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An Integrated Principal Component and Hierarchical Cluster Analysis Approach for Groundwater Quality Assessment in Jazan, Saudi Arabia

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Abstract: Jazan province on Saudi Arabia's southwesterly Red Sea coast is facing significant challenges in water management related to its arid climate, restricted water resources, and increasing population. A total of 180 groundwater samples were collected and tested for important hydrochemical parameters used to determine its adaptability for irrigation. The principal components analysis (PCA) was applied to evaluate the consistency/cluster overlapping, agglomeration in the datasets, and to identify the sources of variation between the 11 major ion concentrations (pH, K^+, Na^+, Mg^{2+}, Ca^{2+}, $SO_4{}^{2-}$, Cl^-, $HCO_3{}^-$, $NO_3{}^-$, TDS, and TH). The EC values ranged from excellent to unsuitable, with 10% being excellent to good, 43% permissible, and 47% improper for irrigation. The SAR classification determined that 91.67% of groundwater samples were good to excellent for irrigation, indicating that they are suitable for irrigation with no sodium-related adverse effects. Magnesium hazard values showed that 1.67% of the samples are unsuitable for irrigation, while the remaining 98.33% are suitable. Chloro-alkaline indices signify that most groundwater samples show positive ratios indicating that ion exchange is dominant in the aquifer. The Gibb's diagram reflects that evaporation, seawater interaction, and water–rock interaction are the foremost processes impacting groundwater quality, besides other regional environmental variables. A strong positive correlation was declared between TDS and Na^+, Mg^{2+}, Ca^{2+}, Cl^-, $SO_4{}^{2-}$ in addition to TH with Mg^{2+}, Ca^{2+}, Cl^-, $SO_4{}^{2-}$, TDS, and also Cl^- with Na^+, Ca^{2+}, Mg^{2+} were major connections, with correlation coefficients over 0.8 and $p < 0.0001$. The extracted factor analysis observed that TH, Ca^{2+}, TDS, Cl^-, and Mg^{2+} have high positive factor loading in Factor 1, with around 52% of the total variance. This confirms the roles of evaporation and ion exchange as the major processes that mostly affect groundwater quality, along with very little human impact. The spatial distribution maps of the various water quality indices showed that the majority of unsuitable groundwater samples were falling along the coast where there is overcrowding and a variety of anthropogenic activities and the possible impact of seawater intrusion. The results of the hierarchical cluster analysis agreed with the correlations mentioned in the factor analysis and correlation matrix. As a result, incorporating physicochemical variables into the PCA to assess groundwater quality is a practical and adaptable approach with exceptional abilities and new perspectives. According to the study's findings, incorporating different techniques to assess groundwater quality is beneficial in understanding the factors that control groundwater quality and can assist officials in effectively controlling groundwater quality and also enhancing the water resources in the study area.

Keywords: water quality indices; multivariate statistical approaches; principal component analysis; GIS

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1. Introduction

In arid and semi-arid regions such as Saudi Arabia, groundwater is the most essential water resource. Saudi Arabia ranks among the driest and hottest countries. The Kingdom's yearly average precipitation varies between 80 and 140 mm, with summer temperatures frequently exceeding 45 °C. High temperatures and low precipitation make Saudi Arabia one of the world's most water-short countries [1,2]. Water consumption has increased from 227 L/c/d in 2009 to 278 L/c/d in 2018 [3]. Groundwater, desalinated water, treated sewage, and renewable surface sources meet the Kingdom's water requirements. According to Chowdhury and Al-Zahrani [4], the yearly recharge was recorded for the non-renewable groundwater reservoirs as 886 MCM, and overall precipitation water recharge as 2.4 BCM, while the yearly water production from the desalination facilities was 1.06 BCM. Up until now, new desalination plants have been created to comply with expanding domestic water needs.

The Jazan region occupies the southwestern part of Saudi Arabia. It is a fast expanding coastal city and an important Red Sea port, offering a wide variety of aqua products [5]. It is also one of the most tempting tourist sites in Saudi Arabia due to its varied topography and geology, including farmland, sandy coasts, muddy shores, beautiful islands, valleys, and high mountains [6]. It is home to a number of heavy and light industries, containing petrochemical plants, sewage treatment plants, cement stations, oil refineries, energy and desalination plants, as well as the Jazan Marine Port. Until now, this region has been challenged by a number of geological hazards such as sabkhas, sand dunes, wind erosion, salt domes, and frequent flash floods. These geological hazards are catastrophic situations that can result in environmental destruction [7]. The demand for water in the province is driven by industry, agriculture, and residential needs, and is projected to increase in the future. To promote the long-term usage of water resources in Jazan, it is important to assess the current situation, identify the challenges and opportunities, and develop strategies for sustainable water use [8]. Jazan has limited water resources, with an average annual rainfall of less than 100 mm [9]. The main sources of water in Jazan are groundwater and desalinated water. Due to over-exploitation, the shallow coastal aquifer in the Jazan area is exposed to seawater salinization, where groundwater quality in the coastal plain area has deteriorated. Accordingly, groundwater in the inland areas is fresher than that close to the coast, which justifies the influences of seawater intrusion [10–12]. Al-Bassam and Hussein [13] have carried out 41 vertical electrical soundings to assess the aquifer system along the coastal zone of the Jizan area; their results indicated that the aquifer is hydraulically in contact with the seawater from the Red Sea. Afterward, Masoud et al. [14] proved that the water-bearing deposit, which is composed of gravel, coarse sand, and sand with clay interbedded, makes the groundwater in the coastal region inappropriate due to excessive salinity, TH, and major ion concentrations. In order to explore the general geochemical processes and determine the cause of salt in the groundwater throughout the Jazan aquifer, 80 groundwater samples were recently collected and examined in 2022 by Masoud et al. [15]. The findings show that evaporation and infiltration have a significant influence on the groundwater quality at the research site.

The Jazan Desalination Plant, which has a capacity of 150,000 m^3/day, produces desalinated water from seawater [16]. Water management challenges in Jazan are multifaceted, including climate change, over-extraction of groundwater, and a lack of sustainable water use practices. Over-extraction of groundwater has resulted in declining water levels and increased salinity, posing a threat to both agriculture and domestic use. Water shortage in the region is exacerbated by a lack of sustainable water use practices, such as efficient irrigation techniques and the reuse of treated wastewater [12,16]. Several researchers have already discussed various geotechnical properties and the ecological pollution of Jazan's aquifer, as Mogren [12] who used vertical electrical sounding (VES) surveys to study the marine ecosystem confirmed that the current water wells in Jazan's coastal zone are hazardous because of the pollution of the shallow groundwater aquifer by seawater interference. Additionally, Alfaifi et al. [17] used multivariate statistical techniques to assess groundwater quality; the findings revealed that anthropogenic and ecological causes such as herbicides, pesticides, and fertilizers from agricultural operations had an impact on groundwater quality. Alnashiri [18] studied numerous heavy metals that were found in the waste waters of several cities in the Jazan Region. According to the research, Cd and Mn were present in high concentrations in all samples compared to permissible standards. Likewise, Masoud et al.'s [19] study indicates that 85% of wells are unfit for usage because of excessive hardness and salinity, which are obtained from evaporation, saline sources, and anthropogenic activity. They also discovered that wells with poor quality groundwater appeared on the shoreline.

These facts add to the release of significant metal concentrations into the aquatic environment, changing chemical and biological parameters, which have a direct influence on the Red Sea marine ecology. Subsequently, to guarantee long-term viability water in Jazan, it is important to adopt a holistic approach that integrates traditional groundwater management practices with modern technologies and governance.

Restoring groundwater and/or providing alternate water sources may be costly, so groundwater quality assessment may determine a significant portion of this investment. As a result, gathering valuable data on groundwater quality is technically challenging, encompassing transportation, collection, and experimental analysis. The designer of a groundwater quality assessment program must comprehend, identify, and be aware of the many monitoring techniques that may be used [20].

Several techniques may be used to evaluate the groundwater quality: (1) water quality index approach; (2) statistical analysis approach; (3) trophic status index approach; and (4) biological analysis approach [21]. Nowadays, a range of multivariate statistical approaches are being employed for reliable data analysis, interpretation, and impact factor determination due to the expansion in the physical and chemical characteristics of groundwater, such as by cluster analysis (CA), factor analysis (FA), principal components analysis (PCA), and discriminant analysis (DA) [22]. Recently, groundwater resources in Makkah Al-Mukarramah province, Saudi Arabia, with similar climatic attributes as the study area were assessed using numerous water quality indices (WQIs), GIS technologies, and the partial least squares regression model (PLSR). The findings indicated that 95% of the wells needed proper treatment since they were poor and unsuitable for use [23].

Several studies around the world used the above methods to assess physico-chemical parameters such as electrical conductivity (EC), total dissolved solids (TDS), hydrogen ion concentration (pH), sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), and calcium (Ca^{2+}). The concentrations of these parameters refer to the different contamination levels of groundwater affected by residential, industrial, municipal, agricultural, and commercial activities.

Krishna Kumar et al. [24] and Kaur et al. [25] used the Gibbs diagram, the piper trilinear diagram, and the water quality index (WQI) classification on samples from the study area in India and discovered that a significant percentage of observations fall into the excellent to good water category and are acceptable for use as drinking water. Nazzal et al. [26] used statistical methods to analyze the data distribution, such as histograms, and quantile plots for each interval variable to visualize the extent to which variables are normally distributed. According to the findings of the KSA study, all of the metal pairs have positive relationships. Boateng et al. [27] used PCA, CA, and the WQI in Ghana, and the results showed that with the exception of phosphate, all physico-chemical measurements were found to be below WHO permitted limits for drinkable water. Eldaw et al. [28] developed_irrigation_water quality index (IWQI) for rating the water quality of shallow and deep aquifers in North Sudan, and the findings showed that most samples are suitable for irrigation. Several recent studies in various countries around the world, including Egypt [29–34], Indonesia [35,36], Bangladesh [37], Saudi Arabia [38], Turkey [39], and Algeria [28], used different hydrochemistry, graphical plots, and multivariate statistical analyses to assess the groundwater quality. As a result, they discovered that incorporating various techniques to assess groundwater quality is beneficial in understanding the factors that control groundwater geochemistry, and can aid in administering and handling groundwater quality effectively.

The objectives of this research are to investigate the hydro-geochemistry of groundwater in the Jazan coastal aquifer; identify the main processes influencing the ion enrichment of the groundwater; and, finally, evaluate the suitability of groundwater for irrigation purposes. These could be achieved using physicochemical parameters, different water quality indices, multiple graphical approaches (GIS), and multivariate statistical analysis.

2. Materials and Methods

2.1. Study Area Describtion

The study area, including locations along a coastal strip that extends for a distance of 300 km, has a boundary between longitudes 42°31′20″ and 43°20′16″ East and latitudes 16°49′40″ and 17°25′13″ North as shown in (Figure 1). Jazan has a total area of 12,200 km^2, 19 m above sea level. There are more than 80 islands in the Red Sea area, the most famous of which are the Farsan Islands. The area covers an area of 16,000 km^2, with a percentage of 0.7% of the total area of the Kingdom.

Jazan's climate is defined as dry, with an annual average relative humidity of 68%; the average high temperature during the moderate summer is 38.5 °C and the average low temperature is 30 °C during the winter [16]. The evaporation is about 2600 mm/year and yearly precipitation is about 1.3 cm. Dominant winds range in speed from 2 to 50 km/h, coming out of the west in the summer and the southwest in the winter [6,40].

Geologically, the majority of the study area is alluvial, generated by the soil eroding via the main valleys and drainage canals that drain into the sea from the land. The interaction of brackish groundwater and marine sediments is the primary source of Cl^- in the soil [41]. Quaternary sediments fill the 40 km wide coastal plain of Jazan, which is surrounded by 5 km Quaternary and Tertiary sediments [17].

The shallow alluvial aquifer is composed mainly of the Quaternary wadi deposits [10]. The maximum thickness of the water bearing formation is more than 100 m, which varies in depth from 5 m to 35 m [13]. Transmissivity values range from 540 to 5400 m^2/day (avg. 2190 m^2/day), which indicates the aquifer has good storage and conductive properties that enhance horizontal seawater intrusion into the aquifer. The main recharge components of the aquifer are from flood spates that fall directly at the east and southeastern elevated areas, and/or from local surface water infiltrations through the wadi beds [12,42].

2.2. Sampling and Analysis

To consider a good representation of the spatial variability of quality indicators across the section of water quality monitoring, sampling locations were selected carefully throughout the study area; 180 samples were collected from both public and private shallow dug wells, and boreholes tapping the Quaternary alluvial aquifer were collected (Figure 1). Most of these wells are used for domestic and agricultural purposes within Jazan province. The depths of the wells sampled ranged from 15 to 97 m above sea level.

The water samples were collected in 1 L polyethylene bottles. To reduce the possibility of contamination, these bottles were disinfected before being filled with water. The samples were preserved, collected, and analyzed in accordance with the protocols established by the American Public Health Association (APHA) [43]. Field measurements such as temperature, total dissolved solids TDS, electrical conductivity EC, and pH were all measured in the field. The field pH values were determined using the digital pH meter (Model Cole Parmer). EC was determined using the EC meter (Model WPA cm 35).

The major cations (Na^+, Mg^{2+}, K^+, and Ca^{2+}) were examined using an atomic absorption spectrophotometer. Chloride (Cl^-) and bicarbonate (HCO^{3-}) were investigated using volumetric methods. Sulfate ($SO_4{}^{2-}$) was determined using a turbidimetric method. Ion chromatography was used to analyze nitrate ($NO_3{}^-$). To assess the variability of groundwater data resulting from sample collection and laboratory analysis, all samples were collected in duplicate and analyzed in replicate. The chemical analysis results were checked for reliability against the anion–cation balance, where the assessment of the quality control data resulted in <5% error from the different replicates.

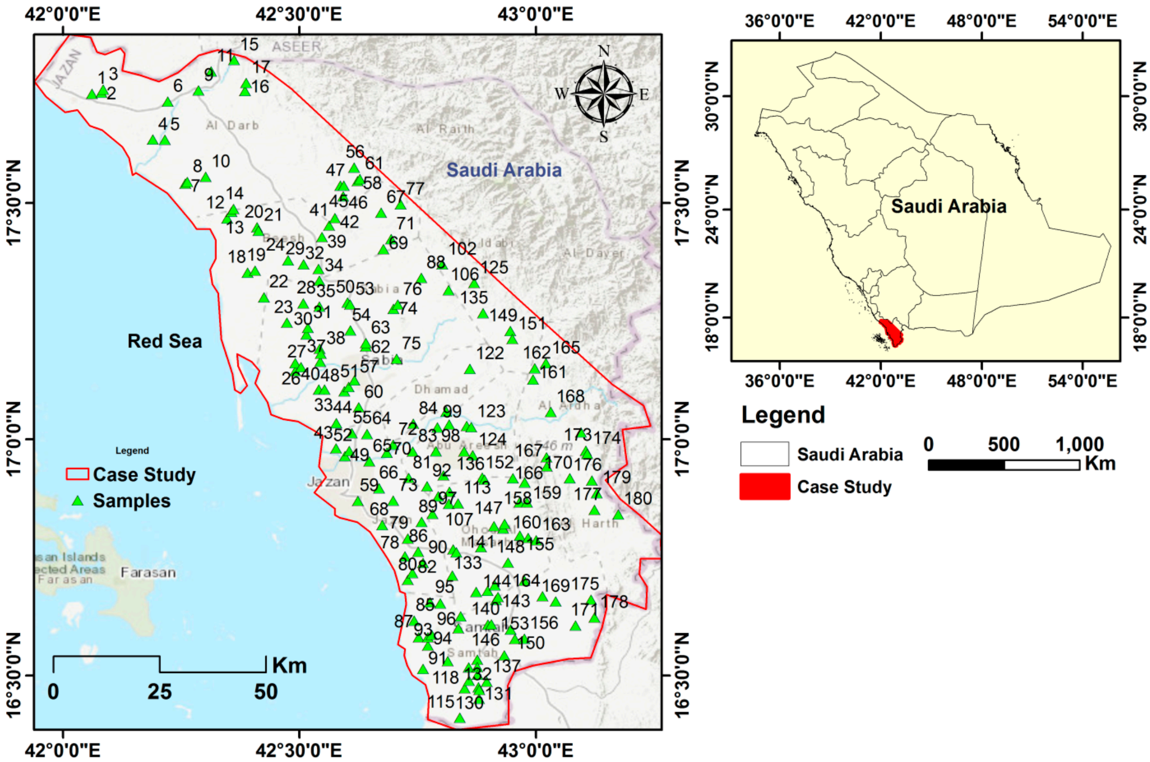


Figure 1. The study area and locations of samples.

2.3. Data Processing and Analysis

The adequacy of the water for irrigation was determined using the groundwater quality metrics used globally for evaluating water suitability, i.e., EC, Na%, SAR, PS, KR, MH, PI, CAI-I, and CAI-II. The equations in Table 1 are used to calculate these parameters. All concentrations were given in milliequivalents per liter. Moreover, the spatial distribution maps of the water quality indices were interpreted using ArcGIS with the inverse distance weighted (IDW) technique to categorize groundwater and determine if it is suitable for agricultural use by determining various factors based on the chemical parameters of water.

Table 1. Different water quality indices (WQIs) formulas were used in this study.

Equation	Description	Source
$\mathrm{Na\%} = \frac{(\mathrm{Na^{2+}}+\mathrm{K^{+}})}{(\mathrm{Ca^{2+}}+\mathrm{Mg^{2+}}+\mathrm{Na^{2+}}+\mathrm{K^{+}})} \times 100$	Sodium percentage (Na%)	[44]
$\mathrm{SAR} = \frac{\mathrm{Na^{2+}}}{\sqrt{(\mathrm{Ca^{2+}}+\mathrm{Mg^{2+}})/2}}$	Sodium Adsorption Ratio (SAR)	[45]
$\mathrm{PS} = \mathrm{Cl^{-}} + \frac{1}{2}\mathrm{SO_4^{2-}}$	Potential salinity (PS)	[46]
$\mathrm{KR} = \frac{\mathrm{Na^{2+}}}{(\mathrm{Ca^{2+}}+\mathrm{Mg^{2+}})}$	Kelley's ratio	[47]
$\mathrm{MH} = \frac{\mathrm{Mg^{2+}}}{(\mathrm{Ca^{2+}}+\mathrm{Mg^{2+}})} \times 100$	Magnesium hazard	[44]
$\mathrm{PI} = \frac{\mathrm{Na^{+}} \pm \sqrt{\mathrm{HCO_3^{-}}} \times 100}{\mathrm{Ca^{+2}}+\mathrm{Mg^{+2}}+\mathrm{Na^{+}}+\mathrm{K^{+}}}$	Permeability index	[46]
$\mathrm{CAII} = \mathrm{Cl^{-}} - \frac{(\mathrm{Na^{+}}+\mathrm{K^{+}})}{\mathrm{Cl^{-}}}$ $\mathrm{CAIII} = \mathrm{Cl^{-}} - \frac{(\mathrm{Na^{+}}+\mathrm{K^{+}})}{[\mathrm{SO_4^{2-}}+\mathrm{HCO_3^{-}}+\mathrm{NO_3^{-}}+\mathrm{CO_3^{2-}}]}$	Chloroalkaline Index (CAI)	[48]

3. Results and Discussion

3.1. Ionic Dominance

The whisker and box plots of anionic and cationic dominance are shown in Figure 2. The figure shows that the cationic dominance was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the anionic dominance was $Cl^- > SO_4^{2-} > HCO_3^- > NO_3^-$. Ion dispersion in water samples links to the interaction of water and rock, which occurs as water flows through the ground and reacts to different degrees with nearby minerals and other components [49]. Furthermore, the presence of alkali earth elements (Ca^{2+} + Mg^{2+}) in excess of HCO_3^- in some groundwater samples of the study area suggests that they are provided by reverse ion exchange reactions within the aquifer.

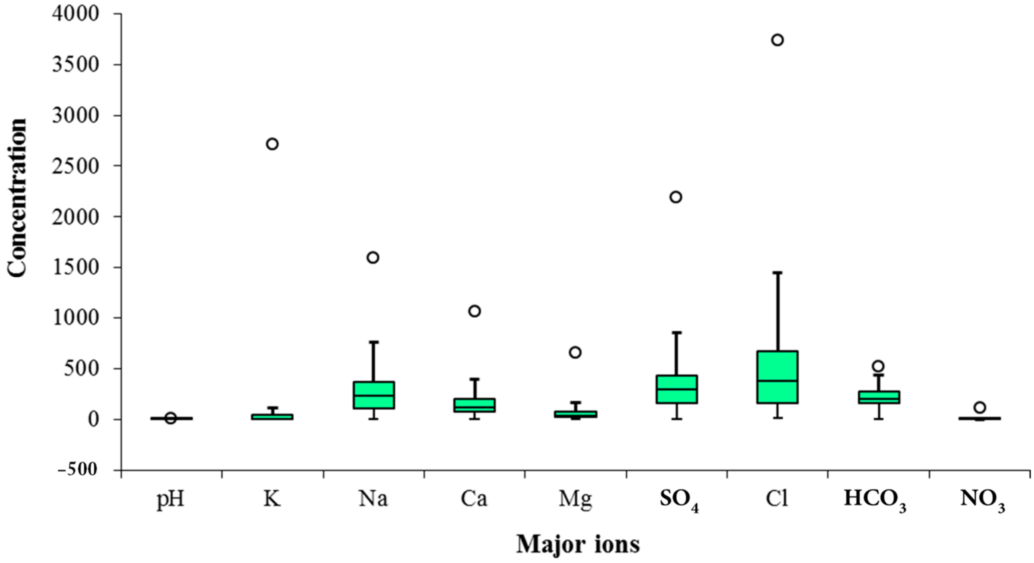


Figure 2. Box plot showing a comparison of major ion concentration (mg/L) in the groundwater samples of the study.

3.2. Irrigation Water Quality Assessment

The following groundwater hydro-chemical parameters are important in determining its suitability for irrigation: EC, Na%, SAR, PI, PS, KR, MH, CAI-I, and CAI-II. The results of the statistical analysis for all of the water quality indicators are shown in Tables 2 and 3 and Figure 3. According to Table 3, the observed EC values for groundwater samples from the study area range from good to unsuitable for irrigation, with 10% being good, 43% being permissible, and 47% being improper for irrigation (Table 3 and Figure 3a). SAR values for groundwater samples range from 0.11 to 41.7, with an average of 8.25 (Table 2 and Figure 3c). According to the SAR classification, the SAR values for 91.67% of groundwater samples in the study area range from good to excellent for irrigation (Table 3), showing that they are suited for irrigation with no sodium-related adverse effects. In terms of PI values, 77% of the groundwater samples are moderately suitable for irrigation, while the remaining 21% are good and 2% are poor (Table 3 and Figure 3d). Potential salinity PS values range from 0.95 to 117 meq/L, with an average of 20 meq/L. It indicates that 7.87% of the collected groundwater samples are excellent to good for irrigation, 8.89% are good to injurious, and the majority (83.33%) are injurious to unsatisfactory for irrigation uses (Table 3 and Figure 3e). Magnesium hazard values indicate that 1.67% of the samples are unsuitable for irrigation, while 98.33% are classified as suitable for irrigation purposes (Table 3 and Figure 3f). Based on Kelley's ratio (KR) values, about 45% of the groundwater samples are suitable for irrigation, while 55% have a Kelley's ratio of >1, indicating that the water is unsuitable for irrigation (Table 3 and Figure 3g). The PS, PI, and Cl^- vs. Na^+ and TDS correlations indicate that seawater has an impact on the hydrochemical conditions of the studied area, particularly its southeastern coast, as shown in Figure 3.

Table 2. Statistical analysis for all of the water quality indicators.

	Minimum	Maximum	Average	Std. Deviation	Variance	Skewness	Kurtosis
Na%	1.9	97.1	56.06	16.21	262.83	−0.35	0.49
SAR	0.01	41.7	8.25	6.50	42.29	2.15	7.04
PI%	5.5	79.9	58.98	17.36	301.28	−0.10	−0.28
PS	0.95	117.0	19.89	20.47	419.14	2.43	7.34
MH%	4.0	56.9	24.36	9.61	92.26	1.05	1.17
KR	0.01	19.19	1.49	1.75	3.06	6.46	59.06
CAI (I)	−42.97	104.23	14.24	19.69	387.79	2.25	7.43
CAI (II)	−1.68	101.37	14.70	18.22	332.06	2.73	9.06
Gibbs ratio1	0.07	0.98	0.69	0.20	0.04	−0.59	−0.42
Gibbs ratio2	0.02	0.98	0.62	0.16	0.03	−0.73	1.30
r(Na + K)/rCl	0.03	43.27	1.78	3.42	11.71	10.22	121.17
rCa/rMg	0.74	47.69	3.99	4.00	16.01	8.03	81.42
rSO_4/rCl	0.06	19.50	1.00	1.69	2.85	7.82	80.57

Table 3. Classification of the different water quality indices (WQIs).

Water Quality Indices	Water Type	Range	No. of Samples	%
EC (μS/cm)	<250	Excellent	1	0.56
	250–750	Good	17	9.44
	750–2250	Permissible	77	42.78
	2250–5000	Doubtful	63	35.00
	>5000	Unsuitable	22	12.22
The sodium percentage (Na%)	<20	Excellent	3	1.67
	20–40	Good	24	13.33
	40–60	Permissible	78	43.33
	60–80	Doubtful	65	36.11
	>80	Unsuitable	10	5.56
Sodium adsorption ratio (SAR)	<10	Excellent	131	72.78
	10–18	Good	34	18.89
	18–26	Doubtful	11	6.11
	>26	Unsuitable	4	2.22
Permeability Index (PI)	>75	Good	38	21.11
	75–25	Moderate	139	77.22
	<25	Poor	3	1.67
Potential salinity (PS)	<3	Excellent to good	14	7.78
	3–5	Good to injurious	16	8.89
	>5	Injurious to unsatisfactory	150	83.33
Magnesium hazard (MH)	>50%	Unsuitable	3	1.67
	<50%	Suitable	177	98.33
Kelley's ratio (KR)	>1	Unsuitable	99	55.00
	<1	Good	81	45.00

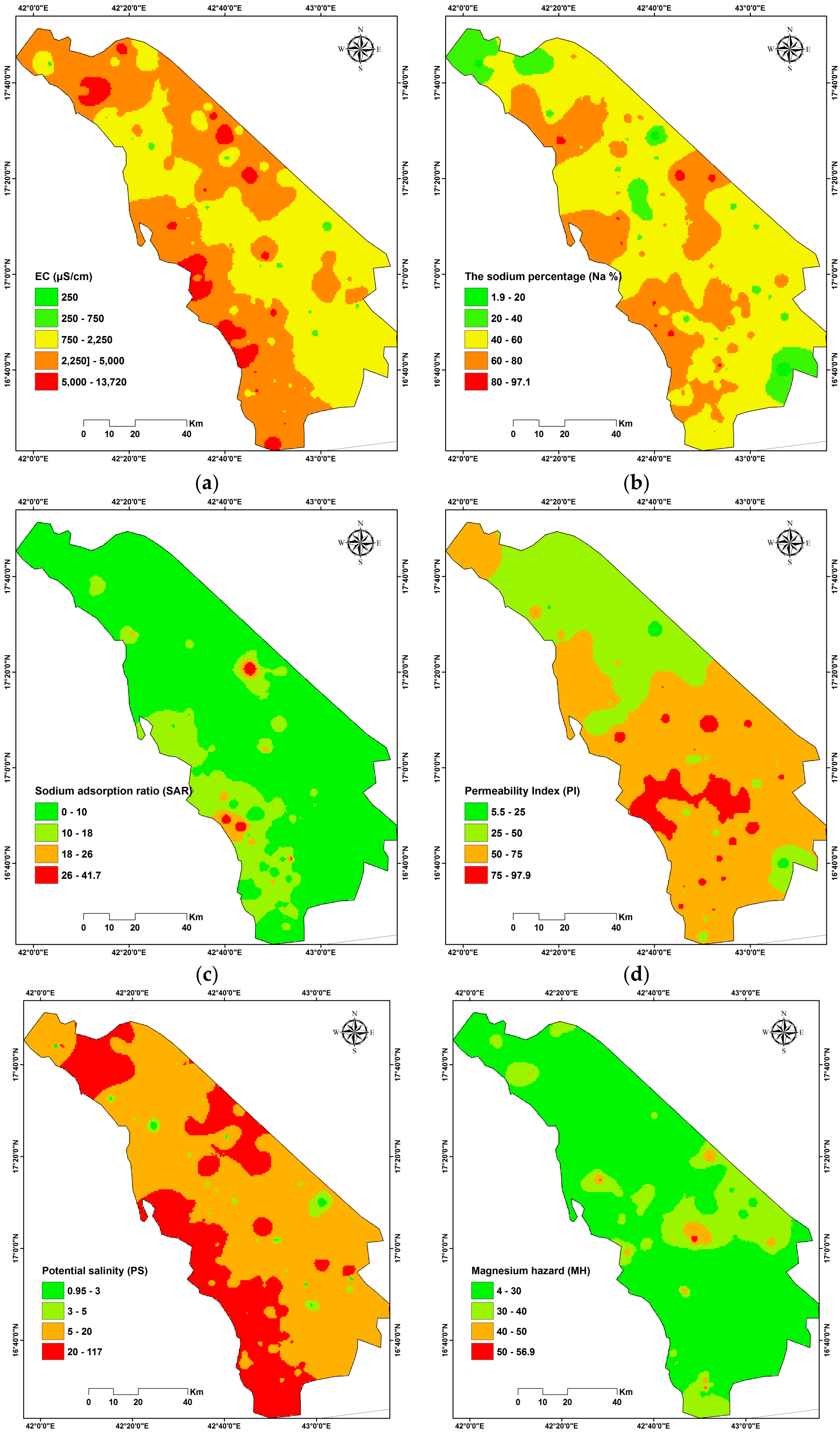
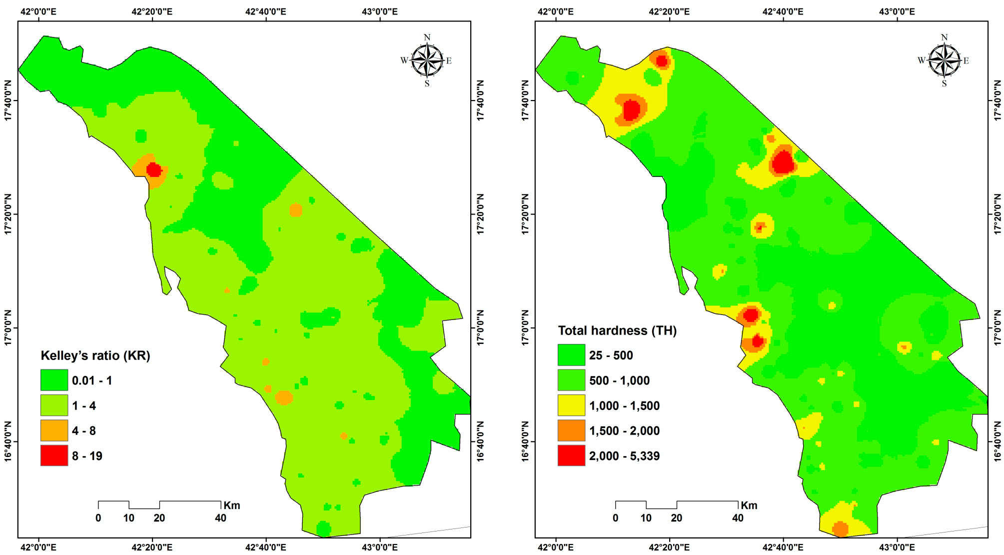


Figure 3. *Cont.*



(**g**) (**h**)

Figure 3. Special distribution for water quality indices: (**a**) EC; (**b**) the sodium percentage (Na%); (**c**) sodium adsorption ratio (SAR); (**d**) permeability Index (PI); (**e**) potential salinity (PS); (**f**) magnesium hazard (MH); (**g**) Kelley's ratio (KR); (**h**) total hardness (TH).

3.3. Ion Exchange Processes

3.3.1. Chloro-Alkaline Indices CAI-1 and CAI-II

The mechanism of water–rock interaction is critical for validating different variants in groundwater geochemical processes during their residence or transport in the groundwater. Schoeller [48] proposed the chloro-alkaline indices CAI-I, II, which indicate the exchange of sodium and/or potassium ions with calcium and/or magnesium ions between groundwater and its surrounding locations (the exchanger of aquifer materials, typically clay minerals). The chloro-alkaline indexes used in the base exchange assessment are determined by applying the formulas shown in Table 1. Positive values indicate ion exchange (direct base exchange) reactions, which involve the substitution of Na^+ and K^+ ions from groundwater for Ca^{2+} and Mg^{2+} ions from the aquifer substance. This process reduces the Ca^{2+} and Mg^{2+} content and increases the Na^+ concentration in the groundwater. While negative indices values indicate reverse ion exchange in the aquifer, this means that Ca^{2+} and Mg^{2+} ions form groundwater interactions with Na^+ and K^+ ions from the aquifer substance. According to the calculated values of the chloro-alkaline indices, the CAI-I values are ranging between −42.97 and 104.23 with mean values of 12.24, while CAI-II values lie between −1.68 and 101.37 with mean values of 14.70 (Table 2 and Figure 4). The results revealed that 88.89% of the CAI-I and 97.78% of the CAI-II values for the collected groundwater samples show positive ratios (direct base-exchange reaction). While the rest of the samples, 11.11% of the CAI-I and 2.22% of the CAI-II values, are negative chloro-alkaline indices, reflecting reverse ion exchange in the aquifer where the Ca^{2+} and Mg^{2+} in the aquifer matrix have been replaced by Na^+ at favorable exchange sites. The high chloride concentration detected in groundwater is mostly due to base exchange of Na^+ for Ca^{2+} and Mg^{2+} within the aquifer and/or agricultural return-flow.

3.3.2. Hydrochemical Ratios and Chemical Water Type

The hydrochemical parameters such as r(Na + K)/rCl, rCa/rMg, and rSO_4/rCl (meq/L) were used to determine the genesis of the groundwater and to detect any mixing processes in Jazan aquifer (Table 2). The ratio of r(Na + K)/rCl could be useful to detect the salinity sources of groundwater through the flow path. Approximately 57% of groundwater samples showed a ratio greater than unity reflecting the meteoric origin, where more Na was released from silicate weathering and ion exchange processes. The ratio of rCa/rMg suggests the dissolution of calcite and dolomite from the aquifer materials. Most of the groundwater samples (98%) showed a rCa/rMg ratio greater than unity, supporting the silicate weathering processes as well as gypsum and/or calcite dissolution. The rSO_4/rCl ratio is a good indicator for detecting any excess of sulphate in groundwater-associated gypsum dissolution. About 77% of groundwater samples showed rSO_4/rCl ratio less than unity, where the other 33% have a ratio greater than unity, which indicates a long residence time and an additional source of SO_4^{2-} from gypsum dissolution.

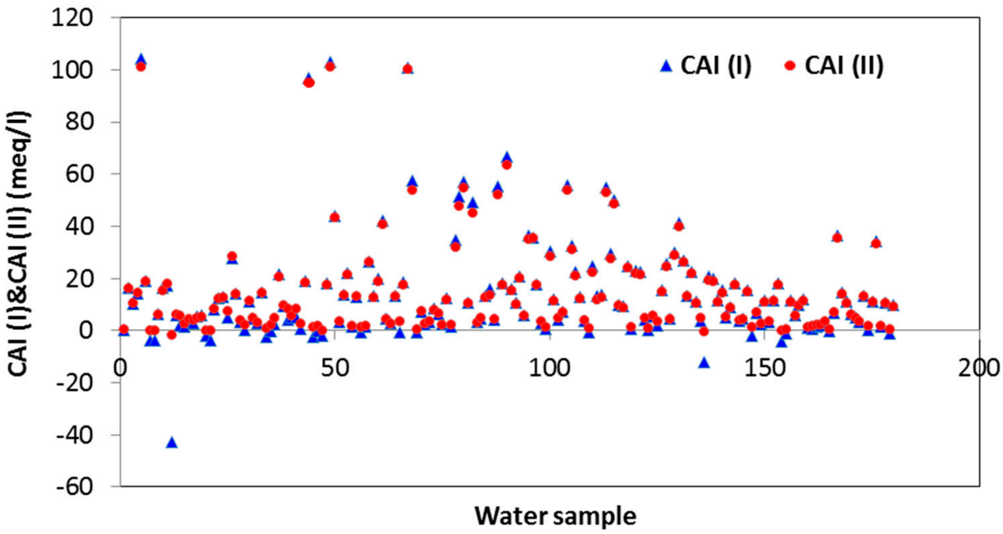


Figure 4. Scatter Plots of CAI-I and CAI-II for groundwater samples from the study area.

3.3.3. Mechanisms of Controlling Groundwater Chemistry

Gibbs [50] proposed a scatter diagram to describe the relationship among dissolved chemical constituents in groundwater and aquifer lithology, and this explains the mechanism of major ion chemistry of groundwater such as precipitation dominance, rock dominance, and evaporation dominance. The Gibbs diagram represents the ratio of dominant ions plotted against the TDS values in groundwater; it shows the three main important natural mechanisms controlling various hydrogeochemical processes including precipitation, evaporation, and rock dominance. The Gibbs ratio was determined using the formulas as follows:

$$\text{Gibbs ratio 1 (anion)} = \frac{Cl^-}{Cl^- + HCO_3^-}$$

$$\text{Gibbs ratio 2 (cation)} = \frac{Na^+ + K^+}{Na^+ + K^+ + Ca^{2+}}$$

According to the Gibb's diagram, all of the obtained groundwater samples are located in the evaporation and seawater mixing dominance areas (Figure 5). This denotes that the dominant processes controlling the quality of groundwater in the area are evaporation and seawater mixing processes, followed by water–rock interaction. Furthermore, the higher evaporation processes as a result of extreme aridity and the seawater intrusion and, to some extent, irrigation return-flow from the irrigated fields in the study area increase the salinity of groundwater. The contribution of seawater in groundwater varies from less than 0.01% in the western parts (inland areas) to 17% in the southeastern part (close to the coast), which justifies the influences of seawater intrusion along with cation exchange linked to seawater intrusion [10]. Therefore, Jazan province is heterogeneous in terms of hydrochemistry, and different factors may determine the composition of groundwater depending on the place of intake and its distance from the coast.

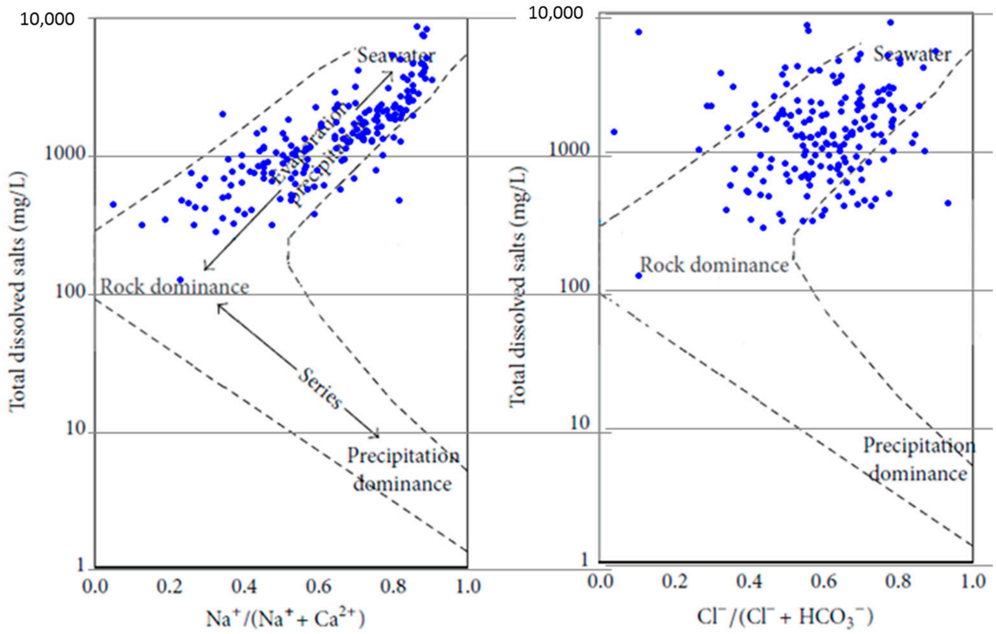


Figure 5. Gibbs Scatter diagram depicting the dominant mechanism controlling groundwater chemistry.

The scatter diagrams of Na^{+} versus HCO_3^{-} and Ca^{2+} + Mg^{2+} vs. HCO_3^{-} + SO_4^{2-} can assist with identifying the origin of these ions by analyzing the trend line created by these ions (Figure 6). The data plots showed that most of the groundwater samples suggest both ion exchange and, to some extent, reverse exchange processes. Figure 6a shows that the points are falling on both sides of the equiline 1:1, where approximately 66% of the groundwater samples are falling right below the equiline, indicating ion exchange process dominance which involves the depletion of Ca^{2+} + Mg^{2+} as compared to HCO_3^{-} + SO_4^{2-} (Figure 6a). Therefore, Na^{+} must balance the relative deficiency of Ca^{2+} + Mg^{2+} and the excess HCO_3^{-} + SO_4^{2-} as shown by the excess Na^{+} concentration (Figure 6b), where more Na^{+} is released from ion exchange processes and/or the dissolution of NaCl. Regarding the rest of the groundwater samples, 34% are falling left/above the equiline which involves the excess of Ca^{2+} + Mg^{2+} as compared to HCO_3^{-} + SO_4^{2-}, indicating reverse ion exchange [51], while the points approaching the equiline give an indication of silicate weathering as well as gypsum, anhydrite, calcite, and dolomite dissolution. Moreover, HCO_3^{-} is released from silicate and carbonate weathering to balance the Ca^{2+} + Mg^{2+} in the groundwater. Here, the weathering of silicate minerals regulates the concentration of major ions such as Na^{+}, Ca^{2+}, Mg^{2+}, and K^{+} in the groundwater [51].

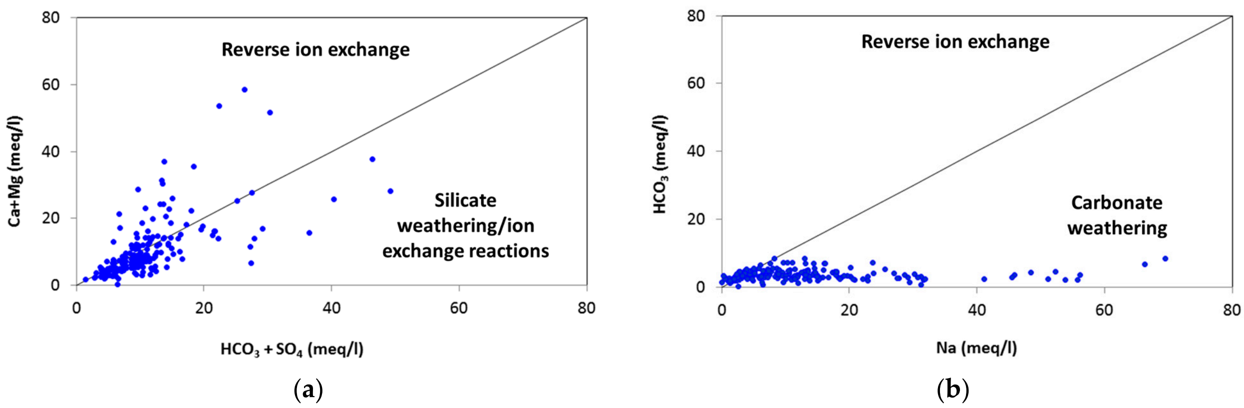


Figure 6. Plots of (**a**) Ca^{2+} + Mg^{2+} vs. HCO_3^{-} + SO_4^{2-} and (**b**) Na vs. HCO_3^{-} values for groundwater samples in the study area.

3.4. Principal Component Analysis (PCA)

3.4.1. Correlation Coefficients

Data reduction was aided by principal components analysis (PCA) to assess the clustering/similarities in the datasets, the consistency/overlap of the clusters, and to identify the sources of variation between parameters. Statistical analysis was carried out by calculating Pearson's correlation coefficient (r) value to identify relationships and differences between the groundwater samples using physico-chemical parameters and main ion concentration. The values were sorted according to the parameters so that the data could be analyzed. The correlation coefficient of all the variables (pH, K^+, Na^+, Mg^{2+}, Ca^{2+}, $SO_4{}^{2-}$, Cl^-, $HCO_3{}^-$, $NO_3{}^-$, TDS, and TH) were determined and tabulated as a matrix in Table 4, respectively.

Table 4. Correlation matrix (r) of studied physico-chemical parameters.

Variables	pH	K^+	Na^+	Mg^{2+}	Ca^{2+}	$SO_4{}^{2-}$	Cl^-	$HCO_3{}^-$	$NO_3{}^-$	TDS	TH
pH	**1**										
K^+	−0.239	**1**									
Na^+	−0.107	0.456	**1**								
Mg^{2+}	−0.251	0.274	0.424	**1**							
Ca^{2+}	−0.283	0.279	**0.505**	**0.795**	**1**						
$SO_4{}^{2-}$	−0.221	**0.577**	**0.590**	0.441	**0.580**	**1**					
Cl^-	−0.167	0.286	**0.809**	**0.786**	**0.805**	0.412	**1**				
$HCO_3{}^-$	−0.276	0.241	0.078	0.128	0.042	0.079	0.004	**1**			
$NO_3{}^-$	−0.043	0.489	0.166	0.193	0.248	0.479	0.089	0.131	**1**		
TDS	−0.228	0.426	**0.850**	**0.804**	**0.852**	**0.650**	**0.957**	0.094	0.230	**1**	
TH	−0.283	0.292	0.494	**0.937**	**0.957**	**0.545**	**0.841**	0.085	0.235	**0.876**	**1**

Note(s): **Bold** values indicate high correlation between variables.

Several parameters were shown to have statistically significant correlations with one another in the correlation matrix (Table 4). A strong positive correlation was declared between TDS and Na^+, Mg^{2+}, Ca^{2+}, Cl^-, and $SO_4{}^{2-}$ in addition to TH with Mg^{2+}, Ca^{2+}, Cl^-, $SO_4{}^{2-}$, and TDS, and also Cl^- with Na^+, Ca^{2+}, and Mg^{2+} were significantly related, with correlation coefficients over 0.8 and $p < 0.0001$, suggesting that these ions may have a similar source.

The observed salt combinations suggest the influence of seawater on the hydrochemical conditions of the studied area, especially its southeastern parts, i.e., close to the coast.

The observed salt combinations may be obtained through the erosion of rock salts, hydrated lime aquifers, and agricultural runoff flow. The nitrate content is most likely due to human activity. In addition, the correlation matrix shows significant positive correlations between Mg^{2+} with Ca^{2+} and Cl^-, with correlation coefficients over 0.75 and $p < 0.0001$; this demonstrated the significant reliance of hardness on calcium, magnesium, and chloride. The moderate correlation between $SO_4{}^{2-}$ with K^+, Na^+, Mg^{2+}, and Ca^{2+}, highlights the presence of limy magnesium minerals in the aquifer.

3.4.2. Factor Analysis

Factor analysis (FA) explains the correlations among findings of the dependent variables, which are not directly measurable [29]. It decreases as attributes range from an excessive number of variables to a lesser number of factors. The variables with similar characteristics were grouped, and some excessive information was removed. Some new factors were produced, which might be the linear group of original variables and could explain the observed variance in the more significant number of variables.

Table 5 displays the findings of the factor analysis, along with the factor-loading matrix, total cumulative variance, eigenvalues, and community values. From the principal components analysis, three factors were extracted that accounted for 77.18% of the total variance. The extracted factor observed that TH, Ca^{2+}, TDS, Cl^{-}, and Mg^{2+} have high positive factor loading in Factor 1, with around 52% of the total variance; it suggests that these parameters are caused by higher evaporation processes as a result of extreme aridity, seawater intrusion, cation exchange related to seawater intrusion, and irrigation return-flow. Factor 2, which describes 14.37% of the total variance, has positive loading for NO_3^{-} and K^{+}; this element may be related to human sources, such as household and agricultural land recharge. Factor 3 accounts for 10.7% of the total variance. It has a positive load factor on the variables of pH, and HCO_3^{-}, implying that it is a comprehensive measure of groundwater alkalinity. A biplot of F1 axis vs. F2 axis based on principal component analysis of sample element concentrations is shown in Figure 7.

Table 5. Factor-loading matrix, eigenvalues, total, and cumulative variance values of the study area.

	F1	F2	F3
pH	0.103	0.058	0.487
K^{+}	0.272	0.441	0.021
Na^{+}	0.574	0.000	0.071
Mg^{2+}	0.719	0.054	0.034
Ca^{2+}	0.801	0.040	0.006
SO_4^{2-}	0.515	0.155	0.061
Cl^{-}	0.802	0.114	0.002
HCO_3^{-}	0.022	0.222	0.382
NO_3^{-}	0.124	0.428	0.092
TDS	0.950	0.018	0.004
TH	0.850	0.051	0.018
Eigenvalue	5.731	1.581	1.178
Variability (%)	52.097	14.374	10.708
Cumulative%	52.097	66.472	77.180

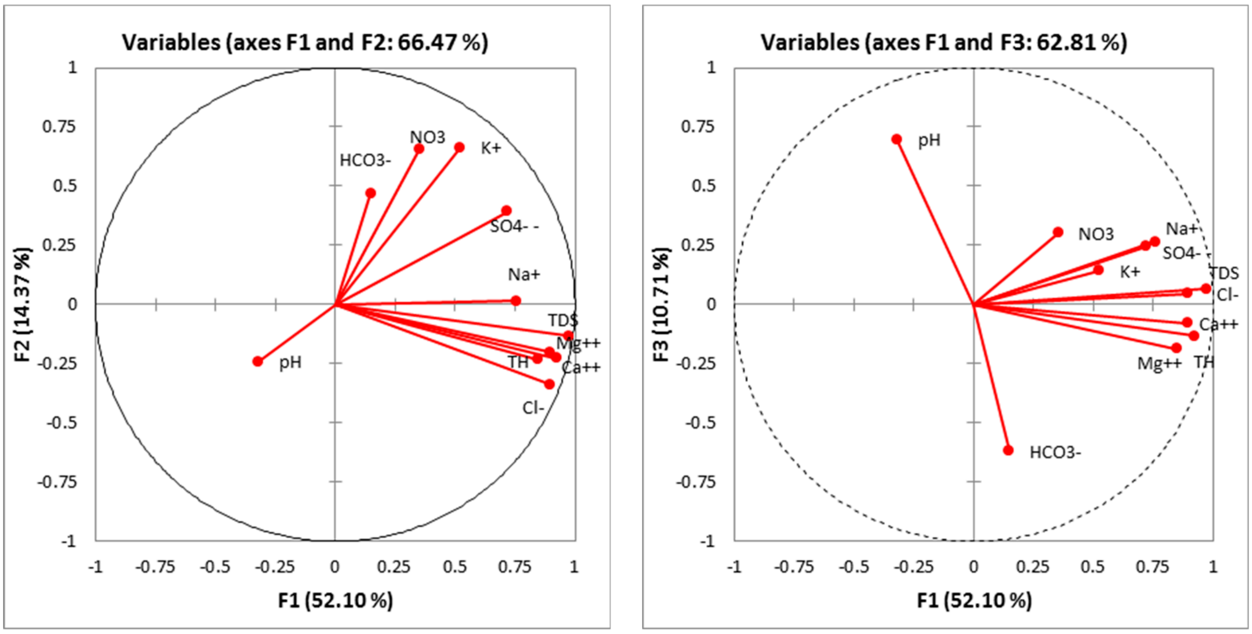


Figure 7. Biplot of F1 axis vs. F2 axis and F3 axis based on principal component analysis of sample element concentrations.

3.5. Hierarchical Cluster Analysis (HCA)

The objective of hierarchical cluster analysis (HCA) is to find homogenous subgroups of instances within a set of groups that reduce within-group variance while maximizing between-group variation. This method produces dendrograms, which reflect the relative magnitude of the proximity coefficients at which examples are joined (Figure 8).

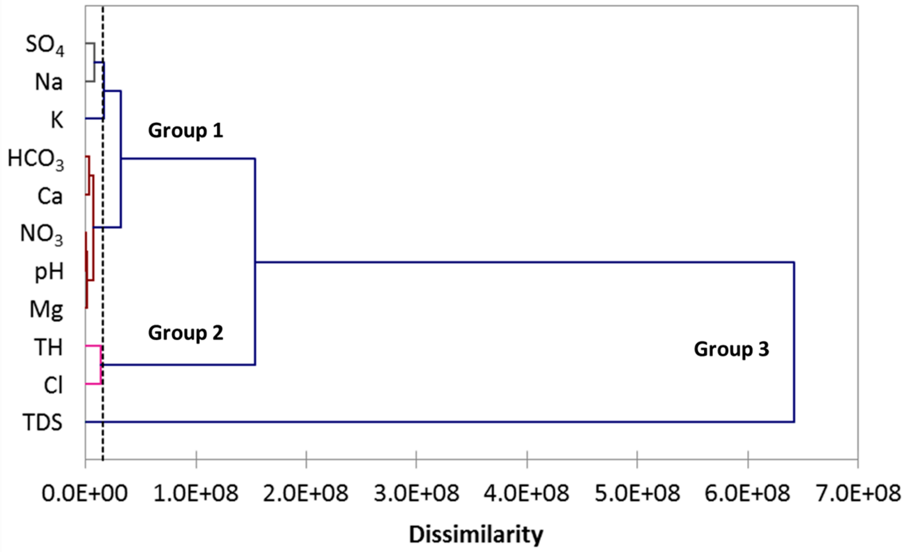


Figure 8. Cluster tree of the variables for water samples (measure: Pearson's correlation coefficient; linkage method: furthest neighbors).

Taking both the outputs of the cluster tree and the geochemical parameters of the variables into account, they may be broadly categorized into three major groups. Parameters (pH, K^+, Na^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, HCO_3^-, NO_3^-) were all part of (Group 1) with very good correlation. Parameters (Cl^-, TH) constructed (Group 2); this group is closely related to Group 1, which indicates that the rise in the concentration of some factors may be the same. (Group 3) consisted of Groups 1 and 2 with TDS. The findings were in agreement with the correlations mentioned in the factor analysis and correlation matrix. As a result, adding physico-chemical variables to the PCA to assess groundwater quality is a practical and adaptable approach with an extraordinary ability and new perspectives.

4. Conclusion and Recommendations

The present study uses a combination of primary and secondary data sources, including field surveys, GIS, and statistical analysis, to provide a comprehensive overview of the groundwater situation in Jazan. The major dominant mean concentrations for cations are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the anions are $Cl^- > SO_4^{2-} > HCO_3^- > NO_3^-$. Most of the samples were classified as suitable and within the permissible limits, but the presence of unsuitable samples along the coastal strip was highlighted. This is seen as a critical environmental concern that has a negative impact on the region's blue economy and coastal ecosystems. Chloro-alkaline indices calculations show that 88.89% of the CAI-I and 97.78% of the CAI-II values for the collected groundwater samples show positive ratios, indicating exchange of Na^+ and K^+ from water with Mg^{2+} and Ca^{2+} from the rock, hence the dominance of the direct base-exchange reaction in the aquifer. Gibb's diagram suggests evaporation is the predominant process, followed by rock–water interaction controlling the ion concentrations in groundwater. Taking both the outputs of the cluster tree and the geochemical parameters of the variables into account, they may be broadly categorized into three major groupings with very good correlation for parameters (pH, K^+, Na^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, HCO_3^-, NO_3^-, Cl^-, TH, and TDS), suggesting that these ions may have a similar source. As a result, including physicochemical factors into the hierarchical cluster analysis and principal component analysis to assess groundwater quality is a practical and flexible approach with exceptional capability and innovative perspectives.

The study findings are consistent with those of Abdalla [10], Mogren [12], and [13], who reported on the role of seawater intrusion and ion exchange processes associated with seawater intrusion in regulating groundwater salinity. According to the findings of the study, sustainable groundwater management in Jazan requires a comprehensive approach that combines traditional water management practices with modern technologies and governance. The current study may be useful in assisting planners and decision-makers in safeguarding our limited groundwater resources for future generations.

It can be concluded that long-term scenarios, such as establishing a seawater intrusion monitoring well network, injection wells along the coast as a managed aquifer recharge, and water quality monitoring measures, can be implemented to reduce or control the deterioration of groundwater quality in the study area. The investigation of the aforementioned management scenarios can be considered in future work.

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References

1. Alkolibi, F.M. Possible effects of global warming on agriculture and water resources in Saudi Arabia: Impacts and responses. *Clim. Chang.* **2002**, *54*, 225–245. [CrossRef]
2. Sharma, S.K. A novel approach on water resource management with Multi-Criteria Optimization and Intelligent Water Demand Forecasting in Saudi Arabia. *Environ. Res.* **2022**, *208*, 112578. [CrossRef]
3. Fazel, H.K.; Abdo, S.M.; Althaqafi, A.; Eldosari, S.H.; Zhu, B.-K.; Safaa, H.M. View of Saudi Arabia Strategy for Water Resources Management at Bishah, Aseer Southern Region Water Assessment. *Sustainability* **2022**, *14*, 4198. [CrossRef]
4. Chowdhury, S.; Al-Zahrani, M. Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia. *J. King Saud Univ. Sci.* **2015**, *27*, 68–82. [CrossRef]
5. MEWA (Ministry of Environment Water & Agriculture). Anural Report. 2021. Available online: https://www.mewa.gov.sa/ar/Pages/default.aspx (accessed on 15 January 2023).
6. Alzubieri, A.G.; Bantan, R.A.; Abdalla, R.; Antoni, S.; Al-Dubai, T.A.; Majeed, J. Application of GIS and remote sensing to monitor the impact of development activities on the coastal zone of Jazan City on the Red Sea, Saudi Arabia. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2018**, *XLII-3/W4*, 45–50. [CrossRef]
7. Youssef, A.M.; Pradhan, B.; Sabtan, A.A.; El-Harbi, H.M. Coupling of remote sensing data aided with field investigations for geological hazards assessment in Jazan area, Kingdom of Saudi Arabia. *Environ. Earth Sci.* **2012**, *65*, 119–130. [CrossRef]
8. Zanaty, N.; Mansour, K.; Fathi, H. Satellite-based assessment of the anthropogenic impacts on environmental sustainability in Jazan region, Red Sea. *Egypt. J. Remote. Sens. Space Sci.* **2023**, *26*, 117–127. [CrossRef]
9. SODP (Saudi Open Data Portal). Available online: https://od.data.gov.sa/en/home (accessed on 15 January 2023).
10. Abdalla, F. Ionic Ratios as Tracers to Assess Impacts of Seawater Intrusion into a Coastal Aquifer, Jazan, Saudi Arabia. *Arab. J. Geosci.* **2016**, *9*, 40. [CrossRef]
11. SWPC (Ministry of Environment Water & Agriculture). Seven Year Statement for KSA's Water. Available online: https://idadesal.org/wp-content/uploads/2020/09/SWPC-7-Year-planning-Statement-2020-%E2%80%93-2026-Eng.pdf (accessed on 15 January 2023).
12. Mogren, S. Saltwater Intrusion in Jizan coastal zone, southwest Saudi Arabia, inferred from geoelectric resistivity survey. *Int. J. Geosci.* **2015**, *6*, 286. [CrossRef]
13. Al-Bassam, A.M.; Hussein, M.T. Combined Geo-Electrical and Hydro-Chemical Methods to Detect Salt- Water Intrusion. *Manag. Environ. Qual. Int. J.* **2008**, *19*, 179–193. [CrossRef]
14. Masoud, M.H.; Basahi, J.M.; Rajmohan, N. Impact of flash flood recharge on groundwater quality and its suitability in the Wadi Baysh Basin, Western Saudi Arabia: An integrated approach. *Environ. Earth Sci.* **2018**, *77*, 395. [CrossRef]

15. Masoud, M.; Rajmohan, N.; Basahi, J.; Schneider, M.; Niyazi, B.; Alqarawy, A. Integrated Hydrogeochemical Groundwater Flow Path Modelling in an Arid Environment. *Water* **2022**, *14*, 3823. [CrossRef]
16. El-Hamid, A.; Hazem, T.; Hafiz, M.A.; Wenlong, W.; Qiaomin, L. Detection of environmental degradation in Jazan region on the Red Sea, KSA, Using mathematical treatments of remote sensing data. *Remote Sens. Earth Syst. Sci.* **2019**, *2*, 183–196. [CrossRef]
17. Alfaifi, H.; El-Sorogy, A.S.; Qaysi, S.; Kahal, A.; Almadani, S.; Alshehri, F.; Zaidi, F.K. Evaluation of heavy metal contamination and groundwater quality along the Red Sea coast, southern Saudi Arabia. *Mar. Pollut. Bull.* **2021**, *163*, 111975. [CrossRef] [PubMed]
18. Alnashiri, H.M. Assessment of physicochemical parameters and heavy metal concentration in the effuents of sewage treatment plants in Jazan Region, Saudi Arabia. *J. King Saud Univ. Sci.* **2021**, *33*, 101600. [CrossRef]
19. Masoud, M.H.; Rajmohan, N.; Basahi, J.M.; Niyazi, B.A. Application of water quality indices and health risk models in the arid coastal aquifer, Southern Saudi Arabia. *Environ. Sci. Pollut. Res.* **2022**, *29*, 70493–70507. [CrossRef]
20. Chapman, D.V.; World Health Organization; UNESCO; United Nations Environment Programme. *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring*, 2nd ed.; Deborah, C., Ed.; E & FN Spon: New York, NY, USA, 1996; Available online: https://apps.who.int/iris/handle/10665/41850 (accessed on 5 January 2023).
21. El-Rawy, M.; Fathi, H.; Abdelrady, A.; Negm, A.M. Environmental Impacts of Treated Wastewater Contaminates on Groundwater Quality in the Nile River Valley, Egypt. In *Sustainability of Groundwater in the Nile Valley, Egypt*; Springer International Publishing: Cham, Switzerland, 2022; pp. 91–120.
22. Taşan, M.; Demir, Y.; Taşan, S. Groundwater quality assessment using principal component analysis and hierarchical cluster analysis in Alaçam, Turkey. *Water Supply* **2022**, *22*, 3431–3447. [CrossRef]
23. El Osta, M.; Masoud, M.; Alqarawy, A.; Elsayed, S.; Gad, M. Groundwater Suitability for Drinking and Irrigation Using Water Quality Indices and Multivariate Modeling in Makkah Al-Mukarramah Province, Saudi Arabia. *Water* **2022**, *14*, 483. [CrossRef]
24. Krishna Kumar, S.; Logeshkumaran, A.; Magesh, N.S.; Godson, P.S.; Chandrasekar, N. Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India. *Appl. Water Sci.* **2015**, *5*, 335–343. [CrossRef]
25. Kaur, T.; Bhardwaj, R.; Arora, S. Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Malwa region, southwestern part of Punjab, India. *Appl. Water Sci.* **2017**, *7*, 3301–3316. [CrossRef]
26. Nazzal, Y.; Ahmed, I.; Al-Arifi, N.S.; Ghrefat, H.; Batayneh, A.; Abuamarah, B.A.; Zaidi, F.K. A combined hydrochemical-statistical analysis of Saq aquifer, northwestern part of the Kingdom of Saudi Arabia. *Geosci. J.* **2015**, *19*, 145–155. [CrossRef]
27. Boateng, T.K.; Opoku, F.; Acquaah, S.O.; Akoto, O. Groundwater quality assessment using statistical approach and Water Quality Index in Ejisu-Juaben Municipality, Ghana. *Environ. Earth Sci.* **2016**, *75*, 489. [CrossRef]
28. Eldaw, E.; Huang, T.; Mohamed, A.K.; Mahama, Y. Classification of groundwater suitability for irrigation purposes using a comprehensive approach based on the AHP and GIS techniques in North Kurdufan Province, Sudan. *Appl. Water Sci.* **2021**, *11*, 126. [CrossRef]
29. El-Rawy, M.; Ismail, E.; Abdalla, O. Assessment of groundwater quality using GIS, hydrogeochemistry, and factor statistical analysis in Qena Governorate, Egypt. *Desalination Water Treat.* **2019**, *162*, 14–29. [CrossRef]
30. Elsayed, S.; Hussein, H.; Moghanm, F.S.; Khedher, K.M.; Eid, E.M.; Gad, M. Application of Irrigation Water Quality Indices and Multivariate Statistical Techniques for Surface Water Quality Assessments in the Northern Nile Delta, Egypt. *Water* **2020**, *12*, 3300. [CrossRef]
31. Ibrahim, H.; Yaseen, Z.M.; Scholz, M.; Ali, M.; Gad, M.; Elsayed, S.; Khadr, M.; Hussein, H.; Ibrahim, H.H.; Eid, M.H.; et al. Evaluation and Prediction of Groundwater Quality for Irrigation Using an Integrated Water Quality Indices, Machine Learning Models and GIS Approaches: A Representative Case Study. *Water* **2023**, *15*, 694. [CrossRef]
32. Awad, A.; Eldeeb, H.; El-Rawy, M. Assessment of surface and groundwater interaction using field measurements: A case study of Dairut City, Assuit, Egypt. *J. Eng. Sci. Technol.* **2020**, *15*, 406–425.
33. El-Rawy, M.; Abdalla, F.; Negm, A.M. Groundwater Characterization and Quality Assessment in Nubian Sandstone Aquifer, Kharga Oasis, Egypt. In *Groundwater in Egypt's Deserts*; Negm, A., Elkhouly, A., Eds.; Springer Water; Springer: Cham, Switzerland, 2021. [CrossRef]
34. Gad, M.; Gaagai, A.; Eid, M.H.; Szűcs, P.; Hussein, H.; Elsherbiny, O.; Elsayed, S.; Khalifa, M.M.; Moghanm, F.S.; Moustapha, M.E.; et al. Groundwater Quality and Health Risk Assessment Using Indexing Approaches, Multivariate Statistical Analysis, Artificial Neural Networks, and GIS Techniques in El Kharga Oasis, Egypt. *Water* **2023**, *15*, 1216. [CrossRef]
35. Yustika, R.D.; Ariani, R. Water quality in Cidurian watershed, Indonesia. *E3S Web Conf.* **2021**, *306*, 04009. [CrossRef]
36. Eid, M.H.; Elbagory, M.; Tamma, A.A.; Gad, M.; Elsayed, S.; Hussein, H.; Moghanm, F.S.; Omara, A.E.-D.; Kovács, A.; Péter, S. Evaluation of Groundwater Quality for Irrigation in Deep Aquifers Using Multiple Graphical and Indexing Approaches Supported with Machine Learning Models and GIS Techniques, Souf Valley, Algeria. *Water* **2023**, *15*, 182. [CrossRef]
37. Parvin, F.; Haque, M.M.; Tareq, S.M. Recent status of water quality in Bangladesh: A systematic review, meta-analysis and health risk assessment. *Environ. Chall.* **2022**, *6*, 100416. [CrossRef]
38. Masoud, M.; El Osta, M.; Alqarawy, A.; Elsayed, S.; Gad, M. Evaluation of groundwater quality for agricultural under different conditions using water quality indices, partial least squares regression models, and GIS approaches. *Appl. Water Sci.* **2022**, *12*, 244. [CrossRef]

39. Gaagai, A.; Aouissi, H.A.; Bencedira, S.; Hinge, G.; Athamena, A.; Haddam, S.; Gad, M.; Elsherbiny, O.; Elsayed, S.; Eid, M.H.; et al. Application of Water Quality Indices, Machine Learning Approaches, and GIS to Identify Groundwater Quality for Irrigation Purposes: A Case Study of Sahara Aquifer, Doucen Plain, Algeria. *Water* **2023**, *15*, 289. [CrossRef]
40. Basyoni, M.H.; Aref, M.A. Composition and origin of the sabkha brines, and their environmental impact on infrastructure in Jizan area, Red Sea Coast, Saudi Arabia. *Environ. Earth Sci.* **2016**, *75*, 105. [CrossRef]
41. Abdalla, F.; Al-Turki, A.; Al Amri, A. Evaluation of groundwater resources in the Southern Tihama plain, Saudi Arabia. *Arab. J. Geosci.* **2015**, *8*, 3299–3310. [CrossRef]
42. Hakami, A.; Ghrefat, H.; Elwaheidi, M.; Galmed, M.; Yahya, M.A. Assessment of the corrosivity of the Southern Red Sea coastal sabkha soil: An integrated mineralogical, geochemical, and GIS approach. *Environ. Earth Sci.* **2022**, *81*, 225. [CrossRef]
43. APHA. *Standard Methods for the Examination of Water and Wastewater*, 19th ed.; American Public Health Association Inc.: New York, NY, USA, 1995.
44. Raghunath, H.M. *Groundwater*; Wiley Eastern Ltd.: Delhi, India, 1987.
45. Karanth, K.R. *Groundwater Assessment, Development and Management*; Tata McGraw Hill: New Delhi, India, 1987.
46. Doneen, L.D. *Water Quality for Agriculture*; Department of Irrigation, University of California: Davis, CA, USA, 1964; p. 48.
47. Kelly, W.P. *Alkali Soils—Their Formation Properties and Reclamation*; Reinhold Pub.: New York, NY, USA, 1951.
48. Schoeller, H. Qualitative evaluation of groundwater resources. In *Methods and Techniques of Groundwater Investigations and Development*; UNESCO: Paris, France, 1965; p. 5483.
49. Amadi, A.N.; Nwankwoala, H.O.; Olasehinde, P.I.; Okoye, N.O.; Okunlola, I.A.; Alkali, Y.B. Investigation of aquifer quality in Bonny Island, Eastern Niger Delta, Nigeria using geophysical and geochemical techniques. *J. Emerg. Trends Eng. Appl.* **2012**, *3*, 183–187.
50. Gibbs, R.J. Mechanisms controlling world water chemistry. *Science* **1970**, *170*, 1088–1090. [CrossRef]
51. Rajmohan, N.; Elango, L. Identification and evolution of hydrogeochemical processes in the groundwater environment in an area of the Palar and Cheyyar River Basins, Southern India. *Environ. Geol.* **2014**, *46*, 47–61. [CrossRef]