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Arabian Journal of Chemistry

journal homepage: www.sciencedirect.com



Original article

# Characterization of groundwater in Quaternary aquifer of the Yanbu Al-Nakhl Basin, Al-Madinah Al-Munawarah Province using pumping tests and hydrochemical techniques

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## ARTICLE INFO

## Article history:

Received 9 March 2023

Accepted 2 October 2023

Available online 5 October 2023

## Keywords:

Quaternary aquifer

Pumping tests

Hydraulic parameters

Hydrochemical characteristics

Irrigation quality indices

GIS

## ABSTRACT

In the Yanbu Al-Nakhl Basin, Quaternary aquifer is the main source of groundwater supply for different uses. The groundwater wells that have been drilled in this area are now not subject to local government regulation in terms of distances and daily pumping rates. This may lead to declines in groundwater levels and deterioration of its quality. The primary goal of this research is to characterize the Quaternary aquifer using measurements of hydraulic parameters and groundwater quality. To achieve this purpose, all aquifer parameters such as thickness, lithology, depth to water, water table, well loss, formation loss, well efficiency, transmissivity and hydraulic conductivity were measured. Moreover, chemical analysis for major ions as well as minor and trace elements of 14 samples were carried out to determine the physicochemical properties, groundwater facies, controlling mechanisms and five irrigation water quality indices (IWQIs). The results revealed that, groundwater originates mainly from highly permeable Quaternary alluvial sediments of (60 m thickness), and flows generally from north to south. The calculated hydraulic parameters indicated that, the average of well efficiency ( $\gamma$ ) ranges from 42.21% to 72.2%, transmissivity ( $T$ ) varies between 88.2 and 105.4 m<sup>2</sup>/day, and hydraulic conductivity ( $K$  in m/day) ranges from 4.41 to 9.3. In hydrochemical point of view, there are various types for groundwater in the study area including Ca - HCO<sub>3</sub>, Na - Cl, mixed Ca - Mg - Cl - SO<sub>4</sub>, and Na - Ca - HCO<sub>3</sub>. The processes of evaporation and rock - groundwater interaction were significantly influenced the groundwater quality in the Wadi. The computed IWQIs (TDS, TH, SAR, PS, MH, and RSC) had mean values of 1537.685, 678.31, 3.940625, 2.140625, 25.85687 and -10.8068 respectively, indicated that no restriction range for agriculture uses characterizes the majority of groundwater in Wadi Yanbu Al-Nakhl basin.

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## 1. Introduction

Water scarcity is recognized as a major problem, especially in developing countries, due to poor exploration methods and insufficient water supplies to meet the needs of the population (Shandu and Atif, 2023). Groundwater is usually defined as the water

present in the pore spaces of rocks and soils, accounts for approximately 30% of the earth's fresh water, and has particularly important functions in the water cycle (Bekele, 2021; Abdalla et al., 2020; Moodley et al., 2022). Among the countries in the arid regions, Saudi Arabia has limited water resources, making groundwater a necessary supply for different uses. As the kingdom has developed rapidly during the past few decades, both agricultural and anthropogenic activities have affected groundwater quality and accessibility. There are two main water-bearing formations (groundwater aquifers) in Saudi Arabia (Al-Shaibani 2008): (1) deep, non-renewable aquifer under sedimentation that covering the Arabian Shield, and (2) shallow, renewable aquifer under fractured Precambrian basements and alluvial deposits in West and Southwest Saudi Arabia. Western Saudi Arabia gets its water primarily from shallow alluvial Quaternary aquifer found in the major Wadies. Therefore, the shallow aquifer is relatively close to cities

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Peer review under responsibility of King Saud University.



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with a high population density and is sensitive to human activity. Thus, shallow alluvial aquifer near major cities are always at risk of water level decline and contamination. Due to urbanization, industry, and intensive farming, groundwater resources in desert areas like Saudi Arabia have experienced increased demand (Tayfur et al., 2008; Aghazadeh and Moghaddam 2010; Alqarawy et al., 2022; Alqarawy 2023). Therefore, in order to effectively use, safeguard, and predict the alteration in groundwater behaviors, it is vital to define the characterizations of groundwater in terms of hydrogeological and hydrochemical aspects (Edmunds et al. 2006; Bozda and Gömez 2013; El-Rawy et al., 2021).

Characterizing the groundwater aquifers in semi-arid and arid regions like Saudi Arabia (KSA) is essential for agricultural, domestic, industrial, and economic sustainability. The rapid growth of the world population, which may reach 9.5 billion by 2050, poses a serious challenge to sustainable groundwater resource development (Hiscock et al., 2002; Gleeson et al., 2012; United Nations, 2012). In the Middle East and North Africa, limited water resources are the primary cause of fresh water shortages, rather than decreased rainfall, according to the National Meeting on Hydrogeology (Italy, 2017). Schaible (1999) recommends water resources management plans for handling issues such as decline in groundwater level, salinity increasing, and saltwater intrusion under the aquifer stress. Groundwater characterization relies on a huge hydrogeological dataset of aquifers and hydrochemical characteristics, which provides reliable results to do unusual management strategies that will prevent the undesirable impacts of random drilling of wells and high exploitation of groundwater, as well as the degradation of water quality. In the Al Madinah Al Munawarah province, groundwater is derived from different water bearing formations include Precambrian fractured basement rocks, Paleozoic

sedimentary rocks, and alluvial deposits in dry Wadies (Khashoggi and El Maghraby, 2013). The majority of groundwater in this region is meteoric, and its chemical components are created through water–rock interactions, in which weak CO<sub>2</sub>-charged precipitation at low pH attacks various silicates and further minerals to form major, minor and trace elements (El Maghraby, 2014). Agricultural activities are predominant in the Wadies courses near Al Madinah Al Munawarah city and industrial activities are concentrated in Wadi Al Aqiq (El Maghraby, 2013 and 2014). Water from this area and other areas is pumped into an unlined landfill approximately 3 km from the Wadi Al Aqiq. Trace metals such as Fe, As, Ba, V, and Al are released into the groundwater at the site.

In the Yanbu Al-Nakhl Basin, there is a lack of hydrogeological and hydrogeochemical studies. Because of mismanagement of groundwater system in this area, water levels have declined and salinity has increased. Farm owners drilled unlicensed groundwater wells and discharged water at random, resulting in over-exploitation of the aquifer, thereby depleting it qualitatively and quantitatively. In this research, we have carried out a regional-scale quantitative and qualitative study of the Quaternary aquifer system to define the hydrogeological parameters, to characterize the hydrogeochemistry of groundwater, to identify the areas prone to be affected by declining in water levels and the increasing salinity and to evaluate the groundwater suitability for agricultural use, based on different techniques such as pumping tests and hydrochemistry as well as irrigation water quality indices (IWQIs). The obtained results could be used as a tool to help evaluate the best locations for groundwater extraction and to determine how vulnerable aquifers are to pollution, allowing for the protection and management of the most vulnerable aquifer places to be contaminated by saltwater intrusion and other sources.

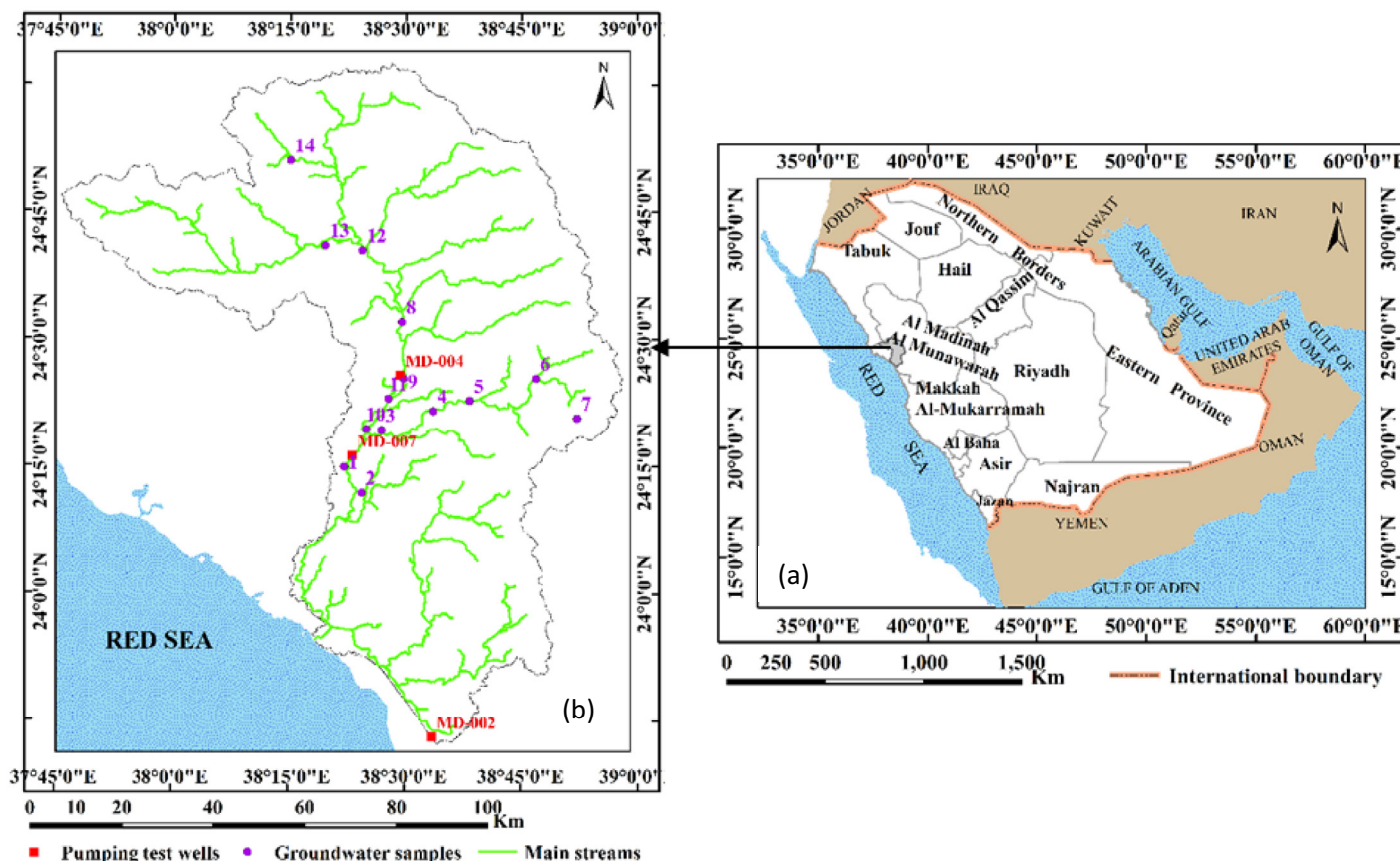


Fig. 1. (a) Key map of Wadi Yanbu Al-Nakhl, Al-Madinah Al-Munawarah Province and (b) locations of groundwater wells.

## 2. Study area

Wadi Yanbu Al-Nakhl selected for this study is considered one of the most important Wadies of Al-Madinah Al-Munawarah, KSA. It is situated between latitudes 23° 45' – 25° 00' N and longitudes 37° 45' - 39° 00' E with a total area of 8300 Km<sup>2</sup> (Fig. 1a&b).

The main activity in this Wadi is agriculture, using unlicensed, unregulated drilled wells. Where surface water is scarce, irrigation water have been exploited from the Quaternary aquifer (Delgado et al. 2010; Li et al. 2013; El Maghraby et al. 2013). Climatically, the studied Wadi is characterized by an arid to the hyper-arid condition, like other parts of KSA. High temperatures and low rainfall

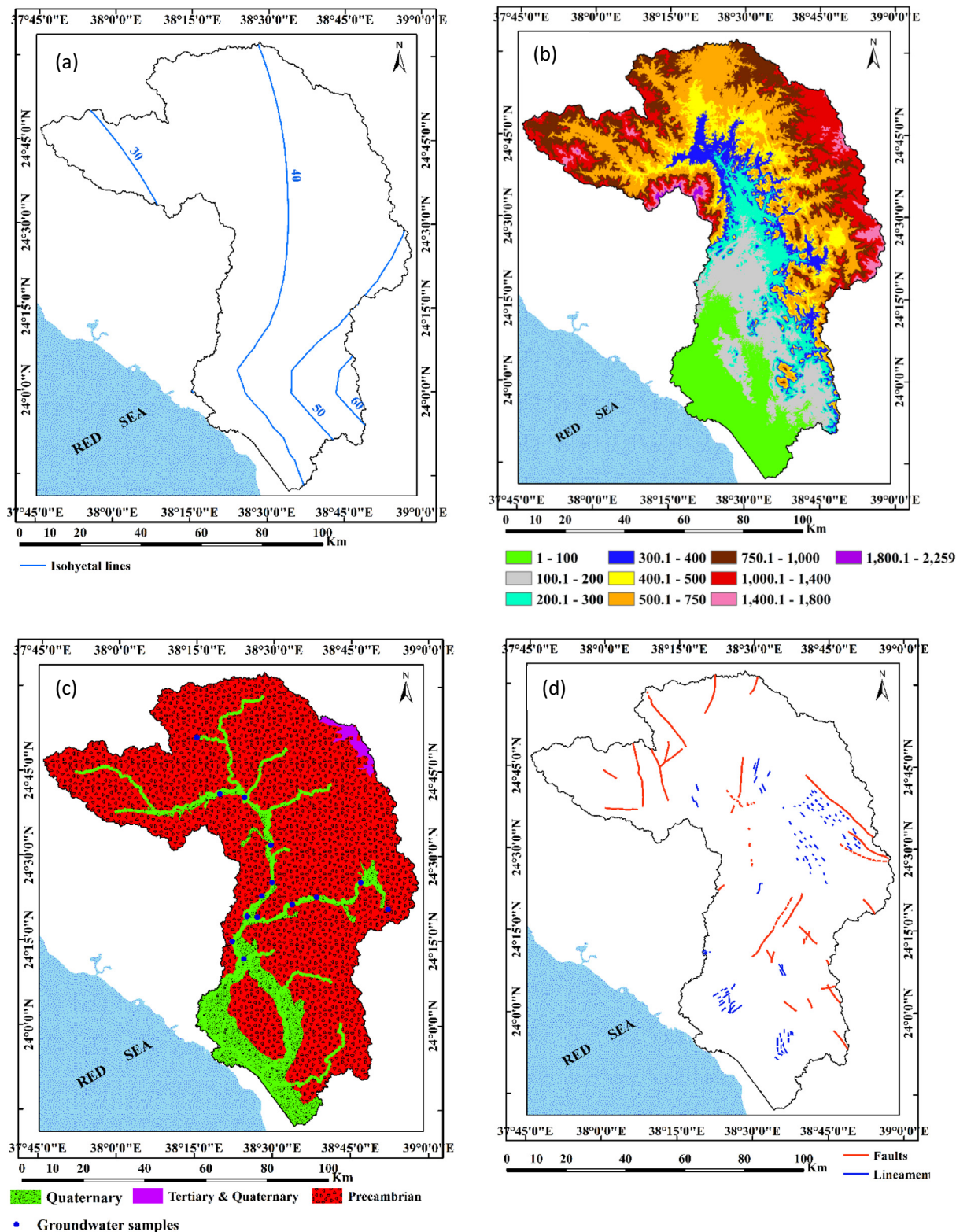


Fig. 2. Distribution of annual rainfall (a), Digital Elevation Model (DEM) in meter (b), geological map (c) and a complex network of fractures and faults (d) of Wadi Yanbu Al-Nakhl, Al-Madinah Al-Munawarah Province.

are characteristic of this region. Rainfall distribution map of (Fig. 2a) indicated that the precipitation ranging from 5 to 40 mm. Rainfall generally increases from west to east and there is rarely any rainfall, sometimes it is stormy, and it lasts for a few minutes. The most frequent months for rain to occur in sporadic storms are November to December and March to April, while some years may be entirely dry. In July and August, the average daily temperatures range from 28 to 42°Celsius, and in December and January, they range from 11 to 24°Celsius.

Topographically, the studied Wadi is characterized by a wide range of elevations, which is ranging between > 100 m in the south at the Red Sea coast and 2259 m at the Hijaz Mountains in the northern portion of the region (Fig. 2b). Coastal plains (lowlands) are located between the sabkhas and the foothills and are normally inundated by flash floods as they cross the drainage basins. These low lands are characterized by alluvial deposits, which are suitable for groundwater recharge. From the coastal plain to the mountainous range, the foothills (hilly areas) rise to about 400 m above sea level. This area is gently sloping and partly plateaued, and it is made up of boulders and alluvial deposits with high permeability for water infiltration. Stream networks mostly originate from Hijaz mountainous series crossing hilly regions to the coastal plain. The Hijaz Mountains (highland areas) extend east and north of the hilly areas parallel to the Red Sea and are marked by steep elevations that reach about 2259 m (amsl).

Geologically, Wadi Yanbu Al-Nakhl composed of a wide range of geological periods extending from Precambrian to Quaternary times. The main geologic formations are extending from fractured igneous and metamorphic rock (basements), sedimentary, Wadi deposits and lava flows (Harrat) in the northeastern sides as shown in Fig. 2c. Most of the studied Wadi is composed of Precambrian basement rocks that were folded, metamorphosed, granitized, and intruded prior to the Cambrian (Pellaton, 1981). A complex network of fractures and faults, mostly planar and highly variable in density, characterizes the basement rocks. Faults often appear as conjugate structures with normal kinematics, often associated with ductile deformation (Fig. 2d). This area contains small exposures of hugely schistose rhyolitic tuff and breccia that dates from the Tertiary Period (El Maghraby et al., 2013). Alluvial deposits, sabkhas and khabras, and Wadi fill deposits of the Quaternary period form the bedrock of the main Wadi channel (Pellaton, 1981).

### 3. Field trips and methodology

In order to reach the goal of this study, which is to define the characteristics of groundwater for the purpose of management and sustainable development, based on the assessment of aquifer, pumping tests and physicochemical parameters, we used a variety of field works and methods including:

#### 3.1. Field trips

During the field trips between 2021 and 2022, the following activities and data acquisition are performed:

- The hand-held Magellan GPS-315 was used to conduct a comprehensive survey of 14 production groundwater wells during (Fig. 1b).
- The static groundwater levels are measured from the ground surface to construct a water table map for groundwater flow in the Wadi,
- Fourteen groundwater samples were collected from the Quaternary aquifer (600 ml) to study the physicochemical parameters (major, minor, and trace elements) of the groundwater. Prior to

sampling, groundwater was pumped for approximately 15 min to remove standing water to ensure accuracy. In addition, duplicate samples were collected to consider analysis of both major and trace elements. The collected water samples were scientifically sealed and stored at a temperature below 4 °C before being transported to the laboratory for chemical analysis.

- Field-based water parameters including electrical conductivity (EC), temperature, and pH.
- In collaboration with the Ministry of Environment, Water & Agriculture (MEWA), data on pumping tests was obtained for three wells.

#### 3.2. Methodology

To achieve the aim of this study, we used the following methods due to the above collected data:

1. By integrating the Geographic Information System (GIS 10.2) and Surfer (v14), some thematic maps are created based on hydrogeological data, including, depth to water, water level and flow direction as well as total dissolved solids (TDS).
2. Using the AQUIFER TEST (2016), three pumping tests data (long duration and step drawdown) had been analyzed in this study for the purpose to determine both aquifer and well hydraulic parameters as follows:
  - Step drawdown pumping tests analysis:

A step drawdown-pumping test is essential for determining the efficiency of a well and determining its discharge (Rotzoll, 2007; Masoud, 2020). Laminar flow in the formation (formation loss) and turbulent flow through the well screen and casing (well loss) are the two most common causes of well drawdown (El Osta, 2012). In this study, step drawdown test data for three wells have been analyzed using the following equation of (Rorabaugh, 1953 (Kruseman and de Ridder, 1990):

$$S = BQ + CQ^2 \quad (1)$$

In this equation: S indicates the expected drawdown (m), Q is the rate of discharge (m<sup>3</sup>/h), B is the formation loss factor (h/m<sup>2</sup>), and C indicates the well loss factor (h<sup>2</sup>/m<sup>5</sup>).

During a pumped well operation, the drawdown (S) is the sum of the loss in the formation (BQ) and the well loss (CQ<sup>2</sup>). In the above equation, the drawdown is divided by the rate of discharge, so the equation is as follows:

$$S/Q = B + CQ \quad (2)$$

Well S/Q measures the specific drawdown. Furthermore, well efficiency can also be calculated by applying the equation below at any pumping rate:

$$\gamma = BQ / (BQ + CQ^2) \quad (3)$$

- Long duration pumping tests analysis:

Long duration pumping tests are a common method for determining hydraulic parameters, such as transmissivity and hydraulic conductivity. The following methods of analysis are applied to the data collected from three constant discharge tests in the study area (Jacob, 1950). In this method, the drawdown (s) is schemed against the corresponding time (t) on a single logarithmic paper, and the best-fit straight line was drawn between them. Transmission (T) values in m<sup>2</sup>/day were considered by using the following equation:

$$T = 2.3Q/4\pi\Delta s \quad (4)$$

In which:  $Q$  = the discharge rate (m<sup>3</sup>/h) and  $\Delta s$  = slope of a straight line per log cycle.

Through dividing Transmission ( $T$ ) values in m<sup>2</sup>/day by the aquifer thickness ( $H$ ) in meter, the Hydraulic conductivity ( $K$ ) in m/day can be obtained as follows:

$$K = T/H \quad (5)$$

3. Chemical analysis for 14 groundwater samples were done in an accredited and dedicated laboratory (DRCL, Egypt). The American Society for Testing Materials (ASTM, 2002), Fishman and Friedman (1985), and Rainwater and Thatcher (1960) have all used the measuring methodologies. Major ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{CO}_3^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{Cl}^-$ ), some minor and trace elements ( $\text{SiO}_2$ , F, Br, I,  $\text{NO}_3^-$ ,  $\text{PO}_4^-$ , Al, Cu, Fe, Mn, Pb, Si and Sr) were obtained by these analyses. Ion chromatography was used to measure the parameters' concentrations ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) (ICS-1100 systems). By titrating against 0.01 N  $\text{H}_2\text{SO}_4$  and utilizing phenolphthalein and methyl orange as indicators,  $\text{CO}_3^-$  and  $\text{HCO}_3^-$  contents were calculated. Trace and heavy elements were detected using the Thermo-Jarrell Elemental Company's inductively coupled plasma-optical emission spectroscopy (ICP-OES).
4. To detect groundwater recharge and salinization as well as the primary mechanism affecting groundwater chemistry, the data-sets were graphically represented using Piper (Piper, 1944), Gibbs (Gibbs, 1970) and HEF diagrams. The primary goal of the Gibbs graph is to emphasize the critical elements that affect the quality of the groundwater. Instead, other, more complex diagrams (like the Piper plot) will improve our comprehension of the hydrogeochemical mechanisms governing the features of groundwater.
5. Analysis of groundwater quality indices for irrigation (IWQIs).

The suitability of irrigation groundwater was assessed utilizing a standard formula for the following water quality parameters (Table 1):

## 4. Results and discussions of the observations

### 4.1. Groundwater aquifer

Nowadays, many agricultural projects rely on the renewable groundwater aquifers in the western part of the KSA. The infiltration of precipitation from the soil area of Wadies into the aquifers is the main source of groundwater recharge in this region. The studied Wadi is located west Al-Madinah Al-Munawarah city by about 70 km and characterized by drainage lines that flow to the south (Fig. 1b). Groundwater of this Wadi originates in the alluvium highly permeable sediments of the Quaternary period. The

Lithological description of the Quaternary alluvial deposits is that from 0 to 21 m, there is gravel consisting mainly of polymictic gravel, sand traces, and silt traces, and from 21 m to about 60 m, mainly indicate the presence of dark gray basaltic conglomerates (40% unrounded). The groundwater wells as shown in Fig. 1b were haphazardly drilled by the owner without strategic plan for drilling. This may cause decline in water levels in the Wadi. Initial depth to groundwater in 2022 ranges from 1.85 m to 28.8 m with below the ground surface (BGS). The depth to water increases from west to east as shown in Fig. 3a. Based on the water depth measurements and elevation data of ground surface, water table was calculated the distribution map and flow direction were constructed (Fig. 3b). It appears from this map that the groundwater movement is generally directed from north to south in the northern part and from east to west and southwest in the other parts of the study area. This flow direction is similar to the prevailing direction of the Wadi's drainage network. According to closely spaced contour lines as shown in Fig. 3b, the hydraulic gradient of groundwater generally runs east–west. Faults and fractures that dissect the basement rocks with different magnitudes are mainly responsible for such steep gradients. This reflects that, the essential source of recharging the Quaternary aquifer is from the rainfall, which falls on the Wadi, as well as the upward leakage from the dissected basement rocks especially in the upstream portion. The study area receives an average annual rainfall of 25 mm (Fig. 2a). According to Bazuhair and Wood (1996) and Al-Shaibani (2008), precipitation-weighted chloride concentrations for regions along the western border of KSA range between 6 and 12 mg/L. Accordingly, precipitation recharge to groundwater in this region is about 6.58%, depending on the equation of chloride mass balance (Al-Shaibani 2008). Therefore, an optimal management of groundwater in Wadi Yanbu Al-Nakhl involves not over-extracting of groundwater and maintaining a safe distance between drilled wells to avoid interference between wells due to limited amount of recharge from rainfall.

### 4.2. Hydraulic parameters

In the context of groundwater management and especially in light of surface water scarcity, rules on land are crucial, for example, those related to well location, spacing between wells, groundwater withdrawal. In addition, another factor is the interaction between the water bearing formation and the drilled well represented by the hydraulic parameters that govern this relationship. In this work, more and more attention has been paid for determining of these parameters depending on the results obtained from the analysis of step and constant pumping tests analyses, since the problem in most groundwater legislation lies in its implementation and manageability. Therefore, hydraulic parameters play an important role in managing and sustaining groundwater resources (Uhl, 1986). There are several parameters to predict hydraulic head

**Table 1**  
Groundwater quality indices for irrigation (IWQIs), formula and reference.

Parameter	Symbol	Formula	References
Total dissolves solids	TDS	$(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+ + \text{Cl}^- + \text{SO}_4^{2-} + \text{HCO}_3^- + \text{CO}_3 + \text{NO}_3)$	(Ayers and Westcot, 1994)
Total hardness	TH	$(2.5 \times \text{Ca}^{2+}) + (4.2 \times \text{Mg}^{2+})$	Todd and Mays 2005
Sodium adsorption ratio	SAR	$\left( \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}} \times 100 \right)$	(Richards, 1954)
Potential salinity	PS	$\text{Cl}^- + (\text{SO}_4^{2-}/2)$	(Doneen, 1964)
Magnesium hazard	MH	$[\text{Mg}^{2+}/(\text{Ca}^{2+} + \text{Mg}^{2+})] \times 100$	(Raghunath, 1987)
Residual Sodium Carbonate	RSC	$(\text{HCO}_3^- + \text{CO}_3) - (\text{Ca}^{2+} + \text{Mg}^{2+})$	(Eaton, 1950)

All parameters are considered in meq/L excluding TDS and TH in mg/L.

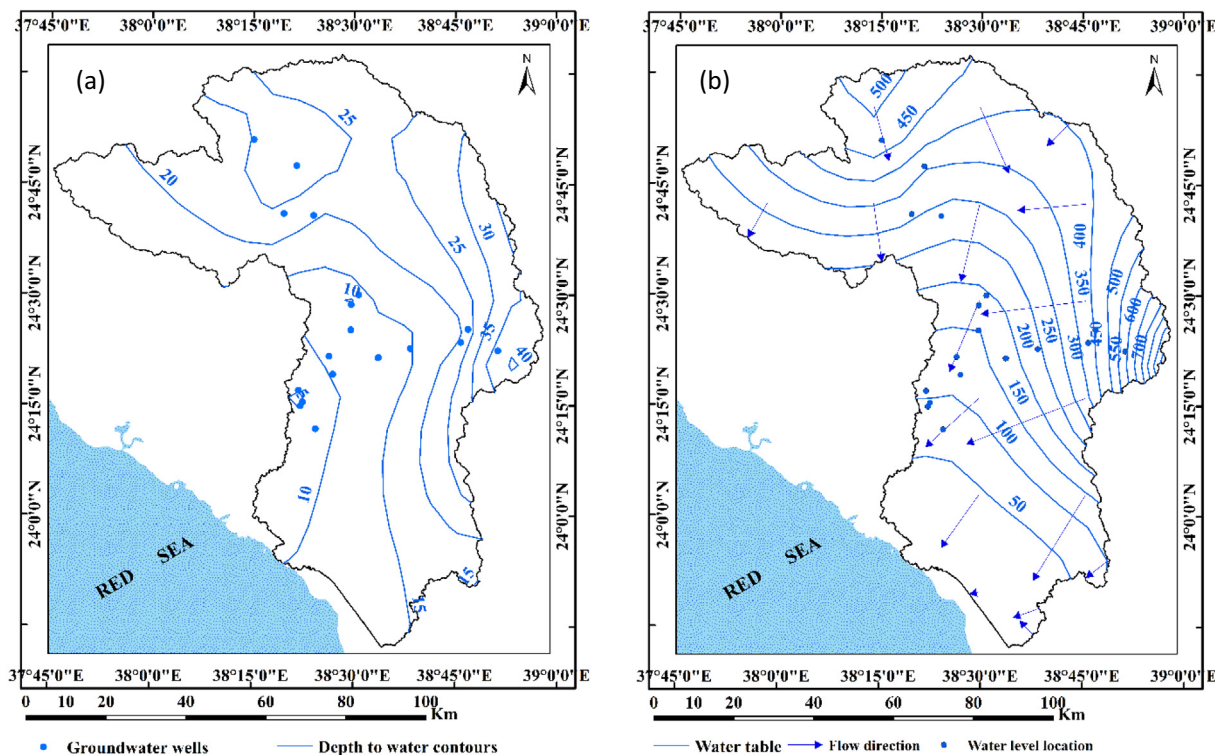


Fig. 3. Distribution maps of depth to water (a) and water table (b) in Wadi Yanbu Al-Nakhl, Al-Madinah Al-Munawarah Province.

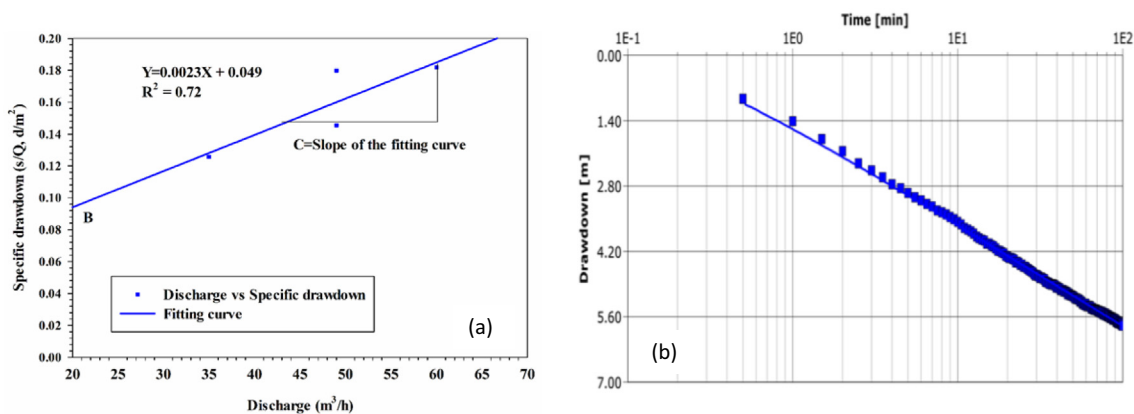


Fig. 4. Example of step (a) and long duration (b) pumping tests of the study well no. MD002.

Table 2

Results of hydraulic parameters obtained from analysis of step-drawdown and long duration pumping tests.

Well No	Step test analysis									Long-duration test analysis	
	Step No.	Draw-down S (m)	Discharge Q (m³/d)	Formation loss coef. B (h/m²)	Well loss coef. C (h²/m⁵)	Aquifer loss (BQ)	Well loss (CQ²)	Well Efficiency (γ) %	Aver. of (γ) %	Transmissivity T (m²/day)	Hydraulic cond. K (m/day)
MD 002	1	4.4	35.00	0.088	0.002	3.08	2.45	55.70	50.11	88.2	4.41
	2	7.13	49.00	0.088	0.002	4.312	4.80	47.32			
	3	8.81	49.00	0.088	0.002	4.312	4.80	47.327			
	4	10.91	60.00	0.088	0.002	5.28	7.20	42.31			
MD 004	1	16.41	1137.02	0.01475	0.000005	16.77	6.46	72.20	66.60	105.4	9.3
	2	20.97	1338.34	0.01475	0.000005	19.74	8.96	68.80			
	3	27.32	1637.28	0.01475	0.000005	24.15	13.40	64.30			
	4	31.74	1882.66	0.01475	0.000005	27.77	17.72	61.05			
MD 007	1	0.98	599.16	0.00163	0.0000014	0.976631	0.50	66.14	61.8	95.4	8.3
	2	1.29	719.00	0.00163	0.0000014	1.17197	0.72	61.94			
	3	1.69	864.00	0.00163	0.0000014	1.40832	1.05	57.29			

drawdown in aquifer under proposed pumping tests, including, well loss, formation loss, well efficiency, transmissivity, hydraulic conductivity. These parameters were determined using Aquifer test 2016 software (Fig. 4 and Table 2) as follows:

As shown in Table 2, the results of the step pumping tests indicated that the well loss coefficients range from  $1.4 \times 10^{-6}$  to 0.002 ( $\text{h}^2/\text{m}^5$ ) for well nos. MD007 and MD002 respectively, while the formation loss coefficients vary between 0.00163 in  $\text{h}/\text{m}^2$  (well no. MD007) and 0.088 ( $\text{h}/\text{m}^2$ ) (well no. MD002). Additionally, graphical method estimates the total drawdown (well loss + formation loss) very closely to the actual drawdown. The average of well efficiency ( $\gamma$ ) ranges from 42.21% (well no. MD002) to 72.2% (well no. MD004). In contrast, average well loss percentages range from 27.8 % (well no. MD004) to 57.79 % (well no. MD002). Based on these results, it appears that well losses are relatively high in Wadi Yanbu Al-Nakhl. The clogging of well screens or the degradation of well screens can lead to an increase in well losses especially in old wells as well as most of existing wells are drilled by the people, not the companies.

On the other hand, obtained results of long duration pumping test analysis (transmissivity and hydraulic conductivity) show the Quaternary aquifer in Wadi Yanbu Al-Nakhl have relatively low values of transmissivity (T) between 88.2 and 105.4  $\text{m}^2/\text{day}$  (Table 2). Based on the classification of Gheorghie (1979) for aquifer potentiality depending on T values, it can be decided that the Quaternary aquifer is low to moderate in potential. According to calculated data of the hydraulic conductivity (K), the Quaternary aquifer has moderate values of K vary from 4.41 to 9.3  $\text{m}/\text{day}$  (Table 2). These hydraulic parameters confirmed that large quantities of groundwater should not be withdrawn by reducing the well operating hours, along with the recommendation to avoid drilling new wells with many wells in order to prevent interference between them and the sharp drop in water levels.

#### 4.3. Hydrochemistry of groundwater

Within the present research, the hydrogeochemistry of groundwater in Wadi Yanbu Al-Nakhl had been studied through the following sections:

##### 4.3.1. Physiochemical parameters

The Physiochemical characteristics of groundwater in Wadi Yanbu Al-Nakhl are listed in Table 3. It has been shown that the pH values in the analyzed samples ranged between 7.37 and 7.68 with a mean value of 7.55 ( $\text{pH} > 6.5$ ) and they are suited to agricultural use (Ayers and Westcot, 1994; Elhaddad and Al-Zyoud). The average EC value was 2446  $\mu\text{S}/\text{cm}$ , with values ranging from 776  $\mu\text{S}/\text{cm}$  in the eastern upstream portion of the Wadi (Well no. 6) to 7300  $\mu\text{S}/\text{cm}$  in the downstream area close to the Red Sea (Well no. 1). These findings showed that 21% of samples (well nos. 1, 2, and 3) were not appropriate for irrigation ( $\text{EC} > 3000 \text{ S}/\text{cm}$ ) due to high solute dissolution, with the exception of few plant species that, according to FAO 1994, can survive high salinity of water. Groundwater quality ranges from fresh to brackish, with levels of TDS ranging from 408  $\text{mg}/\text{L}$  in the eastern to 4583  $\text{mg}/\text{L}$  in the southwestern portions of the Wadi. The concentrations of the main dissolved constituents (major cations and anions), as indicated in Table 3, were likewise quite varied. The fact that there are such vast variations in ionic concentrations reflect many hydrochemical processes altering the groundwater quality.

The concentration of major cations and anions in water samples showed the following ranges:  $\text{Na}^+$  is 56.33–258.27  $\text{mg}/\text{L}$ ,  $\text{Ca}^{+2}$  is 68.94–546.29  $\text{mg}/\text{L}$ ,  $\text{Mg}^{+2}$  is 1.99–149.53  $\text{mg}/\text{L}$ ,  $\text{K}^+$  is 2.52 – 22.66  $\text{mg}/\text{L}$ ,  $\text{Cl}^-$  is 88.97–880.61  $\text{mg}/\text{L}$ ,  $\text{SO}_4^{2-}$  is 80.61–2064.52  $\text{mg}/\text{L}$ ,  $\text{CO}_3^{2-}$  is 0.00 – 30.00 and  $\text{HCO}_3^-$  is 82.35–280.60  $\text{mg}/\text{L}$ . Therefore, the ionic dominance of groundwater in the study area indicates

$\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ ;  $\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^- > \text{CO}_3^{2-}$  (11 samples), and  $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ ;  $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{CO}_3^{2-}$  (three samples). In 78% of the analyzed groundwater samples  $\text{Na}^+$  was the predominant cation due to cation exchange of  $\text{Ca}^{2+}$  for  $\text{Na}^+$  on Na-rich minerals (El Maghraby et al., 2013). An increase in dissolved sodium is caused by the substitution of calcium for sodium, which also causes more carbonate minerals to dissolve in water. Groundwater samples with high calcium concentrations (22%) may be attributed to the existence of calcium-rich silicate minerals and gypsum in the alluvium deposits of the Quaternary aquifer in the region (El Maghraby et al. 2013; El Osta et al. 2020; El Osta et al., 2022 a, b). With the exception of three wells (4, 8, and 6), where chloride concentration only slightly exceeded sulphate concentrations; sulphate was the major anion in 78% of the analyzed water samples. The influence of the industrial wastewater disposal site and dissolution of gypsum in the soil zone could both be responsible for the high  $\text{SO}_4^{2-}$  level in the Quaternary aquifer (El Maghraby, 2014). With an average value of 143.41  $\text{mg}/\text{L}$ , alkalinity values varied from 74.98 to 254.95  $\text{mg}/\text{L}$ , which is within acceptable limits for irrigation (FAO, 1994).

The average concentrations of minor and trace elements  $\text{SiO}_2$ , F, Br, I,  $\text{NO}_3$ ,  $\text{PO}_4$ , Al, Cu, Fe, Mn, Pb, Si and Sr of the analyzed groundwater was 24.85, 0.98, 0.50, 0.052, 42.66, 0.25, 0.1538, 0.0338, 0.1725, 0.03077, 0.124, 11.61 and 2.17 respectively. A variety of sources contributes to the presence of these elements in groundwater, including weathering, dissolution, soil leaching, and human activity. Low amounts of metal contamination in the groundwater samples, such as Br, I,  $\text{PO}_4$ , Al, Cu, Fe, Mn, and Pb were found to be below statutory drinking standards. On the other hand, silicates ( $\text{SiO}_2$ ) and Silicon (Si) have relatively moderate concentration in the groundwater of the studied area. These elements were evenly distributed within the aquifer matrix, indicating that silicate mineral dissolution was their primary source (El Maghraby et al. 2013; Alqarawy 2023). Due to the use of nitrogen fertilizers in agricultural and/or contamination by human or animal waste, nitrate concentrations in groundwater can reach high levels (WHO, 2008). A wide range of nitrates ( $\text{NO}_3$ ) concentrations was observed between 0.02  $\text{mg}/\text{L}$  and 104.6  $\text{mg}/\text{L}$ . This is mainly due to the complex hydrochemical processes as well as soil drainage (Silva and Williams 2001; Bujnovský et al., 2022; She et al., 2022).

##### 4.3.2. Groundwater chemical facies and controlling mechanisms

The hydrochemical analysis of groundwater in relation to water-bearing formations exposes the quality of groundwater in its undisturbed state. Different hydrochemical facies can show differences in groundwater chemistry both within and between aquifers (Gad and El Osta, 2020). In this research, Piper (1944), Gibbs (1970) and HFE diagrams were utilized to classify water types of groundwater and their governing processes. Fourteen groundwater samples were plotted on a Piper-diagram, which depends upon the concentration (in meq %) for the major ions (cations and anions) as shown in Fig. 5. The distribution of cations and anions in the plot determines the type of groundwater. As a result, there are four groundwater types: (1) Ca- $\text{HCO}_3$ ; (2) Na-Cl; (3) mixed Ca-Mg-Cl- $\text{SO}_4$ , and (4) Na-Ca- $\text{HCO}_3$  in most locations (Fig. 5). The present chemical content is strongly impacted by weathering and the aquifer's matrix. Gibbs diagrams are frequently used to illustrate the connection between the groundwater component and aquifer formation. In this diagram, TDS is plotted against  $(\text{Na} + \text{K})/(\text{Na} + \text{K} + \text{Ca})$  and  $\text{Cl}/(\text{Cl} + \text{HCO}_3)$  in order to show the basic regulatory processes that control groundwater geochemistry. The distribution of the groundwater points throughout evaporation and rock-water dominance areas, two key factors influencing groundwater quality. Fig. 6a illustrates how evaporation dominates the majority of the samples, leading to a major rise in  $\text{Na}^+$ ,  $\text{Cl}^-$ , and TDS (Gad and El Osta, 2020; Alqarawy, 2023). This result also suggests that the

**Table 3**  
Chemical data of the analyzed groundwater samples in Wadi Yanbu Al-Nakhl Basin.

Well No.	pH	EC	TDS	Cations in mg/L				Anions in mg/L				Alk. mg/L	TH mg/L
				Ca	Mg	Na	K	CO <sub>3</sub>	HCO <sub>3</sub>	SO <sub>4</sub>	Cl		
1	7.37	7300	4583	546.29	135.22	872.91	22.66	12.00	97.60	2064.52	880.61	99.98	1919.04
2	7.41	4590	2790	311.71	149.53	434.66	8.87	12.00	82.35	1055.51	776.29	87.48	1392.59
3	7.52	3980	2466	293.53	81.02	400.19	10.85	6.00	100.65	940.97	683.29	92.48	1065.53
4	7.43	2680	1579	262.60	64.32	200.54	7.43	6.00	152.50	478.41	483.85	134.97	919.67
5	7.68	1036	561	95.73	15.26	86.46	4.20	12.00	176.90	117.50	141.63	164.97	301.61
6	7.66	776	408	80.30	10.96	56.33	3.69	6.00	155.55	80.61	91.98	137.47	245.39
7	7.65	1192	654	68.94	1.99	172.37	2.52	0.00	91.50	186.34	175.94	74.98	180.20
8	7.61	1135	661	92.16	20.15	116.07	4.66	15.00	122.00	209.04	142.87	124.98	312.80
9	7.59	1347	810	121.15	25.98	128.68	5.03	12.00	134.20	278.36	171.91	129.97	409.10
10	7.48	2020	1421	183.10	46.17	225.15	5.89	6.00	152.50	488.74	389.66	134.97	646.69
11	7.61	1505	956	139.79	28.15	145.74	5.44	21.00	140.30	343.66	201.98	149.97	464.54
12	7.54	1084	629	81.51	21.65	107.78	3.70	30.00	106.75	194.70	136.71	137.48	292.38
13	7.48	1077	592	77.82	24.01	107.71	5.86	15.00	280.60	132.15	88.97	254.95	292.89
14	7.68	1332	783	103.43	12.94	148.48	4.74	12.00	268.40	208.94	158.22	239.95	311.27
Min.	7.37	776	408	68.94	1.99	56.33	2.52	0.00	82.35	80.61	88.97	74.98	180.20
Max.	7.68	7300	4583	546.29	149.53	872.91	22.66	30.00	280.60	2064.52	880.61	254.95	1919.04
Average	7.55	2446	2810	192.08	49.31	258.27	7.55	12.19	151.55	557.79	343.34	143.41	678.31
Minor and trace elements in mg/L													
Well No.	SiO <sub>2</sub>	F	Br	I	NO <sub>3</sub>	PO <sub>4</sub>	Al	Cu	Fe	Mn	Pb	Si	Sr
1	20.28	1.07	1.79	0.078	104.58	0.18	<0.01	<0.006	<0.02	<0.002	0.234	9.478	6.338
2	29.40	1.92	1.30	0.057	67.50	1.16	<0.01	<0.006	0.245	<0.002	0.147	13.74	4.331
3	13.90	1.95	0.78	0.204	0.02	0.03	0.305	0.011	<0.02	0.07	<0.008	6.496	4.775
4	40.55	0.50	0.69	0.046	62.42	0.31	<0.01	0.032	0.114	0.029	0.213	18.95	3.233
5	33.93	0.08	0.16	0.027	34.95	0.05	<0.01	0.049	0.272	<0.002	0.022	15.86	0.8005
6	26.38	0.25	0.12	0.021	36.34	0.04	<0.01	0.05	<0.02	<0.002	<0.008	12.33	0.4607
7	15.49	3.12	0.18	0.073	0.75	0.04	<0.01	<0.006	<0.02	<0.002	<0.008	7.238	1.269
8	29.40	0.46	0.16	0.018	38.04	0.11	<0.01	<0.006	<0.02	<0.002	0.018	13.74	0.9519
9	22.44	0.36	0.16	0.018	33.93	0.13	<0.01	<0.006	<0.02	0.024	<0.008	10.49	0.9638
10	30.23	1.04	0.23	0.023	58.02	0.14	0.099	<0.006	<0.02	0.006	<0.008	14.13	1.78
11	21.89	0.11	0.18	0.018	48.43	0.18	0.144	<0.006	<0.02	0.049	<0.008	10.23	1.174
12	21.72	0.75	0.14	0.015	39.83	0.09	<0.01	<0.006	0.034	0.019	0.155	10.15	0.6691
13	16.96	0.66	0.11	0.013	18.47	0.11	0.035	<0.006	0.237	0.005	0.196	7.926	0.4898
14	20.54	0.18	0.14	0.013	34.77	0.16	<0.01	<0.006	<0.02	<0.002	0.01	9.6	0.6971
Min.	13.90	0.08	0.11	0.013	0.02	0.03	0.035	0.011	0.034	0.005	0.01	6.496	0.4607
Max.	40.55	3.12	1.79	0.204	104.6	1.16	0.305	0.05	0.272	0.07	0.234	18.95	6.338
Average	24.85	0.98	0.50	0.052	42.66	0.25	0.1538	0.0338	0.1725	0.03077	0.124	11.61	2.17

- TDS (Total Dissolved Solids) and EC (Electric Conductivity) are calculated in mg/L and  $\mu\text{S}/\text{cm}$  respectively.

- Alk. means alkalinity and TH means total hardness.

processes of evaporation and rock – groundwater interaction were significantly influence groundwater quality in Wadi Yanbu Al-Nakhl basin. According to the HFE plot results (Fig. 6b), evaporite dissolves in aquifer materials rich in sulphate and chloride. The most of groundwater samples indicate a mixed water type (Ca-Mg-HCO<sub>3</sub> and Na-Cl), which contained significant levels of calcium and sodium contents. This is due to sodium-rich clays in aquifer sediments and the surrounding volcanic rock sequences in the Wadi. As well, groundwater samples collected within the downstream area of the Wadi are believed to be affected by seawater intrusion. Because of shallow groundwater depths, salinization of groundwater and soils in the concerned area is mainly caused by high evaporation rates (Alqarawy, 2023).

#### 4.4. Evaluation of groundwater for agriculture

Agriculture is the main objective of groundwater exploitation in Wadi Yanbu Al-Nakhl. In this study, water quality index parameters; TDS, TH, SAR, PS, MH and RSC were calculated based on the equations listed Table 1 to determine the suitability of groundwater for irrigation purposes. The results and classification of these indices are presented in Table 4. The calculated TDS of all the samples ranged widely from 444 to 4688 mg/L (Table 4). It showed that 93% of wells (13 samples) have salinity values > 3000 mg/L, which indicates no restriction for irrigation in six samples and slight to moderate restriction in seven samples. In contrast, agriculture is required to follow severe restriction great sensitivity crops adapted

to salt-water that grow in loose soil without compacting, particularly in 7 % of the totals samples, which have a salt level of >3000 mg/L. Fig. 7 indicates that TDS increases towards the southwest of the study area. The recharge from rainfall in the upstream of the Wadi, lithologic characteristics and facies variations of the water-bearing formation, as well as salt-water intrusion, notably in the downstream of the Wadi, are the causes of differences in salinity as showed in the TDS distribution map (Fig. 7).

The total hardness (TH) in groundwater samples ranged between 180.20 and 1919.04 mg/L. These results indicated that all groundwater samples fell into high to very high hardness (USEPA, 1986). The lithology of the aquifer matrix, which is predominantly made up of weathering products of surrounding basic and intermediate igneous rocks as well as the anthropogenic activity are often responsible for the relatively high TH values in the area (Alqarawy, 2023). In addition, during the dissolution of rocks, calcium and magnesium are released into the groundwater, which increases its TH (Giri et al., 2022). Accordingly, all these influences lead to high irrigation water hardness, which is harmful to forage and vegetable crops as high hardness inhibits plant growth (Singh et al. 2013; Giri et al., 2022).

The sodium adsorption ratio (SAR) is a critical index since groundwater with a high sodium level may affect the soil to become harder and less permeable (low rate of soil water percolation). It contrasts the proportions of calcium and magnesium ions to sodium ions in water. The Richards' (1954) equation as shown in



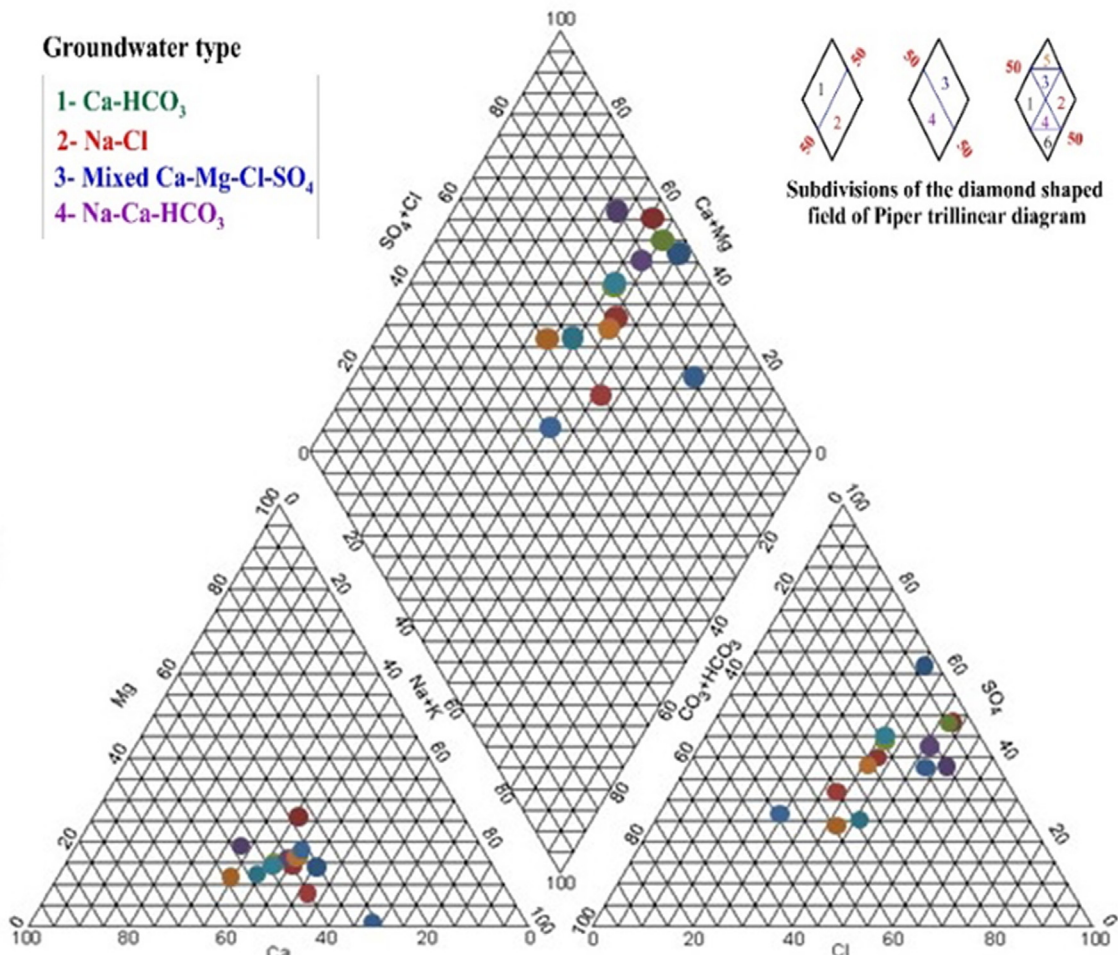


Fig. 5. Piper trilinear diagram for Groundwater facies in Wadi Yanbu Al-Nakhl basin.

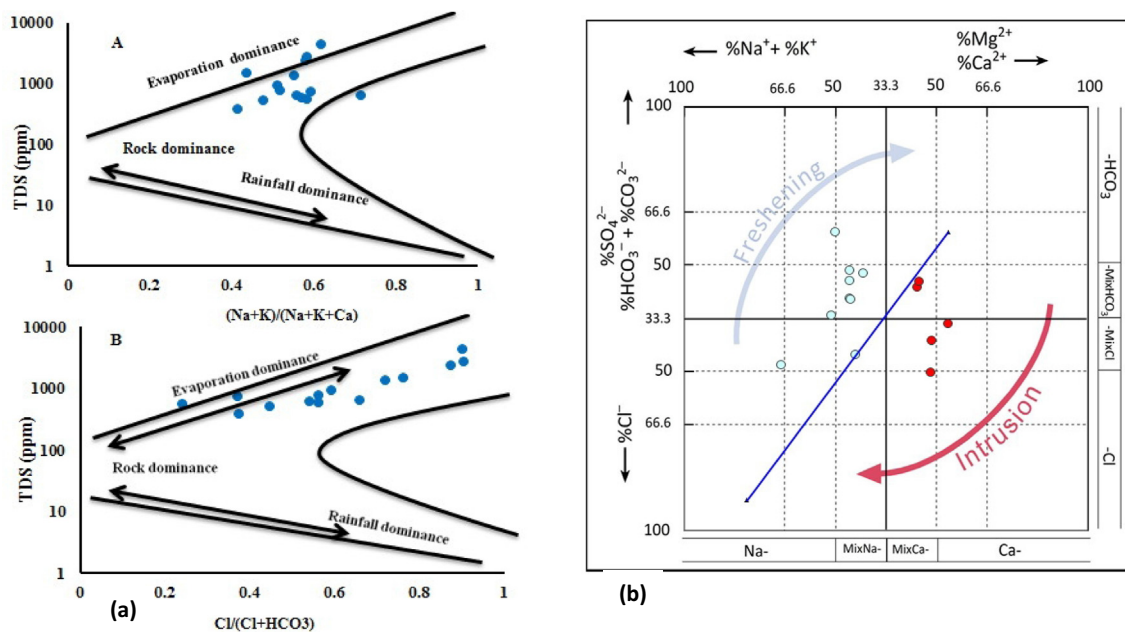
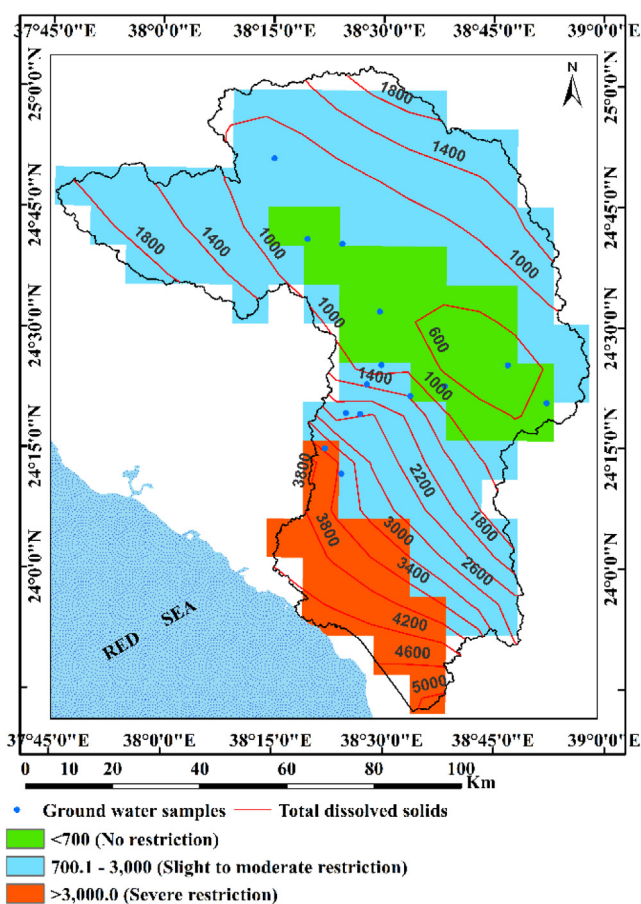


Fig. 6. Geochemical controlling mechanisms for groundwater in Wadi Yanbu Al-Nakhl basin: (a) Gibbs diagram and (b) Hydrochemical facies evolution diagram (HFE).

**Table 4**  
Classification of groundwater suitability for irrigation in Wadi Yanbu Al-Nakhl.

Irrigation Water quality indices (IWQIs)	Min.	Max.	Average	Range	Water category	Number of Samples (%)
Total dissolves solids (TDS)	444	4688	1537.685	< 700 700–3000	No restriction Slight to moderate restriction	6 (43.0%) 7 (50.0%)
Total hardness (TH)	180.20	1919.04	678.31	>3000 0–60 60–120 120–180 > 180	Severe restriction Soft Moderate Hard Very hard	1 (7.0%) 0 (0.0%) 0 (0.0%) 0 (0.0%) 14 (100.0%)
Sodium adsorption ratio (SAR)	1.56	8.67	3.940625	< 10 10–18 18–26 > 26	Excellent Good Doubtful or Fairly poor Unsuitable	14 (100.0%) 0 (0.0%) 0 (0.0%) 0 (0.0%)
Potential salinity (PS)	1.16	3.27	2.140625	< 3 3 to 5 > 5	Excellent to good Good to Injurious Injurious to Unsatisfactory	12 (86.0%) 2 (14.0%) 0 (0.0%)
Magnesium hazard (MH)	4.55	44.15	25.85687	> 50% < 50%	Unsuitable Suitable	0 (0.0%) 14 (100.0%)
Residual sodium carbonate (RSC)	–36.38	–0.76	–10.8068	< 1.25 1.25–2.5 > 2.5	Safe Marginal Unsuitable	14 (100.0%) 0 (0.0%) 0 (0.0%)



**Fig. 7.** Spatial distribution map of TDS in Wadi Yanbu Al-Nakhl basin.

Table 1, which represents all ion concentrations in meq/L, can be used to calculate the sodium adsorption ratio in groundwater samples. In Wadi Yanbu Al-Nakhl, all groundwater samples (approximately 100%) were rated excellent irrigation suitability throughout the SAR results, with a mean value of 3.940625. Fig. 8 shows the representation of samples on the US Salinity Laboratory Staff, (USSL, 1954). The findings showed that 10 samples were located inside C3S1 field indicating a high salinity hazard

and a low sodium hazard. On clay soil, these groundwater wells can be used for irrigation; however, particular crops should be chosen based on their salt acceptance behaviors (El Maghraby et al., 2013). Meanwhile, four groundwater samples were collected within C4S1 (one samples) and C4S2 (three samples) fields specify high -salinity hazards and low to medium - sodium hazards respectively. Groundwater from these fields should only be used to irrigate salt-tolerant crops, especially the three samples located in C4S2.

Moreover, chloride (Cl<sup>-</sup>) and half of sulphate (SO<sub>4</sub><sup>2-</sup>) contents in groundwater have been used to determine the PS value (Doneen, 1964). This gives a logic of the appropriateness of irrigation water. In this study, there was a range of PS values from 1.16 to 3.27, with a mean value of 2.140625. These results mean that 86% (12 samples) are excellent to good candidates for irrigation, while 14% (2 samples) are good to damaging (Table 4).

The Magnesium hazard (MH) represents the magnesium absorption rate (Giri et al., 2022). There is usually a greater value of magnesium ions in groundwater due to higher exchangeability of sodium ions in irrigated soils. As a result of high magnesium concentrations in agricultural water, the soil becomes alkaline, resulting in low crop yields (Sundaray et al. 2009; Cymes et al., 2022). The magnesium ratio measures the opposing effects of magnesium in irrigated water. Raghunath (1987) introduced an index called “Magnesium Hazard”, which is considered as magnesium ratio (MH) by the formula listed in Table 1. MH values in Wadi Yanbu Al-Nakhl range from 4.55 to 44.15% with an average value of 25.85687%. All MH values (14 samples) are below 50% and groundwater can be used for agriculture.

Irrigating water suitability is highly dependent on the carbonate and bicarbonate concentrations. In the presence of excess carbonate (residual) concentrations, carbonate and calcium ions combine to form scales, solid materials that settle out of water when carbonate concentrations exceed calcium and magnesium concentrations. Due to calcium and magnesium settling out of the water, sodium levels increase, which results in deteriorating effects on plants. Residual sodium carbonate (RSC) is an excess of carbonates and bicarbonates of the alkaline earth metals (Ca<sup>2+</sup> and Mg<sup>2+</sup>) (Sundaray et al. 2009; Elhaddad and Al-zyoud, 2017; Santacruz-De León, et al., 2022). Table 1 lists the method Eaton (1950) proposed for determining RSC. This study found RSC values ranging from –36.38 to –0.761 meq/L in groundwater samples. All samples had RSC values below 1.25 meq/L, indicating that groundwater quality is at a “safe” level for irrigation in the study area. Ground-

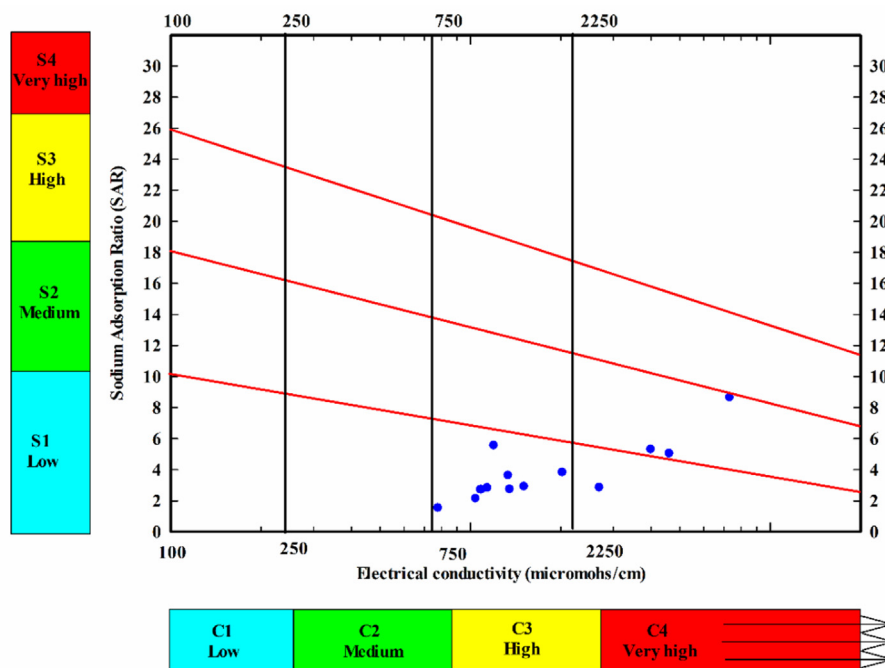


Fig. 8. US salinity diagram of the groundwater samples in Wadi Yanbu Al-Nakhl basin.

water samples had negative RSC values, indicating that calcium and magnesium are not precipitated (Sundaray et al. 2009; Srinivasamoorthy et al. 2014). According to the results of this work, optimal groundwater management in the study area requires controlling the daily withdrawals from the productions wells (optimum safe yield), the proposed drilled wells in the Wadi should subject to local government regulation in terms of distances and daily pumping rates in addition to the periodic measurements of the groundwater levels and quality.

## 5. Conclusion

Groundwater of the Quaternary aquifer is the main source of irrigation in the Wadi Yanbu Al-Nakhl. No strategic plan has been developed for drilling wells. As a result, groundwater quality deteriorates and water levels drop. The aim of this research is to characterize this groundwater resource focusing mainly on all aquifer parameters, physicochemical properties, groundwater facies, controlling mechanisms and the irrigation water quality indices. In light of the obtained results, groundwater occurs under unconfined condition and moves generally from north to south in the northern part, and from east to west and southwest (toward the Red Sea). Aquifer hydraulic parameters indicated that, the average of well efficiency ( $\gamma$ ) ranges from 42.21% to 72.2%, and the aquifer have relatively low values of transmissivity and hydraulic conductivity. Therefore, large quantities of groundwater should not be withdrawn from this aquifer by reducing the well operating hours, along with the recommendation to avoid drilling new wells in order to prevent interference between them and the sharp drop in water levels. In addition, the processes of evaporation and rock – groundwater interaction were significantly influenced the groundwater quality in Wadi Yanbu Al-Nakhl basin. A variety of sources contributes to the presence of minor and trace elements, including weathering, dissolution, soil leaching, and human activity. The suitability of groundwater for irrigation was determined based on TDS, TH, SAR, PS, MH, and RSC indices. The computed mean values of these indices were 1537.685, 678.31, 3.940625, 2.140625, 25.85687 and  $-10.8068$  respectively, indicated that

most of groundwater samples located within the no restriction class for agriculture uses in Wadi Yanbu Al-Nakhl.

Therefore, the following future directions and recommendations can be summarized in the following points:

- New piezometers are being drilled in the concerned area for monitoring groundwater levels.
- Groundwater quality must be continuously monitored.
- Maintain an interval spacing of at least 500 m between succeeding new drilled wells to reduce interference drawdown, especially when running them simultaneously.
- Since human activity is the primary cause of groundwater pollution, public knowledge is the most effective instrument for protecting it.

## Institutional review board Statement

Not applicable.

## Informed consent Statement

Not applicable.

## Authors contributions

Not applicable (I am a sole author).

## Funding

“This research work was funded by Institutional Fund Project under grant no. (IFPIP: 1698–155-1443) The authors gratefully acknowledge technical and financial support provided by the Ministry of Education and King Abdulaziz University, DSR, Jeddah, Saudi Arabia”.

## 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.

## Acknowledgments

“This research work was funded by Institutional Fund Project under grant no. (IFPIP: 1698-155-1443) The authors gratefully acknowledge technical and financial support provided by the Ministry of Education and King Abdulaziz University, DSR, Jeddah, Saudi Arabia”.

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