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Original article

Assessment of the Biyadh groundwater quality and geochemical process in Saudi Arabia using statistical, modelling, and WQI methods

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ABSTRACT

This research aimed to understand the variations in the groundwater quality and hydrochemical processes in the Biyadh aquifers in central Saudi Arabia. The Biyadh Aquifer in the Riyadh area is the primary natural water resource for Wadi Sahba and Wasia Well Fields. The present study collected thirty groundwater samples from the Biyadh aquifer in the outcrop and confined parts. The samples were evaluated by multivariate statistical methods and hydrochemical modelling to understand the geochemical processes that control the groundwater. Also, it used various indexes to find the groundwater's suitability for drinking, agricultural, and industrial purposes. The analysis revealed a general evolution in groundwater quality as groundwater flowed east and northeast. The TDS increases from 1730 mg/l in WS to 2370 mg/l in WWF. The groundwater facies developed from Ca-Mg-SO_4-Cl to Ca-Na-Mg-SO_4-Cl in WS and ended with Ca-Na-SO_4-Cl in WWF. Applying Pearson's correlation matrix, cluster analyses, and factor analyses indicate that the ions significantly influence groundwater mineralization. The geochemical modelling revealed that the dissolution of the calcite, halite, anhydrite, and gypsum minerals increases with the direction of groundwater flow. In addition, the agriculture activities in Wadi Sahba mixed with irrigation return water to groundwater and increase nitrate (NO_3) concentration. Biyadh groundwater has a better quality for drinking in the confined aquifer than in the unconfined aquifer, and both areas are suitable for irrigation. The TH indicates that the groundwater becomes more suitable for industrial purposes as it flows toward the confined part of the aquifer.

1. Introduction

Groundwater is a significant component of the Earth's water cycle and is essential for sustaining human life. This critical resource is being challenged by urbanization, climate change, and population growth. As there are issues obtaining sufficient water to meet the increasing demand, groundwater research is becoming more crucial to understanding the long-term sustainability of water resources, how climatic change affects the water cycle, how natural disasters affect groundwater sources, and how groundwater quality affects human health (Richey et al., 2015; DeNicola et al., 2015).

Groundwater plays a vital role in the economic and social development of arid countries like Saudi Arabia. With rising demands for water, especially from agriculture and urban sectors, groundwater resources must be managed to ensure balanced use and sustainable withdrawal. Riyadh, the capital of Saudi Arabia, is experiencing rapid economic growth due to tourism projects, resulting in abundant jobs and increased internal migration rates (Almatar, 2022). This continuous increase in population was accompanied by high groundwater exploitation, which affected its quantities and qualities (Alzahrani et al., 2022; Alharbi & Zaidi, 2018).

Wasia Well Field (WWF) and Wadi Sahba (WS) are the two important sites for providing water to Riyadh. They extract groundwater from the Biyadh aquifer in central Saudi Arabia. WWF provides 20% of the city's drinking and domestic needs, besides the 80% provided by desalination plants in the Arabian Gulf. Wadi Sahba is the main irrigation water for the Al Kharj area's agricultural fields and the primary food product supplier for Riyadh city (Al-Omran et al., 2015; Al-Harbi & Hussain, 2009). After

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decades of production, we need to check the groundwater quality in the Biyadh aquifer (Fallatah, 2020).

Previous studies of groundwater in Wadi Sahba and Wasia Well Field (Al-Harbi & Hussein, 2009; Alharbi & Zaidi, 2018; Khogali et al., 2020; Zaidi et al., 2016; Alfaifi et al., 2017) focused on ionic relationships and groundwater types to understand the hydrogeochemical processes that influence the Biyadh groundwater. Multivariate statistical analysis, particularly cluster and factor analysis, was used to determine the underlying processes driving groundwater chemistry in the aquifer. None of these studies investigates the differences in groundwater quality in Biyadh between the unconfined aquifer in WS and the confined beds in WWF.

It is crucial to conduct research tracking the spatial changes in the Biyadh groundwater quality from the outcrop to the confined beds. The current research addresses how the groundwater quality changed from the WS to the WWF regarding chemical processes and mineral saturation. Besides, the study will determine the groundwater's suitability for drinking, agricultural, and industrial uses. These objectives were achieved by determining the groundwater types using a Piper diagram, using various statistical techniques, identifying hydrogeochemical trends, and comparing the geochemistry in WWF and WS.

2. Study area

The research region is located in Saudi Arabia's centre, between 47° – 48°E and 24°–25.30°N. The research focuses on two sites, Wadi Sahba and Wasia Well Field (Fig. 1).

2.1. Topography and geology

The study area is underlain by series of sedimentary formations interrupted by Wadi Sahba, major depression in the south of *WWF.* This wadi primarily consists of recent deposits such as silt, sand, and conglomerate (Powers et al. 1966; BRGM, 1976; Alharbi & Zaidi, 2018). The area's elevation from west to east ranges from 954 m to 337 m AMSL. The lowest height in the area is the *WS*'s alluvial sediments in the south and southeast (Fig. 1a). The Biyadh formation outcrop in the Wadi Dawasir is about 515 m; it decreases in thickness to 360 in the north of WS, then gradually disappears in the north. (Powers et al. 1966; BRGM, 1976). The Biyadh formation consists of conglomeratic to fine-grained sandstone with siltstone, mudstone, and claystone beds (Fig. 2). The Biyadh formation average thickness in *WS* is 400 m and 425 m in WWF (Keller et al., 2019; Jaju et al. 2016).

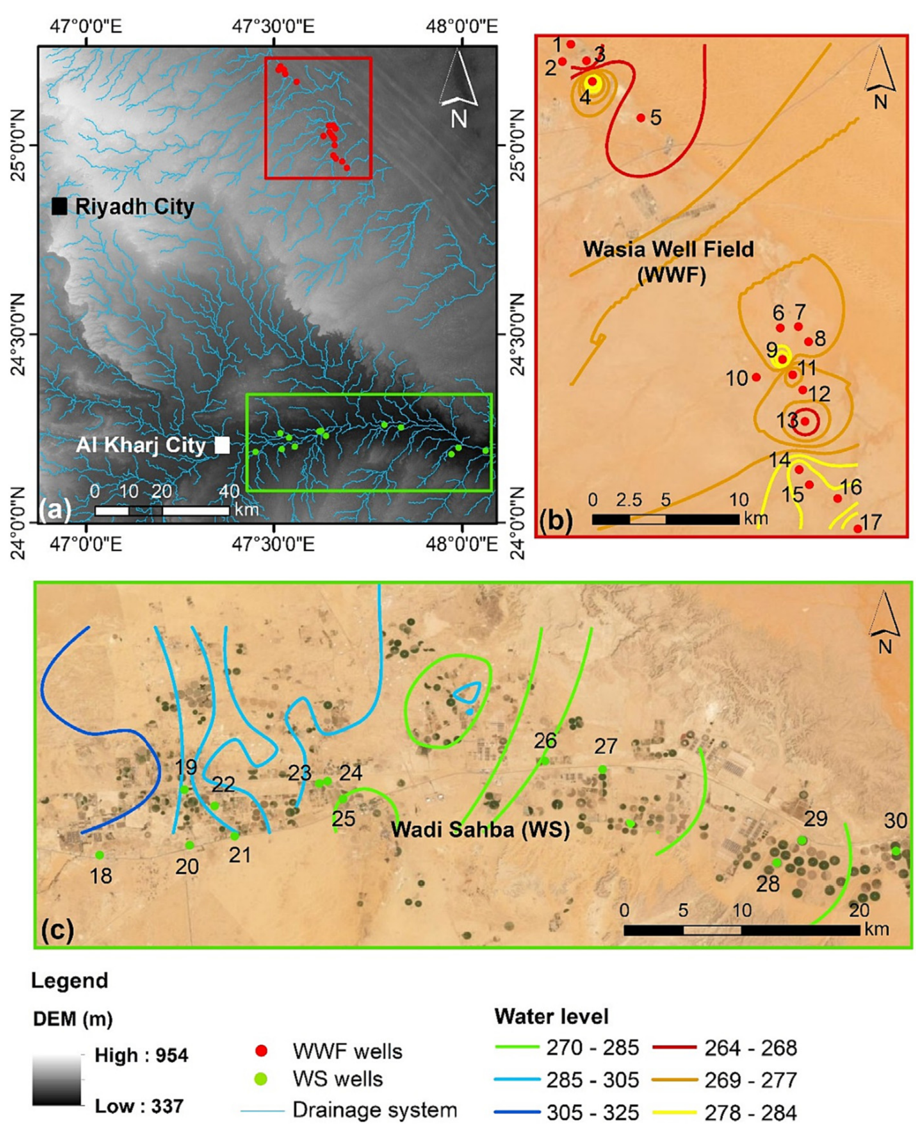

Fig. 1. (a) Map showing the location of the study area and the drainage system. (b) Map showing the sampling locations of the Wasia Well Field (*WWF*) and the groundwater level map for the Biyadh aquifer in WWF. (c) Map showing the sampling locations of the Wadi Sahba (*WS*) and groundwater level map for the Biyadh aquifer in Wadi Sahba.

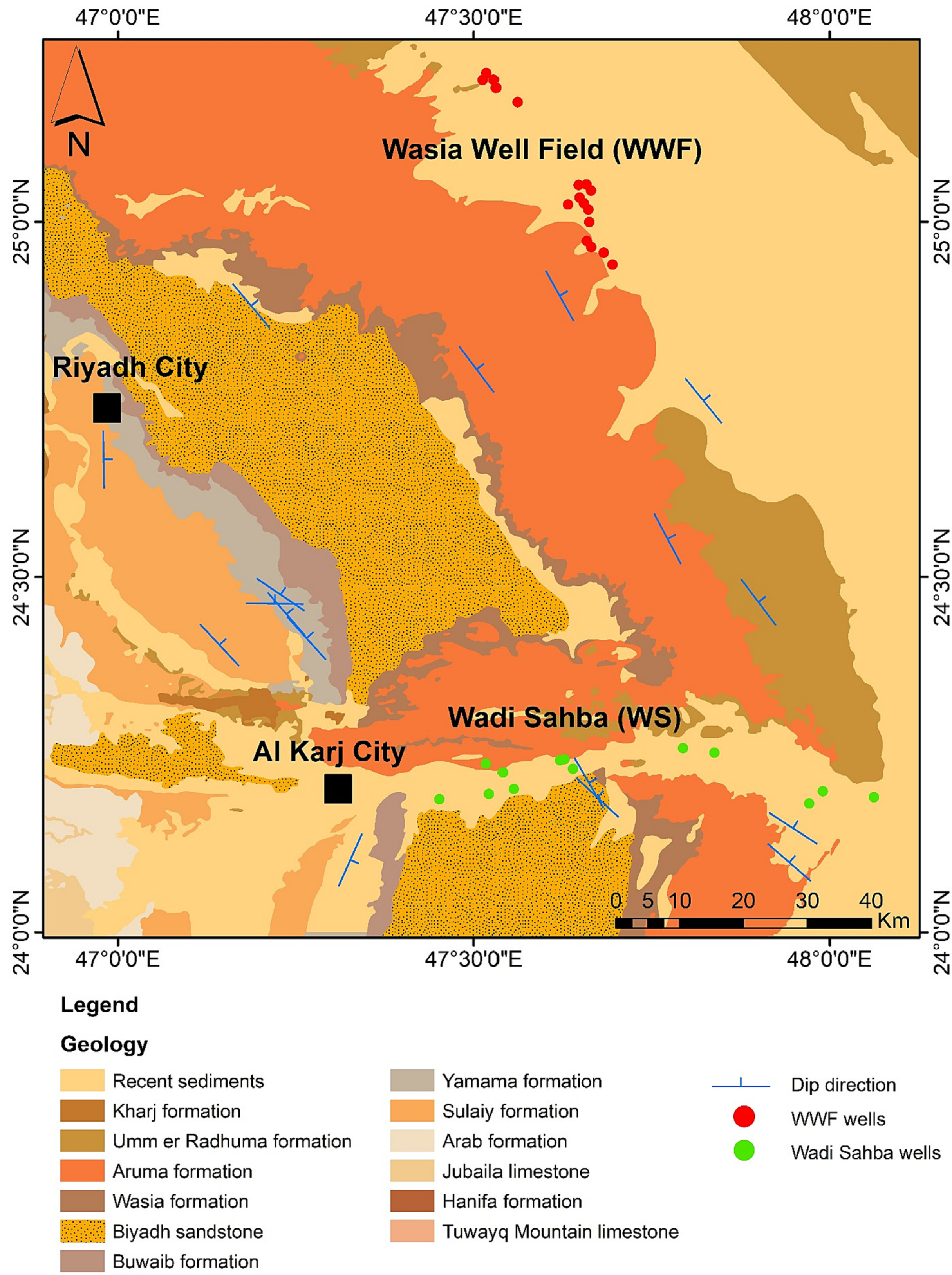

Fig. 2. Geological map of the Biyadh formation and the main formation in the study area.

2.2. Hydrogeology and climate

The Biyadh aquifer is recharged by rainfall from the outcrop area and adjoining valleys in the area (Fig. 1a). As a result that the Biyadh is in an arid region, a low amount of rainfall is received yearly. Researches revealed that the yearly average rainfall in Saudi Arabia is 59 mm/y, and about 1.8 mm is recharged to the aquifers (Uitto & Schneider, 1997; Alsharhan et al., 2001).

The groundwater level of the Biyadh Aquifer in *WS* ranges from 325 to 275 m AMSL, with groundwater flowing from the west to east (Fig. 1c). In the WWF, the Biyadh Aquifer water level is below 285 m AMSL (Fig. 1b). From the *WS* to *WWF*, the water level is decreasing and follows with the regional topography. The Biyadh groundwater depth below ground level varies in *WS* from 92 to 130 m and 270 to 285 m in *WWF*.

The study area has a high seasonal record range. In the winter season, from December to March, the temperature in day and night times varies between 21 and 28 °C and 6–12 °C, respectively. This season, the humidity has high records reach 54%, but the evaporation records in its lowest levels, reaching 3 mm. From May to August, the temperature and evaporation records are very high, 41 °C and 12 mm, respectively, and the humidity has a minimum record rate of 27% because there is little to no rain during the summer (Alharbi & Zaidi, 2018).

3. Data sources and methods

The hydrochemical and hydrological data used in this study were collected from two sources; the first was obtained from geological field trips to *WS* in the Al Kharj area. In these trips, thirteen groundwater samples were collected, and hydrogeological records were measurements for this study. The Ministry of Environment, Water, and Agriculture provided the second data source. These data include hydrological and hydrochemical data for seventeen groundwater wells in *WWF*. These wells are mainly pumped from the Biyadh aquifer. The two sources provide 30 groundwater samples that were studied in this research.

Using portable meters, TDS, EC, and pH were measured on field trips. Besides, groundwater samples were collected in polyethylene bottles from the wells after they had been pumped for 10 min to prevent contamination. Chemical tests were done on the groundwater samples in the Central Lab Facility in the College of Science at King Saud University. These tests were done in line with APHA (2005) standards. The ionic balance equation is used to confirm the chemical analysis's correctness and remove all groundwater samples with errors exceeding ±5%. After this process, all the 30 groundwater samples in this study were approved (Supplementary table).

Several software programs were used to analyze the groundwater chemical analysis data in order to identify the groundwater facies, compute the minerals' saturation indices, and suggest their suitability for different purposes. They were also employed in the statistical analysis to show the correlations between the chemical ions and determine the key components in groundwater chemistry. The water quality was calculated and statistically analyzed using IBM SPSS 23, a software package that enables advanced statistical analysis, and Microsoft Excel, which provides spreadsheets to create formulas for data calculations. Geochemical modeling was done with the help of PHREEQC, a computer program that simulates chemical reactions in water, and Aquachem, a program that analyzes data about water quality. The digitizing, creating, and displaying maps were done with ArcGis 10.7.

4. Results and discussion

4.1. Hydrochemical characteristics

The physical and chemical hydrochemical parameters determined at WWF and WS sites are summarized in Table 1. The total dissolved solids mean in WWF is 2370 mg/l and 1729 mg/l in WS. Calcium, with a mean content of 340 mg/l in WWF, is the most abundant cation at both locations, followed by sodium, with a mean concentration of 203 mg/l, and magnesium, with a mean concentration of 117 mg/l. Sulfate is the most abundant anion in the WWF and WS, with mean values of 340 and 771 mg/l, respectively. Sulfate has a wide range in *WS*, where the minimum value is 888 mg/l, and the maximum is 4752 mg/L. After sulfate, chloride had a mean concentration of 501 mg/l in WWF and 825 mg/l in WS. The bicarbonate ion follows up chloride ion with mean concentrations value 179 mg/l in *WWF* and 231 mg/l in *WS*. Nitrate varies from minor amounts 4 to 17 mg/l in *WWF* to higher values reach 46 mg/L in *WS*, which exceeds the prescribed limits by the Saudi Standards, Metrology and Quality Organization (SASO 2000) and WHO (2011).

4.2. Hydrochemical classification

In this research, the groundwater facies of the Biyadh Aquifer were categorized using a Piper diagram (Fig. 3). The cationic triangle shows that all the samples from WWF and WS fall into the Ca-dominant type and SO_4-dominant in the anionic triangle, indicating the dissolution of gypsum, anhydrite, and calcium minerals. Nevertheless, most groundwater facies of the Biyadh aquifer in the *WWF* site classified into the Ca-Na-SO_4-Cl type (15 samples), and only two samples have Ca-Mg-SO_4-Cl type. These groundwater facies show the influence of the dissolution of gypsum and anhy-

Table 1
Showing descriptive statistics of groundwater samples (N = 30) in the study area.

Site	*Statistic*	*TDS*	*EC*	*Ca*	*Mg*	*Na*	*Cl*	*HCO_3*	*SO_4*	*NO_3*
WWF	*Mean*	2370	3121	340	117	203	501	179	883	7
	Median	2493	3278	344	107	224	520	179	900	6
	Standard Deviation	364	459	44	37	66	76	17	129	3
	Range	1207	1558	192	136	228	252	81	475	11
	Minimum	1520	2006	240	53	70	338	149	625	4
	Maximum	2727	3564	432	190	298	590	229	1100	15
	Count	17	17	17	17	17	17	17	17	17
WS	*Mean*	1729	3527	771	65	422	825	231	1807	37
	Median	1888	3850	609	54	378	708	224	1430	41
	Standard Deviation	520	1060	520	37	325	566	25	1321	14
	Range	1571	3204	1524	111	969	1727	83	3864	40
	Minimum	875	1786	406	36	156	323	202	888	6
	Maximum	2446	4990	1930	147	1125	2050	285	4752	46
	Count	13	13	13	13	13	13	13	13	13

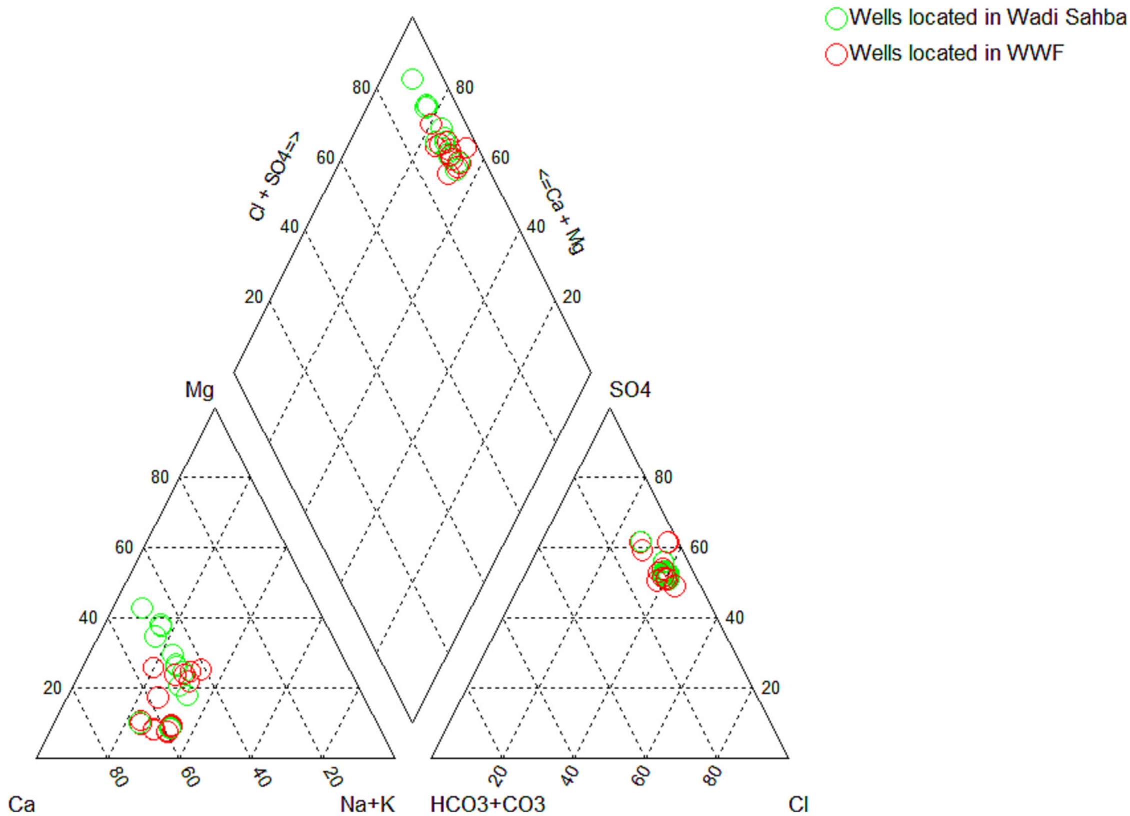

Fig. 3. Piper's Trilinear Diagram for wells located in Wadi Sahba and Wasia Well Field.

drite minerals. In the *WS* site, the groundwater types shift with the direction of groundwater flow. In well number 18, the water type is Ca-Mg-SO_4-Cl and becomes Ca-Mg-Na-SO_4-Cl in well number 24 and finally develops Ca-Na-Mg-SO_4-Cl in well number 28. This shift suggests that the dissolving rate of halite minerals in WS rises with the direction of groundwater flow.

4.3. Correlation matrix

The Correlation coefficients among ions could help identify the processes contributing to groundwater salinization (Helsel & Hirsch,1992). Table 2 presents the results of the analyses. The WS groundwater exhibit a typical positive relationship between EC-TDS and a strong positive relationship between Ca-Cl, Ca-SO_4, Mg-Cl, Mg-SO_4, Cl-SO_4, and HCO_3-NO_3, which demonstrates that the mineralization has a major impact on groundwater. The strong relationship between Ca and Cl may occur because of limestone rocks' reaction with hydrochloric acid to increase Ca and Cl ions in the groundwater. Calcium and sulfate have strong positive relationships, which could mean that Ca and SO_4 ions come from the dissolution of anhydrite and gypsum.

Moreover, the strong relationship between Mg with Cl and SO_4 may imply that fertilizers are a dominant contributor of these ions. However, there is no strong negative relationship found between all ions. HCO_3 and NO_3 have a strong relationship. The possible interpretation of this relation is the agriculture activities in *WS*. When mixed with fertilizers in agricultural areas, irrigation water infiltrates through the rock layers and may reach the groundwater, which increases its concentration of NO_3. The presence of organic matter increases carbon dioxide and is then mixed with groundwater to produce carbonic acid and bicarbonate.

The results of Pearson's correlation matrix for *WWF* wells are shown in Table 2. It demonstrates a significant positive correlation between Ca-Na, Ca-Cl, Ca-HCO_3, Na-Cl, Na-HCO_3, Na-SO_4, Cl-HCO_3, Cl-SO_4, HCO_3-SO_4; and a typical strong relationship between Ca-SO_4. These relationships revealed that groundwater mineralization is affected by these ions. The strong relationship between Ca and Cl may occur because of limestone rocks' reaction with hydrochloric acid to increase Ca and Cl ions in the groundwater. The Ca against SO_4 shows typical strong positive relationships, indicating that anhydrite and gypsum's dissolutions are the Ca and SO_4 ions' natural sources.

Furthermore, Na and Cl display a strong correlation, indicating that the dissolution of the halite mineral is the source of the two ions. In the *WWF*, the relationship between HCO_3 and NO_3 was different from the *WS* site. It is characterized as medium to week relationship. Since the WWF samples were taken from a greater depth than the WS samples, the shallow aquifer's groundwater had no effect on the NO_3 concentration.

4.4. Multivariate statistical methods

Multivariate statistical analyses consist of several methods applied to several practical investigations, including the classification of hydrochemical facies (Belkhiri & Narany, 2015). These methods were proposed to be used for the classification of hydrochemical facies. This analysis involves Cluster Analysis (CA) and Factor Analysis (FA) (Pathak, 2012). These two techniques better understand the groundwater systems and the hydrochemical processes that govern them through data reduction and classification (Kolsi et al., 2013; Yidana et al., 2010). The analysis in these methods involves concentrations of chemical species (cations: calcium (Ca), magnesium (Mg), sodium (Na); and anions: bicarbonate (HCO_3), chloride (Cl), sulfate (SO_4), and Nitrate (NO_3).

Cluster analysis attempts to find the group of variables based on attribute information about the variables and display them in groups on a tree diagram known as a dendrogram, which showing the grouping according to the order in which they were joined during clustering (Aggarwal & Reddy, 2013). Groundwater samples

Table 2
Showing the Pearson correlation matrix of the groundwater samples in *WS* and *WWF*.

Site	Statistic	EC	TDS	Ca	Mg	Na	Cl	HCO_3	SO_4	NO_3
WS	*EC*	1.00								
	TDS	1.00	1.00							
	Ca	0.20	0.22	1.00						
	Mg	0.68	0.70	0.58	1.00					
	Na	0.01	0.03	0.38	−0.05	1.00				
	Cl	0.52	0.54	**0.87**	**0.71**	0.55	1.00			
	HCO_3	−0.27	−0.25	0.54	0.30	0.56	0.51	1.00		
	SO_4	0.38	0.41	**0.87**	**0.71**	0.58	**0.93**	0.65	1.00	
	NO_3	−0.25	−0.23	0.51	0.12	0.41	0.39	**0.71**	0.47	1.00
WWF	*EC*	1.00								
	TDS	0.73	1.00							
	Ca	0.67	0.28	1.00						
	Mg	0.38	0.76	0.35	1.00					
	Na	0.73	0.35	**0.98**	0.31	1.00				
	Cl	0.77	0.44	**0.98**	0.45	**0.98**	1.00			
	HCO_3	0.61	0.01	**0.89**	−0.07	**0.87**	**0.84**	1.00		
	SO_4	0.68	0.32	**1.00**	0.40	**0.98**	**0.99**	**0.85**	1.00	
	NO_3	0.17	−0.37	0.33	−0.38	0.40	0.25	0.45	0.33	1.00

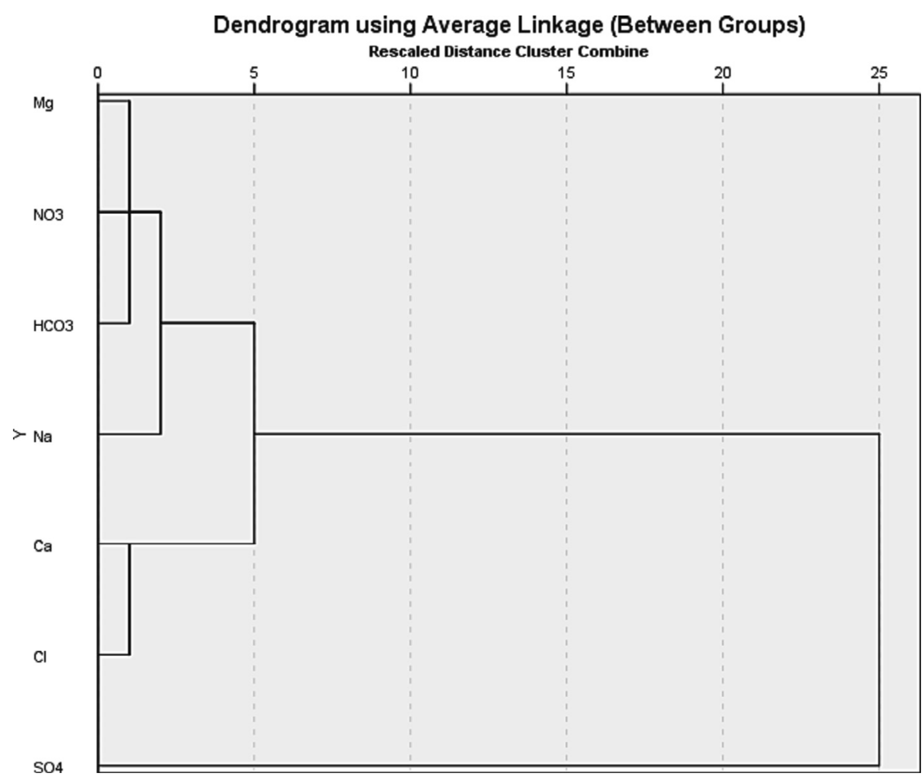

Fig. 4. A Dendrogram showing the clustering of elements linked by their geochemical similarity within the samples.

from Biyadh aquifer in *WWF* and *WS* sites were clustered using the SPSS software package. Fig. 4 revealed the resulting dendrogram for the variables. It was interpreted to have classified the major ions in 30 groundwater samples into four groups using seven variables. The first group shows a similarity between Mg, NO_3, and HCO_3, which probably represents the effects of agriculture fertilizers on groundwater in *WS*. The second group is represented by Na, which derive from the dissolution of halite mineral in the *WWF* and Sahba groundwater. The third group includes Ca, Cl, which probably means the effects of limestone rocks' reaction with hydrochloric acid. Finally, the fourth group is represented by SO_4, which could correspond to the dissolution of anhydrite and gypsum.

Factor analysis was used to find out what ions have in common and group them into small components (Kim et al., 2005). The most used approach to factor analysis is Principal Component Analysis (PCA). It works to find a linear set of variables. Then the maximum variance is removed from the variables and seeks a second linear combination that explains the maximum proportion of the remaining variance (Senapathi et al., 2019). The analysis yields two factors that are responsible for about 93% of the variation in groundwater chemistry. Factor 1 controlled 71% of the groundwater chemistry and has high loadings on Ca, Na, Cl, HCO_3, SO_4 (Fig. 5). This component indicates the effect of these ions on the overall mineralization of groundwater and the dissolution of calcite and gypsum minerals. Factor 2 has high positive loading on Mg that anhydrite can explain its significant effect on 22% of groundwater chemistry variation.

4.5. Hydrochemical modelling

PHREEQC is a Hydrochemical model extensively used to understand and calculate the saturation indices of groundwater with respect to mineral phases (Parkhurst & Appelo, 1999). Through

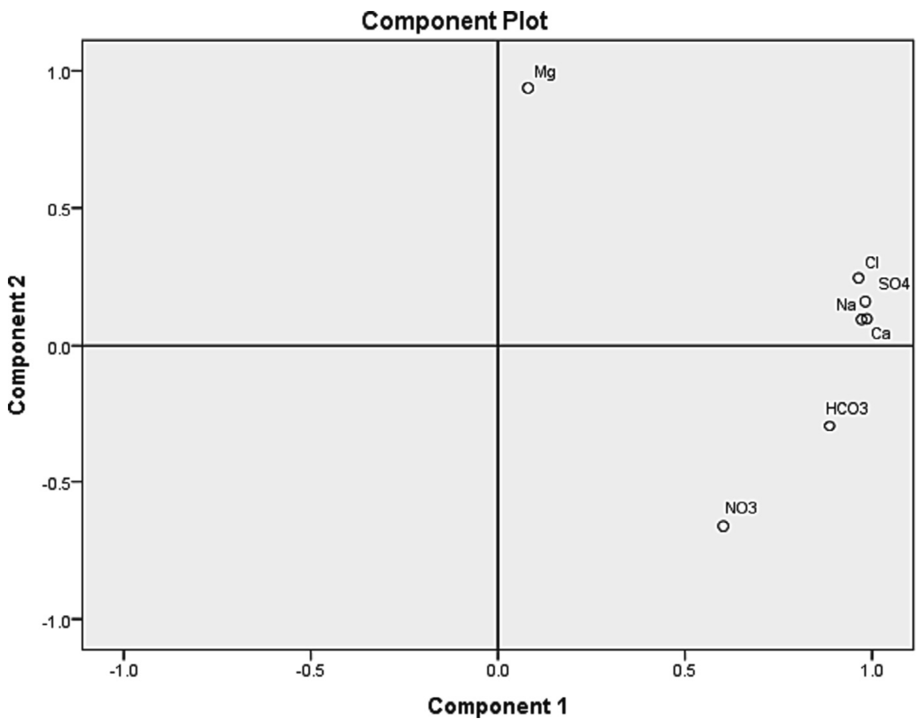

Fig. 5. Principal component analysis (PCA) plot showing the similarities and dissimilarities among the elements.

thermodynamic calculations of ionic activities, it could indicate the equilibrium state between groundwater and aquifer materials. The United States Geological Survey created this program for the aqueous elements' dissolution and precipitation to solid phases.

4.6. Saturation indices

The saturation index (SI) can measure the equilibrium state between minerals and groundwater. When the SI of a mineral is zero, it means that the aquifer's groundwater is in an equilibrium state concerning that mineral. If it is less than zero, groundwater is undersaturated and can dissolve the mineral. However, if SI is more than zero, this means the water is oversaturated for that mineral and can precipitate it (Saleh et al., 1999).

The following equation calculates the saturation index:

$$Saturation\ \ index(SI) = log(IAP/Ks) \tag{1}$$

where IAP is the ionic activity of the ions and Ks is the mineral's solubility. The saturation state of the minerals: anhydrite, aragonite, calcite, dolomite, and gypsum are shown in Fig. 6. The SI of calcite ranges in the Biyadh aquifer from −0.13 to 0.58 with an average of 0.09. Most of the samples are oversaturated on the *WWF* site. The exception is that well number 14 is in an equilibrium state, and wells number 15, 16, and 17 are undersaturated. And vice versa, all the samples in the *WS* site are undersaturated for calcite minerals. The saturation index for the aragonite mineral shows that three samples are saturated, nine are undersaturated, and well number 22 is oversaturated. The calculated average of dolomite SI is −0.27, where the minimum value is −0.71, and the maximum is 0.33. Most of the samples are undersaturated, except wells number 6, 12, and 22 are oversaturated. The SI for gypsum and anhydrite minerals are all under saturated except for two wells, 6 and 12. The average value for gypsum is −0.28, and it is −0.51 for anhydrite. The saturation state for these minerals imply that the groundwater has the potential to dissolve them. Furthermore, Fig. 6 shows that as the groundwater moves away from the outcrop site in WS towards the WWF, it undergoes more dissolution processes until it reaches saturation.

4.7. Groundwater quality for Drinking, Irrigation, and industrial purposes

4.7.1. Groundwater quality for drinking purpose

At WWF and WS sites, the study evaluated Biyadh groundwater for drinking, irrigation, and industry usage (Bhunia et al., 2018). The Water Quality Index (WQI) is widely used to define and rank the suitability of groundwater to drink (Abbasnia et al., 2018; Gabr et al., 2021). This equation required calculation in several steps and evaluated based on Saudi Standards, Metrology, and Quality Organization (Table 3) (SASO 2000; Bhunia et al., 2018; Lateef, 2011).

The parameters used for the calculations involve pH, TDS, Ca, Mg, Na, K, Cl, SO_4, and NO_3 (Annapoorna & Janardhana, 2015). These parameters are assigned weights depending on their importance on the water quality for drinking and health effects (Ugochukwu et al., 2019). The parameters have the highest rank of five, including TDS, Cl, SO_4, and NO_3, since they have a significant role in assessing water quality for drinking (Lateef, 2011); Na and pH are given weight four and three for Ca and Mg (Table 3). TDS, Cl, SO_4, and NO_3, are the primary parameters in determining the quality of drinking water (Gabr et al., 2021; Abbasnia et al., 2018). SASO 2000 defined that concentrations that exceed the maximum permissible level of these ions in water are not toxic to drinking but may affect people's health (Shil et al., 2019). After weighting the concentrations, the *Wi* values calculated using the following equation:

$$Wi = wi/\sum_{i=1}^{n} wi \tag{2}$$

The equation computes the relative weight of each variable, *wi* is the variable weight, *Wi* is the relative weight, and *n* is the number of variables in the equation.

The quality rating scale (qi) for the variables is calculated next by dividing the water sample concentration level by the SASO 2000 standard and multiplying by 100, as indicated in the following equation:

$$qi = (Ci/Si) \times 100 \tag{3}$$

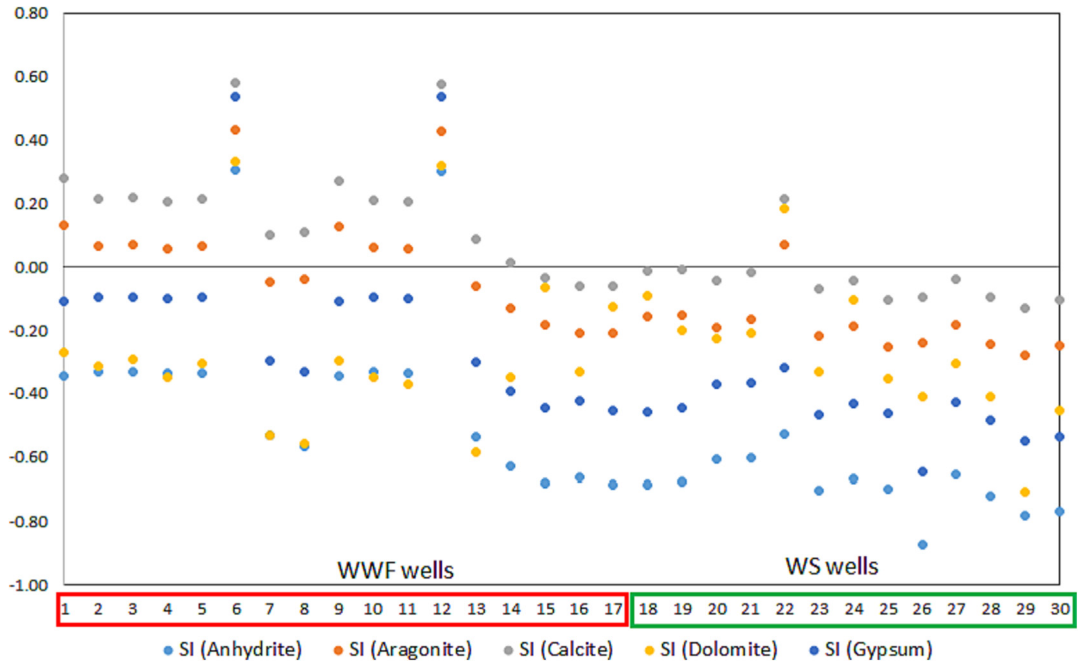

Fig. 6. X-Y plot showing the saturation state for anhydrite, aragonite, calcite, gypsum, and anhydrite minerals in WWF and WS sites.

Table 3
Weight and Relative Weight for Each Parameter in the study area.

Physicochemical parameter	SASO (2000)	*Weight (wi)*	*Relative weight (Wi)*
pH	6.5–8.5	4	0.12
TDS	1,000	5	0.15
Ca_2	200	3	0.09
Mg_2	150	3	0.09
Na	200	4	0.12
Cl	250	5	0.15
SO_4	250	5	0.15
NO_3	50	5	0.15

In the equation, *qi* indicates the quality rating, *Si* is the SASO 2000 standard for drinking water parameters in mg/l, and *Ci* is the parameter concentration in mg/l (Lateef, 2011). *SIi* computes the chemical parameter based on the two flowing equations, and SI is then used to calculate WQI.

$$SIi = Wi \times qi \tag{4}$$

$$WQI = \sum_{i=1}^{n} SIi \tag{5}$$

SIi represents the parameter's subindex, *qi* represents the quality rating, and *WQI* is the water quality type (Mahmud et al., 2020). Based on the Water Quality Index, the groundwater categorize as excellent, good, poor, very poor, and unsuitable when its value range <50, 50–100, 100–200, 200–300, and >300, respectively. The result of the WQI calculations presents in Table 4. It shows WQI values range from 120 to 184 on the *WWF* site, and all its samples are classified as poor drinking water. In contrast, the WQI for WS ranges from 134 to 618 and has 38% of the samples classified as poor water, 46% as very poor water, and 15% water unsuitable for drinking. Generally, The *WWF* shows poor water in its groundwater related to the strong water–rock interaction in the Biyadh Aquifer. *WS* site has poor drinking water quality compared to the *WWF* because of the groundwater's overexploitation and agricultural activities.

4.7.2. Groundwater quality for irrigation purpose

The sodium concentration of groundwater is the primary factor determining its appropriateness for irrigation. Irrigating farms with a high concentration of Na water will negatively affect soil permeability and crop productivity. Several equations have been recommended to scale the sodium content in water for irrigation purposes (Singh, 2019). These equations compare the Na concentration to total cations within the water, and all expressed in meq/l. The current study examines and categorizes the appropriateness of Biyadh groundwater for irrigation using the Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Permeability Index (PI), and Magnesium Ratio (MR). Classifying the Biyadh groundwater can be identified based on the SAR equation:

$$SAR = Na/[(Ca + Mg)/2]^{1/2} \tag{6}$$

Based on the equation, any SAR values below ten are classified as very good water, the values between 10 and 18 are good water, the SAR values from 18 to 26 are classified as poor water, and anything above 26 means the groundwater is very poor for irrigation (Glover, 1996). The calculations presented in Table 4 shows SAR values in the *WWF* range from 0.75 to 3.5 and in the *WS* from 3 to 4. Consequently, the results indicate that all the Biyadh Aquifer groundwater in *WWF* and *WS* sites are suitable for irrigation purposes.

Another critical evaluator in determining water suitability for irrigation is the Sodium Percentage (Na %). The percentage of sodium in groundwater is vital in defining irrigation quality since sodium results in soil hardness, thus reducing soil permeability (Singh, 2020). The calculation of Na % can be done using the below equation:

$$Na\% = (Na + K)x100/Ca + Mg + Na + K \tag{7}$$

Table 4 shows the classification of groundwater samples based on Na% findings. The *WWF* calculations vary from 8 to 33 and in the *WS* from 22 to 32. The majority of the samples in both locations are rated as excellent to good for irrigation use.

Table 4
Showing the quality of the groundwater in the study area for drinking, irrigation, and industrial purpose.

No.	*Aquifer*	*WQI*	*Type of water*	SAR	SAR Classif.	Na%	Na% Classif.	MH	MH Classif.	PI	PI Classif.	TH	TH Classif.
1	*WWF*	120	Poor	2.79	Very good	32	Good	32	Suitable	35	Suitable	53	Soft
2	*WWF*	173	Poor	1.51	Very good	16	Excellent	45	Suitable	18	Unsuitable	103	Moderately hard
3	*WWF*	120	Poor	2.11	Very good	26	Good	23	Suitable	29	Suitable	54	Soft
4	*WWF*	169	Poor	3.52	Very good	34	Good	38	Suitable	36	Suitable	76	Moderately hard
5	*WWF*	130	Poor	1.67	Very good	20	Excellent	32	Suitable	23	Suitable	68	Soft water
6	*WWF*	155	Poor	2.90	Very good	30	Good	34	Suitable	32	Suitable	72	Soft water
7	*WWF*	168	Poor	2.64	Very good	26	Good	35	Suitable	29	Suitable	83	Moderately hard
8	*WWF*	168	Poor	2.91	Very good	29	Good	34	Suitable	31	Suitable	78	Moderately hard
9	*WWF*	158	Poor	1.45	Very good	16	Excellent	41	Suitable	18	Unsuitable	92	Moderately hard
10	*WWF*	169	Poor	3.53	Very good	33	Good	26	Suitable	36	Suitable	72	Soft
11	*WWF*	165	Poor	1.52	Very good	16	Excellent	45	Suitable	19	Unsuitable	98	Moderately hard
12	*WWF*	166	Poor	3.15	Very good	31	Good	35	Suitable	33	Suitable	76	Moderately hard
13	*WWF*	165	Poor	0.74	Very good	8	Excellent	46	Suitable	11	Unsuitable	109	Moderately hard
14	*WWF*	171	Poor	2.73	Very good	27	Good	32	Suitable	29	Suitable	82	Moderately hard
15	*WWF*	184	Poor	2.41	Very good	23	Good	38	Suitable	25	Suitable	97	Moderately hard
16	*WWF*	183	Poor	2.68	Very good	26	Good	36	Suitable	28	Suitable	92	Moderately hard
17	*WWF*	178	Poor	3.32	Very good	30	Good	29	Suitable	32	Suitable	90	Moderately hard
18	*WS*	228	Very poor	3.93	Very good	32	Good	12	Suitable	34	Suitable	93	Moderately hard
19	*WS*	614	Unsuitable	6.64	Very good	31	Good	11	Suitable	32	Suitable	290	Hard
20	*WS*	230	Very poor	3.94	Very good	32	Good	13	Suitable	34	Suitable	94	Moderately hard
21	*WS*	199	Poor	2.50	Very good	23	Good	11	Suitable	25	Suitable	96	Moderately hard
22	*WS*	201	Poor	2.51	Very good	23	Good	11	Suitable	25	Suitable	97	Moderately hard
23	*WS*	140	Poor	1.98	Very good	22	Good	13	Suitable	25	Suitable	65	Soft water
24	*WS*	134	Poor	1.99	Very good	23	Good	13	Suitable	26	Suitable	63	Soft water
25	*WS*	142	Poor	1.99	Very good	22	Good	14	Suitable	25	Suitable	66	Soft water
26	*WS*	231	Very poor	3.94	Very good	32	Good	14	Suitable	34	Suitable	96	Moderately hard
27	*WS*	232	Very poor	3.94	Very good	32	Good	14	Suitable	34	Suitable	97	Moderately hard
28	*WS*	618	Unsuitable	6.64	Very good	31	Good	11	Suitable	32	Suitable	291	Hard
29	*WS*	228	Very poor	3.97	Very good	32	Good	13	Suitable	34	Suitable	94	Moderately hard
30	*WS*	231	Very poor	3.94	Very good	32	Good	14	Suitable	34	Suitable	96	Moderately hard

The permeability index (PI) is also applied to determine the suitability of groundwater for irrigation, and it is calculated as follows:

$$PI = 100x[([Na]+[HCO_3]^{1/2}/2)/[Na]+[Ca]+[Mg] \quad (8)$$

The classification of PI includes three classes based on permeability levels. Class I values above 75 %, Class II between 25% and 75 %, and class III involve values below 25 % (Singh, 2020). Since Class II and Class I show at least 25% permeability, there are suitable for irrigation. On the other hand, Class III waters are not ideal for irrigation since the maximum permeability level is below 25%. The results show that all PI in *WS* classified in Class II. Consequently, the equation revealed 13 samples of *WWF* have fallen in Class II and four samples classified as class III (Table 4).

The magnesium ratio (MR) has also been proposed as a metric for determining groundwater suitability for irrigation (Rawat et al., 2018). A high Mg level harms the soil when groundwater has increased salinity levels and results in more alkalinity levels in soil, influencing agriculture production (Abbasnia et al., 2018). The MR equation is represented as the ratio of Mg ion concentration to the concentration of Mg and Ca ions combined (Bhunia et al., 2018). The result is then multiplied by 100, as shown in the equation.

$$MR = [Mg/(Ca + Mg)] \times 100 \quad (9)$$

If the equation's outcome is more than 50, the groundwater is considered unsuitable for irrigation since it would cause adverse effects on agriculture production (Rawat et al., 2018). All Biyadh groundwater samples are categorized as suitable for irrigation (Table 4).

4.7.3. Groundwater quality for industrial purpose

Various formulae help determine the acceptability of water for industrial use; in this study, the total hardness (TH) was employed to determine the industrial suitability of the Biyadh groundwater.

Due to the presence of Ca and Mg, total hardness is produced. Hard water will be coating in the pipes with deposits such as $CaCO_3$, $CaSO_4$, and $Mg(OH)_2$. Water hardness is categorized into four classes, over 300 as very hard water, from 150 to 300 as hard water, 75 to 150 as moderately hard water, and below 75 soft water (Todd & Mays, 2018). Using the following formula, the TH can be determined:

$$TH = 2.5 \times Ca + 4.1 \times Mg \quad (10)$$

The calculations classify 23% of the *WS* groundwater as soft water, 62% as moderately hard water, and 15% as hard water. Therefore, 30% of *WWF* samples are classified as soft water, and 70% as moderately hard water (Table 4).

5. Conclusions

Thirty groundwater samples from the Biyadh aquifer in Wasia Well Field and Wadi Sahba were analyzed to assess the evolution of groundwater quality, hydrochemical processes, and its consumption for drinking, agriculture, and industry. The groundwater TDS values increase from the outcrop toward the WWF, and the water type changes from Ca-Mg-SO_4-Cl to Ca-Na-SO_4-Cl in WWF groundwater. The correlation matrix calculations of Pearson indicate that ions have a considerable effect on groundwater mineralization. Cluster and factor studies suggest that agricultural fertilizers and the dissolution of halite, anhydrite, and gypsum minerals may affect the groundwater in Wadi Sahba. The geochemical modeling reveals that the direction of groundwater flow increases the dissolution processes involving anhydrite, aragonite, calcite, dolomite, and gypsum minerals. According to the WWF, Biyadh's drinking water quality is poor. In addition, 38% of water samples in WS are of poor quality, 46% are of very poor quality, and 15% are unsuitable for consumption. The aquifer is classified as appropriate for irrigation and industrial reasons.

The importance of this research lies in providing sufficient information for decision-makers in the city of Riyadh to determine the appropriate groundwater sites for residential, agricultural, and industrial projects. For future work, the study recommends investigating the amount of rainfall recharge to the Biyadh aquifer and comparing the outcome with the volume of groundwater withdrawn.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2023.102847.

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