital ecosystem water requirements are threatened, particularly during water scarcity periods (Treidel et al. 2012; Turrall et al. 2011; Wu et al. 2020; Obianyo 2019; Várallyay 1994). As the Kingdom of Saudi Arabia (KSA) is located in arid environment, it is suffering from accelerated groundwater deterioration due to limited precipitation and warming climate (Al-Omran et al. 2016; Aly et al. 2016; Kløvea et al. 2014; Alghamdi et al. 2021).

Climate change affects (both directly and indirectly) groundwater quantity and quality in many complex ways (Alghamdi et al. 2021; Kløvea et al. 2014; Taylo et al. 2011; NOAA 2017).

For example, Xiaolong and Boufadel (2017) used field measurements and numerical modeling to investigate the effect of evaporation and rainfall rates on subsurface salinity and groundwater dynamics. They found that increased evapotranspiration rates increased pore water salinity in the surface 10 cm layer. In addition, climate change can greatly affect recharge rates, depth of groundwater, and water consumption for human activity and irrigation (Ludwig and Moench 2009). Furthermore, low recharge

rates in dry regions increase groundwater depletion, affecting both quantity and quality of groundwater (Treidel et al. 2012).

As an essential constituent of the hydrologic cycle, groundwater is highly vulnerable to climate changes i.e., increased temperature, especially with the rapid changes in terms of increased temperature observed nowadays in comparison to historical patterns. It is expected that these rapid changes will have far-reaching consequences for Saudi's water resources (Al-Barakah et al. 2020).

It is mostly significant to recognize that alarming problems with regard to increased groundwater depletion and groundwater quality deterioration are starting to already exist in Saudi Arabia in response to observed climate change (Aly 2015). Climate change may enlarge or accelerate long standing stresses determined by human population growing, temperature increase and diminishing groundwater reservoir. These stresses are more severe in arid and semi-arid areas where aquifer recharge rates are low, and the demand for groundwater for irrigation purposes is higher (Turrall et al. 2011). Therefore, temporal monitoring of groundwater quality is of critical importance in changing climate under arid climatic conditions to avoid potential hazardous impacts on human health and agricultural production. Groundwater recharge depends on precipitation, evapotranspiration, and land cover. Warmer summer temperatures can reduce the amount of groundwater due to the increase of evaporation and more groundwater abstraction (Jyrkama and Sykes 2007). In addition, aquifer type and properties affect groundwater recharge. Shallow and unconfined aquifers react promptly to elevated temperature; however, confined aquifers respond slowly (Lee and Lawrence 2006). Therefore, deep and confined aquifers will be less delicate to the direct impact of temperature (Wada et al. 2012). During groundwater recharge, an increase in the risk of contaminants leaching is anticipated

(Okkonen et al. 2010). Moreover, excessive use of nitrate fertilizers and pesticide in agricultural areas may led to their leaching to groundwater (Bloomfield et al. 2006).

Water management decisions regarding groundwater use a dominant role in dictating the extent of climate impact on state of aquifers and streams (Taylo et al. 2011). If a considerable increase in the groundwater net volume withdrawal is used to address global warming problems, there are likely to be severe and detrimental effects on groundwater storage and quality. In KSA, groundwater resources are considered the main source of irrigation requirements for plants (Al-Omran et al. 2016). However, increased groundwater depletion and deterioration in the quality of groundwater in KSA have been reported over the past two decades owing to extreme temperatures (Aly et al. 2016; Aly 2015), which necessitates increased effort to monitor and assess the quality of groundwater in KSA .

Al-Baha region, located in the southwest of KSA, is the smallest provinces of KSA and due to the arid conditions, the groundwater in Al-Baha is considered a very valuable natural resource. Until recently, Al-Baha region was considered as one of the least developed regions in Saudi Arabia. However, over the past few years, there has been an increased interest in the socioeconomic development of the region, particularly as Al-Bahaa enjoys a natural variation of terrestrial ecosystems, moderate climate and natural resources. However, AL-Baha region is facing a continuous increase in temperature, while

significant decline in rate of precipitation. These climatic variations are likely to influence the quality and volume of groundwater to a substantial level. Al-Baha region was characterized by an increase in mean temperatures by 1.1°C–1.6°C, and a decrease in annual rainfall by 24–41% during the years 1995–2019. However, very limited studies are available for the assessment of groundwater quality for irrigation and drinking purposes in this region under rapidly changing climatic conditions (Al-Barakah et al. 2020). Therefore, current study was conducted to (1) evaluate the suitability of groundwater in Al-Baha region; 2) evaluate the suitability of groundwater in Al-Baha region for domestic and irrigation purposes using water quality index (WQI) analyses; and (2) characterize the hydrochemical composition and mineral saturation indices of groundwater in Al-Baha region under changing climatic conditions.

Materials And Methods

Study location

Al-Baha region is located between latitudes 19° 27'17" and 20° 49'75" N and longitudes 40° 46' 30 and 42° 10'10" E (Fig. 1). The total area of Al-Baha region is 11221 km². It has six administrative governorates (Al-Aqiq, Belgrashi, Al-Mandq, Al-Qora, Al-Mkhwah, and Qolwah) in addition to Al-Bahaa city. Al-Baha region is characterized by diverse soils, varied plant cover, and different patterns of topography and climate. Al-Baha region is located on the Arabian Shield, and its soils are mostly consisting of crystalline basement composed of Precambrian continental crust (Mohammed 2011). The weather is generally moderate to hot in summer and warm to cold in winter, with average temperatures ranging between 12° and 23°C. The average annual precipitation rate is about 150–200 mm, with moisture between 50–70% (Al-Barakah et al. 2020).

In this study, we focused our investigation on the area representing the middle part of Al-Baha region, which is known as Sarat Al-Baha, and is consisting of Al-Qora, Al-Mandq, Al-Baha, and Belgrashi Governorates (Fig. 1). The area of Sarat Al-Baha represents only 26.7% of the total area of Al-Baha region. Nevertheless, Sarat Al-Baha has the largest population percentage in the entire Al-Baha region. In addition, Sarat Al-Baha area includes the largest cultivated area, forest and mountainous areas, and, therefore, is a major area of interest for future socioeconomic development in Al-Baha region. With groundwater being a major resource for drinking and irrigation in Al-Baha region, it is, therefore, of crucial importance to assess its quality as impacted by climatic changes in the region. We obtained historical daily climatological reports for Al-Baha region from the General Authority for Meteorology and Environmental Protection in KSA. The data included average daily temperature and precipitation for 25 years (1995–2019) in Al-Baha region.

Groundwater sampling and analysis

Groundwater samples were collected from 88 locations in 1.0 L air tight plastic bottles during August 2020 (Fig. 2). Five different samples were collected from each location, which were placed in ice-boxes and moved to the laboratories in the Department of Soil Sciences at King Saud University, Riyadh for

analyses. A portion of the groundwater sample was acidified by concentrated HNO_3 to a $\text{pH} < 2$ for accurate determination of heavy metal concentration (APHA 1998).

The samples were analyzed for pH using pH meter (pH meter - CG 817), and total dissolved salts (TDS) by measuring electrical conductivity (EC) in dS m^{-1} at 25°C (Test Kit Model 1500_20 Cole and Parmer). Magnesium and calcium ions were determined by titration by versenate as described by Sparks (1996). The potassium and sodium ions were measured by flame photometer (Corning 400) (Matiti 2004). Bicarbonates and carbonates ions were determined by acid titration (Sparks 1996). Chloride ion was determined by titration with silver nitrate (Matiti 2004). Sulfate was measured by the turbidity method (Tabatabai 1996), while the phenoldisulfonic acid method was used for the determination of nitrate (NO_3^-) (APHA 1998). Heavy metal concentrations of As, Co, Cd, Cr, Fe, Cu, Pb, Ni, Mo, Mn, and Zn were determined by inductively coupled plasma (ICP) (Perkin Elmer Model 4300DV).

Blanks and standard solutions examination were frequently run to check for probable inaccuracies in the analysis. The accuracy of the chemical analysis was estimated by calculating ion balance errors (IBEs). The IBE was determined based on the measured concentrations of cations and anions in the collected groundwater (Appelo and Postma 1996). IBE values equal to $\pm 3\%$ were considered satisfactory. Samples with an IBE out of this range were re-estimated. More than 97% of the analyzed water samples were in the acceptable range with regard to the IBE values, indicating the suitability of the obtained results to carry out geochemical modeling and assessment of groundwater quality in the study area.

The hydrochemical characterization of major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , Cl^- , and SO_4^{2-}) of groundwater samples were plotted on Piper, Gibbs, and US salinity diagrams for the identification of groundwater type and quality (Piper 1944; Gibbs 1970; Richards 1954). The ratios of

$\text{Na}^+ + \text{K}^+ / (\text{Na}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ as a function of TDS were employed to evaluate the sources (e.g. rock dominance, precipitation dominance, and evaporation dominance) of dissolved chemical compounds in groundwater (Gibbs 1970)..

Calculation of Water Quality Index (WQI)

WQI was computed to assess the quality of groundwater for drinking and irrigation purposes in the study area. Computation of WQI was carried out according to Al-Barakah et al. (2017). Ten measured parameters (i.e.: pH, TDS, Fe, Zn, Cu, Cd, Cr, Pb, As, and $\text{NO}_3\text{-N}$) were included in the calculation of WQI. Each parameter was allocated a weight (w_i) conferring to its significance in the quality of groundwater (Table 1). Parameters with the largest significance (i.e.: As, Pb, Cd, and $\text{NO}_3\text{-N}$) were given a weight of 5. Whereas, parameters with the lowest significance (i.e.: Fe, Zn, and Mn) were given a weight of 1 (Ramakrishnah et al. 2009). The remaining parameters (i.e.: pH, TDS, Cu, and Cr) were given a weight value between 1 and 5 (Table 1). A Relative weight (RW_i) was calculated for each measured parameter (i) according to the equation:

$$RWi = \frac{wi}{\sum_{i=1}^n wi} \quad (1)$$

where RWi is the relative weight of the i^{th} parameter, Wi is the weight assigned to i^{th} parameter, and n is the total number of measured parameters. RWi values of measured parameters are presented in Table 1.

Table 1

Standards of the World Health Organization (WHO), assigned weights and relative weights values for the calculation of Water Quality index (WQI) of groundwater in Sarat Al-Baha region.

Assessment criteria	Measured parameters									
	(mg L ⁻¹)									
	pH	TDS	Fe	Zn	Cu	Cd	Cr	Pb	As	NO ₃ ⁻ N
WHO Standards	8.5	700	0.30	5.0	2.0	0.003	0.05	0.01	0.01	50
Weight (Wi)	3	3	1	1	3	5	2	5	5	5
Relative weight (RWi)	0.09	0.09	0.03	0.03	0.09	0.15	0.07	0.15	0.15	0.15

A Quality Rating Scale ($QRSi$) was calculated for each measured parameter (i) according to the equation:

$$QRSi = \frac{Ci}{Si} \times 100 \quad (2)$$

Where Ci is the measured value of the i^{th} parameter (mg L⁻¹), and Si is the WHO acceptable standard limit of the i^{th} parameter (Alexakis 2011; WHO 2011).

A parameter index value (PIi) was calculated by multiplying the relative weight (RWi) by the quality rating scale ($QRSi$) for each measured parameter. The final value of the WQI was calculated as the sum of all computed parameter index values (PIi) according to the equation:

$$WQI = \sum_{i=1}^n PIi \quad (3)$$

where PIi is the parameter index value of the i^{th} parameter, and n is the total number of measured parameters. According to Ramakrishnalal et al. (2009), the quality of groundwater, for drinking purposes, based on the values of the WQI is classified into five classes: excellent, good, poor, very poor, and unsuitable for drinking, with value ranges of < 50, 50.1–100, 100.1–200, 200.1–300, and > 300, respectively.

Geochemical modeling

Interactions amongst the groundwater and the surrounding rocks are the main processes controlling the chemical features of groundwater. The water's deviation from equilibrium with respect to dissolved minerals is defined by the saturation index (*SI*). The *SI* of a mineral is calculated using the following equation:

$$SI = \log IAP/k_t \quad (4)$$

where *IAP* is the ion activity product of the dissociated chemical species in solution and k_t is the equilibrium solubility product of the chemical involved (Alexakis 2011). The PHREEQC model (Ramakrishnah et al. 2009) was used to obtain the *SI* of groundwater samples in Sarat Al-Baha region with respect to the main mineral phases. Saturation indices (*SI*) are usually used to assess mineral dissolution in groundwater. If the *SI* of the mineral is equal to zero, the mineral is in equilibrium with groundwater. *SI* values smaller than zero indicate that the mineral is under-saturated, whereas *SI* values greater than zero indicate the mineral is over-saturated.

Results And Discussion

Historical climatic conditions in Sarat Al-Baha

Records of climatic data over the past 25 years (1995–2019) in Al-Baha region revealed mean temperature periodic cycles approximately every 2–3 years, whereas, annual rainfall showed slightly longer periodic cycles of 4–5 years (Fig. 3). During the period 1995–2019, average temperature in Al-Baha region was 23.2°C. However, a clear evidence of the impact of climate change on mean annual temperatures in the region was the observed gradual increase in mean temperatures by 1.1–1.6°C that was noticed between the years 1995 and 2019 (Fig. 3, A). In contrast, there was a gradual decrease in total annual rainfall that ranged between 24–41% during the same period (excluding the extremely dry period that took place from 2010 to 2014) (Fig. 3, B). Previously, Al-Baha region, which indicates that Al-Baha is a fragile ecosystem, highly vulnerable to climate change and subsequent environmentally, induced water resource degradation (Al-Barakah et al. 2020). Improper water management will further increase the adverse impacts of climate change, and will accelerate problems associated with the degradation of groundwater quality in Al-Baha region (Aly et al. 2016).

Characterization of groundwater resources in Sarat Al-Baha

The digital elevation model (DEM) of Sarat Al-Baha region showed considerable variations in topography, with an average elevation of 1882 m above sea level (Fig. 4, A). Areas in the northern parts of Al-Baha governorate and in the southern parts of Al-Qora and Al-Mandaq governorates showed the highest elevation that reached 2446 m above sea level. On the other hand, the northern parts of Belgrashi and Al-Qora governorates showed the minimum surface elevation of 1318 m above sea level. The large variability in elevation in Sarat Al-Baha region emphasizes the unique nature of the hydrogeology in the

region. It is, therefore, anticipated that the quantity and quality of groundwater in Al-Baha depend mainly on rainfall rate. Consequently, we can say that the Al-Baha groundwater has a meteoric origin, which means that the water comes from precipitation in the form of rain with a short residence time of water flow through the vadose zone to the aquifers (Craig 1961; Good et al. 2014). The maximum depth to groundwater in Sarat Al-Baha was 190 m, which was observed in Al-Mandaq governorate. However, the average well depth was found to be 48.3 m from the soil surface (Fig. 4, B). These results suggest that most groundwater in Sarat Al-Baha are present in shallow, and as such will likely to be more sensitive to be adversely impacted by climate change in the region (Lee and Lawrence 2006; Wada et al. 2012).

Groundwater in Al-Baha region is considered the main source for drinking, irrigation, and livestock purposes. Therefore, the quality of groundwater in terms of its salinity and mineral content is extremely important to maintain sustainable development in the region. In particular, salinity is highly significant when groundwater is used for irrigation to reduce the hazards of soil salinization (Aly 2020). Approximately, 40% of the tested wells showed total dissolved salts (TDS) values between 500–1000 ppm (Table 2), indicating acceptable levels for the cultivation of most crops and low potential for soil salinity problems. However, the majority of the collected groundwater samples showed higher salinity levels (> 1000 ppm), making this groundwater unsuitable for drinking. Furthermore, using groundwater having this level of salinity for irrigation could have adverse impacts on soil quality. Secondary salinization is particularly anticipated under the arid and hot environment of Sarat Al-Baha region (Taylor et al., 2011). The observed increase in mean temperatures in Al-Baha region, and the accompanied decrease in average annual precipitation over the past 25 years, could have contributed to the increasing rates of salination observed in groundwater. Other reasons could include excessive depletion of groundwater and agricultural expansion in the region (Wu et al. 2020; Aly 2015).

Evaluation of groundwater quality for drinking

To facilitate the assessment of the quality of groundwater in Sarat Al-Baha region, a map showing all sampling locations along with well numbers is presented in Fig. 5. Calculations of WQI were used to evaluate the quality of groundwater for drinking. We found that 20.5% of collected groundwater samples were excellent for drinking (class I), 70.5% were good for drinking (class II), 8.0% were poor water for drinking (class III), and approximately 1.0% were very poor for drinking (class IV) (Fig. 6). The area showing very poor groundwater quality for drinking was around well number 75 in Al-Mandq governorate (Al-Barakah et al. 2020).

Table 2

Descriptive statistics of pH, EC, soluble ions, and heavy metal concentrations in groundwater samples (n = 88).

Parameters	Max.	Min.	Mean	St. Dev.	Variance	St. error	Median	Skewness
pH	8.39	6.72	7.70	0.29	0.54	0.08	7.74	-0.40
EC (dS m ⁻¹)	4.27	0.11	1.10	0.68	0.83	0.10	0.98	2.06
Cations (meq L ⁻¹):								
Ca ⁺⁺	16.00	0.60	3.28	2.45	1.56	0.13	2.89	3.07
Mg ⁺⁺	28.00	1.40	6.26	4.05	2.01	0.15	5.60	2.84
Na ⁺	6.13	0.05	2.31	1.45	1.20	0.12	2.23	0.57
K ⁺	0.93	0.01	0.25	0.31	0.56	0.08	0.12	1.43
Anions (meq L ⁻¹):								
Cl ⁻	40.00	1.00	8.49	5.19	2.28	0.16	7.50	2.99
HCO ₃ ⁻	5.12	0.32	1.01	0.83	0.91	0.10	0.80	2.72
SO ₄ ⁻⁻	24.50	0.00	1.71	2.99	1.73	0.14	0.90	5.39
Heavy metals (mg L ⁻¹):								
As	0.16	0.00	0.01	0.02	0.13	0.04	0.01	7.34
Cd	0.01	0.00	0.00	0.00	0.04	0.02	0.00	5.76
Co	0.01	0.00	0.00	0.00	0.02	0.01	0.00	1.27
Cr	0.06	0.00	0.01	0.01	0.10	0.03	0.01	2.93
Cu	0.12	0.00	0.02	0.02	0.14	0.04	0.02	1.89
Fe	1.11	0.00	0.31	0.23	0.48	0.07	0.25	1.20
Mn	0.03	0.00	0.00	0.00	0.07	0.03	0.00	2.89
Mo	0.25	0.00	0.08	0.05	0.22	0.05	0.08	0.38
Ni	0.02	0.00	0.01	0.01	0.07	0.03	0.01	1.25
Pb	0.04	0.00	0.00	0.01	0.07	0.03	0.00	4.20
Zn	0.49	0.00	0.04	0.08	0.28	0.06	0.02	4.13

Parameters	Max.	Min.	Mean	St. Dev.	Variance	St. error	Median	Skewness
NO ₃ -N (mg L ⁻¹)	25.72	0	4.14	3.45	1.86	0.15	2.90	3.42

It is worth mentioning that arsenic (As) concentration in groundwater collected from well 75 showed the maximum concentration (0.163 mg L⁻¹) in the entire study region. The WHO (2011) recommended standard for As concentration in drinking water is 0.01 mg L⁻¹ (Table 1), which can explain the very poor quality of groundwater obtained from well 75 based on WQI value. Our results are slightly different from Al-Barakah et al. (2020) who used WQI to assess groundwater quality for drinking in Al-Baha region in 2016, and concluded that approximately 97% of groundwater samples were class I and class II in quality. The slight deterioration in groundwater quality between the years 2016 and 2020 could be attributed to increased groundwater salinity (Sharaf, 2013).

Evaluation of groundwater quality for irrigation

The method of the Food and Agriculture Organization (FAO) (Ayers and Westcot 1985) was used to evaluate the suitability of Al-Baha groundwater for irrigation. Results indicate that 29.5% of groundwater samples showed acceptable salinity levels (EC < 0.7 dS m⁻¹), and good quality for irrigation without any restriction. However, the majority of groundwater samples (68.2%) in Sarat Al-Baha had larger EC values (0.7-3.0 dS m⁻¹), and were classified as having slight to moderate degree of restriction for irrigation. Groundwater samples with salinity levels exceeding 3.0 dS m⁻¹ were classified as having severe restriction for irrigation. These samples represented only 2.3% of groundwater samples collected from the study region, and were mainly located in the eastern parts of Al-Baha governorate (e.g. wells 30, 49, 50, 51, and 52), and the western part of Al-Mandq governorate (e.g. well 80). The concentration of heavy metals and nitrate were within the acceptable safe limit for irrigation for all studied wells, with the exception of one sample (well 75 in Al-Mandq governorate), which had As concentration much larger than recommended level (Al-Barakah et al. 2017; Aly et al. 2013).

The combined effect of alkalinity and salinity on the quality and classification of groundwater used for irrigation was evaluated using the salinity diagram of the U.S. Salinity Laboratory (Richards 1954). Based on the characteristics of the groundwater samples from Sarat Al-Baha, the sodium hazard was low (class S1) for all groundwater samples, indicating low potential for alkalinity problems (Fig. 7). In contrast, only 4.5% of groundwater samples showed low salinity hazard, giving groundwater in these areas a final classification of C1-S1. These areas were mainly found around wells 74 and 76 in Al-Mandq governorate. Groundwater samples showing medium salinity and low sodium hazards (i.e. class C2-S1) also represented 4.5% of total samples. These results indicate that only 9% of groundwater samples collected from Sarat Al-Baha had low potential for salinity problems, and were considered suitable for the irrigation of most field crops, vegetables and tree plants without the need for special practices to control salinity levels in the soil. The majority of groundwater samples (80.7%) had high salinity and low sodium hazards

(i.e. class C3-S1), while approximately 10.3% had very high salinity and low sodium hazards (i.e. class C4-S1), indicating the lowest quality of groundwater for irrigation.

In 2016, the study of Al-Barakah et al. (2020) used the salinity diagram of the U.S. Salinity Laboratory (Ramakrishnah et al. 2009) to classify groundwater in Al-Baha region, and found that the class C3-S1 (i.e. groundwater having high salinity and low sodium hazards) represented 60% (compared to 80.7% in our study) of all collected groundwater samples. Taking into consideration the variations that exist between the study of Al-Barakah et al. (2020) and this research in terms of the number of groundwater samples and their locations, we still can see a clear trend of increase in groundwater salinity in Al-Baha during the period 2016–2021. The fact that 10.3% of collected groundwater samples had very high salinity (i.e. class C4-S1) can be considered as an alarming warning of quick trend of deterioration in the quality of groundwater in Sarat Al-Baha region (Aly and Benaabidate 2010). Our findings indicate that groundwater in most of the sampling locations (91%) had excessive amount of salts, and hence it cannot be used for irrigation of most crops without special measures for salinity control such as the planting of salt-tolerant plants, proper water management, and the application of additional leaching requirements (Lauchli and Epstein 1990).

Hydrochemical characterization

Results of the chemical analyses of groundwater samples were plotted on a Piper trilinear diagram (Piper, 1944) (Fig. 8). Piper trilinear diagram offers a suitable method to classify groundwater types based on the ionic composition (Aly and Benaabidate 2010). The diagram illustrates that all groundwater in Sarat Al-Baha were calcium-magnesium, and chloride-sulfate type water. Therefore, the anticipated predominant groundwater type in Sarat Al-Baha should be $Mg/CaSO_4$, which is commonly due to the geology of the area that contains gypsum, anhydride, and dolomite minerals (Al-Barakah et al. 2020).

The concentration of ions present in groundwater were plotted on Gibbs's diagrams (Fig. 9). The diagram helps to determine main factors affecting the quality of groundwater. Results indicated that the chemical weathering of rock-forming minerals is affecting groundwater quality in Sarat Al-Baha. Most groundwater samples were located in the rock dominance section of the diagram, suggesting that rock–water interaction is the major source of dissolved ions for most groundwater in Sarat Al-Baha region. The rock–water interaction process includes chemical weathering, dissolution–precipitation of secondary carbonates, and ion exchange between water and clay minerals (Subba 2006). The increase in air temperatures and evaporation rates could significantly increases the ion concentrations formed by chemical weathering, leading to a higher salinity (Kumar et al. 2006).

Geochemical modeling

Variations in pH greatly affects the calculated values of SI. Inaccuracy in the determination of pH, and/or variations in pH of groundwater as water flows can result in an inaccurate calculation of SI. Therefore, it is recommended that SI should be taken in a wider range ($-1 < SI < +1$) to minimize the impact of pH variations on the calculation of SI values (Nasher et al. 2013). Calculation of SI in groundwater samples showed that all groundwater samples in Sarat Al-Baha were under-saturated with respect to the following

minerals: Halite (NaCl), Anhydrite (CaSO₄), Gypsum (CaSO₄: 2H₂O), Manganite (MnOOH), Jarosite-K (KFe₃(SO₄)₂(OH)₆), Hausmannite (Mn₃O₄), Pyrolusite (MnO₂:H₂O), Pyrochroite (Mn(OH)₂), Melanterite (FeSO₄: 7H₂O), and Sylvite (KCl) (Fig. 10). In contrast, SI values showed that all groundwater samples were over-saturated with respect to Hematite (Fe₂O₃) (as indicated by the positive SI values) (Fig. 11). Our findings indicate that there is a possibility of increasing the concentration of iron, calcium, magnesium, sodium, chloride and sulfate in groundwater in Sarat Al-Baha due to possible further dissolution of under-saturated minerals (Appelo and Postma 1996; Jalali 2006).

Conclusions

Groundwater in Sarat Al-Baha is the main resource for domestic and irrigation purposes. To evaluate the quality and hydrochemical characterizations of groundwater, 88 groundwater samples were collected from Sarat Al-Baha. Calculation of water quality indices showed that most groundwater in Sarat Al-Baha had acceptable concentrations of heavy metals and nitrate, and were good for drinking. Only 8% of the collected groundwater samples were classified as having poor and very poor quality for drinking, mainly because of increased concentrations of As and NO₃-N. Assessing the quality of groundwater for irrigation using the salinity diagram of the U.S. Salinity Laboratory showed that only 9% of the collected groundwater had low (C1-S1) and medium (C2-S1) salinity hazards. The majority of groundwater samples (80.7%) had high salinity and low sodium hazards (i.e. class C3-S1), while approximately 10.3% had very high salinity and low sodium hazards (i.e. class C4-S1), indicating the lowest quality of groundwater for irrigation. Saturation index showed that groundwater samples were over-saturated with Hematite, and under-saturated with respect to other minerals (Halite, Anhydrite, Gypsum, Manganite, Jarosite-K, Hausmannite, Pyrolusite, Pyrochroite, Melanterite, and Sylvite). Therefore, there is a possibility of increasing the concentration of iron, calcium, magnesium, sodium, chloride and sulfate due to the dissolution of under-saturated minerals.

Comparing our results to the findings of previous studies in the region showed a trend of groundwater deterioration, particularly with increased salinity levels. More than 90% of the groundwater samples collected showed low quality for irrigation. Thus, it is necessary for decision makers to formulate an action plan to minimize the effect of prospective climate change, and decrease the potential of further deterioration in the quality of groundwater. Therefore, it is imperative to control groundwater discharge, strictly prevent the drilling of new wells, and closely monitor the quality of groundwater in the region. It is also important to implement management practices to minimize agricultural water demand by changing the crop patterns and enhancing water productivity. In particular, policy-makers should enforce regulations and guidelines to control excessive use of fertilizers and pesticides in agricultural production, and implement proper water management to maintain socioeconomic development and sustain groundwater resources in Sarat Al-Baha region.

Declarations

Author Contributions: Conceptualization, A.A., H.I., M.M., and A.A.; methodology, A.A., H.I., and A.A.; software, A.A., and H.I.; validation, A.A., H.I. and A.A.; formal analysis, H.I. and A.A.; investigation ,A.A., H.I. and A.A.; resources, A.A., H.I., A.A., and M.M.; data curation, H.I. and A.A.; writing—original draft preparation, H.I. A.A., and A.A.; writing—review and editing, H.I. A.A., and A.A.; visualization, H.I., A.A., and M.M.; supervision, A.A., H.I. and A.A.; funding acquisition, A.A., H.I. and A.A.

Funding: This project was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (2-17-04-001-0025).

Acknowledgement: The authors would like to thank the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (2-17-04-001-0025) for supporting this work.

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

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Figures



Figure 1

Location map of Al-Baha region and the study location representing the area of Sarat Al-Baha (Al-Qora, Al-Mandq, Al-Baha, and Belgrashi Governorates).

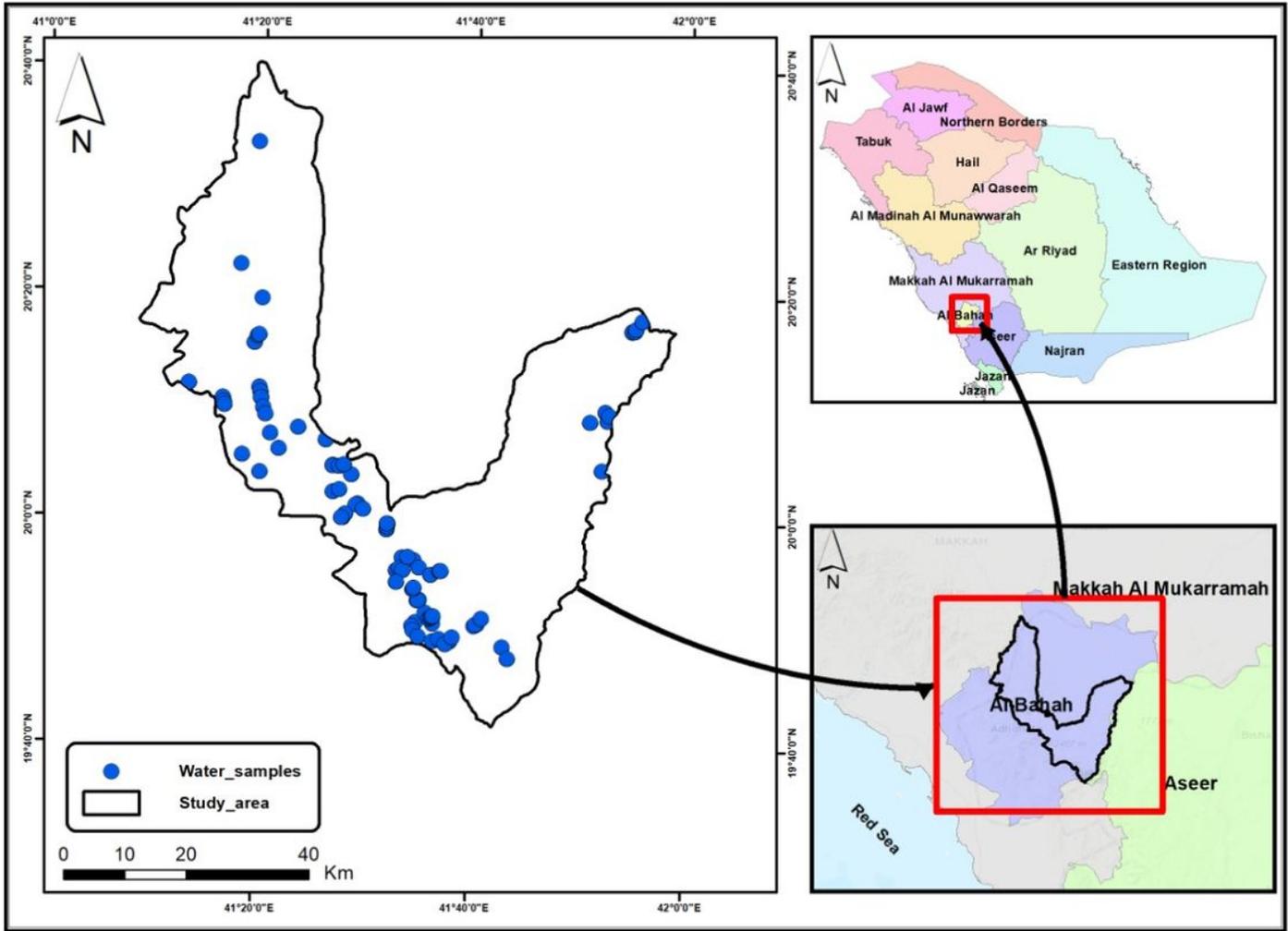


Figure 2

Locations of groundwater sampling in the study area.

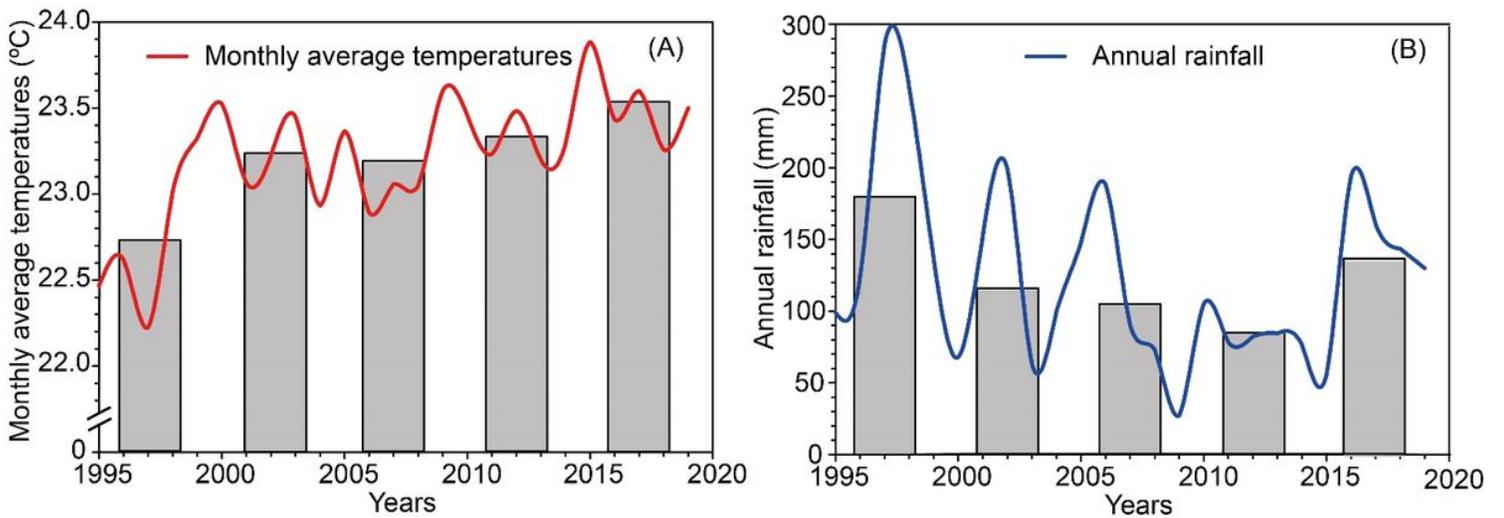


Figure 3

Monthly average temperatures ($^{\circ}\text{C}$), (A); and annual rainfall (mm), (B) during the period 1995-2019 in Al-Baha region. Shaded rectangles represent data averages over the periods: 1995-1999, 2000-2004, 2005-2009, 2010-2014, and 2015-2019.

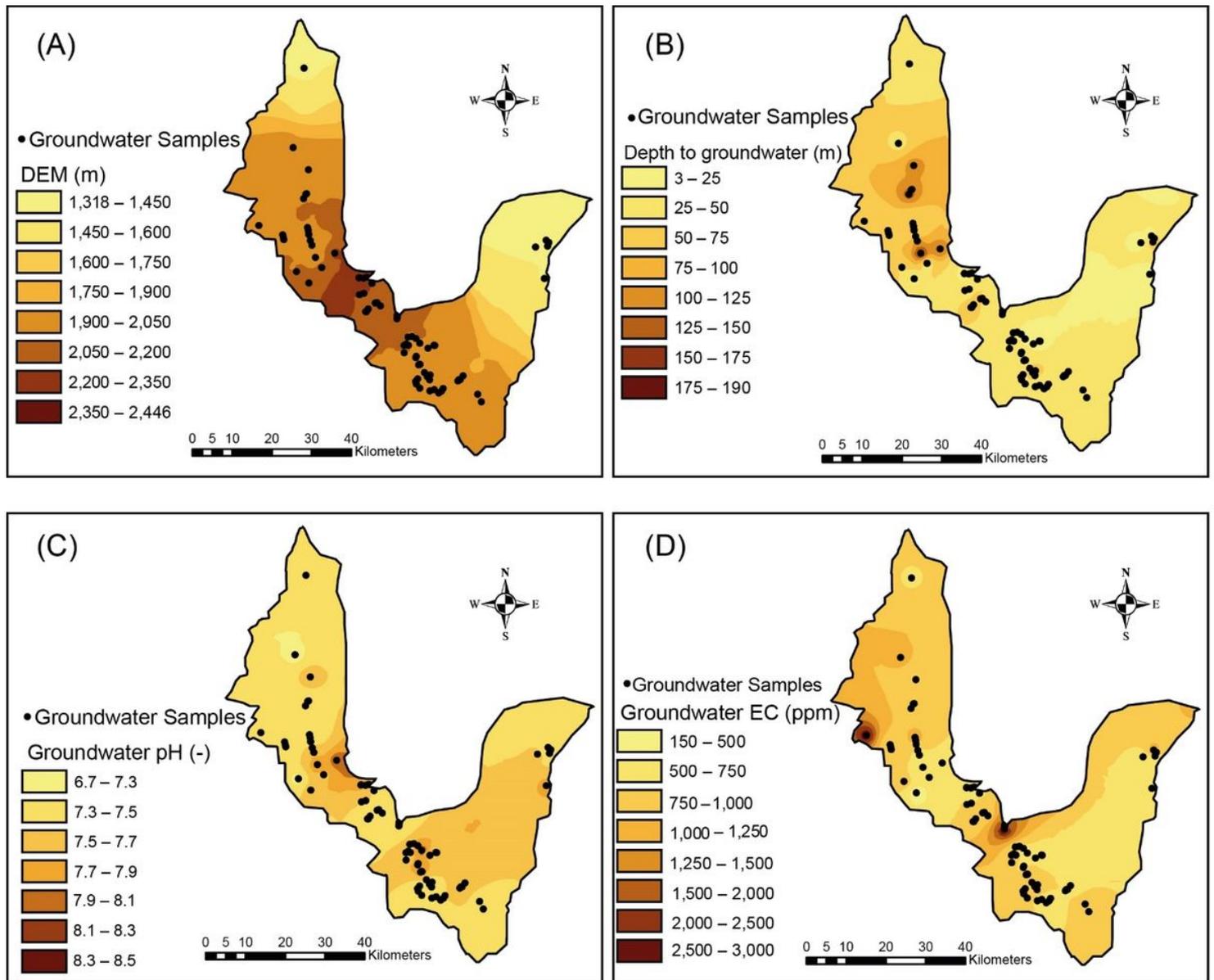


Figure 4

Digital elevation model (DEM) in Sarat Al-Baha region, (A); and spatial distributions of the depth to groundwater in sampling locations, (B); pH of groundwater samples, (C); and electrical conductivity (EC) in groundwater samples.

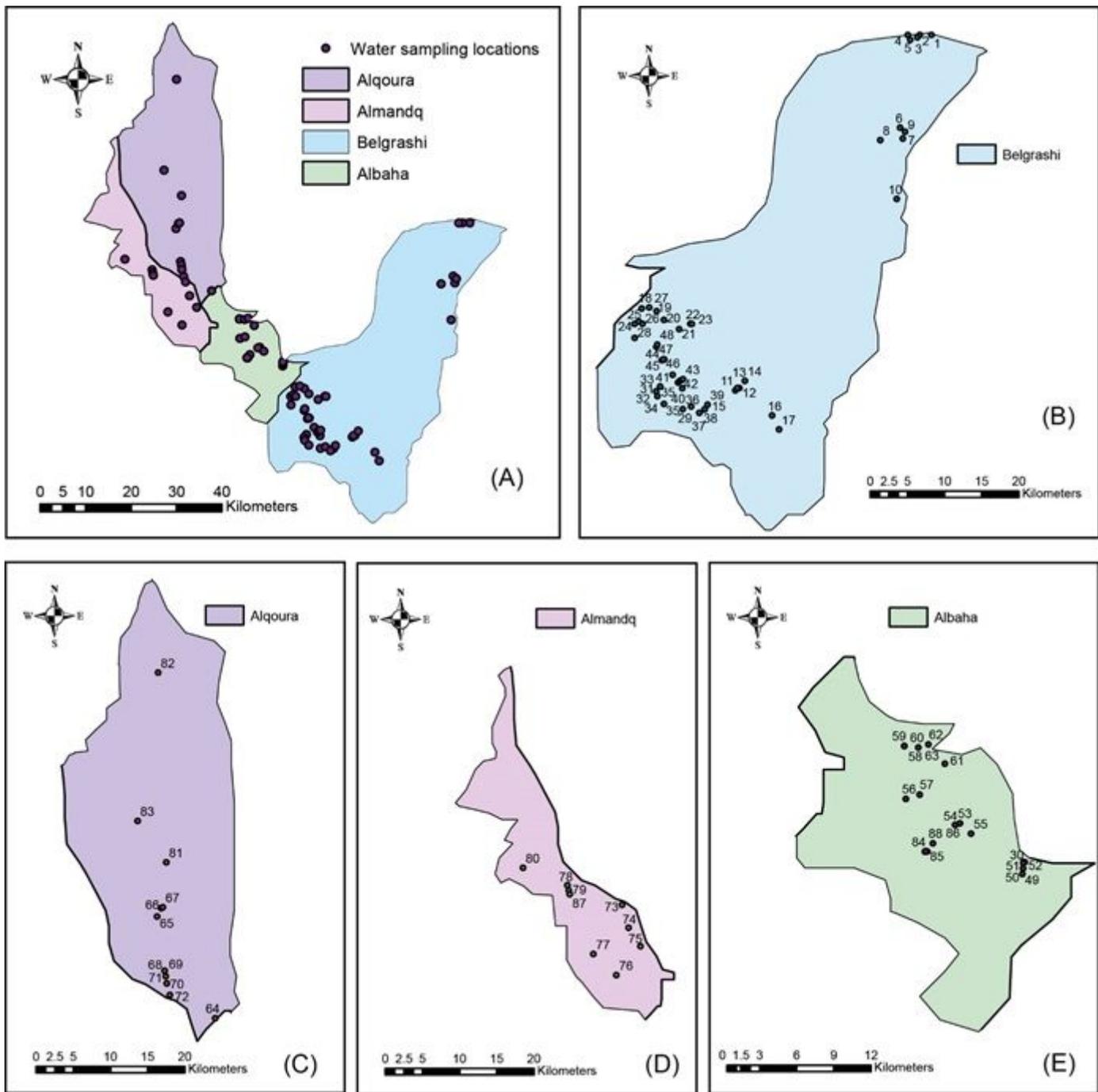


Figure 5

Water sampling locations showing well numbers in Sarat Al-Baha region, (A); Belgrashi, (B); Alqoura, (C); Almandq, (D); and Albaha, (E) governorates. Note the different scaling bars.

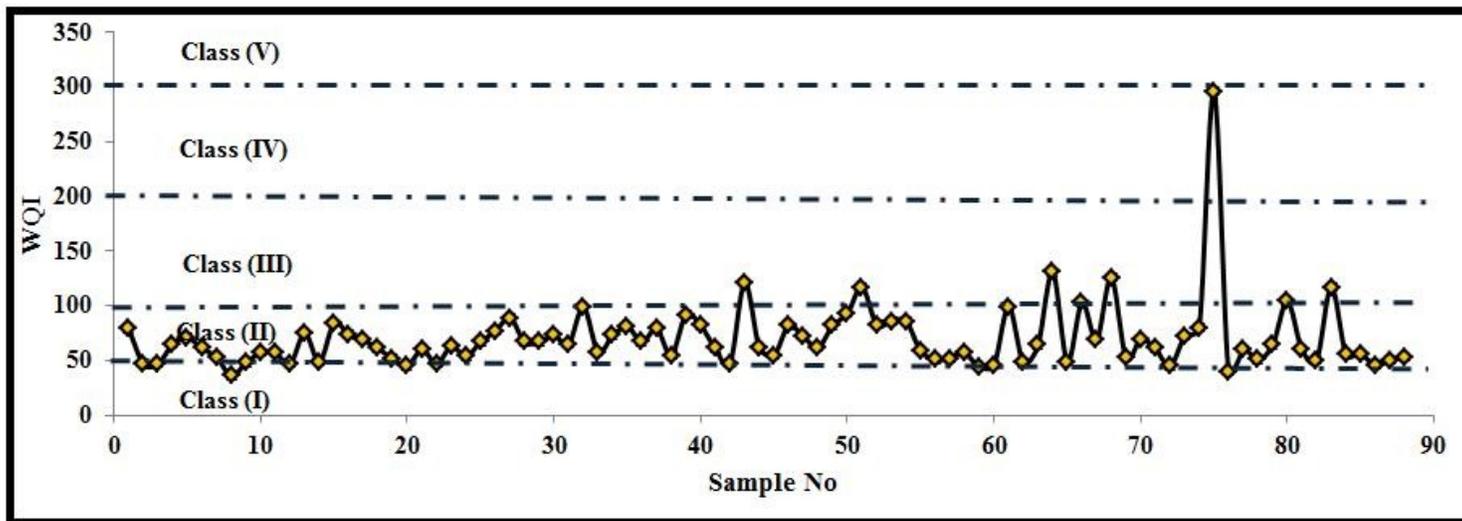


Figure 6

Water quality index (WQI) in groundwater samples collected from Sarat Al-Baha region.

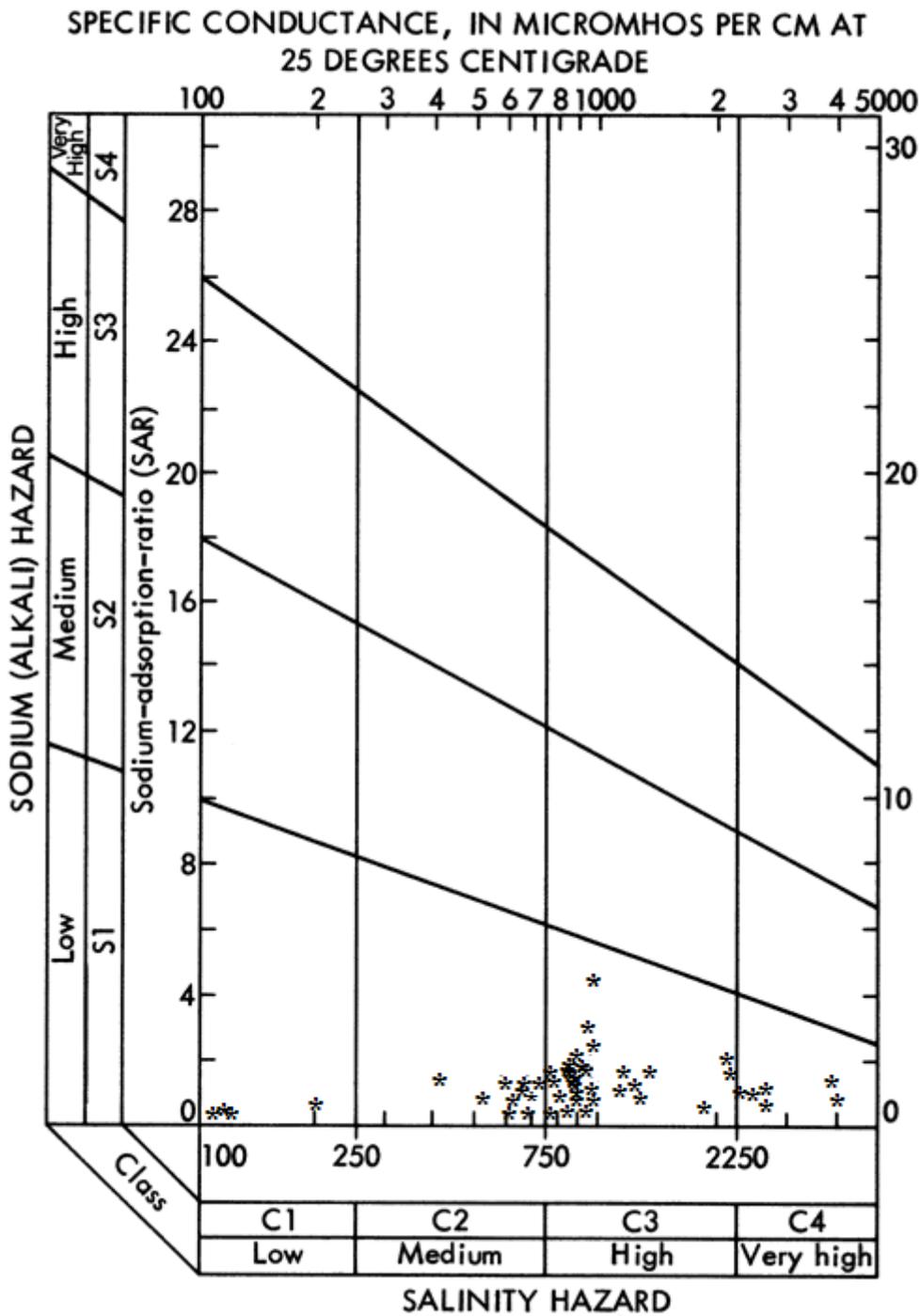


Figure 7

Diagram of the U.S. Salinity Laboratory for the evaluation and classification of the combined effect of alkalinity and salinity in water used for irrigation.

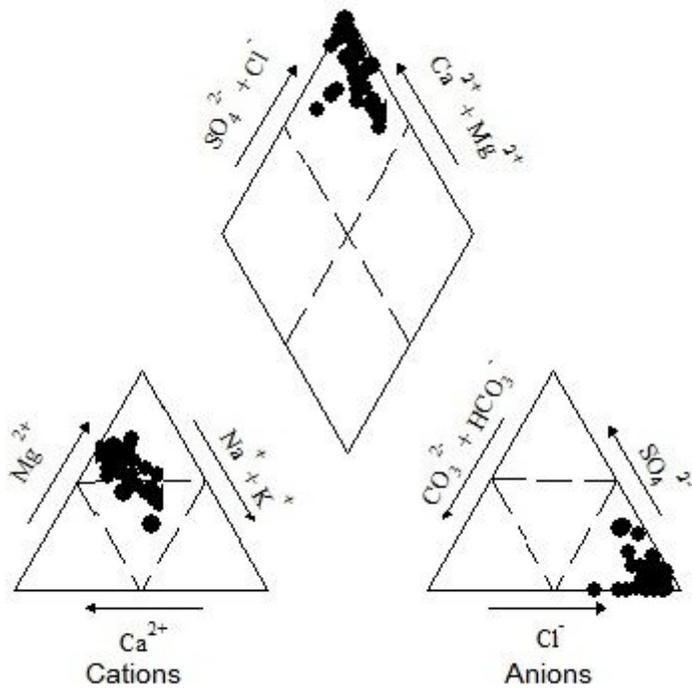


Figure 8

Piper trilinear diagrams of groundwater samples in Sarat Al-Baha.

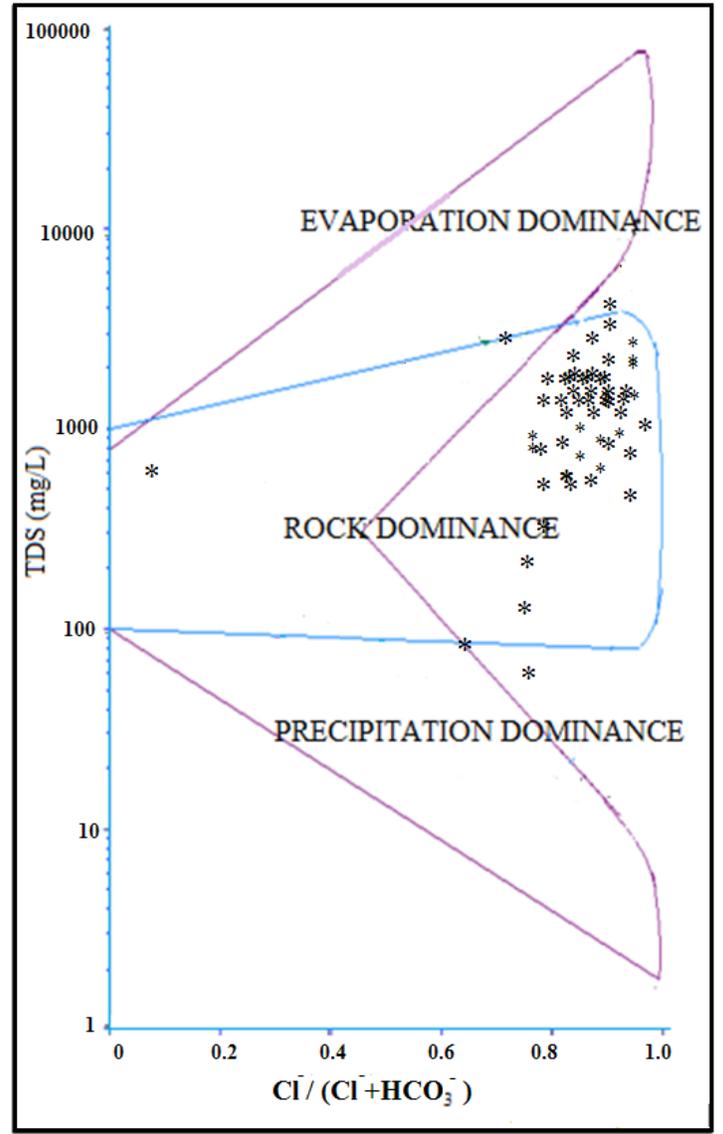
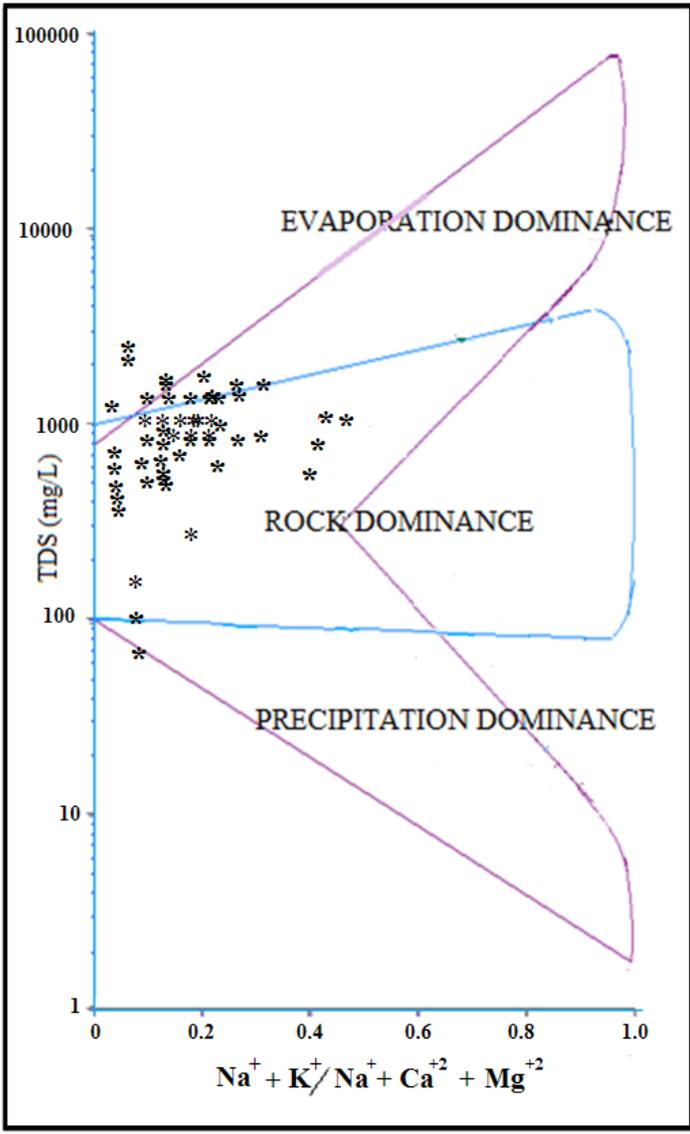


Figure 9

Gibbs's diagrams of groundwater samples in Sarat Al-Baha.

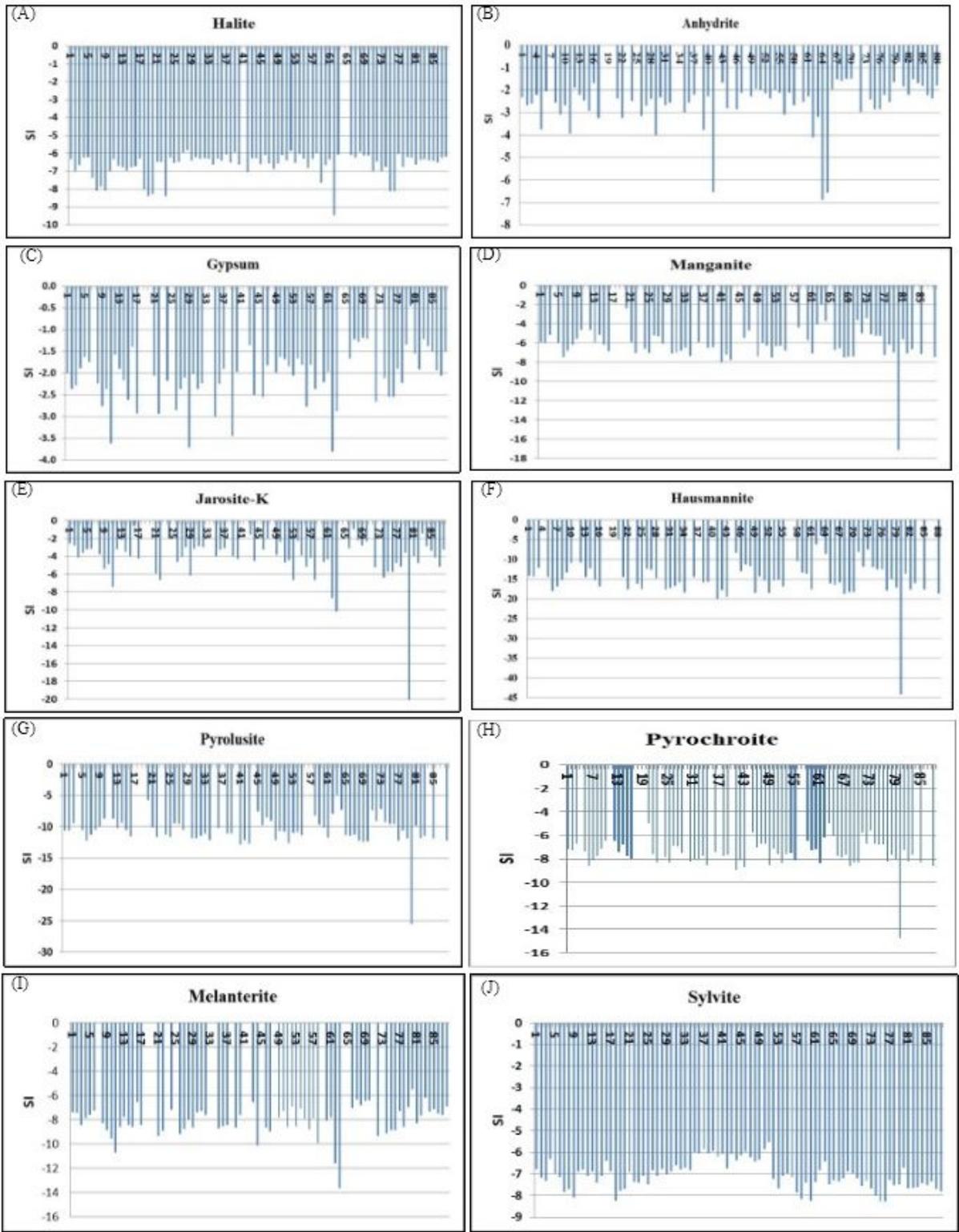


Figure 10

Saturation indices (SI) of under-saturated minerals in groundwater samples of Sarat Al-Baha: Halite, A; anhydrite, B, Gypsum, C; manganite, D; Jarosite-K, E; Hausmannite, F; Pyrolusite, G; Pyrochroite, H; Melanterite, I; and Sylvite, K).

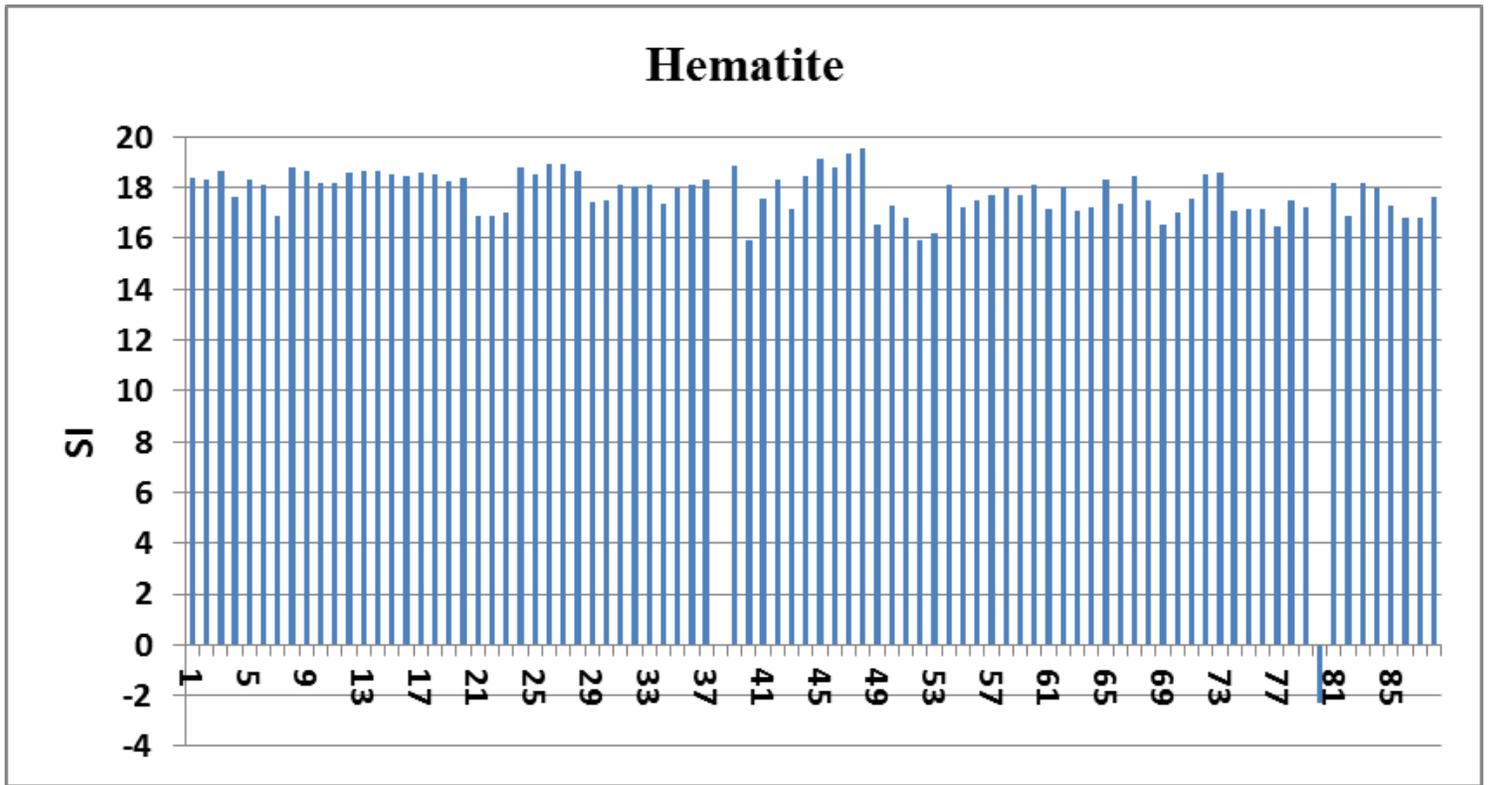


Figure 11

Saturation indices (SI) of over-saturated Hematite mineral in groundwater samples of Sarat Al-Baha.