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Authors	Al-Kalbani, Mohammed Saif;Price, Martin F.;Ahmed, Mushtaque;Abahussain, Asma;O'Higgins, Timothy
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ORIGINAL ARTICLE

Environmental quality assessment of groundwater resources in Al Jabal Al Akhdar, Sultanate of Oman

Mohammed Saif Al-Kalbani[1] · Martin F. Price[2] · Mushtaque Ahmed[3] · Asma Abahussain[4] · Timothy O'Higgins[5]

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Abstract The research was conducted to assess the quality of groundwater resources of Al Jabal Al Akhdar, Oman. 11 drinking water sources were sampled during summer and winter seasons during 2012–2013 to evaluate their physico-chemical quality indicators; and assess their suitability for drinking and other domestic purposes. Sample collection, handling and processing followed the standard methods recommended by APHA and analyzed in quality assured laboratories using appropriate analytical methods and instrumental techniques. The results show that the quality parameters in all drinking water resources are within the permissible limits set by Omani and WHO standards; and the drinking water quality index is good or medium in quality based on NFS-WQI classification criteria, indicating their suitability for human consumption. There is an indication of the presence of high nitrate concentrations in some groundwater wells, which require more investigations and monitoring program to be conducted on regular basis to ensure good quality water supply for the residents in the mountain. The trilinear Piper diagram shows that most of the drinking water resources of the study area fall in the field of calcium and bicarbonate type with some magnesium bicarbonate type indicating that most of the major ions are natural in origin due to the geology of the region. This study is a first step towards providing indicators on groundwater quality of this fragile mountain ecosystem, which will be the basis for future planning decisions on corrective demand management measures to protect groundwater resources of Al Jabal Al Akhdar.

Keywords Groundwater · Piper trilinear diagram · Water quality index · Hydrochemistry · Al Jabal Al Akhdar · Oman

✉ Mohammed Saif Al-Kalbani
Kmohd2020@yahoo.com

Martin F. Price
Martin.Price.perth@uhi.ac.uk

Mushtaque Ahmed
ahmedm@squ.edu.om

Asma Abahussain
asma@agu.edu.bh

Timothy O'Higgins
tim.ohiggins@ucc.ie

[1] Ministry of Environment and Climate Affaires, P. O. Box 323, PC 100 Muscat, Sultanate of Oman

[2] Centre for Mountain Studies, Perth College, University of the Highlands and Islands, Crieff Road, Perth PH1 2NX, UK

[3] Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, P. O. Box 34, Al-Khod, 123 Muscat, Sultanate of Oman

[4] Department of Natural Resources and Environment, College of Graduate Studies, Arabian Gulf University, Manama 26671, Kingdom of Bahrain

[5] Environmental Research Institute, University College Cork, Beaufort Building, Haulbowline Road, Ringaskiddy, Co. Cork, Ireland

Introduction

Groundwater resources—from boreholes, hand-dug wells and springs (Anudu et al. 2011; Al-Khashman and Jaradat 2014)—play a significant role in arid and semi-arid regions, where they are the main sources of freshwater for drinking, agriculture and other domestic purposes. Due to rapid increase in population and urbanization, and associated anthropogenic activities, in these regions, their groundwater resources are prone to pollution from different

sources (Khattak et al. 2012; Kata et al. 2014; Li et al. 2014). This leads to poor drinking quality, high cleanup costs, loss of water supply and high costs for alternative water supplies and may cause potential health problems (Adhikary et al. 2012; Duan et al. 2014; Huang et al. 2014).

Like its quantity, the quality of water is of great importance in the planning and management of water supplies; this must be supported by water quality monitoring and assessment. If not properly managed, water quality can be a serious limiting factor to economic development and public health, which may result in enormous long-term costs to society (Sadat-Noori et al. 2014; Nasrabadi and Abbasi Maedeh 2014). Water quality is primarily governed by the extent and composition of dissolved solids (Tomar et al. 2012; Huang et al. 2014) and is a function of physico-chemical parameters, influenced by natural and anthropogenic factors including local climate, geology and human activities (Tatawat and Chandel 2008; Al-Harbi et al. 2014; Gueroui et al. 2014). The hydrochemical characteristics of groundwater determine its quality and suitability for drinking and other uses, and may also vary seasonally.

Generally, the movement of groundwater along its flow paths increases chemical concentrations (Kortatsi 2007; Khashogji and El Maghraby 2013; El Maghraby et al. 2013). Hence, its chemistry can reveal important information on the geological history of the aquifers, the degree of chemical weathering of various rock types, quality of recharge water and inputs from sources other than water rock interactions (Aghazadeh and Mogaddam 2011; Al-Khashman and Jaradat 2014). Several studies have tried to investigate the hydro-chemical facies and water type in order to provide preliminary information about the complex hydro-chemical processes in groundwater (e.g., Tatawat and Chandel 2008; Chowdhury and Gupta 2011; Samanta et al. 2013; Ewusi and Kuma 2014). A number of techniques and methods have been developed to interpret the hydro-chemical data of groundwater and evaluate its suitability for drinking by interpreting the analyses of water quality and illustrating its characteristics on maps (Sadat-Noori et al. 2014; Magesh et al. 2013). Some of these techniques (e.g., Piper 1944; Gibbs 1970; Wilcox 1955; Doneen 1964; Chadha 1999) can present such analyses in graphical form and have been used in many parts of the world including arid and semi-arid regions (Kortatsi et al. 2009; Ayuba et al. 2013; Aly et al. 2014; Nazzal et al. 2014; Kraiem et al. 2014) to show ionic concentrations in groundwater samples.

This study interprets and classifies the hydro-chemical quality of groundwater resources in Al Jabal Al Akhdar, Sultanate of Oman, and evaluates their suitability for drinking. No such study has previously been conducted in this fragile mountainous region. Because of its strategic and military importance, access to the area was prohibited until recently. Previous studies on water quality (e.g., Al-Ujaili 1997; Victor and Al-Ujaili 1998, 1999; Al-Haddabi 2003; Ahmed et al. 2006; Jashoul 2008; Al-Haddabi et al. 2009; Victor et al. 2009) focused only on the area's dams and aflaj (irrigation channels). This paper presents a comprehensive assessment of the quality of the government water supply from groundwater aquifers, the only available resources for drinking and domestic consumption in Al Jabal Al Akhdar. It focuses on the physico-chemical characteristics of groundwater resources in the area, investigates the mechanisms controlling groundwater composition, and provides an environmental assessment on drinking water quality indices.

Regional and hydrogeological setting

Al Jabal Al Akhdar (Green Mountain) forms the central part of the northern mountains of the Sultanate of Oman (Fig. 1), with altitudes from 1500 to 3000 m above sea level (Dorvlo et al. 2009). The area of Al Jabal Al Akhdar is not exactly identified or formally designated. According to Ashura Council (2010), the whole area of the mountain is estimated at approximately 2600 km^2. The extent area addressed by this study is Niyabat Al Jabal Al Akhdar, which is 404 km^2 (Al-Mukhtar 2013). In this area, temperatures drop during winter to below 0 °C and rise in summer to 22 °C, and the annual mean rainfall (300–400 mm) is higher than on the desert plains (DGMAN 2014). Due to its location and unique weather, the Green Mountain produces a variety of perennial fruits, especially pomegranates, and roses.

The geology of Al Jabal Al Akhdar consists of tectonically emplaced late Paleozoic and Mesozoic continental margin and Tethyan deep sea sediments along with a slab of Cretaceous oceanic crust and mantle: the Samail ophiolites (Glennie et al. 1974; Stanger 1986). They include the oldest rocks in the area: phyllites, mudstones, limestones and meta-volcanics (Al-Fahdi 2011). The limbs of the anticline are formed by rocks of the Hajar Super Group, a sequence of shallow marine carbonates which were laid down unconformably on the pre-Permian basement between the Permian and Cretaceous periods (Hanna 1995). The rocks consist of relatively uniform dark gray crystalline limestones and dolomitic limestones with abundant corals, gastropods, and bivalves. Thin yellow and pink siltstones occur throughout the sequence. The pre-Permian formations consist of a wide variety of rock types including green, maroon and pale yellow slates, tan and gray limestones and conglomerates (Glennie 2005).

The Hajar Super Group is the most important carbonate rock aquifer of northern Oman's Mountains. The carbonate

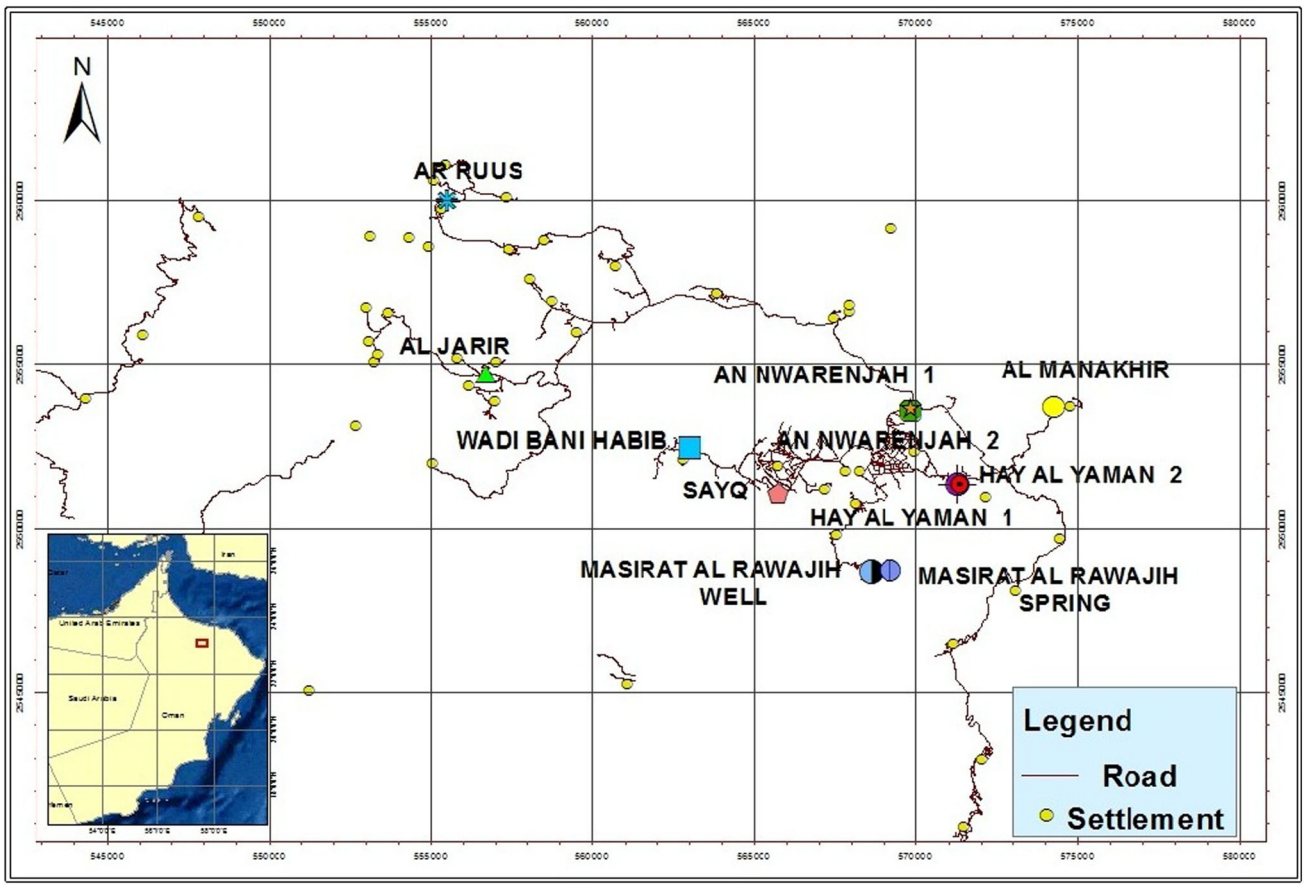


Fig. 1 The locations of sampled groundwater resources of the study area

rocks are highly fractured with karstic topography, allowing groundwater to be stored, migrate over long distances and emerge at the surface via many different springs along the boundary of the formations (Nagieb et al. 2004; Matter et al. 2006). The deeper fractures are likely to be more compressed that the shallow fractures. This implies that the groundwater in the deeper fractures is more confined; movement takes place along the intersection of two joints or a joint and bedding (Mott MacDonald 1992; Mount et al. 1998). The groundwater in the area is found at <5 to 30 m from the surface, and the static water depth ranges between 450 and 2000 m (Al-Fahdi 2011).

Due to its hydrogeological setting, Al Jabal Al Akhdar is very important as a water catchment area, with three natural freshwater resources: groundwater (wells), *aflaj* and *wadis*. Groundwater is the only freshwater available for drinking in the area, accessed via wells established by the Omani government, which supplies the water through networks or water trucks to local communities as well as other governmental offices, armed forces and private businesses. *Aflaj* (singular *falaj*) are surface and/or underground channels fed by groundwater, springs, or streams, built to provide water for agriculture (MRMWR 2008). *Aflaj* are maintained by designated local people who are responsible for the efficient system of water distribution for irrigation; government agencies are not involved in these indigenous governance structures (Al-Marshudi 2007; MRMWR 2008). *Wadis* (singular *wadi*) are seasonal valleys or dry ephemeral riverbeds that contain water only during times of rainfall, and are intercepted by artificial surface storage dams. Water from *aflaj* and dams is mainly used for agriculture and livestock.

As an arid mountain, water is the lifeline of Jabal Akhdar's ecosystems. Any adverse effects on its water resources will impact all ecosystems including humans; lack of water is a major constraint to local people (Al-Kalbani 2015). The existing water resources are under threat due to an increase in over-abstraction of water from government wells, the only available water resources for domestic purposes; and excessive use of water from *aflaj* and dams, the only available resources for agricultural purposes (Al-Kalbani 2015). Water quantity and quality are interconnected, since any changes in water quantity may affect its quality by various ways. The rapid increase in urbanization in the area, together with climatic change (Al-

Kalbani et al. 2014), is leading to a decrease in water quantity and therefore a deterioration in water quality.

Materials and methods

Water sampling and analytical methods

All sources of groundwater were sampled from a valve connected directly to their reservoirs. These include 10 government wells and one natural spring (Fig. 1). The sampling regime was 3 months in winter and 3 months in summer during 2012–2013, taking into account that seasonal events such as rainfall and storms may influence sampling; and to obtain a reasonable range of data in each season. Sample collection, handling and processing followed the methods recommended by the American Public Health Association (APHA 2005); water quality parameters were selected according to Chapman (1996). Major physico-chemical parameters were analyzed in quality assured laboratories in Oman using the analytical methods and instrumental techniques shown in Table 1. The accuracy of the chemical analysis was verified by the calculation of ion-balance errors of 5% for all the sampled water resources. The respective values for all these parameters are compared with standard limits recommended by Omani standards for Un-bottled Drinking Water 8/2006 (MD 2007) and the World Health Organization (WHO 2011a).

Hydrochemical water quality

Cation–anion exchange reaction

Assessment of changes in the chemical composition of water during subsurface movement is essential to understand the dissolution of undesirable constituents in water. Schoeller (1977) suggested chloro-alkaline indices, which indicate ion exchange between groundwater and its host environment during residence or travel. This index is positive if Na^+ and K^+ ions in water are exchanged with Ca^{2+} and Mg^{2+}; indicating a direct base exchange reaction. If the index is negative, the exchange is indirect, indicating chloro-alkaline disequilibrium. The chloro-alkaline indices (CAI-1 and CAI-2) were used for the assessment of cation–anion exchange reaction and calculated using the following formula:

$$\text{CAI-1} = \text{Cl}^- - (\text{Na}^+ + \text{K}^+) / \text{Cl}^-,$$

$$\text{CAI-2} = \text{Cl}^- - (\text{Na}^+ + \text{K}^+) / \left(\text{CO}_3^{2-} + \text{HCO}_3^- + \text{SO}_4^{2-} + \text{NO}_3^-\right),$$

where the concentrations are expressed in meq l^{-1}.

Table 1 Determination of physico-chemical water quality parameters by different methods/instruments

Parameters	Method/instrument used
Electrical conductivity (EC)	Measured in the field using a battery-operated conductivity meter (SevenGo, Mettler-Toledo AG 8603 Schwerzenbach, Switzerland) and in the laboratory using the Orion Thermo 550A
pH	Determined in the field using a pH meter (SevenGo, Mettler-Toledo GmbH, 8603 Schwerzenbach, Switzerland), and in the laboratory using a pH meter (Mettler Toledo)
Total dissolved solids (TDS)	Gravimetric method
Turbidity	Turbidity meter (Orion AQ 4500), nephelometric turbidity units (NTU)
Alkalinity ($CaCO_3$, HCO_3 and CO_3)	Autotitration
Total hardness (TH) (mg l^{-1})	=2.497 (calcium mg l^{-1}) + 4.118 (magnesium mg l^{-1}) (Todd 2005)
Dissolved oxygen (DO)	Measured in the field using Multi Probe System/data logger, YSI Incorporated 556 Instrument, Bramum Lane and in the laboratory using Mettler Toledo Seven Go Pro
Biochemical oxygen demand (BOD_5)	$BOD_5 = (D_2 - D_1)/P$, where D_1: DO of diluted sample immediately after preparation, mg l^{-1} D_2: DO of diluted sample after 5 days incubation at 20 °C, mg l^{-1} P: Decimal volumetric fraction of sample used
Sodium (Na), calcium (Ca), magnesium (Mg), potassium (K)	Inductively Coupled Plasma (ICP-OES) method (Perkin-Elmer Optima 3300 DV)
Fluoride (F), chloride (Cl), nitrate (NO_3), sulfate (SO_4), phosphate (PO_4)	Metrohm Professional Compact Ion Chromatography System 881 with Metrohm 858 Professional Sample Processor
Heavy metals	Inductively Coupled Plasma (Perkin-Elmer Optima 3300 DV)
Coliform bacteria	IDEXX Quanti-Tray (51-Well Quanti-Tray) quantification methods (most probable number)
Escherichia coli	Spectroline Model (EA-160/FE), ultraviolet light (365 nm)

Groundwater–aquifers relationship

The chemical components of drinking water and its relationship with their aquifers play a significant role in water quality. Gibbs (1970) has recommended diagrams in which ratio of dominant anions and cations are plotted against total dissolved solids (TDS). These diagrams are widely used to assess the functional sources of dissolved chemical constituents in relation to aquifers, such as chemistry of rock types, precipitated water, and rate of evaporation. The ratio 1, for cations, and ratio 2, for anions, in the sampled drinking water resources were calculated using the following equations.

$$\text{Gibbs ratio 1 for cations} = \left(Na^+ + K^+\right) / \left(Na^+ + K^+ + Ca^{2+}\right)$$

$$\text{Gibbs ratio 2 for anions} = Cl^- / \left(Cl^- + HCO_3^-\right).$$

Piper's trilinear diagram

Major cations and anions such as Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, CO_3^{2-}, HCO_3^- and SO_4^{2-} were plotted in Piper's trilinear diagram (Piper 1944) to assess the hydrochemistry of drinking water resources (Fig. 2). The concept of hydrochemical facies using this diagram was developed to understand and identify the water composition in different classes (Sadashivaiah et al. 2008). These trilinear diagrams are useful in bringing out chemical relationships among groundwater samples in more definite terms rather than with other possible plotting methods (Sajil Kumar 2013). To assess the hydrochemistry of groundwater resources of the study area, Piper's trilinear diagram was plotted using GW Chart (USGS 2014).

Water quality index

A water quality index (WQI) is an important parameter for demarcating groundwater quality and a rating technique for its suitability for drinking purposes (Nasirian 2007; Varol and Davraz 2015). It has been considered as one criterion for drinking water classification, based on the use of standard parameters for water characterization (Giriyappanavar and Patil 2013). A commonly used WQI was developed by the National Sanitation Foundation (NSF) in 1970 (Tyagi et al. 2013). Therefore, NSF-WQI is a standardized method for communicating and comparing the quality of various water bodies and simplifying the report of water characterization data into a single number, representing the water quality level (González et al. 2012; Arumugam et al. 2014). The index summarizes results from nine different measurements: temperature, pH, dissolved oxygen, turbidity, fecal coliform, biochemical oxygen demand, total phosphates, nitrates, and total suspended solids (Karbassi et al. 2011; Kushwaha and Kumar 2014). The water quality data are recorded and transferred to a weighting curve chart; the relative weights (Table 2) are preserved for each factor and scaled to obtain a numerical value of Q_i, so that the range remains from 0 (very bad water quality) to 100 (excellent water quality). The mathematical expression for the NSF-WQI is given by:

$$\text{WQI} = \sum (Q_i W_i),$$

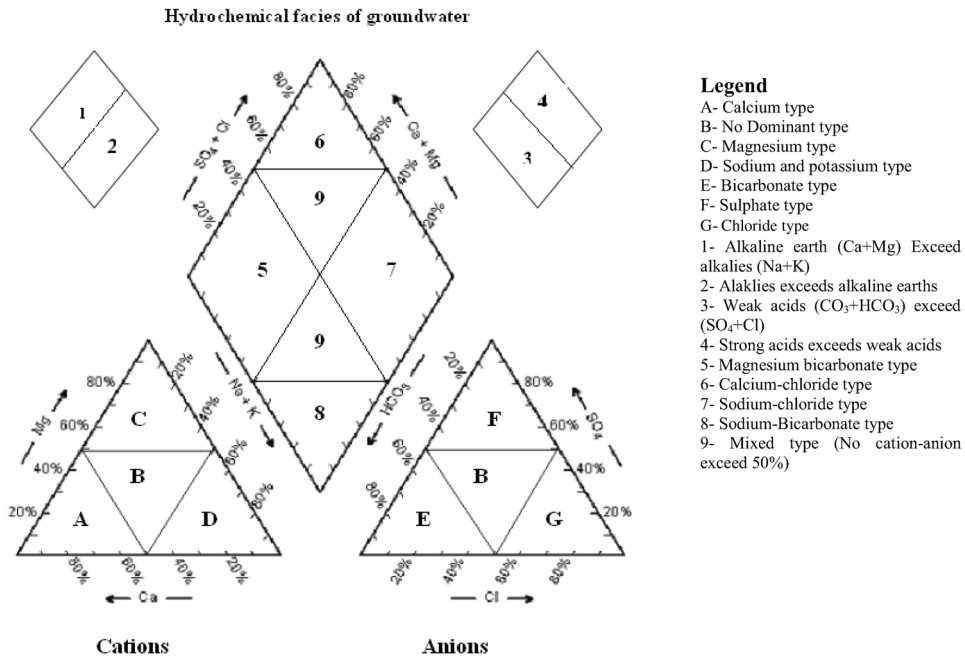


Fig. 2 Piper-trilinear diagram presenting anion and cation facies in the form of major ion percentages. Groundwater types are classified according to the domain in which they occur on the diagram segments (after Sadashivaiah et al. 2008)

Table 2 Water quality parameters and weights based on NSF-WQI (after WU 2014)

Parameter	Units	Weight
Dissolved oxygen	% saturation	0.17
Fecal coliform	MPN 100 ml^{-1}	0.16
pH		0.11
Biochemical oxygen demand	mg l^{-1}	0.11
Temperature change	°C	0.10
Total phosphate	mg l^{-1}	0.10
Nitrates	mg l^{-1}	0.10
Turbidity	NTU	0.08
Total dissolved solids	mg l^{-1}	0.07

Table 3 Classification criteria standards based on NSF-WQI (after Tyagi et al. 2013)

Range	Descriptive status	Category	Remarks
91–100	Excellent	A	Non polluted
71–90	Good	B	Non polluted
51–70	Medium	C	Polluted
26–50	Bad	D	Heavily polluted
0–25	Very bad	E	Heavily polluted

where Q_i is the sub-index for ith water quality parameter; W_i is the weight associated with ith (1 to n) water quality parameter; n is the number of water quality parameters.

The index can be divided into several ranges corresponding to the general ratings of descriptive terms and categories of water quality as shown in Table 3. To calculate the WQI for sampled water resources of the study area, the weighted averages of each parameter were calculated, and the sub-index of each parameter was determined, and WQI was finally calculated using the software available at Wilkes University (WU 2014) website.

Results and discussion

Physico-chemical parameters of groundwater resources

The means, medians, standard deviations, minima and maxima of drinking water quality parameters are presented in Table 4. Electrical conductivity (EC) values ranged from 425 to 1295 µs cm^{-1} (mean 748 µs $cm^{-1)}$ in summer, and from 437 to 1507 µs cm^{-1} (mean 825 µs cm^{-1}) in winter. None of the samples exceed the limits of the recommended Omani standards for Un-bottled Drinking Water (MD 2007) and World Health Organization standard (WHO 2011a). During summer, the pH value ranged from 8.1 to 8.5; during winter, from 7.3 to 8.2. Thus, the water is slightly alkaline. These pH values are within the limits of the recommended Omani and WHO standards (6.5–9.5). TDS values ranged from 238 to 920 mg l^{-1} (mean 449 mg l^{-1}) in summer, and during winter from 317 to 980 mg l^{-1} (mean 535 mg l^{-1}). These were within the

Table 4 Mean, median, standard deviation, minimum and maximum of groundwater quality variables of the study area in 2012–2013

Variables	Mean	Median	Std. deviation	Minimum	Maximum	Omani standard	WHO standard
EC (µS cm^{-1})	786.42	649.95	284.04	431.20	1401.00	160–1600	2000
pH	–	7.98	0.24	7.68	8.35	6.5–9.0	6.5–9.5
TDS (mg l^{-1})	492.22	398.12	198.19	277.44	949.66	120–1000	1000
Turbidity (NTU)	3.27	0.19	7.38	0.05	20.45	1 to <5	NG
Alkalinity ($CaCO_3$) (mg l^{-1})	273.36	261.53	66.92	176.38	379.60	NG	NG
Alkalinity (HCO_3) (mg l^{-1})	297.21	284.85	71.92	189.79	410.95	NG	NG
Total hardness (mg l^{-1})	346.94	327.55	112.22	206.75	566.73	≤200 to 500	500
Sodium (Na) (mg l^{-1})	36.77	26.19	28.98	12.51	97.77	≤200 to 400	200
Calcium (Ca) (mg l^{-1})	77.08	66.76	34.19	35.32	145.60	200	NG
Magnesium (Mg) (mg l^{-1})	31.85	30.06	7.81	22.14	44.42	150	NG
Potassium (K) (mg l^{-1})	2.98	1.70	2.81	0.56	8.21	NG	NG
Fluoride (F) (mg l^{-1})	0.26	0.24	0.14	0.11	0.46	1.5	1.5
Chloride (Cl) (mg l^{-1})	51.91	28.99	46.58	17.44	165.14	≤250 to 600	250
Nitrate (NO_3) (mg l^{-1})	18.49	9.36	23.49	0.73	72.77	50	50
Sulfate (SO_4) (mg l^{-1})	56.64	42.04	35.57	19.06	114.10	≤250 to 400	400
Phosphate (PO_4) (mg l^{-1})	0.16	0.06	0.27	0.02	0.93	NG	NG
Coliforms (MPN 100 ml^{-1})	6.65	0.00	18.22	0.00	61.30	10	10

NG no guideline is recommended

Table 5 The chloro-alkaline indices (CAI-1 and CAI-2) for groundwater resources of the study area sampled during summer and winter 2012–2013

Sample code	Summer		Winter	
	CAI-1	CAI-2	CAI-1	CAI-2
G1	−0.414	0.607	−6.788	−6.216
G2	−0.258	0.624	−9.300	−8.167
G3	−0.196	0.590	−17.026	−10.427
G4	−0.263	0.560	−14.603	−10.947
G5	1.083	1.674	−0.286	0.114
G6	0.682	1.837	−2.108	0.278
G7	−0.318	0.735	−12.239	−5.481
G8	−0.307	0.686	−4.859	−4.454
G9	−0.027	0.437	−5.850	−7.850
G10	1.160	2.658	−2.493	0.417

permissible levels of TDS (120–600 mg l^{-1}, maximum 1200 mg l^{-1}) in the Omani standard; the WHO standard allows for a maximum level of 1000 mg l^{-1}. Hardness of groundwater results from the presence of divalent metallic cations of which concentration of Ca^{2+} and Mg^{2+} are most abundant in groundwater. Both Omani and WHO standards allow a maximum of 500 mg l^{-1} for total water hardness. Of the 11 groundwater samples analyzed, only one well located at Sayq village had a total hardness of 516 mg l^{-1} in summer and 617 mg l^{-1} in winter. The mean total hardness of all drinking water resources was 333 and 361 mg l^{-1} during summer and winter, respectively. Adopting Sawyer (1994, 2003) classification criteria, groundwater of the entire study area is hard to very hard as the total hardness ($CaCO_3$) is in the range of 150–300 and more than 300 mg l^{-1}. The hardness of the water is due to the presence of alkaline earths such as calcium and magnesium, and anions such as carbonate, bicarbonate, chloride and sulfate.

Concentrations of all cations and anions in the samples were not significantly different between summer and winter; except fluoride. The mean concentration of cations (in mg l^{-1}) in the samples was: $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ (Table 5). The mean concentration of anions (in mg l^{-1}) was: $HCO_3^{-} > SO_4^{2-} > Cl^{-} > NO_3^{-} > CO_3^{2-} > F^{-} > PO_4^{2-}$. According to Omani and WHO standards, all cations and anions concentrations in all samples were within the permissible limits. However, nitrate concentrations in some groundwater wells were higher than the desirable limit of 50 mg l^{-1} for drinking water (Fig. 3). For example, Hayl Al Yaman well (2) showed a high concentration of nitrate of 101.45 mg l^{-1} in the winter sample, and a high concentration of 42.75 mg l^{-1}, not exceeding the limit, in the summer sample. Nearby Hayl Al Yaman well (1) showed a nitrate concentration of 44.10 mg l^{-1} in the summer sample. Other samples did not exceed the standards limit, but increased from summer to winter: Al Manakhir well (31.05–38.68 mg l^{-1}); Sayq well (22.78–40.22 mg l^{-1}). The possible sources of high nitrate in these wells are from the seepage of sewage water from unlined septic tanks in some of the households near these wells. Most of the households in the study area are not connected to a sewer system. Nitrate as such is not poisonous but when reduced to nitrite in the stomach it can be toxic, particularly to bottle-fed babies (blue baby syndrome or methemoglobinemia (WHO 2011b). High nitrate concentration in drinking water can also create problems including cyanosis, goiter, oral cancer, cancer of the colon or rectum, other gastrointestinal cancers, lymphoma and dyspnea (Tatawat and Chandel 2008).

Although the amount of dissolved oxygen (DO) often gives a good indication of water quality, Omani and WHO

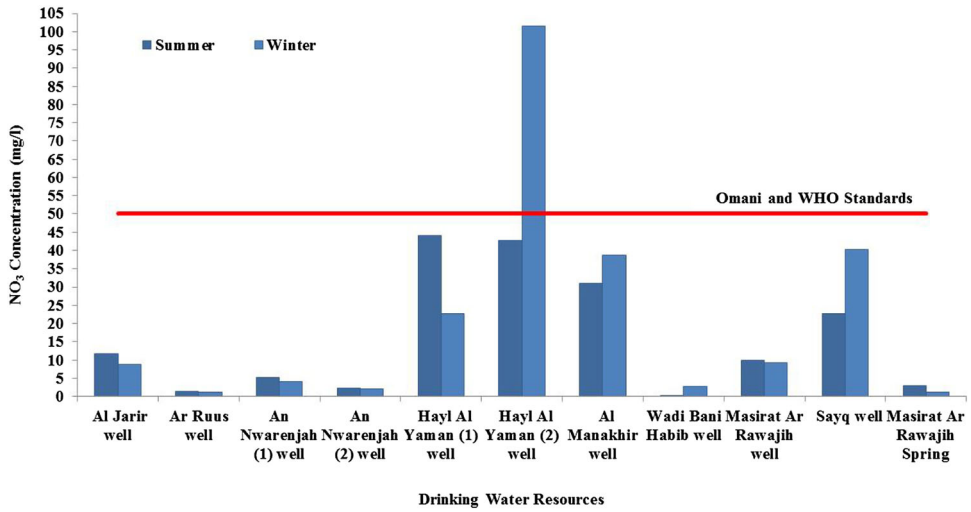


Fig. 3 Nitrate concentration in groundwater resources of the study area sampled during summer and winter 2012–2013

Table 6 Ratio 1 for cations and ratio 2 for anions of groundwater resources of the study area sampled during summer and winter 2012–2013

Sample code	Summer		Winter	
	Ratio 1 cations	Ratio 2 anions	Ratio 1 cations	Ratio 2 anions
G1	0.216	0.192	0.256	0.175
G2	0.222	0.171	0.491	0.137
G3	0.142	0.127	0.495	0.097
G4	0.142	0.122	0.166	0.123
G5	0.284	0.364	0.609	0.404
G6	0.574	0.397	0.262	0.433
G7	0.166	0.122	0.187	0.158
G8	0.158	0.144	0.248	0.228
G9	0.245	0.149	0.444	0.121
G10	0.594	0.385	0.358	0.472
G11	0.214	0.149	0.236	0.169

standards do not recommend guidelines regarding the acceptability of low levels. Generally, concentrations in unpolluted waters are usually close to, but less than 10 mg l^{-1}; concentrations below 5 mg l^{-1} may adversely affect the functioning and survival of biological communities (Chapman and Kimstach 1996). All samples had DO concentrations close to, but less than, 10 mg l^{-1}, taking into account changes in field water temperatures. The mean field measurements of DO in samples ranged from 6.86 to 8.35 mg l^{-1} (mean 7.85 mg l^{-1}) in summer and from 7.30 to 8.97 mg l^{-1} (mean 7.99 mg l^{-1}) in winter. Omani and WHO standards also do not set guideline values for biochemical oxygen demand (BOD_5). However, unpolluted waters typically have BOD_5 values of 2 mg l^{-1} or less whereas those receiving wastewater may have values up to 10 mg l^{-1} or more (Chapman and Kimstach 1996). The mean BOD_5 for all samples was 1.26 mg l^{-1}; values ranged from 0.36 to 1.74 mg l^{-1} during summer and ranged from 0.08 to 1.24 mg l^{-1} (mean 0.57 mg l^{-1}) during winter. The Omani and WHO standards for coliform bacteria allow the most probable number (MPN) of 10 per 100 ml. In both guidelines, total *E. coli* should be 0 per 100 ml of a sample. Of the 11 summer samples, only 3 showed the presence of total coliform bacteria; during winter, only one sample was positive. No sample showed any presence of *E. coli*, indicating that this water is safe to use and drink.

Hydrochemical quality of groundwater resources

Around 91% of the samples had negative chloro-alkaline indices (CAI-1 and CAI-2), indicating indirect exchange and therefore chloro-alkaline disequilibrium (Table 5). These results show that there is ion exchange between the water and its host environment during its travel in the subsurface, with the dissolution of undesirable constituents in water.

The results of ratio 1 (cations) and ratio 2 (anions) in the samples are presented in Table 6. The Gibbs diagrams (Fig. 4) showed that the majority of the samples are in the rock–water interaction dominance field, suggesting that chemical weathering of rocks forming minerals and evaporation are the dominant processes controlling the major ion composition of the water through the dissolution of the rock-forming minerals. Similar results were found by other studies conducted in arid regions (e.g., Magesh et al. 2013; Al-Harbi et al. 2014; Huang et al. 2014; Nazzal et al. 2014; Aly 2014; Saber et al. 2014).

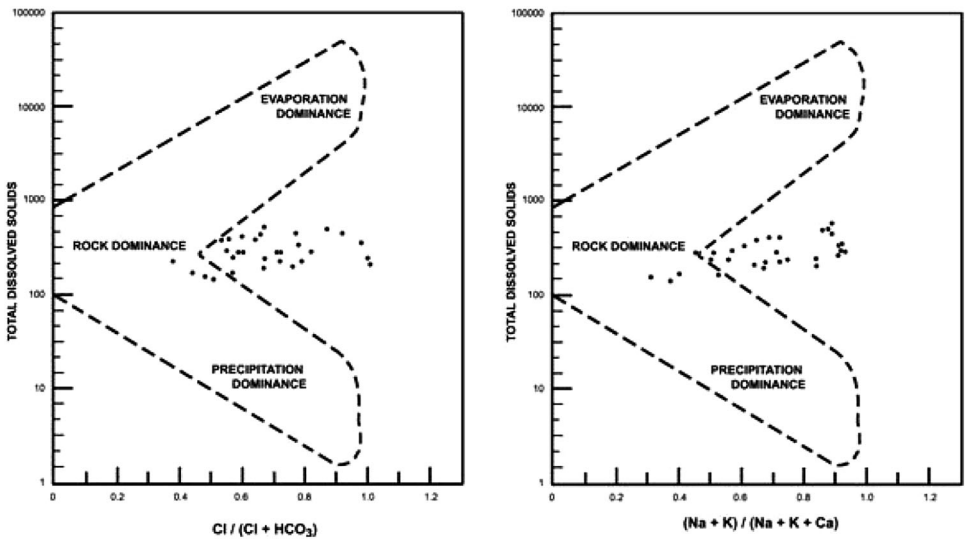


Fig. 4 Gibbs diagrams for hydro-chemical quality of groundwater resources of the study area (after Gibbs 1970)

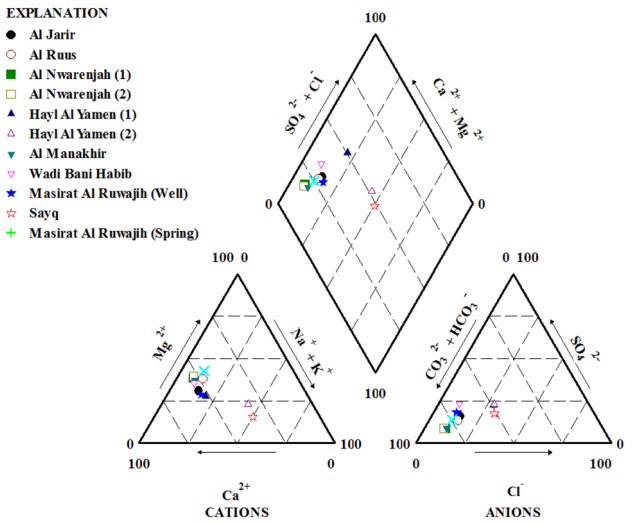


Fig. 5 Piper's trilinear diagram of groundwater resources of the study area sampled during summer 2012–2013

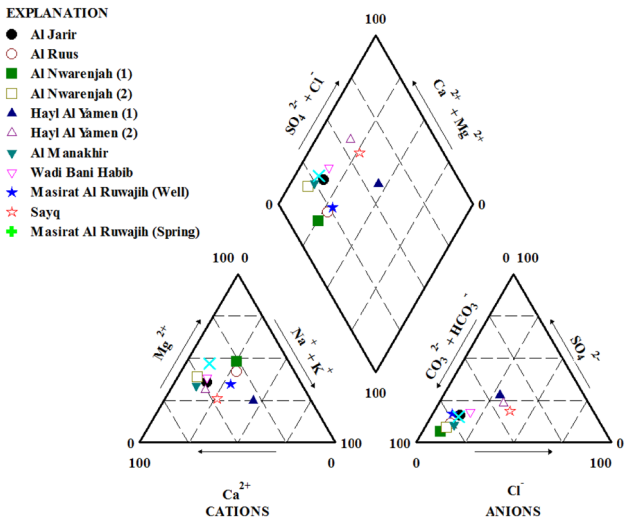


Fig. 6 Piper's trilinear diagram of groundwater resources of the study area sampled during winter 2012–2013

Hydrochemical facies of groundwater resources

Figures 5 and 6 present the chemical data analysis, using Piper's trilinear diagram, of all the samples. These diagrams reveal the analogies, dissimilarities and different types of waters in the study area, which are identified based on domain categories in which they occur on the diagram segments (Table 7). Most of the summer and winter samples fall in the field (A) of calcium and (E) bicarbonate types, representing 27 and 73% of the water samples, respectively.

The characteristics of corresponding subdivisions of diamond-shaped fields show all samples are of field 1 (100%), followed by fields 3 and 5 (each 73%), then fields 4 and 9 (each 27%). These results suggest that most of the groundwater is of calcium and bicarbonate types; alkaline earth (Ca + Mg) dominates over alkalis (Na + K), and weak acids (CO_3 + HCO_3) over strong acids (SO_4 + Cl). These results suggest that the water chemistry is originated mainly from dissolution of carbonate rocks with low salinity. This is in agreement with Matter et al. (2006) who found that groundwater in the recharge areas of Al Jabal Al Akhdar is of Ca–Mg–HCO_3 type water. This type is typical for the Hajar Supergroup aquifer for limestone and dolomite dominated environments. There is no significant change in the hydro-chemical facies between summer and winter, indicating that most of the major ions are natural in origin, due to groundwater passing through relatively insoluble igneous rocks and dissolving only small quantities of minerals. These results are in line with other studies carried out in arid environment (e.g., Ayuba et al. 2013; Aly et al. 2014; Al-Khashman and Jaradat 2014; Alaya et al. 2014; Varol and Davraz 2015).

Correlation of groundwater quality indicators

Correlations analysis using Pearson's coefficient (r) of physicochemical parameters of groundwater quality are presented in Table 8. The terms strongly, moderately and weakly correlations refer to $r > 0.7$, $r = 0.5$–0.7, and $r < 0.5$, respectively. The correlation coefficient matrix for these parameters showed strongly positive correlations, highly significant at $p < 0.01$, between TDS, turbidity, EC, TH, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, and SO_4^{2-}. The strongest positive correlation was between EC and TDS ($r = 0.986$): highly statistically significant at $p < 0.01$. High correlation was also found among TDS with Na^+, Ca^{2+}, Mg^{2+} and Cl^-. Other statistically significant positive correlations ($p < 0.01$) were found between HCO_3^-, EC, TH, Ca^{2+} and Mg^{2+}, and between pH and CO_3^{2-}. Strong positive correlation was found between Ca^{2+} with Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-}. Magnesium was strongly positive and significantly correlated with Cl^- and NO_3, while sodium was positively and strongly correlated with Cl^- and SO_4^{2-}. These observations clearly identify the main elements contributing to the groundwater salinity and mineralization. The strongest and highly significant correlation ($r = 0.789$) between Ca^{2+} and Mg^{2+} indicates the presence of a ubiquitous source of alkaline earths in groundwater. The high moderately significant relationship ($r = 0.602$) between Mg^{2+} and Cl^-, and strongly significant relationship between total hardness with Ca^{2+} ($r = 0.898$) and Mg^{2+} ($r = 0.925$), indicated that the hardness of the water was permanent in nature. The highly significant and strong correlation ($r = 0.851$) between Cl^- and Na^+ confirms their same origin, that is, the dissolution of the halite resulting from the action of water on salts. The concentrations of SO_4^{2-} are tightly correlated with the

Table 7 Characterization of groundwater resources of the study area sampled during 2012–2013 according to the Piper trilinear diagram

Subdivision of the diamond	Characteristics of corresponding subdivisions of diamond-shaped fields	% of samples in this category
1	Alkaline earth (Ca + Mg) Exceed alkalies (Na + K)	100
2	Alaklies exceeds alkaline earths	0
3	Weak acids (CO_3 + HCO_3) exceed (SO_4 + Cl)	73
4	Strong acids exceeds weak acids	27
5	Magnesium bicarbonate type	73
6	Calcium-chloride type	0
7	Sodium-chloride type	0
8	Sodium-bicarbonate type	0
9	Mixed type (no cation–anion exceed 50%)	27
A	Calcium type	27
E	Bicarbonate type	73

Table 8 Correlation matrix among different water quality parameters for groundwater resources of the study area sampled during 2012–2013

	TR	TDS	EC	pH	HCO_3	CO_3	TH	Na	Ca	Mg	K	F	Cl	NO_3	SO_4
TR															
TDS	0.60**														
EC	0.58**	0.99**													
pH	−0.37	−0.35	−0.30												
HCO_3	0.34	0.53*	0.56**	−0.11											
CO_3	−0.24	−0.29	−0.23	0.67**	0.07										
TH	0.61″	0.85**	0.87**	−0.44*	0.75**	−0.24									
Na	0.40	0.78**	0.78**	−0.03	0.21	−0.08	0.39								
Ca	0.49*	0.80**	0.84**	−0.11	0.77**	−0.06	0.90**	0.43*							
Mg	0.57**	0.74**	0.76**	−0.41	0.65″	−0.17	0.93**	0.26	0.79**						
K	−0.20	−0.14	−0.16	−0.37	−0.18	−0.31	−0.12	−0.06	−0.41	−0.20					
F	−0.03	0.002	0.01	0.38	0.37	0.16	0.08	−0.03	0.27	0.03	−0.26				
Cl	0.59″	0.94**	0.94**	−0.18	0.36	−0.20	0.72**	0.85**	0.74**	0.60**	−0.23	−0.01			
NO_3	0.04	0.66**	0.71**	−0.11	0.17	−0.18	0.55**	0.51*	0.59**	0.54**	−0.08	−0.13	0.66**		
SO_4	0.46*	0.82**	0.84**	0.01	0.20	−0.03	0.55**	0.82**	0.62**	0.48*	−0.28	−0.05	0.87**	0.63**	

*Significantly correlated at 0.05 level

**Significantly correlated at 0.01 level

presence of Na^+, Ca^{2+} and Mg^{2+}, which is explained by the dissolution of evaporate minerals. These results also reveal that the concurrent increase/decrease in the cations is mainly the result of dissolution/precipitation reactions and concentration effects (Varol and Davraz 2015).

Water quality index

The WQIs of the sampled groundwater resources were not significantly different between summer and winter ($F = 3.092$, $p = 0.094 > 0.05$). All water samples are good or medium in quality: B or C categories. The WQI of water samples ranged from 64 to 80 (mean 71.64, median 70, standard deviation 5.66) during summer. In winter, it ranged from 68 to 83 (mean 75.82, median 76, standard deviation 5.49). Of the 11 summer samples, 5 were classified as good quality and 6 as medium. In winter, 8 were classified as good quality and only 3 as medium (Table 9). WQI showed highly significant and moderately negative correlation with TDS, EC, Na^+, Ca^{2+}, Cl^-, NO_3^- and SO_4^{2-} (Table 8), explaining the low WQI value and indicating that the groundwater resources of the study area are all suitable for drinking and other human consumption.

Conclusions and recommendations

Environmental quality assessment of the groundwater resources of the study area reveals that all are suitable for drinking and for other domestic purposes; all the quality

Table 9 WQI of groundwater resources of the study area sampled during summer and winter 2012–2013

Sample code	Summer		Winter	
	WQI	WQI class	WQI	WQI class
G1	73	Good	76	Good
G2	80	Good	83	Good
G3	68	Medium	79	Good
G4	79	Good	82	Good
G5	65	Medium	70	Medium
G6	64	Medium	69	Medium
G7	70	Medium	71	Good
G8	79	Good	76	Good
G9	69	Medium	79	Good
G10	68	Medium	68	Medium
G11	73	Good	81	Good

parameters are within the permissible limits set by Omani and WHO standards. However, there are some indications of high nitrate concentrations in some wells, exceeding the limits in Hayl Al Yaman well (2), and not exceeding the limits in Hayl Al Yaman well (1), Al Manakhir well and Sayq well. Overall, the water quality indices are good or medium according to NFS-WQI classification criteria. All groundwater resources are alkaline; major processes controlling water quality are silicate weathering, mineral dissolution and cation exchange. Evaluation of the water types using Piper plot suggests that there is a clear indication of the contribution of the geology of the area from the chemical weathering process of rock formation of mixed calcium and bicarbonate rock types, controlling the major ion composition of groundwater environment. Groundwater is of calcium and bicarbonate type, with some magnesium bicarbonate type; alkaline earth (Ca + Mg) dominate over alkalis (Na + K), and weak acids (CO_3 + HCO_3) dominate over strong acids (SO_4 + Cl); indicating that most of the major ions are natural in origin due to the geology of the region and its effects on the water compositions. Corrective demand management measures, such as water conservation, reuse of treated wastewater effluents, reusing gray water, redesigning septic tanks and expanding sewerage networks, have to be implemented to protect groundwater resources of Al Jabal Al Akhdar. Water quality monitoring programs should be carried out on a regular basis to ensure potable water supplies for human consumption; and more detailed analysis on trace element compositions, microbial investigation and nitrate determination are recommended to further ascertain the quality of groundwater resources in the area.

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