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ORIGINAL ARTICLE

Hydrogeochemical characterization of groundwater resources in Wadi Araba Basin, Southern Jordan

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Abstract

Groundwater quality is an important factor that determines its usage for drinking and irrigational use. This study was carried out along the quaternary alluvial aquifer which extends along Wadi Araba groundwater basins, in southern Jordan. Chemical and physical parameters were measured and analyzed for thirty-seven groundwater samples collected from twenty-one wells in the study area during two periods in the year 2019; the spring season (April–May) was represented by fourteen samples and the autumn season (August–September) represented by twenty-three samples were collected to determine its suitability for drinking and irrigational purposes. The groundwater in the study area is generally of low alkalinity with an average pH value of less than 8 for both spring and autumn seasons. The water of the area is excessively mineralized due to salinity, and the increase in water salinity of the southern Wadi Araba basin is less expressed than in the northern part. The hydrochemical characterization shows that most wells of the study area are characterized by HCO_3–Ca–Mg and HCO_3–SO_4–Ca–Mg types in the eastern escarpments of Wadi Araba (i.e., recharge area) and Cl–SO_4–Na and Cl–Na types in the discharge area. There is no substantial change in the hydrochemical composition during the two seasons. Based on the Piper diagram, most of the groundwater samples (91.8%) belong to class "E" as "earth alkaline water with increased portions of alkalis with prevailing sulfate and chloride." The Durov diagram reveals that most groundwater samples (62.2%) lay in the water genesis "field 6" which indicates that the water may be related to the reverse ion exchange of Na–Cl. The chemical composition of the water samples was compared with the drinking water standards of the World Health Organization and the Jordanian Standard. Groundwater from this area was not suitable to be a source for direct drinking based on total hardness and total dissolved solids. The dominant cation is sodium, while the dominant anion is chloride. The calculations of saturation indices for the two sampling campaigns for different minerals showed negative values of (SI) for carbonates minerals (anhydrite, gypsum, sylvite, and halite). This suggests that the groundwater in the alluvial aquifer is undersaturated with respect to these minerals in most of the study area. This is indicative of the fact that these minerals are undergoing the process of dissolution. The mineral saturation indices suggest that the dominating hydrochemical processes were dissolutions of evaporite minerals (halite and gypsum), carbonate minerals (such as calcite, dolomite, and rhodochrosite), the manganese oxide minerals (such as jarosite-K, hausmannite, pyrochroite, and pyrolusite) and reverse ion exchange.

Keywords Groundwater · Hydrochemical facies · Wadi Araba · Alluvial aquifer · Geochemical modeling

Introduction

Jordan is one of the most water-scarce countries in the world, and groundwater is the main source to meet domestic, industrial, and agricultural water demands (Radaideh 2022). Groundwater is the most important source of water in Jordan and contributes approximately 54% of the total water supply, and it consists of 12 groundwater basins varying in quantity and quality (Fig. 1). Of the twelve groundwater basins, six are being over-extracted, four are balanced with respect to abstraction, and two are underexploited (Odeh

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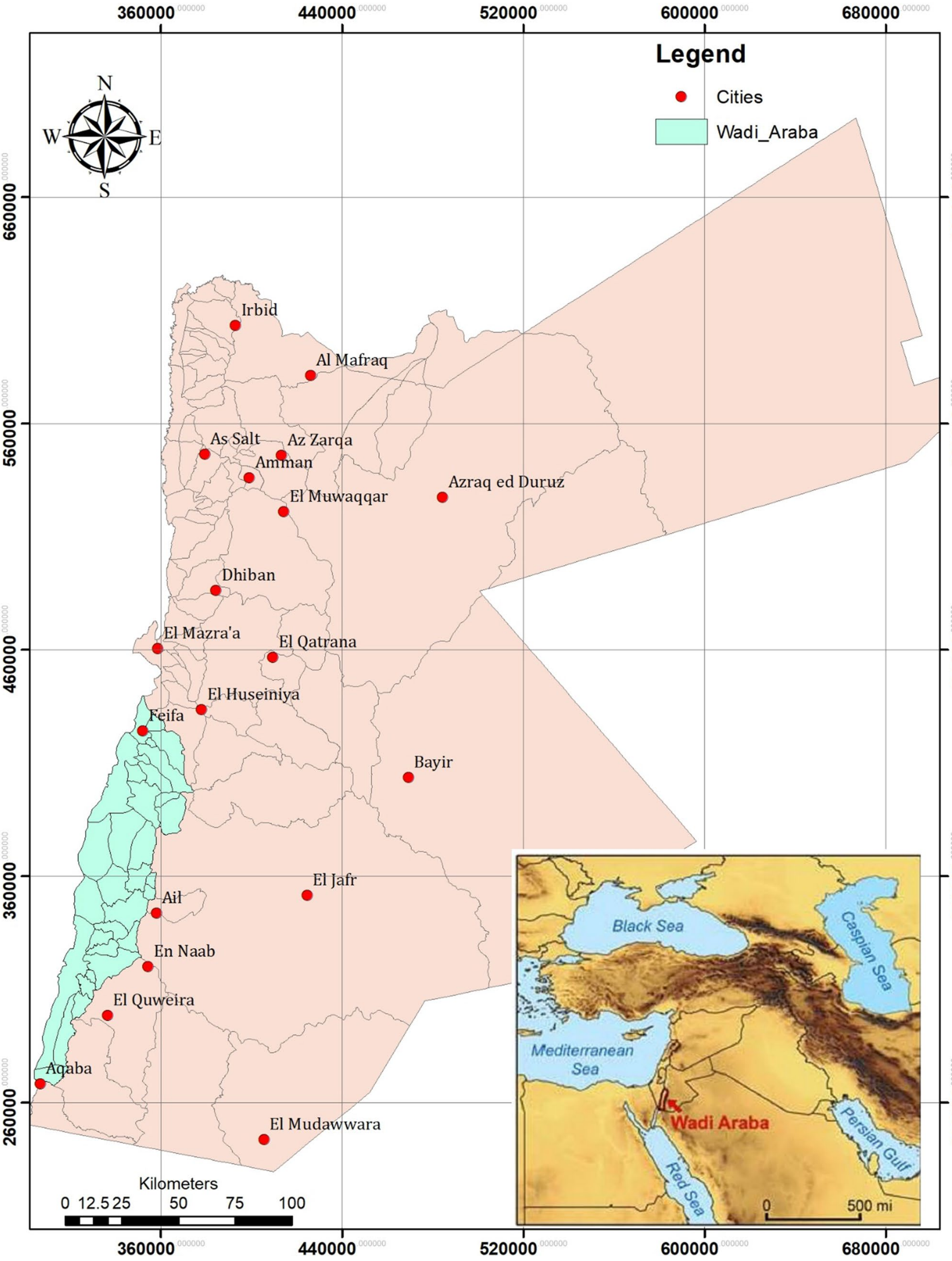


Fig. 1 Location map of Wadi Araba Basin

et al. 2019). The over-exploitation of groundwater resources has degraded water quality and reduced exploitation quantities (Jordan Geography and Population (JGP) 2001). The groundwater basins are subjected to exploitation due to extensive pumping from governmental and private wells (Ministry of Water and Irrigation (MWI 2017). The pumping of groundwater exceeds the safe yield of the aquifers and therefore led to a significant decline in the groundwater levels in the last few decades (Al Wreikat and Al Kharabsheh 2020).

The observed substantial decline in groundwater levels began in the 1980s and has been exacerbated by increased abstraction to address the water demands of a growing population and intensified agricultural development in recent decades (MWI and BGR 2017).

Due to the scarcity of surface water resources, groundwater became the major source of water in Jordan. These constraints led to the decline of the water level. TDS (total dissolved solids) levels increase and change in flow directions. In view of that fact, the conservation of the existing water resources is essential in this region (MWI 2017). Significant groundwater abstractions have resulted in declining groundwater levels within nearly all aquifers, which is evidence that the abstraction rates exceed the natural recharge.

This paper aims to study the hydrogeochemical characterization of the groundwater resources of the alluvium aquifer in Wadi Araba Basin, southern Jordan. The chemical composition of the water samples was compared with the drinking water standards of the World Health Organization (WHO) and the Jordanian Standard (JS). Groundwater from this area was not suitable to be a source for direct drinking based on total dissolved solids and other chemical constituents. However, the groundwater quality was found to be suitable for irrigation in most parts of the study area.

Description of the study area

The study area includes Wadi Araba Basins (North and South) which is considered part of the Jordan Rift Valley, and it occupies approximately 5835 km^2 (Fig. 1). The northern Wadi Araba catchment extends for about 100 km from the Dead Sea shore southward, with a width of 25 to 30 km and a total area of 3080 km^2, while the southern Wadi Araba catchment extends around 75 km north of the Gulf of Aqaba, with a maximum E–W width of 30 km and total catchment area measures 2756 km^2, the alluvial deposits which is the main target aquifer in this study represent approximately 1700 km^2 which extends along the western side of the tow sub-basins (Fig. 1A). According to Dames and Moore (1979), the study area lies entirely within the Jordan Rift Valley which consists of the Wadi Araba–Jordan Graben System. The Wadi Araba and Dead Sea basin represents a northern extension of the East African–North Syrian Fault System. The elevation of the Wadi Araba basin ranges from 1735 m above sea level (at the summit of Jabal Al Hisha) in the southern part of the basin to 425 m below sea level in the floor of Wadi Araba south Ghor Es Safi, the elevation of wells which represents alluvial aquifer in this study ranges from 425 m BSL to 330 m ASL (Fig. 2).

The investigated area is accessible by two main highways: The Wadi Araba Highway and the King's Highway. The Wadi Araba Highway runs straightly parallel to the western boundary of the basin, leading from Ghor Es Safi, the flat area east of the Dead Sea to Aqaba. The King's Highway is one of the most historic and scenic roads in the world (Abu-Zir 1989; NRA 2000) running sinuously from Amman to Aqaba via Karak and Shawbak parallel to the eastern boundary of the basin. It is crossed by the Desert Highway at the southeastern part of the basin. A new track that runs from north of Wadi Enn Mala 10 km north of Bir Madkhure to Al–Beida north of Petra is the only road connection between the Wadi Araba Highway and the King's Highway (El-Naqa and Al Kuisi 2012).

The climate of the Mediterranean basin prevails in the eastern part of the basin, where the moderate temperature in summer, and cold, snow and rainy in winter, which reflects on the vegetation in general and pastoral particularly, the continental hot climate prevails in the western part of the basin.

Hydrogeology of Northern Wadi Araba Basin

The stratigraphy of Wadi Araba is underlain by a Precambrian igneous and metasedimentary basement complex overlain by a series of sandstones, limestones, marls, shales, and evaporites ranging in age from Cambrian through Pleistocene (Bender 1974). Figure 2 shows the classification of hydrogeologic rock units in Wadi Araba basin (Radulovic et al. 2020). The Wadi Araba floor is composed of thick quaternary sediments that have a gentle depositional dip toward the west or northwest mantle of the flat floor of the Wadi Araba. The Upper Cretaceous and Tertiary rocks are outcropping, particularly at Jabal Ar–Risha. The drainage in this province is braided in type with ephemeral stream flow toward the northern and western parts of the basin boundary and reoriented south–southeast in the southern part of the basin. Alluvial fans are the dominant morphological feature in this province with semicircular shape, half-radial drainage, steep gradient, and fast deposition, and flat shape near large Wadis of Huwwar and Khushieba (MWI 1997).

Alluvial deposits of the quaternary, which represent the main target formation are found throughout the Wadi Araba Basins. At the escarpment along the eastern perimeter of the basins, these deposits may be associated with alluvial fans. The deposits associated with the fans typically form shallow freshwater aquifers of a limited areal extent (NWMP 2018).

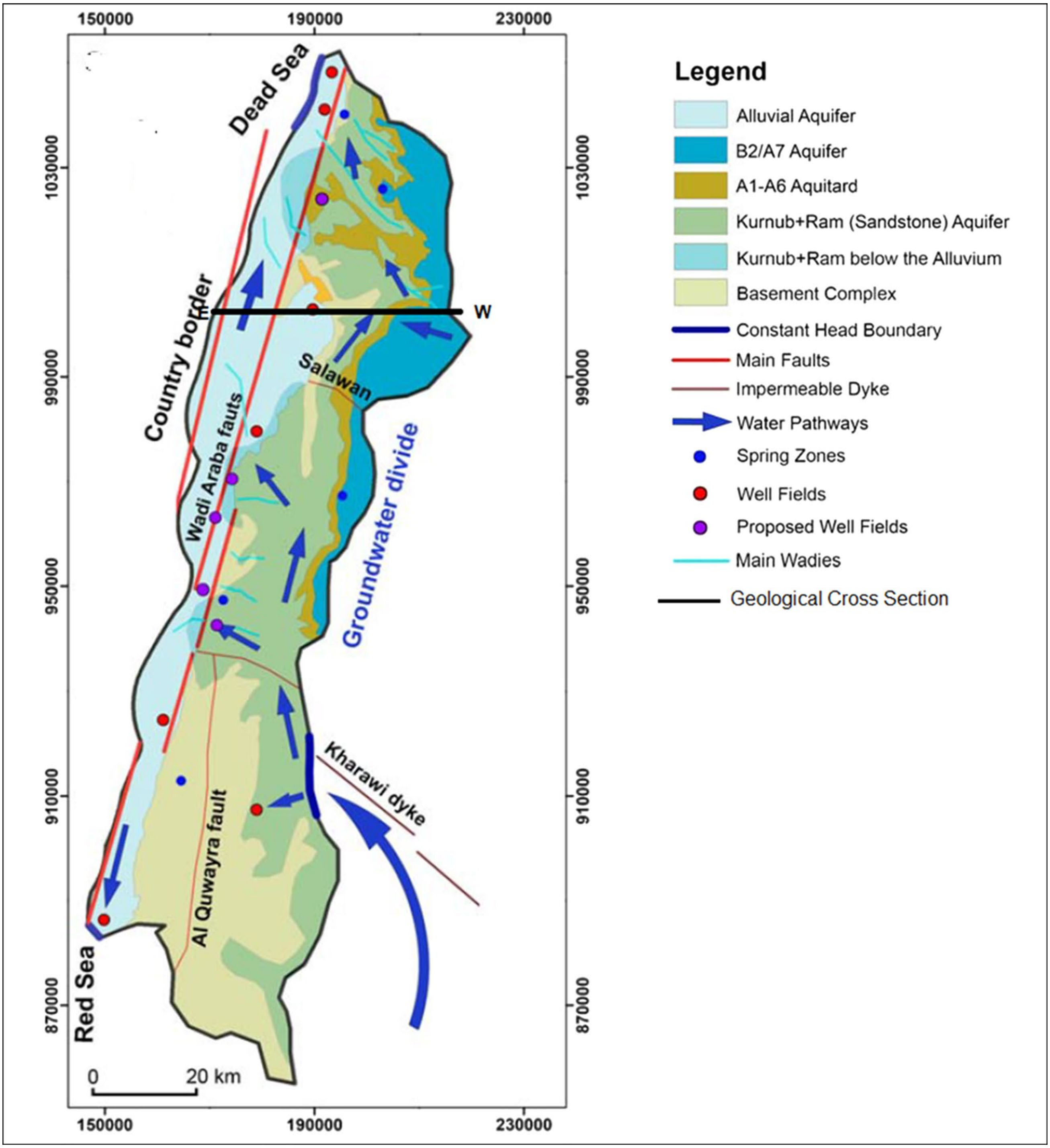


Fig. 2 Hydrogeological rock units of the Wadi Araba Basin (Radulovic et al. 2020)

The depth of the deposits varies but may exceed 200 m in some locations. As one goes to the west toward Jordan's international border, the alluvial deposits may contain more evaporitic materials, and the associated groundwaters typically become more saline and unusable for domestic or agricultural purposes (Rödiger et al. 2017).

The Wadi floor at the Northern Wadi Araba groundwater basin is built up of alluvial sediments brought from the surrounding mountains in the east and west with thicknesses of thousands of meters (EMWATER-Project 2005).

Rainfall in the Wadi Araba basin ranges from 50 mm/year in the area below 300 m above sea level, to more than

250 mm/year in the high eastern mountainous areas of the basin. The amount of rainfall and snow reflects the opportunities for groundwater recharge, as well as the amount of water flowing through the waterways of the basin (El-Naqa et al. 2009). The larger the precipitation, the greater the groundwater recharges and more runoff.

Aquifer systems

Within the study area (Wadi Araba area), the following aquifer systems are distinguished by the National Water Master Plan of Jordan. The deep sandstone aquifer and the alluvium aquifer are the most important aquifers of the Wadi Araba Basin. The deep aquifer is represented by two hydrogeological sandstone units, the Kurnub (upper unit), and Ram (lower unit). They can be pointed out as shown in Fig. 3, and the major aquifers can be summarized as follows (Enegoprojekt Co.–Jafar Tukan and Partners 1990):

- Deep sandstone aquifer (Kurnub and Ram formations) which includes water-bearing sandstones of Cambrian and Ordovician, constituting of Disi Group aquifer system; The Ram Group aquifer (Disi) forms a large aquifer system in Jordan, which underlies the entire area of the country. It crops out only in the southern part of Jordan and along Wadi Araba–Dead Sea Rift Valley. In addition, to Kurnub Group (aquifer consisting of Lower Cretaceous sandstones);
- The aquitard (Lower Ajlun, A1–A6) is distributed in the northeastern part of the basin below the B2/A7 aquifer.
- The Middle aquifer consists of water-bearing carbonate rocks of Upper Cretaceous age constituting the so-called Amman–Wadi Sir (B2/A7) aquifer system; The B2/A7 aquifer is distributed along the northeast boundary of the Wadi Araba Basin. This aquifer is inclined to the east, and the aquifer is recharged by the infiltration of precipitation. Many springs and Wadi base flow issue from this aquifer.
- Alternating water-bearing and water-confining/supporting Upper Cretaceous and Tertiary undifferentiated strata.
- The Shallow aquifer system occurs in the quaternary deposits, i.e., the alluvial deposits of the valley floor of Wadi Araba.

This study deals mainly with the alluvium aquifer system which is the most important aquifer, and it is the main groundwater resource in the Wadi Araba basin. It extends from the southern shore of the Dead Sea in the north to the northern shore of the Gulf of Aqaba in the south and underlies the Wadi Araba floor all over the rift from the Dead Sea to the Red Sea with different lithological units representing valley fills in the quaternary deposits; these deposits may be associated with alluvial fans (Enegoprojekt Co.–Jafar Tukan and Partners 1990). The deposits associated with the fans typically form shallow freshwater aquifers of limited areal extent (Kumari and Rai 2020).

This aquifer consists mainly of interbedded sand, gravel, and clay sediments. The thickness of the alluvial aquifer reaches up to approximately 400 m within the modeled area (COYNE-ET BELLIER 2011). The average depth to groundwater level is around 70 m.

Most of the wells in this area are mainly occurring in the fluvial–lacustrine and fluviatile deposits, which are composed of conglomerate, gravel, and sand, and inter-fingering occasionally within Lisan formation (GTZ 1977).

The thickness of the quaternary water-bearing sediments increases going from the east escarpment foot toward the central portion of Wadi Araba. In total, the

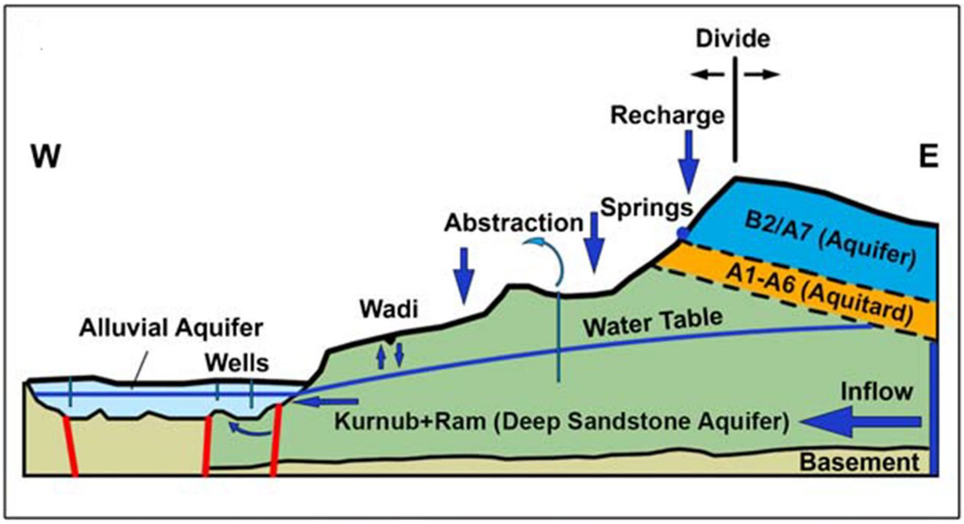


Fig. 3 Hydrogeological cross section of the Wadi Araba Basin (Radulovic et al. 2020)

thickness of these water-bearing sediments is estimated up to 300 m (GTZ 1977).

Recharge to the alluvium aquifers systems occurs almost exclusively as percolation from precipitation events. Seepage into the alluvial deposits is assumed to be extensive in the Wadi beds (MWI 2003). However, several major well fields exist in the areas of Rahma, Wadi Musa, Mithla, Qa'a Saidiyin, Fiefa, Finan, Feedan, Qatar and Ghor Safi.

Rainfall in the Wadi Araba Basin decreases from north to south, from west to east and from higher elevation to lower ones (JMD 2003). The 50 mm/year of rainfall over the surface of the alluvial aquifer does not allow any major recharge into this aquifer to take place. The main recharge into the alluvial aquifers seems to come from precipitation over the eastern escarpment and highlands adjacent to Wadi Araba (Abu-Zir 1989). GTZ (1977) reported that recharge into the alluvial aquifers takes place mainly through the side of Wadi floods during the rainy season and some base flows.

The JVA (1988) reported that the well production of Wadi Araba gave about 252 m^3/year. This quantity of groundwater does not affect the water level in the observed wells. At the Northern Wadi Araba Basin, groundwater is found in the fluviatile deposits, talus, and alluvial fans with a total thickness of about 250 m. The groundwater flows from the mountains at the east toward the west, with a component toward the north, the Dead Sea. Generally, all the groundwater of this area discharges into the Dead Sea. The throughput of water from this area into the Dead Sea was calculated to be around 22 MCM/year (Abu-Zir 1989). Freshwater renewable resources amount to some 8 to 10 MCM/year.

In the Southern Wadi Araba Basin, the groundwater flows east–west and from the north toward the Red Sea in the south. Recharge comes from precipitation falling on the surrounding mountains in the east; it infiltrates in the barren rocks and flows laterally into the fluviatile and alluvial deposits covering the Wadi floor. A part of the recharge takes place along the Wadi courses of the side Wadis and Wadi Araba itself. The throughput of the aquifer is calculated to be around 10 MCM/year composed mostly of brackish water (Abu-Zir 1989).

According to the flow net map, the direction of groundwater movement in the Wadi Araba Groundwater Basin within the alluvial aquifer system is from the escarpment foot toward the Wadi Araba floor and from the south to the north, toward the Dead Sea as shown in Fig. 4 (El-Naqa and Al Kuisi 2012).

Because the groundwater moves from areas of high hydraulic head toward areas of low hydraulic head, the groundwater movement depends upon the hydraulic gradient and "hydraulic conductivity." The hydraulic gradient is the change in static head per unit distance in each direction.

The deepest wells were drilled in Wadi Musa field, while the shallowest ones are located in the Wadi Rahma area. The depths of the Um Methla wells range from 85 to 206 m with an average depth of 132 m of the seven wells drilled in this area, while the drilled wells in Wadi Musa are deeper, ranging between 150 and 341 m with an average depth of 190 m (Enegoprojekt Co.–Jafar Tukan and Partners 1990).

Materials and methods

Several field visits to collect 37 representative water samples from 21 boreholes (4 Private Wells and 17 governmental wells) have been carried out through two periods. The first period during August and September 2019 and the second period during April and May 2019; at many regions along Alluvial deposits of Wadi Musa, Feifa, Feedan, Qatar, Um Mithla, Umurq, Rahma, Q'a Assaidiyin areas, Risha and southern part of the watershed where the private wells) in the Wadi Araba. The samples were collected to be analyzed in cooperation with the Central Laboratories of the Ministry of Water and Irrigation for their chemical and physical constituents. Our water samples were collected from the groundwater wells listed in Table 1.

A reconnaissance field trip was made to locate the water sampling points for the wells in the study area**.** The water samples were collected from 21 wells in polyethylene bottles of one-liter size after washing them twice with samples water to avoid contamination.

Collection of water samples determine the chemistry and quality of groundwater from the targeted aquifer. The 37 samples were collected from 21 wells; each sample was analyzed for physicochemical parameters such as pH, TDS and EC at a temperature of 25C°. The analyses of water samples were checked, and the accuracy of the analysis should not exceed 5%.

The laboratory works include the physical and chemical analyses of water samples**.** The major, minor elements and trace elements analyses were carried out in the Laboratories and Quality Department of the Ministry of Water and Irrigation. These analyses aimed to determine the concentration of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}), the anions (HCO_3^{-}, SO_4^{2-}, Cl^{-}), nitrate (NO_3^{-}) and trace elements (iron, zinc, manganese, arsenic, cadmium, chromium, copper, selenium, boron and nickel), in addition to pH, TDS and EC. The analytical methods used for the analysis of physicochemical parameters are listed in Table 2.

Hydrochemical interpretation

The hydrochemical study of the groundwater includes the interpretation of physical and chemical properties along the alluvial aquifer within the Wadi Araba groundwater basins to determine its suitability for different purposes (drinking and irrigation). Physical properties include temperature, acidity,

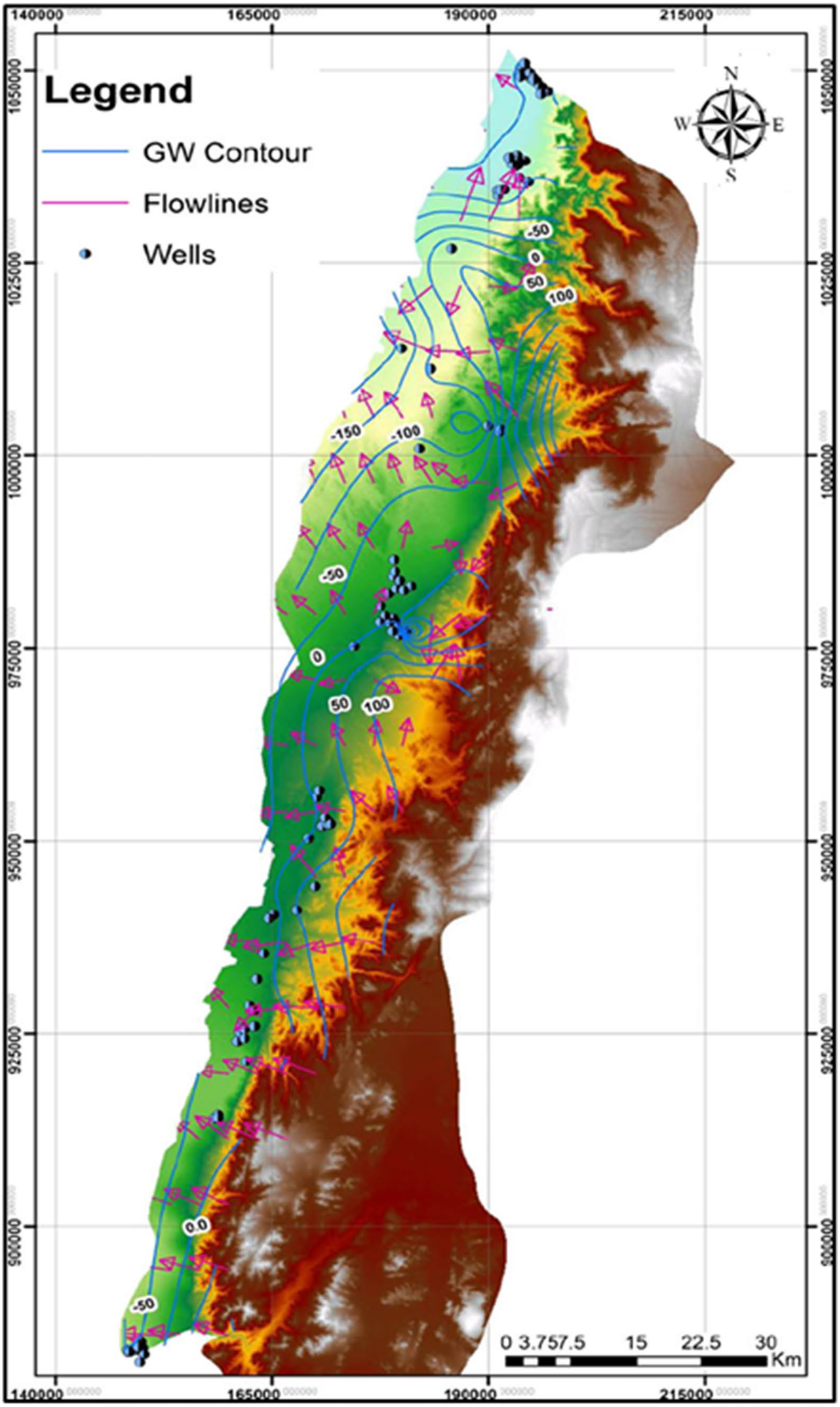


Fig. 4 Groundwater flow direction map of alluvial aquifer system8 (El-Naqa and Al Kuisi 2012)

Table 1 Inventory of groundwater sampling wells from alluvial aquifer in Wadi Araba area

Well number	MWI station ID	Station name	Palestine North	Palestine East	Altitude (m)
1	DA1008	Wadi Musa No.7	982,100	178,500	145
2	DA1010	Feifa No.2	1,038,330	192,860	−327
3	DA1020	Umruq No.2	1,036,040	193,613	−313
4	DA1027	Wadi Musa No.10	978,850	179,000	200
5	DA1029	Wadi Musa No.12	978,350	178,600	203
6	DA1102	Wadi Musa No.1	978,400	177,500	188
7	DE1001	Feedan No.1	1,003,808	189,963	−120
8	DE1003	Feedan No.6	1,003,350	191,000	−142
9	DF1002	Um Mithla No.1A	986,470	179,146	107
10	DF1003	Um Mithla No.1B	986,457	179,146	107
11	DF1005	Um Mithla No.5	984,970	179,250	122
12	DA3039	Um Mithla No.8	984,270	179,040	120
13	EA1005	Rahma No.6	924,405	161,860	129
14	EA1013	Rahma No.7	928,220	162,120	110
15	EA3013	Qatar No.2	913,934	158,298	53
16	EA3018	Q’a Assaidiyin No.2A	952,210	171,810	212
17	DA3046	Wadi Araba No.3 (WA3)/ RISHA	958,327	168,556	231
18	EA3033	Pilot project observation well 1	886,714	149,302	27.5
19	EA3034	Pilot project observation well 2	886,786	149,638	32
20	EA3035	Pilot project observation Well 3	886,607	149,580	31.5
21	EA3036	Pilot project observation well 4	887,866	149,895	38.5

Table 2 Methods of analysis used to determine physical and chemical analyses of groundwater samples

Parameter	Unit	Analytical methods
Electrical conductivity corrected at 25 C°	µs/cm	Field EC meter
pH value	–	Field pH meter
Total dissolved solid (TDS)	mg/l	By calculation
Total harness (TH)	mg/l	By calculation
Sodium, potassium, calcium, and magnesium	mg/l	ICP–MS
Chloride	mg/l	Titration with 0.01 AgNO3 using potassium chromate(K2CrO4) indicator
Sulfate	mg/l	Ultraviolet visible spectrophotometer wavelength 492 nm
Nitrate	mg/l	Ultraviolet visible spectrophotometer–wavelength 206 nm
Phosphate	mg/l	Ultraviolet visible spectrophotometer wavelength 690 nm
Bicarbonate	mg/l	Titration with 0.02N H2SO4 using diphenylcarbazone indicator
Ammonium	mg/l	Ultraviolet visible spectrophotometer wavelength 425 nm
As, Zn, Se, Ni, Fe, Mn, Cu, Cd, Cr, and B	mg/l	ICP–MS

electrical conductivity and total dissolved solids; chemical properties include determination of the concentration of the major cations Ca^{2+}, Mg^{2+}, Na^+ and K^+, major anions CO_3^{2-}, HCO_3^-, SO_4^{2-} and Cl^-, minor ions NO_3^- and PO_4^{3-} as well as the trace elements Fe, Cr, Ni, Cu, Zn, Cd, Mn, As, Se, and B.

The water samples were collected from 21 wells (4 private wells and 17 governmental wells) totaling 37 samples for two seasons; the spring season was during April and May 2019 and the autumn season was during August and September 2019. These samples were collected and analyzed physically and chemically to determine their constituents and quality.

The values of pH in the groundwater samples in this study varied from 6.48 at the private well (Pilot Project Observation Well No.2) to 7.99 at the well (Feedan No.1) with an average value of 7.5. It appears toward alkalinity. Detay (1997) classified the mineralization of water according to EC; therefore, the type of groundwater in the studied area is excessively mineralized water due to salinity. One sample from Feifa and two samples from Feedan area are "highly mineralized waters," and all other samples are "excessively mineralized waters" in accordance to the definition by Detay (1997).

The TDS values of the groundwater samples collected during April–May and August–September periods were obtained from the selected wells. The highest measured TDS was noticed at Qatar well No.2 in the first period, while in the second period, the well of Wadi Musa No.1 was recorded about 2828.8 mg/L; it is slightly lower than that the first period. Generally, most parts of the study area suffer from salinity problems.

The maximum acceptable and potable limit of TDS value for drinking water of the Jordanian standard in the first period found at Feifa, Um Mithla, Risha, Q'a Assaidiyin and in the private wells at the southern part of Wadi Araba basin near Aqaba, whereas lower TDS values of groundwater samples (< 1000 mg/l) in the second period found at the upper part of northern Wadi Araba Catchment (Fefia, Umruq and Feedan), Wadi Musa, Um Mithla and at the middle part of southern Wadi Araba Catchment in the area of Risha and Qatar; then, the TDS values started to increase gradually toward the southern basin (Fig. 7).

Generally, water salinity increases in the direction of groundwater flow, from the areas adjacent to the recharge areas to the discharge areas. In addition, irrigation return flows are gradually leading to groundwater quality deterioration. The increasing salinity is an indicator of that. The development of the groundwater resources of the area for irrigation purposes may be restricted by the salinity of the water which is already showing the effects of additional salinization due to irrigation return flows.

Classification of groundwater samples

Classification of the analyzed 37 groundwater samples collected from the alluvial aquifer within Wadi Araba basin has been done by using the software Aquachem (Waterloo Hydrogeological Inc. 2019) and Diagrammes v.6.72 (Laboratoire d'Hydrogéologie d'Avignon 2019). These classifications were done to determine the water types and the variations of water quality, and these displayed graphical plots depending on the main cations and anions concentrations measured as milligrams per liter (mg/l) or milliequivalents per liter (meq/l).

The chemical composition of groundwater is primarily dependent on the geology as well as on the geochemical processes which take place within the groundwater system. In this study, the hydrochemical data of the collected groundwater samples were interpreted by using the Piper (1944) and Durov (1948).

As water flows through an aquifer, it assumes a characteristic chemical composition because of interaction with the lithologic framework. The term hydrochemical facies is used to describe the bodies of groundwater in an aquifer that differ in their chemical composition. The facies are a function of the lithology, solution kinetics, and flow patterns of the aquifer (Selvam 2019). The TDS values of the collected water samples are plotted in Fig. 5 according to Davis and DeWiest classification (1966).

Ionic concentrations for the first and second periods have been replotted in a Piper diagram to evaluate the geochemical characteristics of the sampled groundwater. Generally, the predominant anion and cation in both periods are chloride and sodium, respectively. The concentration of majority of the analyzed groundwater samples collected from study area during the autumn and spring seasons is summarized in Table 3. These major ions were plotted on Piper diagrams as shown in Fig. 6. According to Furtak and Langguth (1967), water was classified into seven types (facies).

These diagrams reveal that there are three different groundwater types were identified in the study area for both periods which are: The first type of hydrochemical facies shows that 34 out of 37 groundwater samples (91.8%) collected during both seasons lay in the class "E" as Earth Alkaline water with an increased portion of alkalis with prevailing sulfate and chloride (Ca–(Mg)–Na–Cl–SO_4). The major ions fall within the mixed zone (No cation–anion exceeding 50%) and demonstrate the dominance of alkaline earth over alkali (i.e., $Ca + Mg > Na + K$) and strong acidic anions over weak acidic anions (i.e., $Cl + SO_4 > HCO_3$).

The remaining groundwater samples represented the second type of hydrochemical facies about 5.4% of groundwater samples (Pilot Project Observation Well No.2 in the spring season and Qatar No.2 in the autumn season); it lies in the class "G" as alkaline water with prevailing sulfate and chloride (Na–(K)–Cl –SO_4), and it represents that the strong acids (Cl and SO_4) exceed weak acids.

The dominant cation is sodium followed by calcium and magnesium ions, while the dominant anion is chloride followed by sulfate and bicarbonate ions (Fig. 6). The chemistry of water changes along the groundwater flow path and becomes slightly brackish, whereby the high sodium concentration is usually an indication of cation-exchange processes and dissolution of halite layers. Spatial distributions for the groundwater samples in the first and second periods are shown in Fig. 7. There are no substantial changes in the hydrochemical facies that were noticed between the two seasons.

The groundwater samples collected from the study area are plotted on Durov diagrams (Fig. 8). Groundwater plots indicate that most samples have Na–Ca–Cl type for the first period and Na–Ca–Mg–Cl–SO_4–HCO_3 water type for the second period. The pH values of more than 6.4 and less than 8 and TDS range between 500 and 3000 mg/l for both periods. The main purpose of the Durov diagram (Lloyd

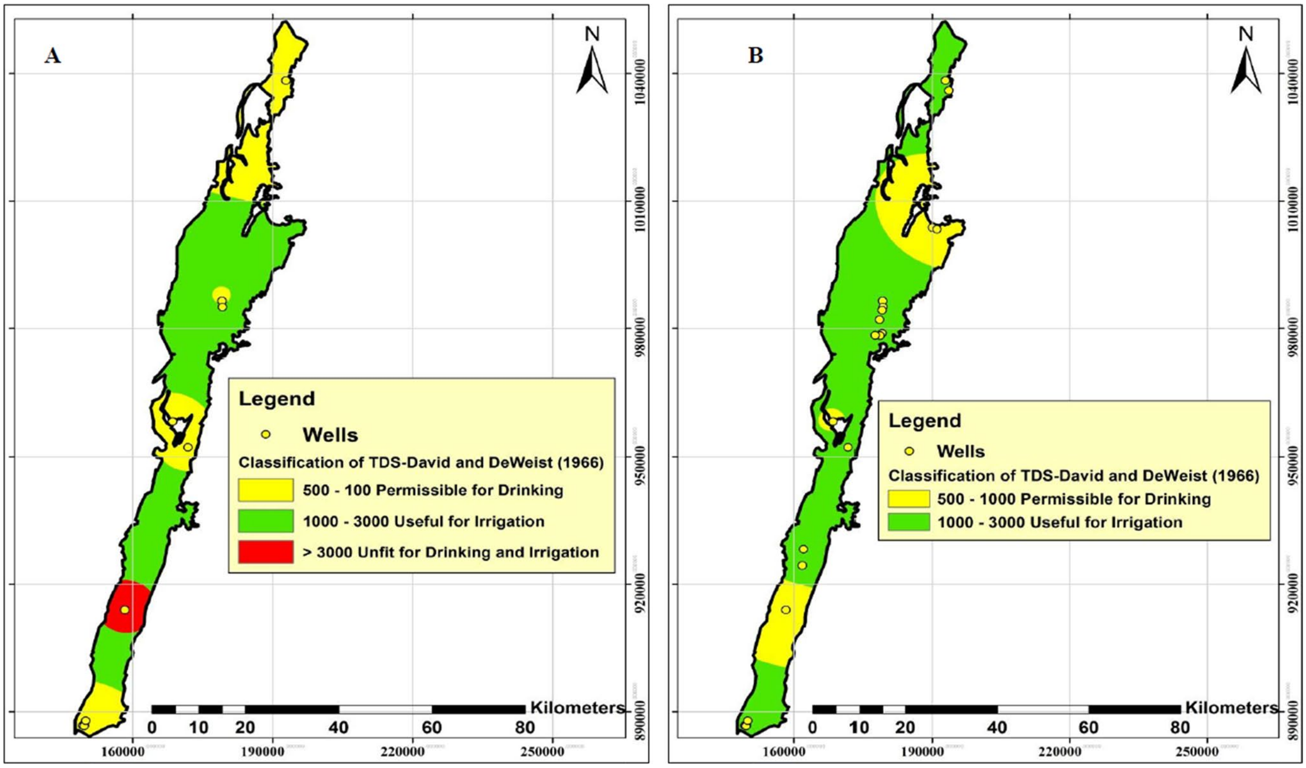


Fig. 5 Spatial variation in TDS (mg/l) of groundwater samples based on Davis and DeWiest classification (1966). **A** Spring season (April–May 2019). **B** Autumn season (August–September 2019)

and Heathcoat 1985) is to cluster the data points indicating the samples with similar chemical composition as well as to reveal useful relationships and properties for a large sample group. This method has been adopted to evaluate the water types from the geochemical process that could have affected the groundwater type and to present the total or absolute concentrations of two selected parameters such as total cation or ion concentration, pH, or TDS.

These Durov diagrams reveal that there are three geochemical processes that could affect the water genesis in the study area for both periods. Most of the groundwater samples, about 24 out of 37 groundwater samples (62.2%), are plotted in field 6. This type of water genesis indicates Cl is dominant anions and Na dominant cations, which indicates that the groundwaters can be related to reverse ion exchange of Na–Cl water, which indicates that the water may be related to reverse ion exchange of Na–Cl resulted from the infiltration of irrigation return water at the discharge area being mixed with the groundwater.

Thirteen (13) out of 37 water samples (35%) are plotted in field 5 of the Durov plot along the dissolution or mixing line. Based on the classification of waters (Lloyd and Heathcoat 1985), this trend can be attributed to fresh recent recharge water exhibiting simple dissolution or mixing with no dominant major anion or cation along the mixing line, i.e., mixing of the infiltrated groundwater recharge with water stored in the aquifer. The third type of hydrochemical process shown in field 3 in which Cl and Na are dominant frequently indicate end-point waters. This type of hydrochemical process was represented only one analyzed groundwater samples (2.7%) which takes from the well of Qatar No.2 in the middle part of southern Wadi Araba catchment area.

Geochemical modeling

As groundwater flows, it interacts with the adjacent minerals of the aquifer. The most important results of speciation calculations are saturation indices (SI) for minerals, which indicate two main geochemical processes (dissolution and precipitation) (Mostafa et al. 2019). These processes are mainly controlled by the ionic activity product and solubility products of the adjacent mineral phases. Saturation index of a mineral (SI) can be calculated with respect to the temperature of the water sample (Freeze and Cherry 1979):

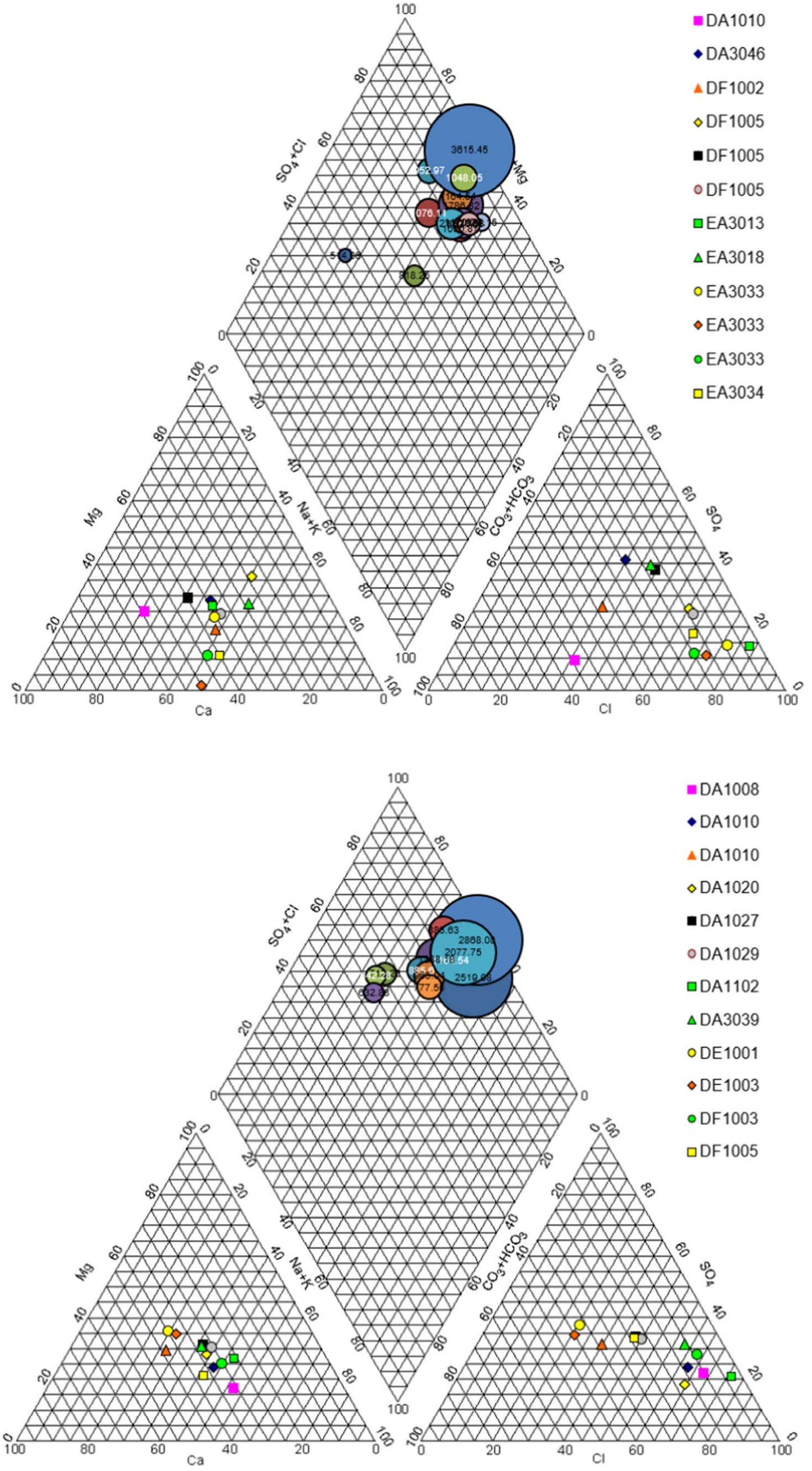
$$\mathrm{SI} = \log\left(K_{\mathrm{IAP}}/K_{\mathrm{sp}}\right)$$

where SI: Saturation index, IAP: Ion activity product, and K_{SP}: Solubility product of the mineral.

Table 3 Chemical analysis (mg/l) and groundwater classifications (long and short term of hydrochemical facies) in the two-sampling campaigns

Well ID	Sampling date	EC	pH	Ca2 +	Mg2 +	Na +	K +	NH4 +	HCO3 −	Cl-	SO42-	NO3-	Short term	Long term
Spring season														
DA1010	02/04/19	772	7.4	85.2	24.0	37.3	2.0	0.1	238.5	94.1	33.1	46.5	Ca–HCO_3	Ca–Mg–Na–HCO_3–Cl
DA3046	13/04/19	1456	7.6	105.2	54.1	130.2	7.0	0.1	245.2	205.6	328.8	0.2	Na–HCO_3	Na–Ca–HCO_3–Cl–SO_4
DF1002	13/04/19	1294	7.6	85.0	27.0	112.0	4.3	0.1	281.8	154.1	154.1	6.4	Na–Cl	Na–Mg–Cl–SO_4
DF1005	13/04/19	2580	7.6	113.4	132.5	315.1	5.9	0.1	245.2	618.1	356.6	7.4	Ca–Cl	Ca–Na–Mg–Cl–SO_4
DF1005	14/05/19	1872.5	7.6	126.7	55.9	109.3	6.7	0.1	155.1	232.9	266.4	9.0	Na–Cl	Na–Ca–Mg–Cl–SO_4
DF1005	28/05/19	1872.5	7.6	126.7	55.9	186.3	6.7	0.1	155.1	417.8	216.0	9.6	Na–Cl	Na–Ca–Mg–Cl
EA3013	13/04/19	5860	6.8	428.3	206.8	556.6	16.8	0.1	110.4	1873.7	422.9	10.7	Na–Cl	Na–Mg–Ca–Cl–SO_4
EA3018	13/04/19	1429	7.7	73.0	51.6	170.0	5.1	0.1	176.9	246.7	307.7	8.8	Na–SO_4	Na–Ca–Mg–SO_4–Cl–HCO_3
EA3033	28/05/19	1898	7.8	142.1	55.9	190.9	5.1	0.1	88.5	454.8	110.9	27.2	Na–Cl	Na–Ca–Mg–Cl
EA3033	13/04/19	1880	7.6	190.2	4.0	209.5	5.9	0.1	184.2	477.1	99.4	12.5	Ca–Cl	Ca–Na–Cl
EA3033	02/04/19	1841	6.9	161.9	24.6	193.4	5.5	0.1	233.0	484.9	108.0	16.9	Na–Cl	Na–Ca–Cl
EA3034	14/05/19	1166	7.5	83.0	14.4	113.9	4.3	0.1	108.6	248.5	91.2	1.3	Na–Cl	Na–Ca–Cl
EA3035	14/05/19	1263	7.7	71.1	19.1	134.6	4.3	0.1	75.6	293.6	87.8	0.3	Na–Cl	Na–Ca–Cl
EA3036	14/05/19	1553	7.9	98.6	24.0	158.7	4.7	0.1	126.3	336.5	121.9	10.2	Na-Cl	Na–Ca–Cl
Autumn season														
DA1008	10/08/19	4160	7.7	250.1	85.4	485.3	6.7	0.1	251.3	1003.9	436.3	7.7	Na–Cl	Na–Ca–ClSO_4
DA1010	06/09/19	1047	7.6	126.7	55.9	186.3	6.7	0.1	155.1	417.8	216.0	3.4	Na–Cl	Na–Ca–Mg–Cl–SO_4
DA1010	10/08/19	1058	7.7	91.8	37.7	62.8	5.1	0.1	220.8	132.8	161.3	2.5	Ca–Cl	Ca–Mg–Na–Cl–HCO_3–SO_4
DA1020	10/08/19	2006	7.8	136.9	71.1	177.1	15.3	0.1	220.8	483.2	183.8	3.3	Na–Cl	Na–Ca–Mg–Cl
DA1027	10/08/19	1298	7.7	86.0	49.9	107.0	7.8	0.1	196.4	214.4	224.2	9.6	Na–Cl	Na–Ca–Mg–Cl–SO_4–HCO_3
DA1029	10/08/19	1510	7.6	88.0	53.4	128.3	8.6	0.1	202.5	245.7	238.6	19.3	Na–Cl	Na–Mg–Ca–Cl–SO_4–HCO_3
DA1102	10/08/19	4800	7.5	261.9	163.6	538.2	10.6	0.1	83.0	1322.7	488.2	12.7	Na–Cl	Na–Mg–Ca–Cl–SO_4
DA3039	10/08/19	882	7.8	105.6	59.2	129.7	5.1	0.1	89.7	286.5	207.8	7.9	Ca–SO_4	Ca–Mg–Na–SO_4–HCO_3–Cl
DE1001	14/09/19	905	8.0	74.2	40.1	50.8	3.9	0.1	213.5	88.4	171.4	6.9	Ca–HCO_3	Ca–Mg–Na–HCO_3–SO_4–Cl
DE1003	14/09/19	3180	7.9	70.1	38.9	55.2	3.5	0.1	226.3	85.2	153.6	3.2	Na–Cl	Na–Ca–Mg–Cl–SO_4
DF1003	10/08/19	1301	7.5	203.2	102.0	349.6	6.7	0.1	183.6	774.3	458.4	8.1	Na–Cl	Na–Ca–Mg–Cl–SO_4–HCO_3
DF1005	10/08/19	1445	7.7	90.0	31.1	112.5	4.3	0.1	171.4	179.6	188.6	6.8	Na–Cl	Na–Ca–Mg–Cl–SO_4

Fig. 6 Piper diagram classifying major hydrochemical facies for groundwater samples during the spring season (April–May) and the autumn season (August–September) (Langguth 1966)



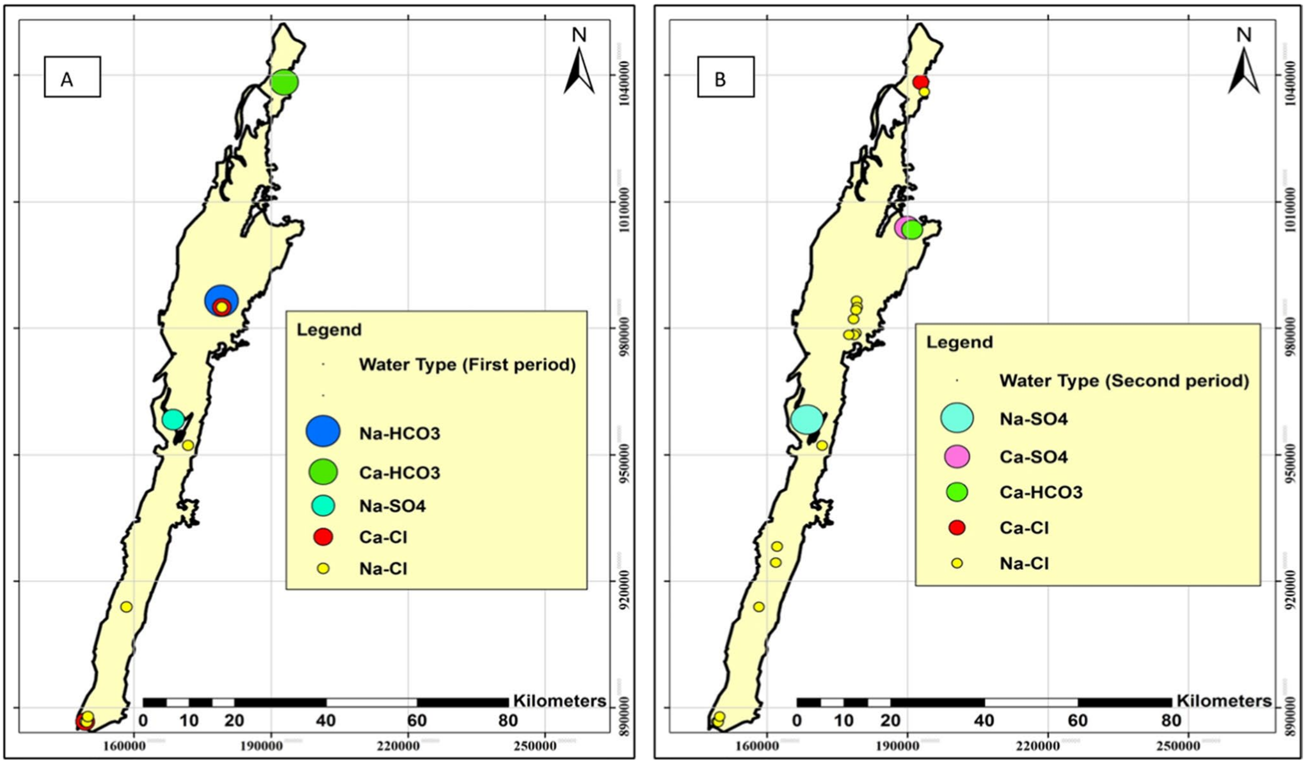


Fig. 7 Spatial distributions of groundwater type of the alluvial aquifer in two sampling campaign in **A** spring season (April–May). **B** autumn season (August–September). The size of circle indicates the salinity of water

The importance of determining the saturation indices is to know the state of water–rock interaction (equilibrium, undersaturation, or supersaturation). Water is at equilibrium with the mineral phase when the saturation index of the mineral is zero. Negative saturation index values indicate undersaturation conditions, and the mineral phase tends to dissolve. Positive saturation index values indicate supersaturation conditions, and the mineral phases tend to precipitate. The major element data on groundwater from the study area was processed by using PHREEQC Interactive version 3.2 (USGS 2020).

The saturation indices for two periods of the different mineral phases of groundwater samples were calculated (Table 4). It is observed from the table that all groundwater samples show negative values of (SI) for carbonates minerals (anhydrite, gypsum, sylvite, and halite), magnetite, hausmannite, jarosite, pyrochroite, and pyrolusite. This suggests that the groundwater in the alluvial aquifer within Wadi Araba groundwater basin is undersaturated with respect to these minerals in most of the study area. The evaporite minerals (anhydrite, gypsum, halite, and sylvite) show negative values of (SI). This is indicative of the fact that these minerals from the study area are undergoing the process of dissolution.

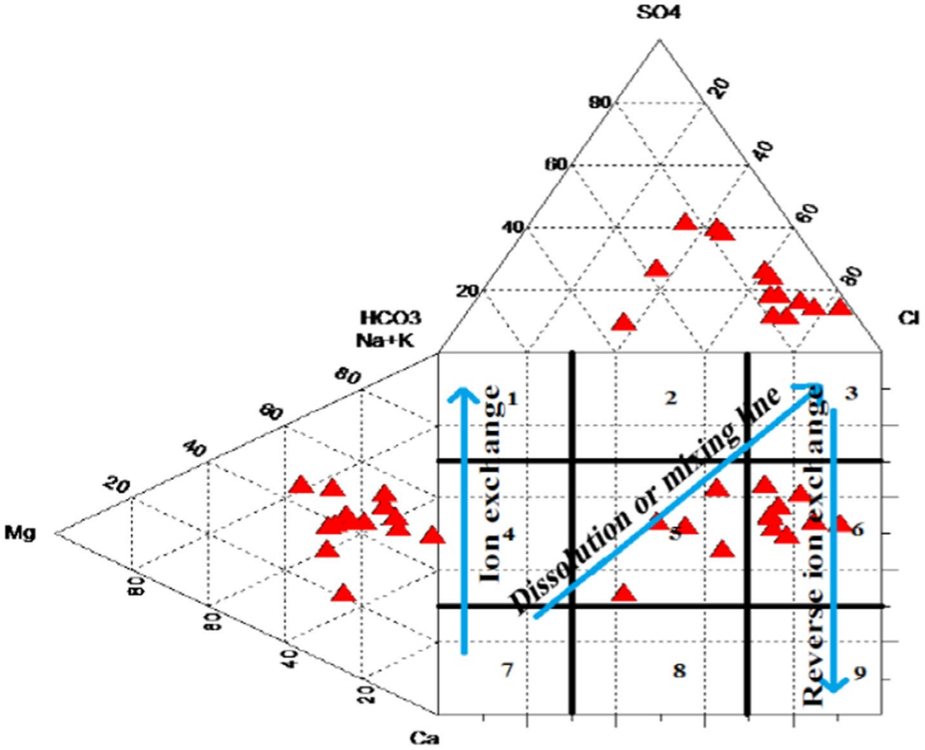
Conclusions

A comprehensive analysis of hydrochemical data in the Wadi Araba Basin was conducted to provide a basis for understanding the major ion's origins, distribution, and associated hydrogeochemical evolutions along the flow path and supporting the local groundwater resource management. The main aquifer in the study area is the quaternary alluvial aquifer system which covers most of the study area and extends along the western side of the northern and southern catchments of the Wadi Araba basin. It is composed of different lithological units representing valley filling (conglomerate, gravel, clay, and sand). The water quantity, the limiting factor of the groundwater development within the study area, appears to be its quality for both irrigation and domestic water supply. It has been reported that the groundwater quality throughout Wadi Araba is quite variable, and its exploitation relates to quality constraints.

The groundwater flows from the mountains at the east toward the west, with a component toward the northern Dead Sea direction. The aquifers of the Wadi Araba Basin can be recharged by infiltration from precipitation,

Fig. 8 Durov diagram depicting hydrochemical processes for groundwater samples during the spring (April–May) and the autumn (August–September) seasons

Durov plot (first period)



Durov plot (Second period)

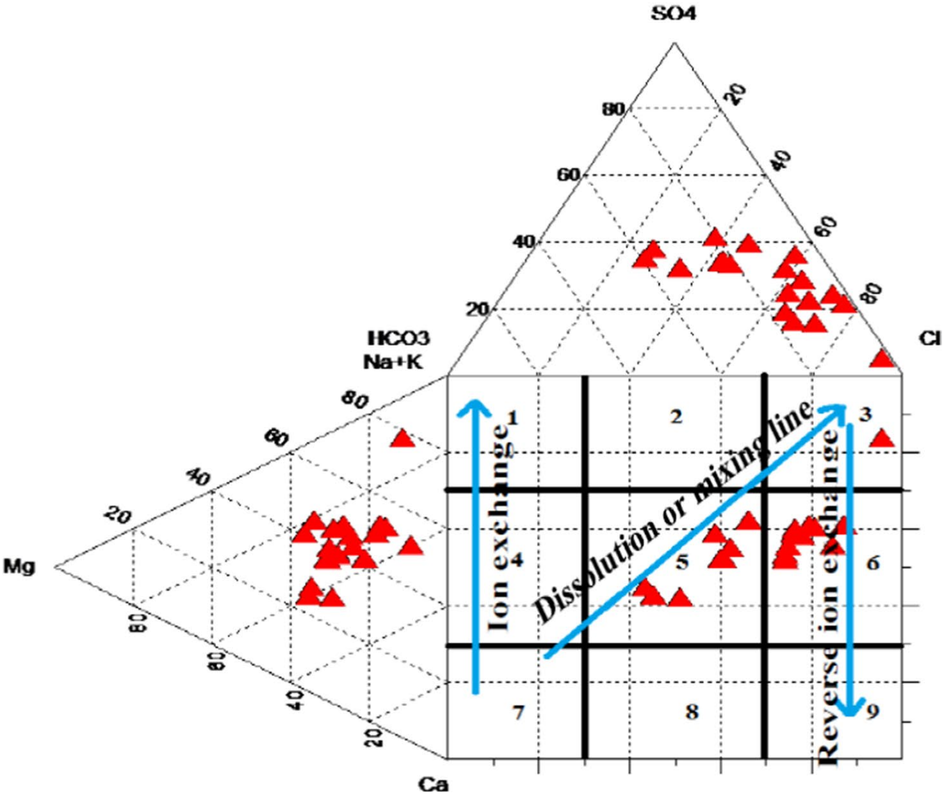


Table 4 Saturation indices of different mineral phases of the quaternary aquifer during the two sampling campaigns in Wadi Araba basins

Well ID	Anhydrite $CaSO_4$	Aragonite $CaCO_3$	Calcite $CaCO_3$	Dolomite $CaMg(CO_3)_2$	Goethite FeOOH	Gypsum $CaSO_4{:}2H_2O$	Halite NaCl	Hausmannite Mn_3O_4	Hematite Fe_2O_3	Jarosite-K $KFe_3(SO_4)2(OH)_6$	Manganite MnOOH	Pyrochroite $Mn(OH)_2$	Pyrolusite MnO_2	Rhodochrosite $MnCO_3$
DA1008	−1.07	0.56	0.70	1.29	8.00	−0.85	−4.98	−12.70	18.00	−2.27	−5.35	−6.86	−9.74	−1.01
DA1010	−2.27	0.04	0.19	0.17	7.52	−2.05	−7.04	−15.23	17.04	−5.22	−6.28	−7.52	−10.94	−1.37
DA1020	−1.54	0.53	0.67	1.41	7.43	−1.32	−5.70	−12.04	16.88	−4.71	−5.07	−6.76	−9.28	−1.12
DA1027	−1.56	0.18	0.32	0.75	8.03	−1.34	−6.25	−12.99	18.06	−2.48	−5.43	−6.98	−9.78	−1.24
DA1029	−1.54	0.14	0.28	0.70	7.80	−1.32	−6.12	−13.39	17.60	−2.94	−5.58	−7.08	−9.98	−1.27
DA1102	−1.07	−0.05	0.09	0.33	7.90	−0.85	−4.83	−14.44	17.81	−2.00	−5.97	−7.35	−10.49	−1.86
DA3039	−1.53	0.00	0.15	0.39	7.58	−1.31	−6.05	−12.16	17.16	−4.38	−5.13	−6.76	−9.40	−1.44
DE1001	−1.68	0.48	0.62	1.32	7.34	−1.46	−6.94	−10.80	16.69	−5.89	−4.60	−6.45	−8.65	−0.97
DF1002	−1.68	0.27	0.41	0.67	7.49	−1.46	−6.37	−13.76	16.99	−4.33	−5.72	−7.18	−10.16	−1.18
DF1003	−1.10	0.16	0.30	0.65	7.38	−0.89	−5.23	−15.02	16.77	−3.44	−6.19	−7.50	−10.78	−1.57
DF1005	−1.43	0.22	0.36	1.13	7.49	−1.21	−5.36	−12.01	16.99	−3.83	−5.13	−6.60	−9.56	−0.71
EA1002	−1.44	0.91	1.06	2.10	7.98	−1.22	−6.57	−4.80	17.97	−4.91	−2.46	−4.72	−6.10	0.17
EA1005	−1.43	−0.41	−0.27	−0.36	7.48	−1.21	−5.77	−14.05	16.97	−3.46	−5.84	−7.23	−10.35	−1.80
EA1013	−1.37	0.22	0.36	1.05	7.21	−1.15	−5.71	−12.59	16.42	−4.79	−5.27	−6.89	−9.55	−1.24
EA3013	−1.00	−0.42	−0.28	−0.52	7.78	−0.79	−4.68	−19.93	17.56	−0.41	−8.03	−8.73	−13.23	−2.44
EA3013	−2.99	−1.74	−1.60	−3.03	7.99	−2.77	−5.83	−15.55	17.99	−3.35	−6.42	−7.57	−11.17	−2.44
EA3018	−1.52	−0.01	0.14	0.47	7.83	−1.30	−6.00	−13.31	17.68	−2.86	−5.55	−7.06	−9.94	−1.32
EA3033	−1.70	0.17	0.31	0.57	7.21	−1.48	−5.69	−9.67	16.43	−6.25	−4.28	−5.96	−8.50	−0.71
EA3034	−1.47	0.13	0.27	0.53	7.66	−1.25	−5.73	−13.32	17.32	−3.51	−5.57	−7.03	−10.01	−1.31
EA3035	−1.47	0.13	0.27	0.53	7.12	−1.25	−5.73	−11.74	16.25	−5.13	−5.04	−6.50	−9.48	−0.78
EA3036	−1.73	0.32	0.46	0.65	7.44	−1.51	−5.88	−7.99	16.88	−5.72	−3.68	−5.48	−7.78	−0.18

whereby the highest values are in the northeastern part of the Wadi Araba Basin, decreasing to the west and south. The amount of infiltration is insignificant in the southern part of the basin, where precipitation is less than 75 mm/year. For areas with precipitation rates higher than 75 mm/year, it is estimated that recharge is approximately 4% of rainfall. Generally, all the groundwater of this area discharges into the Dead Sea. The best groundwater quality exists near the recharge zone and more or less within the alluvial fans of the Wadis. By further movement of the water toward the central part of Wadi Araba, the salinity of water increases along the groundwater flow path toward the west direction.

The groundwater in the study area is generally of low alkalinity with an average pH of less than 8 for sampling campaigns in the spring and autumn seasons. Salinity causes high mineralization, and the increase in salinity in the southern Wadi Araba basin is less expressed than in the northern part. Different types of water are present relating to both anions and cations. Chloride usually prevails, but sulfate and bicarbonate are sometimes dominating constituents of the water's chemical composition. Sodium with potassium is the leading cation, but quite exceptionally concentration of calcium exceeds any other cation constituent. The hydrochemical characterization shows that most wells of the study area are characterized by HCO_3–Ca–Mg and HCO_3–SO_4–Ca–Mg types in the eastern escarpments of Wadi Araba (i.e., recharge area) and Cl–SO_4–Na and Cl–Na types in the discharge area. There is no substantial change in the hydrochemical composition during the two seasons.

Generally, water salinity increases in the direction of groundwater flow, from the areas adjacent to the recharge areas to the discharge areas. In addition, irrigation return flows are gradually leading to groundwater quality deterioration. The increasing salinity is an indicator of that. The development of the groundwater resources of the area for irrigation purposes may be restricted by the salinity of the water which is already showing the effects of additional salinization due to irrigation return flows. It should be mentioned that the high mineralization of groundwater, with total dissolved solids exceeding 2500 ppm corresponds to the mixed cations chloride or sodium chloride type of water. On the other hand, with relatively low mineralization of groundwater, the percentage of the bicarbonate gets more important, accounting very often for mixed anion type of water occurrence. The considerable presence of bicarbonate should indicate recent groundwater recharge into the tapped aquifer.

The dominant cation is sodium followed by calcium and magnesium ions, while the dominant anion is chloride followed by sulfate and bicarbonate ions. The chemistry of water changes along the groundwater flow path and becomes slightly brackish, whereby the high sodium concentration is usually an indication of cation-exchange processes and dissolution of halite layers. There is no substantial change in the hydrochemical composition during the two seasons.

The Durov diagrams showed that the most original of the aquifer water and its chemical processes can be plotted in "field 6." This type of water genesis indicates that Cl is the dominant anion and Na dominant cation, which indicates that the groundwaters can be related to reverse ion exchange of Na–Cl water that the water may be related to reverse ion exchange of Na–Cl resulted from the infiltration of irrigation return water at the discharge area being mixed with the groundwater.

The computation of saturation indices for the two sampling campaigns for different minerals showed negative values of (SI) for carbonates minerals (anhydrite, gypsum, sylvite, and halite). This suggests that the groundwater in the alluvial aquifer is undersaturated with respect to these minerals in most of the study area. This is indicative of the fact that these minerals are undergoing the process of dissolution. The mineral saturation indices suggest that the dominating hydrochemical processes were dissolutions of evaporite minerals (halite and gypsum), carbonate minerals (such as calcite, dolomite, and Rhodochrosite), the manganese oxide minerals (such as jarosite-K, hausmannite, pyrochroite, and pyrolusite), and reverse ion exchange. The results of this study can provide references for further understanding of the groundwater geochemical evolution processes in the Wadi Araba Basin. In addition, the hydrochemistry characteristics and groundwater evolution can guide the selection of water resource fields and provide information for the assessment and development of groundwater resources.

The water quality parameters of groundwater in Wadi Araba Basin showed that the water quality in the study area was unsuitable for direct drinking purposes; however, it can be used for irrigation purposes. The suitability of groundwater for irrigation is contingent upon the effects of the mineral constituents of water on both plants and soil.

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Data availability The data were collected and analyzed primarily by us.

Declarations

Conflict of interest All authors have participated in (a) conception and design or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has neither been submitted to nor is under review at another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical standard This study has been approved by an appropriate ethics committee and has been performed in accordance with the ethical standards of the Hashemite university regulations that have been issued in 2003.

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