



# Hydrochemical characterization of groundwater to align with sustainable development goals in the Emirate of Dubai, UAE

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## Abstract

The Emirate of Dubai is facing ongoing challenges in managing its limited groundwater resources which are mainly used for irrigation and commercial uses whilst domestic supply is largely met by desalinated water. A groundwater investigation was carried out in the emirate with the objective to establish baseline data for the implementation of groundwater management policy. Seventy groundwater samples were collected from a sandy unconfined aquifer in the emirate during March–April 2016, a season which corresponds with post-rain time. The samples were analyzed for 26 physico-chemical, major ions, trace elements and biological parameters. The analysis help classifying groundwater quality into different zones varying from fresh to brackish and saline towards the shoreline sabkhas. The graphical assessment confirmed groundwater to be highly mineralized due to increased resident time, rock–water interaction, irrigation returns and lack of replenishment due to rainfall. Graphical plots and statistical analysis techniques were employed to infer the basic characteristic and genesis of the groundwater. Chemical classification of groundwater was carried out using a Piper trilinear diagram which classified groundwater into predominantly Na–Cl facies type. Various graphs suggest ion-exchange, reverse ion-exchange and evaporation processes drive within groundwater environment. The suitability of groundwater for drinking and irrigation usages was tested using standard techniques. Finally, GIS techniques were employed to process the data and subsequently employed in groundwater management issues such as setting groundwater protection zones, a groundwater monitoring plan and a public awareness program. The hydrogeological investigation coupled with GIS technique gives more insight and reliable information which paved the way to implement various government policies for priority-wise sustainable groundwater management with high accuracy.

**Keywords** Groundwater quality · Piper's diagram · GIS techniques · Sustainable groundwater management · Dubai emirate

## Introduction

The scarcity of freshwater resources has become an important issue worldwide. Groundwater is of particular importance for maintaining food security, especially for the residents of arid and semi-arid regions where there are limited surface water resources. Groundwater resources of arid environment have remained endangered due to excessive usage and limited replenishment. Rapid population growth and internal migration towards the most productive areas have resulted in a severe rise of water needs and consumption.

Consequently, clustering of groundwater demand in specific areas has resulted in permanent lowering of water levels.

The protection of the scarce fresh water resources in the Emirate of Dubai is primarily managed through regulatory measures which include measures for limiting the usage of groundwater and policies for sustainable development. Specifically, Dubai local law No.15 (2008) provides a legal framework for the protection and management of groundwater resources whilst the Dubai groundwater policy provides a clear government policy direction on the sustainable management of groundwater resources for the benefit of the people of the emirate. The Dubai Municipality Strategy 2021 was developed within this policy and regulatory framework and is a strategic initiative that comprises groundwater resource protection, artificial recharge management and the implementation of monitoring measures (DM 2016). In recent decades, the increasing demands for water from

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domestic, industrial and agricultural users in the Dubai emirate have placed a great strain on limited water resources and threaten the availability of groundwater resources needed to cater for basic agricultural activities and strategic reserves. Therefore, much attention is been given to groundwater management through the development and implementation of groundwater protection policies and sustainable groundwater management measures in the emirate.

While managing groundwater resources, both the availability of groundwater and its quality both are equally important in the context of policy making through a single, unified governmental agency (Jeffrey et al. 2013). Rapid urbanization of Dubai emirate has accelerated the consumption of groundwater resources through increased irrigation, recreational and commercial usage, causing groundwater depletion at alarming level. Overexploitation has led to local aquifer depletion and groundwater salinization in some parts of the emirate, a largely irreversible process. Consequently, in some parts of Dubai the shallow aquifer is already exhausted and in the remainder of the emirate all usable water (both fresh and brackish) are likely to be exhausted within the next few years to decade.

No reliable direct estimates of groundwater abstractions are available in Dubai but an indirect estimate for the year 2009 suggested that the annual abstraction rate was approximately 145 million cubic meter (MCM) at this time. The annual abstraction rate subsequently increased to about 200 MCM in 2014 (DM 2014), implying that groundwater remains main source of irrigation in peri-urban areas. Comparison between groundwater abstraction and recharge indicates that most of groundwater resources in the United Arab Emirates are over drafted and becoming depleted (Rizk and Al-Sharhan 2003). Of the 200 MCM of treated water that is produced in Dubai, around 165 MCM is reused for landscaping, recreation, district cooling and agricultural uses (DM 2014). Increasing demands from district cooling, city utilities and recreational activities restricts treated water availability for agriculture sector, adding pressure to the limited groundwater resources in the emirate.

With rapid increases in the population and the growth of industrialization in Dubai, groundwater quality is being increasingly threatened by the disposal of urban and industrial solid wastes and the effects of other land use practices. Once pollution enters the subsurface environment, it may remain concealed for many years, rendering groundwater unsuitable for consumption and other uses (Raju et al. 2011). Groundwater quality is mainly affected by geological factors, the groundwater residence time in the aquifer, climate, land use patterns, point pollution sources, etc. Most groundwater quality monitoring programs require two key factors to be effective: a good spatial coverage of monitoring wells and a sampling frequency that adequately detects changes in water quality over time. The spatial distribution and variability

of chemical constituents in groundwater are influenced by climate, the physical characteristics of the aquifer, land use factors and water table depth (Umar et al. 2009; Nazzal et al. 2014; Mohamed and Hassane 2016). In arid regions, over-exploitation has emerged as a major threat for groundwater sustainability which can reduce groundwater storage and can adversely affect groundwater quality through a variety of processes including: the upward leakage of groundwater from deeper aquifers, changes in flow patterns in the aquifer, and the acidification of shallow groundwater from the lowering of the water table where aquifer sediments contain sulfide minerals. In arid regions such as UAE where aquifer replenishment is very limited, excessive groundwater exploitation is not sustainable. It is feared that with such high abstraction rates, the aquifer in the region may run dry in the near future.

In addition, aquifers differ considerably in their hydrological characteristics and land use type which means that there is no one approach with which to analyze and manage them. This demands unique solutions for an individual aquifer system under a given set of prevailing conditions. A simple demand-side management (DSM) projection of yearly abstractions predicts that there will be steady increases in groundwater consumption in Dubai in coming years. Moreover, groundwater depletion, safe-yield estimates and salinization are key issues identified in this study to be addressed.

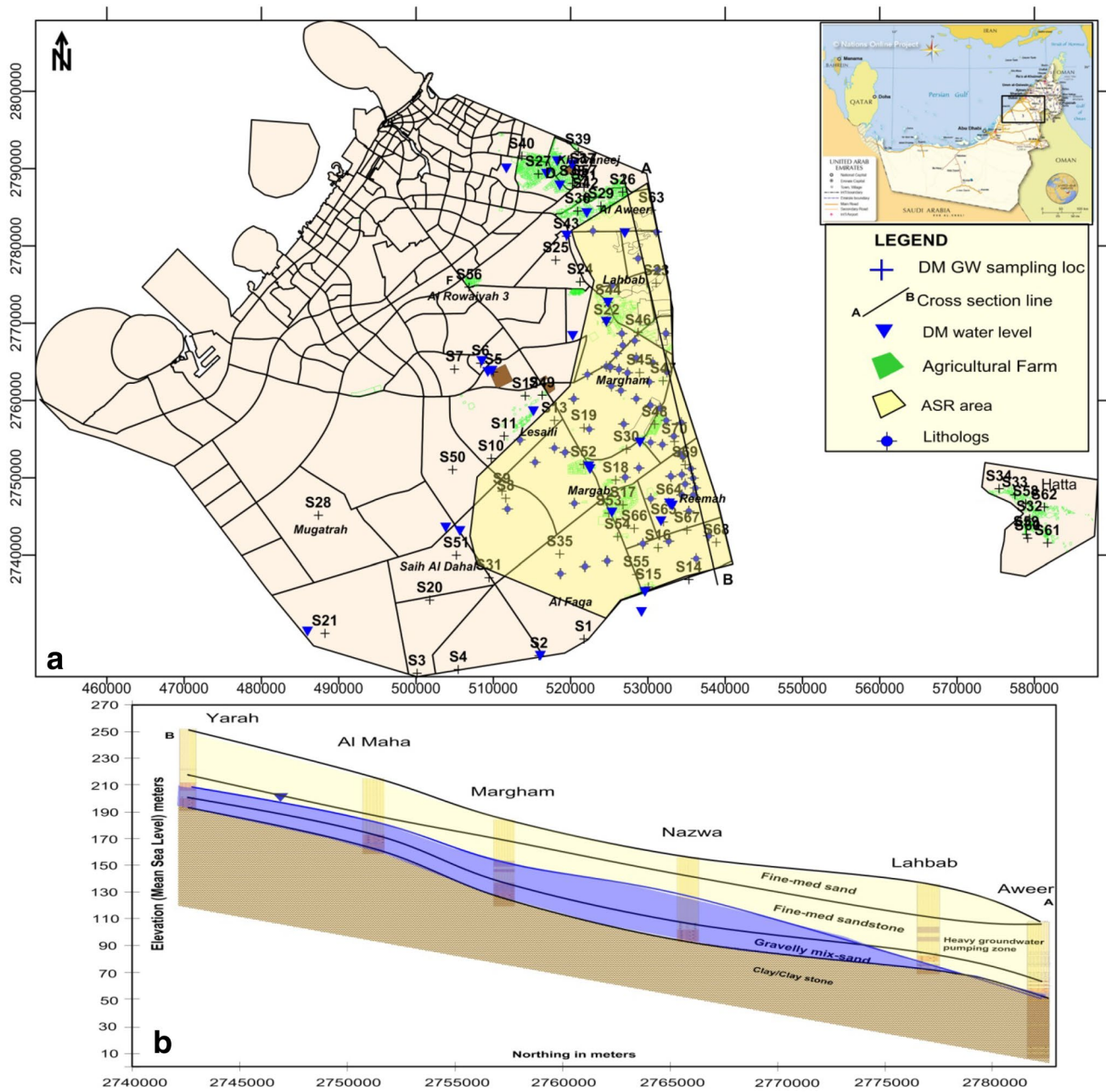
The present study has been carried out to generate baseline information required for the proposed systematic groundwater management study. Efforts have been made to collate various hydrogeological data and information on pertinent issues such as groundwater genesis, quality deterioration, salinization, and point sources of pollution to construct a work plan roadmap for the implementation of groundwater protection policy for the sustainable management of this resource in Dubai.

## Characteristics of the study area

The present study is for the entire Dubai emirate which has a total area of 4105 km<sup>2</sup> (Fig. 1). The city of Dubai is located on the emirate's northern coastline. Dubai is the largest city and it is located on the southeast coast of the Gulf and is the capital of the Emirate of Dubai, one of the seven emirates that make up the United Arab Emirates.

## Climate and physiography

The climate of Dubai is dry sub-tropical (Bwh in the Köppen climate classification system). Rainfall is infrequent and generally occurs during the winter months and early spring. The climate of the main portion of the Dubai emirate is semi-arid to arid, with a long, dry hot summer period between April



**Fig. 1** Map showing **a** base map of the study area, **b** hydrogeological cross-section along A–B

and November. The warm winter period occurs between December and March during which some rainfall may occur. Typically, the average day time temperature in the summer is 35 °C, often with high humidity as cooler air is brought in from the Gulf which heats up and rises over the hot land. Most of the rainfall occurs during the more unsettled four winter months. January is the coolest month with an average temperature of 18 °C. The wettest month on average is February. Average annual rainfall at Dubai International Airport is 51 mm per year. However, the greatest number of days with rainfall generally occurs in March. The majority of the

rainfall occurs as a result of the convergence zones caused by an upper level trough to the west of the Gulf. Short, heavy rainfall produces the best opportunities for aquifer recharge (DMO 2009). During, March 2016, > 150 mm rainfall was recorded in 1 day. Most of the rainfall occurs in the December–March period.

The topographic elevations within Dubai emirate range from 250 m above mean sea level in the SE, gradually decreasing towards the coastline in a NW direction. Hatta enclave is part of Dubai emirate which is geographically separated from Dubai lies to the southeast of Dubai’s main

territory and is about 134 km east of Dubai city. Hatta township is located relatively high in the foothills of Hajjar mountains with elevation ranging from 300 to 650 m asl. Geomorphologically, the emirate can be classified into three main units, which are high sand dunes, coastal fringes, and urban areas. In this study, groundwater monitoring data were considered for the whole Dubai emirate except for urban areas. The urban areas are not included as it is considered that groundwater in these areas is unsuitable for drinking or any other domestic use (MoEW 2010).

## Geology and hydrogeology

The geology of the UAE and of the Arabian Gulf has been substantially influenced by the deposition of marine sediments associated with numerous sea level changes during relatively recent geological time. With the exception of Hatta region in the northeastern part of Dubai, the emirate is relatively low-lying, with the near-surface geology dominated by deposits of Quaternary to late Pleistocene age, including mobile aeolian dune sands, sabkha deposits and marine sands.

The main aquifers in the desert regions of Dubai are Quaternary sands and gravels. The Quaternary-consolidated palaeo-dunes of the Ghayathi Formation are comprised of weakly to moderately well-cemented calcareous sand dunes that occur in a belt along the northernmost exposure of the sand and gravel aquifer. Alluvial deposits in the area consist of Quaternary sands and gravels. The alluvium extends beneath a large area of aeolian sand in the Dubai emirate. The Dubai urban area is built on Miocene strata consisting of Gachsaran Formation of the Fars Group. The top part of this formation is the lateral equivalent to the Dam Formation of Abu Dhabi. The Miocene Epoch was dominated by renewed movement of the Arabian Plate towards the north-east culminating in the formation of the Zagros Mountains. Ongoing uplift and erosion since the Miocene has led to the sedimentation of thick Quaternary fluvial gravel deposits in the eastern mountain wadis onto large series of coalescing alluvial fans along the mountain's feet. The fans in the east (Hili Formation) grade laterally westwards into finer-grained alluvial fan and fluvial sands, with an increasing aeolian component. Along the coast, carbonate cemented palaeo-dunes of Ghayathi Formation are present (Farrant et al. 2012).

The Miocene rocks are overlain by a complex sequence of Quaternary to recent deposits of coastal marine, fluvial and aeolian origin. The main exposed coastal portion of Dubai is formed mainly of marine deposits, and is formed of a patchy distribution of aeolian sands and alluvial deposits. Bedrock consisting of lithified alluvial fan deposits only crops out in isolated locations in the eastern part of the emirate.

Aeolian sands cover a large part of the area, with elongate, branching, linear mega-dune ridges which are oriented

in a SE–NE direction and which are interspersed with low dunes and inter-dune gravel- and sand-flats. Historically, as the climate in the area became increasingly arid, the dunes have increasingly encroached over the alluvial fan surface. Therefore, it is not unusual to find flat, windswept inter-dune areas where older alluvial fan deposits are revealed between the main dune deposits. Hatta enclave is dominated by variety of rock types ranging from peridotites, ophiolites, metavolcanics, schists, mudstones, carbonates, wadi sediments and recent conglomerates (MoEW 2012).

Hydrogeologically, Dubai is characterized by a single unconfined surficial aquifer which extends from the Al Hajar Mountain's foothills to the Gulf coast. The thickness of first aquifer ranges from 40 to 120 m with an average depth of 60 m. The main portion of the Dubai emirate is considered to be underlain by a desert aquifer, where the groundwater flows away from the mountain front recharge area towards the sea (Farrant et al. 2012). A typical hydrogeological cross-section (north–south) shows that the aquifer in this area consists of two distinct hydrogeological formations with horizontal gradational changes and a fining-upward sequence of sediments (Fig. 1b). Both are hydrodynamically connected. The aquifer is characterized by a low storage and a variable transmissivity depending on the depositional environment and the extent to which secondary permeability has developed in sediments. In the western and southwestern parts of the emirate, groundwater is predominantly brackish to saline and is not suitable for irrigation purposes or domestic use. Areas with fresh or slightly brackish groundwater are located mainly in the eastern and SE part of the emirate, forming a more or less contiguous belt. Some pockets of freshwater are also found in the central desert area (e.g. near Rawiya and Lusaili). Nonetheless, the quality of the groundwater is sensitive to the occurrence of rainfall, heavy groundwater abstraction and the effects of diffuse pollution. In some areas, the water table is declining at a rate of more than 2 m/year which is mostly irreversible due to the low rainfall in the region.

## Methodology

Seventy samples were collected during March–April 2016 during the dry summer period within the region. A sampling plan for the investigation was developed early in 2016 to ensure that there was a suitable coverage of wells in the emirate focusing mostly on areas where groundwater abstraction took place for agricultural use. Twenty-seven chemical parameters were selected for analysis based on their importance in revealing the chemical characteristics of groundwater including its chemical evolution and its suitability for drinking and irrigation usage. The sampling program was conducted by dedicated staff following US EPA



guidelines (USEPA 2013). Samples were collected from running wells lying mostly within the agricultural farms. The depth of these wells ranges from 45 to 90 m tapping the same formations. In Hatta region sampling depth is more than 200 m. The samples were collected in polyethylene bottles of 1-L capacity by pumping the bore wells. For micro-biological analysis, sterilized 0.5-L polyethylene bottles were used. Care was taken to pump the bore wells for sufficient time to get rid of the water in the well bore storage before collecting the samples. Prior to filling, sampling bottles were rinsed to minimize the chance of any contamination. The program objectives, sampling techniques and the analytical techniques that were used (APHA 2005) were discussed with Central Laboratory prior to initiation of the program.

The electrical conductivity of groundwater samples was measured employing method APHA 2510 B. The metals  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , Ba, Cu, Fe, and Zn were measured by ICP-OES (APHA 3120) while Cd, Cr, Pb, Mn, Ni, Se, and As were measured by ICP-MS (APHA 3125). The anions  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  were measured by ion chromatography (APHA 4110) and  $\text{HCO}_3^-$  was measured by Titrimetry (AOAC 920.194). The detection and enumeration of coliforms and the *E. coli* content of groundwater was carried out using a chromogenic substrate test (APHA 9223 B).

The accuracy of the chemical analyses was verified by assessing the charge balance error of each sample. All the analyzed samples in the current study had a charge balance error of less than 5% and, therefore, no samples were disregarded in the hydrochemical interpretation of the dataset.

## Hydrochemical characteristics of groundwater in Dubai

### Major ion chemistry

The major ion content was determined for 70 groundwater samples in the study area which indicates that quality of groundwater in the area is highly variable as indicated by the high standard deviation of ionic analyses (Table 1) and concentration of total dissolved solids (Table 2). The content of major ions in the groundwater in the area is in the order  $\text{Na}^+ \gg \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$  for cations and  $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{F}^-$  for anions.

The pH of groundwater ranges from 7.27 to 11.30 with an average of 7.96 which is slightly basic in nature, suggesting buffering by carbonate species is taking place in groundwater. The surface water sample of Hatta Dam shows high pH (9.02). 3 of seven groundwater samples close to Hatta dam show high pH (> 11). The electrical conductivity values of groundwater varied from 441 to 23,590  $\mu\text{S}/\text{cm}$  during the dry season. The salinity of groundwater as represented by TDS shows a wide

variation, ranging from 308 to 16,513 mg/L with an average of 4278.49 mg/L (Table 1).

$\text{Na}^+$  is the dominant cation and has a concentration that varies between 16 mg/L and 3984 mg/L with an average of 1075 mg/L. Linear correlation coefficient (Table 3) shows that the concentrations of  $\text{Na}^+$  in groundwater are also highly correlated with TDS (0.98) and Cl (0.88). The average  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations are 182 mg/L and 120 mg/L, and the concentration of  $\text{Ca}^{2+}$  correlates with  $\text{Mg}^{2+}$  with high correlation coefficient (0.92). In the present investigation,  $\text{SO}_4^{2-}$  concentration ranged from very low, i.e. 1.4 to 3892 mg/L. The  $\text{Cl}^-$  concentration varies widely ranging from 30 to 7640 mg/L with an average of 1523 mg/L. Chloride bears good correlation with TDS (0.96),  $\text{Na}^+$  (0.88),  $\text{Mg}^{2+}$  (0.97), and  $\text{SO}_4^{2-}$  (0.89). Chloride is a widely distributed element in all types of geological formations.  $\text{Cl}^-$  concentration is higher in groundwater which is likely due to high aridity and lack of aquifer replacement through rainfall recharge. Rainfall recharge and irrigation return flows can acquire high  $\text{Cl}^-$  during percolation. Nitrate is generally considered as a good indicator of anthropogenic influence on groundwater environment and concentrations in the study area range from 0.09 mg/L to 287 mg/L with an average of 45 mg/L. The  $\text{NO}_3^-$  distribution in groundwater clearly shows that high concentrations of the chemical constituent corresponds with locations of irrigated areas, suggesting that fertilizers used in agriculture are the most likely source of nitrate contamination in groundwater in the study area.

Concentrations of trace metals are generally within the WHO permissible limits in drinking water except for chromium which varies in concentration between 0.0007 and 0.3441 mg/L. In 53 samples, Cr concentration is higher than WHO permissible limit of 0.05 mg/L. Based on preliminary investigations, Cr seems acquired through geochemical weathering of ultramafic rocks and serpentinites of ophiolite complexes (Oze et al. 2007) present in Hatta enclave bordering Oman, although the possibility of point pollution incidents cannot be ruled out. However, this would require further investigations.

An assessment of linear correlations between various groundwater parameters was carried out using Pearson correlation coefficients (Table 3). One of the striking features of the correlation table is that TDS is highly correlated with all major elements (except  $\text{HCO}_3^-$ ) and with trace elements especially with Cd, Ni and Se. This suggests that evaporative concentration has a large influence on groundwater quality in the region.

### Biological parameters

Biological contamination of ground water is characterized by the deteriorating groundwater quality as a result of

**Table 1** Statistical summary of groundwater quality parameters

Parameters	Unit	Min	Max	Av.	Std. dev	WHO drinking water guidelines	Samples passed
pH		7.27	11.30	7.96	0.77	6.5–8.5	65
EC	μS/cm	441.00	23590.00	6168.40	4950.09	1428.5 <sup>a</sup>	7
TDS	mg/L	308.00	16513.00	4278.49	3495.49	1000	7
Ca	mg/L	13.22	713.00	170.80	182.37	75 <sup>a</sup>	31
Mg	mg/L	0.15	571.00	126.20	119.88	30 <sup>a</sup>	13
Na	mg/L	16.10	3984.00	1075.20	922.53	200 <sup>a</sup>	5
K	mg/L	3.30	102.90	29.07	20.81	10 <sup>a</sup>	11
HCO <sub>3</sub>	mg/L	4.00	377.00	182.96	70.04	250 <sup>a</sup>	58
SO <sub>4</sub>	mg/L	1.40	3892.00	1214.02	1110.13	500	28
Cl	mg/L	30.00	7640.00	1522.93	1410.54	250	4
F	mg/L	0.01	5.20	1.55	1.21	1.5	50
NO <sub>3</sub>	mg/L	0.09	287.00	28.57	45.47	50	58
NH <sub>3</sub> -N	mg/L	0.45	1.30	0.46	0.10	0.5	69
PO <sub>4</sub>	mg/L	0.02	0.02	0.02	0.00	0.5 <sup>a</sup>	70
Cu	mg/L	0.01	0.01	0.01	0.00	2	70
Zn	mg/L	0.01	4.15	0.11	0.50	3	69
Ba	mg/L	0.01	0.40	0.05	0.05	0.7	70
Fe	mg/L	0.04	0.04	0.04	0.00	1–3 <sup>a</sup>	70
As	mg/L	0.0004	0.1009	0.0019	0.0120	0.01	69
Cd	mg/L	0.0004	0.0014	0.0005	0.0002	0.003	70
Cr	mg/L	0.0007	0.3441	0.1039	0.0677	0.05	17
Pb	mg/L	0.0004	0.0004	0.0004	0.0000	0.01	70
Mn	mg/L	0.0004	0.3244	0.0233	0.0450	0.4	70
Ni	mg/L	0.0004	0.0393	0.0077	0.0094	0.07	70
Se	mg/L	0.0004	0.0456	0.0135	0.0091	0.04	69
<i>E. coli</i>	CFU/100 ml	0.00	517.00		69.73	0	53
<i>T. Coliform</i>	CFU/100 ml	0.00	>2420		196.67	0	8
Kelley's ratio	–	0.19	10.59	56.04	2.07	<1 Suitable <sup>b</sup>	2
Mg hazards	–	0.44	83.4	56.04	10.13	<50 Suitable <sup>b</sup>	12

<sup>a</sup>Assigned values<sup>b</sup>Irrigation water quality**Table 2** Classification of groundwater samples based on TDS concentration

TDS class (mg/L)	No. of samples	% samples	Area (Sq-km)	Area (%)	
0	1000	7	10	85.9911	3.24301149
1000	2000	19	28	244.1326	9.20705556
2000	3000	7	10	174.4776	6.58013368
3000	5000	11	16	397.5172	14.9917018
5000	7000	9	13	758.798	28.6168052
7000	9000	9	13	382.7136	14.4334081
>9000		7	10	607.9516	22.9278841

various human activities (Klitoliya 2004). The most serious groundwater contaminations in terms of human health implications worldwide are water-borne disease are typhoid,

cholera, bacterial and amoebic dysentery, polio infections, hepatitis and schistosomiasis (Cunningham 2005). The presence of coliform bacteria does not necessarily indicate recent water contamination by fecal waste; however, the presence or absence of these bacteria in treated water is often used to determine whether water disinfection is working properly. The presence of fecal coliform bacteria in well water may indicate recent contamination of the groundwater by human sewage or animal droppings which could contain other bacteria, viruses, or disease-causing organisms. Coliform bacteria are often considered “indicator organisms” for the potential presence of disease-causing organisms and should alert the person responsible for the water to take precautionary action.

Detection of total coliforms in 62 samples suggests a biological contamination but not of fecal origin. Only seven samples contained *E. coli* which makes water completely

**Table 3** Pearson correlation coefficient showing linear correlation

	TDS	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	As	Cd	Cr	Ni	Se
TDS	1.00														
Ca	0.90	1.00													
Mg	0.94	0.90	1.00												
Na	0.95	0.87	0.88	1.00											
K	0.89	0.90	0.87	0.89	1.00										
HCO <sub>3</sub>	0.13	0.07	0.19	0.10	0.07	1.00									
SO <sub>4</sub>	0.89	0.94	0.93	0.86	0.94	0.08	1.00								
Cl	0.96	0.89	0.97	0.88	0.82	0.18	0.89	1.00							
F	0.28	0.51	0.29	0.24	0.55	0.02	0.52	0.24	1.00						
NO <sub>3</sub>	0.18	0.14	0.27	0.15	0.19	0.28	0.22	0.25	0.07	1.00					
As	0.36	0.57	0.36	0.34	0.57	-0.13	0.52	0.29	0.72	0.08	1.00				
Cd	0.64	0.46	0.59	0.58	0.60	0.16	0.53	0.60	0.07	0.10	-0.03	1.00			
Cr	0.30	0.05	0.10	0.34	0.35	0.08	0.14	0.13	-0.01	-0.17	-0.08	0.42	1.00		
Ni	0.78	0.86	0.83	0.70	0.81	0.04	0.84	0.80	0.52	0.17	0.57	0.52	0.07	1.00	
Se	0.74	0.69	0.71	0.77	0.73	0.11	0.72	0.70	0.22	0.34	0.27	0.63	0.25	0.53	1.00

unfit for human consumption. Tebbutt (1992) noted that pathogenic organisms are rarely found in groundwater, since poor well construction or being associated with bed-rock aquifers in which large openings afford a direct connection between the surface and groundwater causes most well pathogenic contamination. The World Health Organization (WHO) estimated that 2.1 million people die annually from diarrhea attributed to water-borne infection (WHO 2004).

### Hydrochemical evaluation

The major ions were plotted on a Piper diagram (Piper 1944) to determine the groundwater facies occurring in the region (Fig. 2). The cationic triangle is dominated by the presence of Na ions followed by Ca ions. The anionic triangle is dominated by the presence of Cl ions followed by SO<sub>4</sub> ions. On the diamond of the Piper diagram, the majority of the samples fell within the Cl–SO<sub>4</sub> composition field, whereas only a few samples plotted within the Ca(Mg)–Cl(SO<sub>4</sub>) facies.

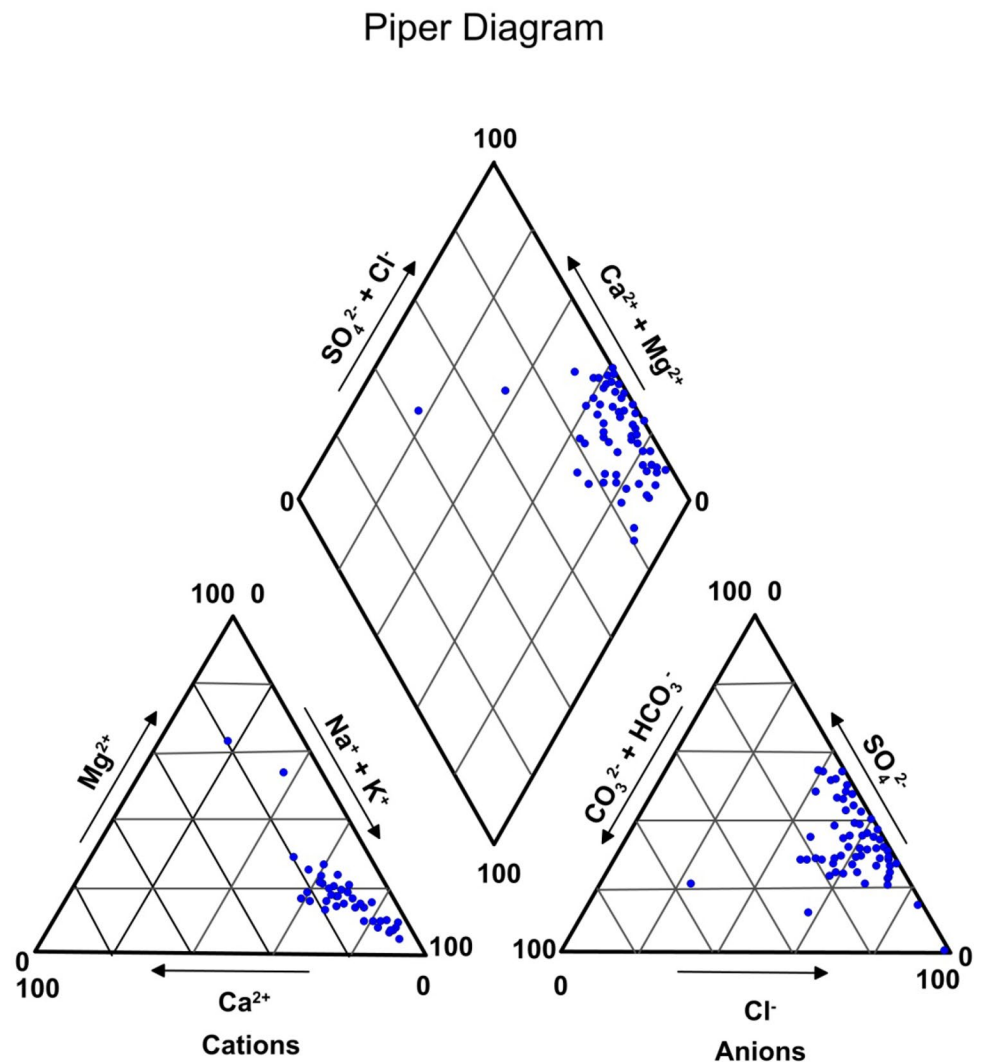
This assessment suggested that groundwater in the emirate is represented by an evolved water composition where the lack of recent groundwater recharge coupled with evaporation and rock–water interactions has resulted in the groundwater losing its initial meteoric characteristics. A closer look at the facies shows that the samples are dominated by the presence of Na and Cl ions. Na–Ca–SO<sub>4</sub>–Cl type of groundwater facies is the most dominant type of facies occurring in the area with almost 60 samples falling within this class. The Na–Ca–Cl–SO<sub>4</sub> type and the Ca–SO<sub>4</sub>–Cl type represent the groundwater samples that are influenced by rock–water interaction mainly gypsum dissolution and ion exchange. The high salt contents are due to marine influence and seemingly

acquired from water interaction from sabkhas and soils. The Na–Ca–Cl–SO<sub>4</sub> type and Na–Ca–SO<sub>4</sub>–Cl type represents the facies is influenced by evaporation as well as the ion-exchange process. The limited number of samples that plot in the Ca–Cl–SO<sub>4</sub> field and the Ca–Na–Cl–SO<sub>4</sub> field on the Piper diagram is likely to have been affected by reverse ion-exchange and mixing processes. One sample plotted in the Ca–Mg–HCO<sub>3</sub> field on the Piper diagram. The chemical composition of groundwater is likely to have been influenced by the deposition of salts of marine origin in rainfall and dust, and by water–rock reactions in the subsurface.

Processes other than ion exchange may influence changes in the chemical composition of groundwater as it flows within an aquifer. In particular, the intense aridity of the emirate indicates that evaporation could be the most important factor controlling the overall water chemistry of the region, and this is supported by a plot of Na<sup>+</sup>/Cl<sup>-</sup> versus EC. This plot indicated that the Na<sup>+</sup>/Cl<sup>-</sup> ratio remains constant with increasing salinity (Fig. 3a), indicating evaporation is a major process governing groundwater chemistry (Jankowski et al. 1997; Mrazovac et al. 2012). Similarly, a plot of the data on a Gibbs plot (Gibbs 1970) (Fig. 3b) also shows that evaporation is the dominant process that controls the groundwater chemistry in the region. A Parson plot classified the majority of the groundwater samples as being Na–Cl-type water, a few samples were classified as Na–SO<sub>4</sub>-type and Ca–Mg–Cl-type water on this plot (Fig. 4a).

The Normalized Difference Dispersal Index (NDDI) was used to assess changes in TDS and NO<sub>3</sub> concentrations for the years 2016 and 2017. The NDDI helps to integrate the vulnerability of sampling locations for the

**Fig. 2** Classification of hydro-chemical facies on Piper plot



potential risk. The degree of spatio-temporal variability was assessed through the use of a net-difference map (2016, 2017). The enrichment and dilution at spot of chemical component was normalized and quantified by applying statistical index is given below:

$$\text{NDDI} = \frac{\text{Average conc. (2016)} - \text{Average conc. (2017)}}{\text{Average conc. (2016)} + \text{Average conc. (2017)}}$$

The changes in the concentrations were assessed by negative NDDI values ranging from 0 to  $-1.0$  which shows gradual accretion whilst scale from 0 to  $+0.1$  designates gradual absolute dilution. The term accretion indicates state of attaining mineralization which is possible through anthropogenic or sometimes geogenic factors. TDS and  $\text{NO}_3^-$  were selected as suitable groundwater quality indicators to represent variation in groundwater quality (Fig. 4b). The dilution denotes an improvement in quality which is probably due to recent rainfall recharge. Most of the samples show state of accretion for  $\text{NO}_3^-$ . The average NDDI value for TDS and

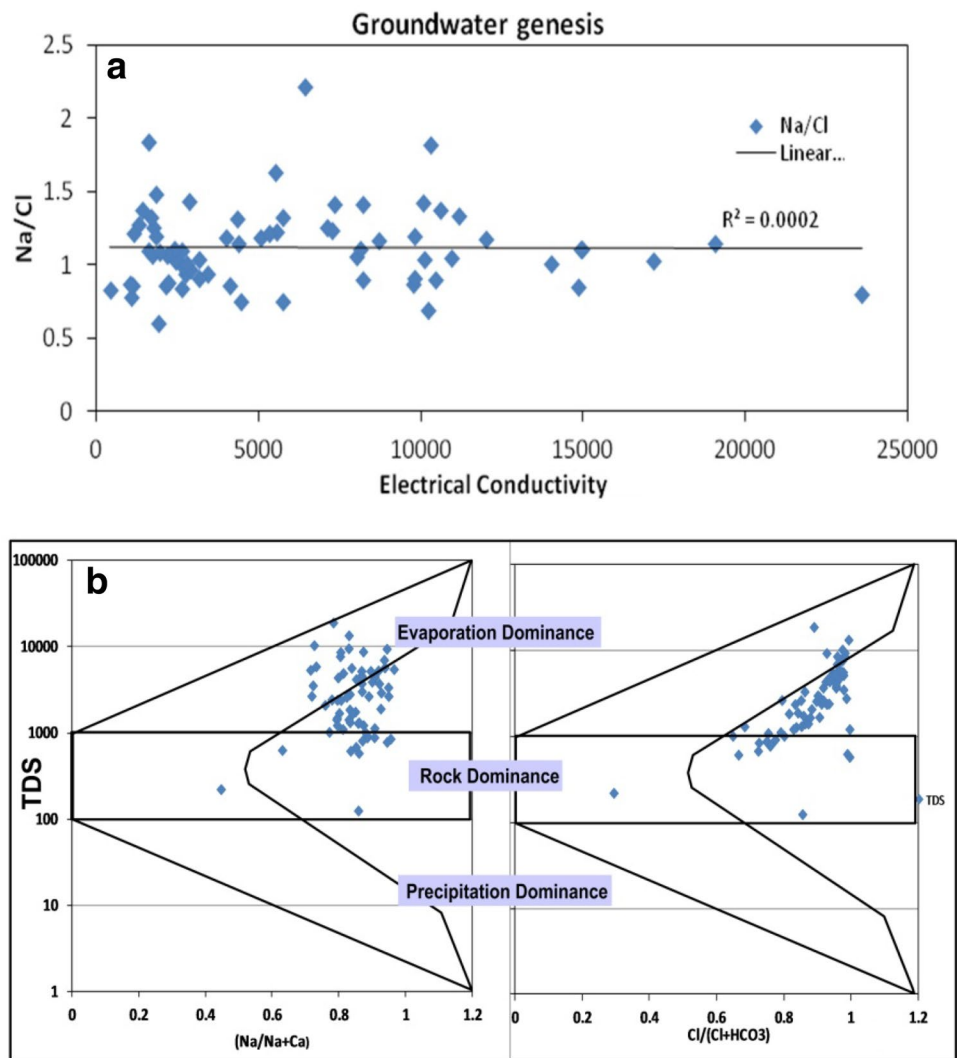
$\text{NO}_3^-$  is  $-0.05$  and  $-0.09$ , respectively, which indicates that the accretion of  $\text{NO}_3^-$  is greater than salinity, probably due to the effects of widespread agricultural activities in the area. The distribution of  $\text{NO}_3^-$  in groundwater is controlled by land use, the thickness and composition of the vadose zone, precipitation, irrigation, groundwater flow, aquifer heterogeneity, dissolved oxygen concentrations, and electron donor availability and dispersion. The distribution, availability, and enrichment of nitrate in the groundwater are mainly controlled by environmental (temperature and precipitation) and anthropogenic factors (Zarabi and Jalali 2012).

Globally, nitrate has been recognized as the main pollutant and contaminator of aquifers (Hussain et al. 2017) and urban sanitation system (Asadi et al. 2016). Some studies arguably show higher average temperature results in lower nitrate contamination, possibly due to increased evapotranspiration (Wick et al. 2012; Rawat et al. 2018).

High TDS concentrations in groundwater are most likely due to a number of factors primarily due to marine



**Fig. 3** Showing groundwater genesis. **a** Electrical conductivity (EC) versus Na/Cl plot and **b** Gibb's plot



influence on geological formations and sabkhas. The sabkha is an Arabic word meaning flat landform and is applicable to both coastal and interior salt flats. The high salt concentration of sabkha soil can vary upto four to six times those presented in typical seawater from the same region (Al-Homidy et al. 2017). The high TDS can also be attributed due to high aridity index, irrigation returns and rainfall recharge (Al-Katheeri et al. 2009). Infiltrated water dissolves salts from interacting with salt laden surface and vadose zones.

**Suitability for drinking purpose**

The suitability of groundwater for drinking purposes was examined using the Water Quality Index (WQI) model. The WQI is assessed using a subjective weight assigned to each parameter based on its perceived significance level. The samples were also assessed against the WHO drinking water guidelines. The use of groundwater during emergencies was

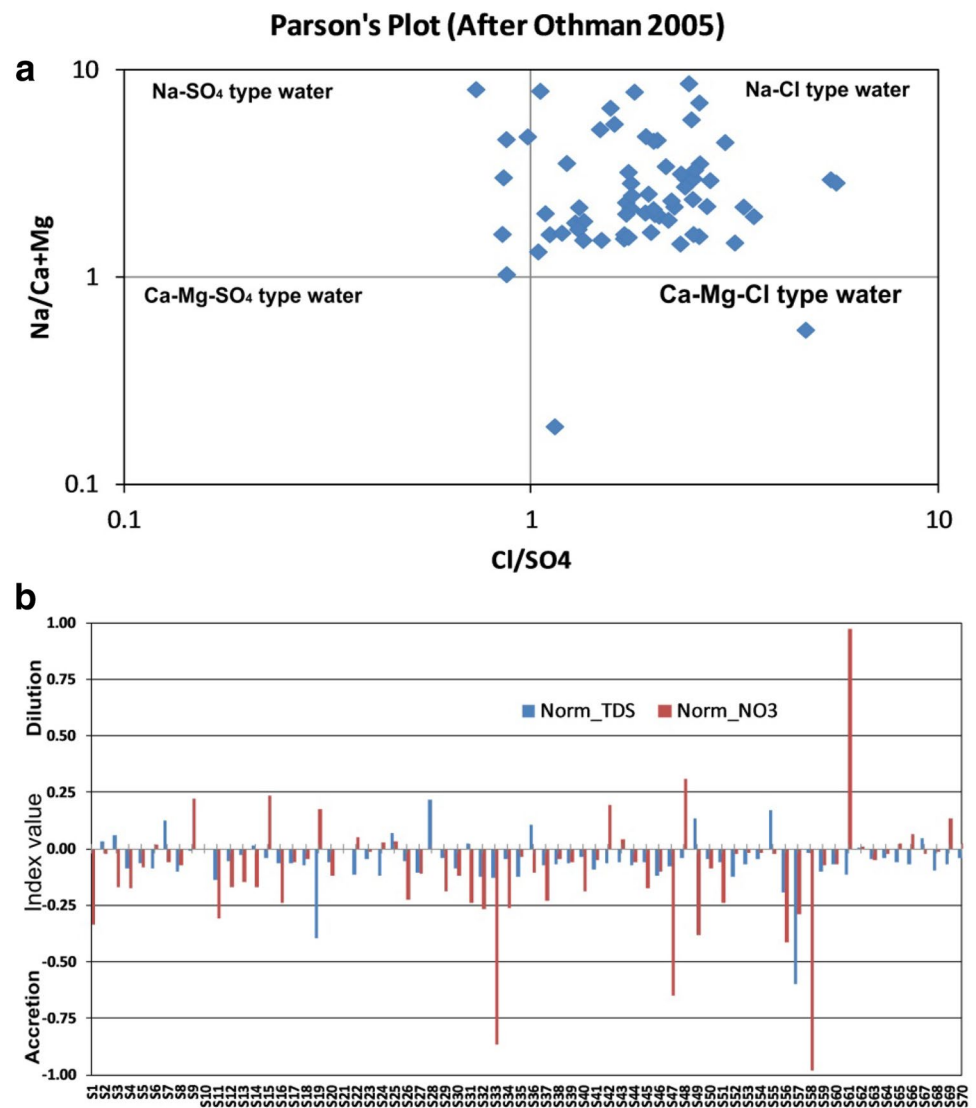
assessed using the WHO guideline maximum permissible limits.

The WQI is a simple and logical presentation of groundwater quality status (Saeedi et al. 2010). This is often a suitable way of presenting information to key policy makers who have received limited training in water quality issues. In WQI method, the quality of the water is assessed through a unique value obtained through WQI model data processing:

$$WQI = \sum_{i=1}^n \left( \frac{Sp_i}{N} \times w_i \right),$$

where (Sp<sub>i</sub>) is number of samples passed the objective for *i*th parameter, (w<sub>i</sub>) weight of individual parameter, (N) total number of samples. In the present study, 23 parameters were grouped into four groups with a unique weight factor. The classification criteria of chemical parameters into different groups were acquired from a US Department of the Interior report (Stoner 1978). To account the impact of

**Fig. 4** Showing groundwater genesis on **a** Parson's plot and **b** NDDI values of TDS and NO<sub>3</sub>



each parameter, individual weights were assigned to each parameter as given in number of scientific studies (Stoner 1978; Ramakrishnaiah et al. 2009; Jerome and Pius 2010).

To assess groundwater quality for drinking purposes during any emergency time, the maximum allowable WHO standard can be used (BIS 2012). Emergency conditions are defined as “an unusual time when there are no other sources of drinking water than groundwater”. In initial sample scrutiny, samples having TDS values greater than 5000 mg/l which were located outside of the fresh groundwater sub-basin were discarded from the analysis. Therefore, 50 of 70 samples were used for the WQI model. As a result of the WQI assessment, 80% of the samples were classified in the “good quality” category (Table 4).

### Suitability for irrigation purpose

Groundwater in Dubai is predominately used for the agricultural activities and consequently its quality must be suitable for achieving maximum crop productivity. The suitability of groundwater for irrigation use was assessed using a number of standard assessment tools. The first of these, the sodium adsorption ratio (SAR), is an important parameter for the determination of the soil alkalinity or alkali hazard in the use of groundwater for irrigation purposes (Richards 1954). Calculation of SAR value for a given groundwater provides a useful index of the sodium hazard in water for soils and crops. The value of SAR can be calculated using the following equation:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{+2} + \text{Mg}^{+2}}{2}}}$$

**Table 4** Results of WQI model analysis of groundwater samples

Parameters	WHO standards	Standards emergency time	Total samples	Samples passed	Group Wt	Parameter Wt	Score
pH	6.5–8.5	No relaxation	50	47	22	4	3.76
TDS	1000	2000	50	24		3	1.44
Ca	75	100	50	30		2	1.2
Mg	30	50	50	15		1	0.3
Na	200	250	50	12		2	0.48
K	10	12	50	14		1	0.28
HCO <sub>3</sub>	250	300	50	49		3	2.94
SO <sub>4</sub>	500	500	50	27		3	1.62
Cl	250	500	50	10		2	0.4
F	2	2	50	47		1	0.94
NO <sub>3</sub>	50	No relaxation	50	43	20	7	6.02
NH <sub>3</sub> -N	0.5		50	49		7	6.86
PO <sub>4</sub>	0.5		50	50		6	6
Cu	2	No relaxation	50	50	33	3	3
Zn	3		50	50		3	3
Ba	2		50	50		3	3
Fe	1		50	50		3	3
As	0.01		50	43		3	2.58
Cd	0.005		50	50		3	3
Cr	0.05		50	11		3	0.66
Pb	0.01		50	50		3	3
Mn	0.4		50	49		3	2.94
Ni	0.07		50	50		3	3
Se	0.04		50	48		3	2.88
<i>E. coli</i>	0	No relaxation	49	37	25	20	15.10
T. coliform	0		49	21		5	2.14
Total					100	100	79.54

Based on the US Salinity diagram (USSL 1954), groundwater samples were classified as having a “high” to “very high” salinity hazard and a “low” to “high” sodium hazard (Fig. 5). On the basis of this assessment, 20 of the 70 samples were classified as being unsuitable for irrigation use.

### Kelley’s ratio

Kelley’s ratio (Kelley et al. 1940) was calculated with the following equation:

$$\text{Kelley's index (KI)} = \frac{\text{Na}^+}{\text{Ca}^{2+} + \text{Mg}^{2+}}$$

Groundwater having a Kelley’s ratio value of less than one is considered to be suitable for irrigation, whereas ratio more than one is not suitable for irrigation and indicates a surplus amount of sodium in water. Kelley’s index values in the present study varied from 0.19 to 10.58 with an average value of 3.09. It is evident from the result that only two samples are suitable for irrigation according to Kelley’s ratio.

### Magnesium hazard

The magnesium hazard (MH) of irrigation water has been proposed by Szabolcs and Darab (1964) and was redefined by Raghunath (1987). MH was calculated with the following equation:

$$\text{MH} = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \times 100.$$

Magnesium ratio values exceeding 50 are considered to be unsuitable for irrigation because of harmful effects on crop yields as the soils become more alkaline (Lakshmanan et al. 2003). The computed values of magnesium hazard from the groundwater of the study area ranged from 0.44 to 83.41 with an average value of 56. The analysis show 12 samples are suitable for irrigation according to the magnesium hazard calculations.

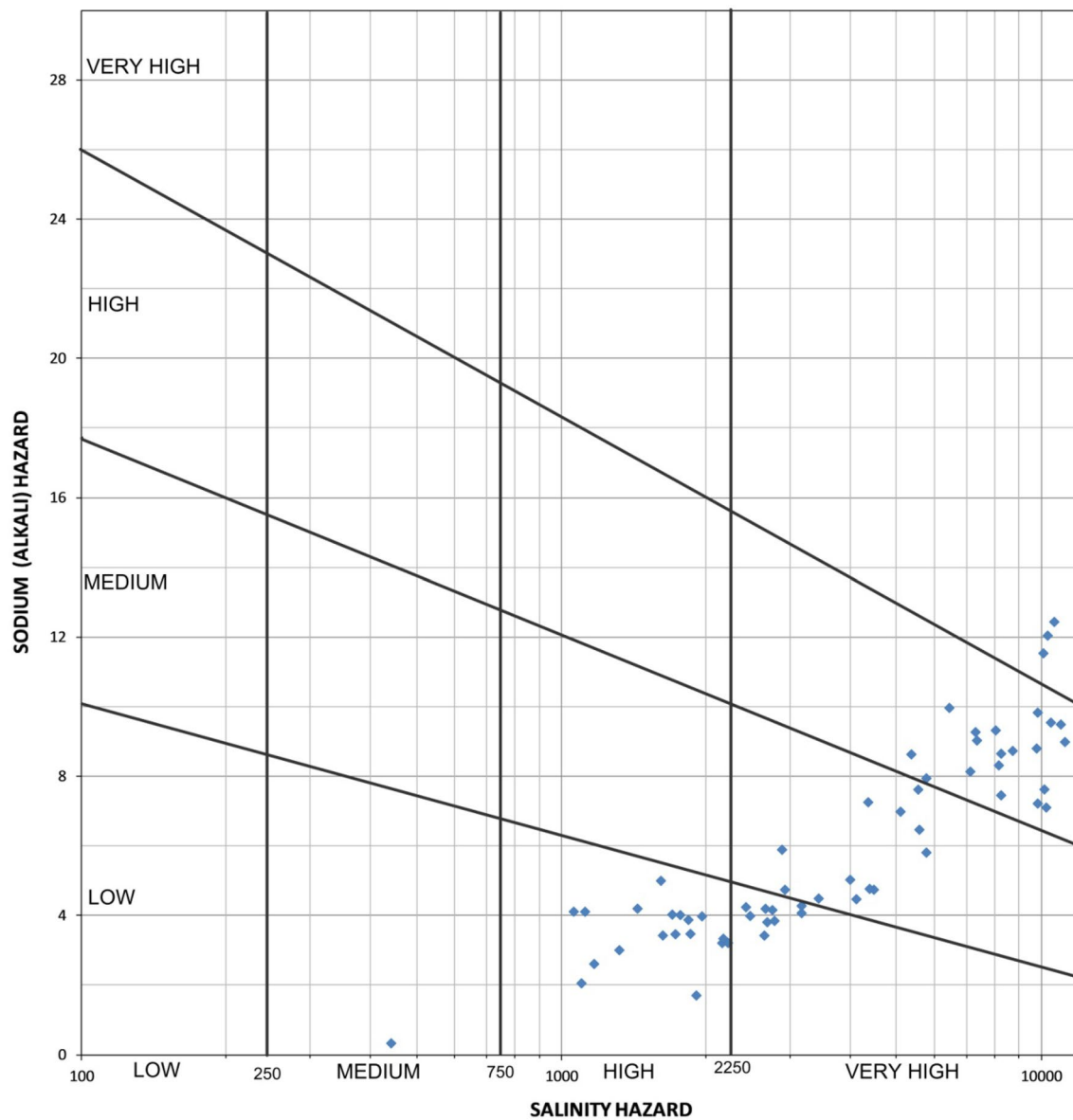


Fig. 5 USSSL diagram for suitability of irrigation water

## Implementation of groundwater resource protection policies

The baseline groundwater characterization has paved the way to execute implementation of groundwater management policy in the Emirate of Dubai. The goal of groundwater management policy is to protect and allow the sustainable use of groundwater resources in the emirate. Sustainable development requires that these resources can deliver continued benefits to the people of today and tomorrow, across all ranges of beneficial uses and in an economically, socially, and environmentally sustainable and acceptable manner. Various programs have been established to achieve this as discussed below.

## Groundwater rights and licensing system

Dubai Law No. 15 (2008) constitutes a sound basis for groundwater management and addresses groundwater rights, the provision of a regulatory framework and the need to conduct advance technical studies to support management and protection policies. In Dubai, the right to abstract and use groundwater is a conditional right, as it constitutes the right to use the water but not its ownership. The permissions to drill well(s) and allocate quantities of groundwater for specific uses are instrumented through well-drilling permits and the licensing of groundwater use. A comprehensive well licensing system has been developed to secure equal rights on groundwater resources and ensure its sustainability. The



drilling and construction of groundwater wells are subject to prior permission while limits for drilling depths, diameters of wells, safe distances from potential environmental receptors, and daily abstraction quantities are fixed following the safe-yield concept.

### Setting up real-time groundwater monitoring stations

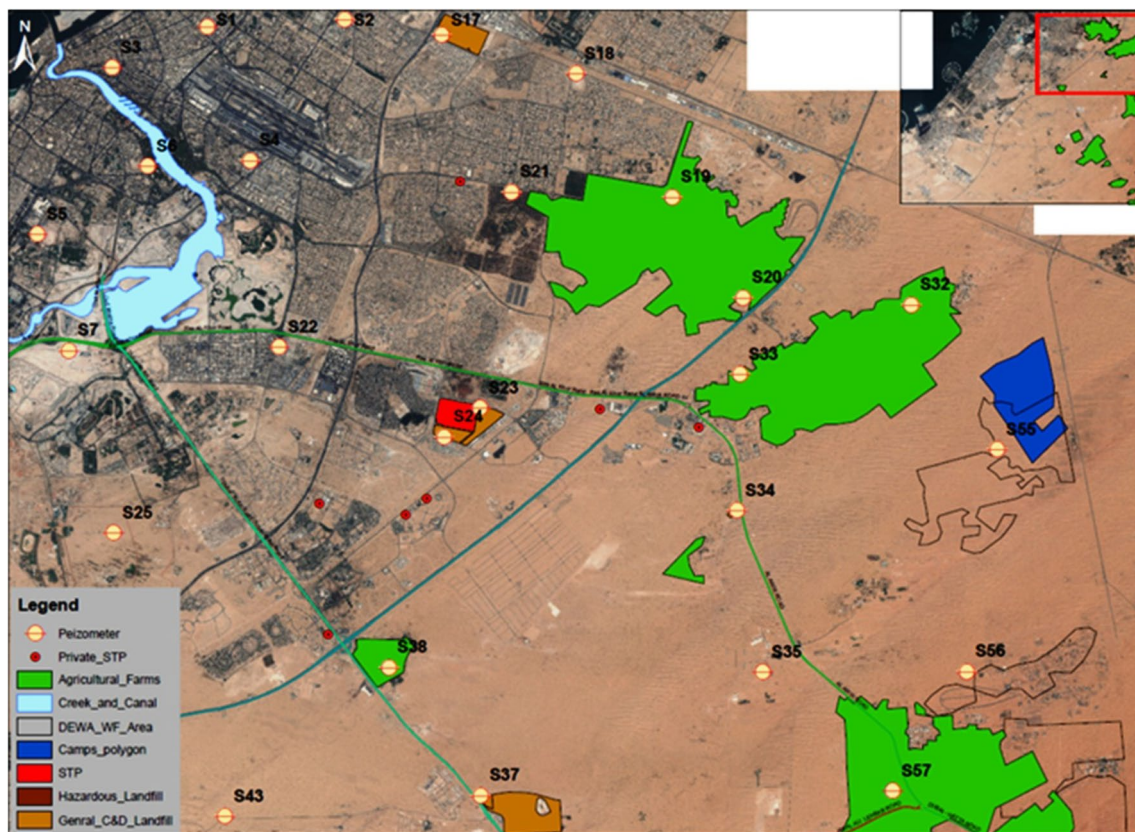
One of the primary requirements for groundwater management is the establishment of a groundwater monitoring network to assess the condition of the resource on an ongoing basis. This requires proper understanding of the hydrogeological setting and land use patterns so that the monitoring can readily assess the dynamics of a groundwater flow system. The mapping of land use types is also important to identify areas which may have an elevated risk of causing impacts on groundwater quality. This is especially the case for areas used for intensive agriculture and areas with urban, commercial or industrial development.

A detailed land use map including the categories of agricultural use, urban areas, desert camps, selected industrial and commercial units, landfill sites and open water features was generated to support the location of proposed

groundwater monitoring stations (Fig. 6). Agricultural areas have a high well density with a high rate of groundwater abstraction for irrigation. In commercial and industrial areas, there is a risk that hazardous substances might pollute the groundwater if released in an uncontrolled manner into the environment. In residential areas, leaking septic tanks and sewage pipes can affect groundwater quality. Industrial activities in Dubai are mainly located in designated industrial areas in and around Dubai City, but there a few plants where building materials are produced or recycled. Some areas are also used for the landfilling of putrescible wastes, but most of the wastes disposed of in the Al Quasis and Le Hemaira are construction and demolition wastes. Slurry from dairy and poultry farms in the study area may also affect groundwater quality.

### Delineation of a groundwater protection area

The delineation of a groundwater protection area or a wellhead protection area is a program to prevent the contamination of groundwater that is used for potable supply. To accomplish this, systems need to provide management zones around public wells and well fields to detect and manage potential sources of groundwater contamination



**Fig. 6** A land use map showing various land use pattern and proposed monitoring station's location

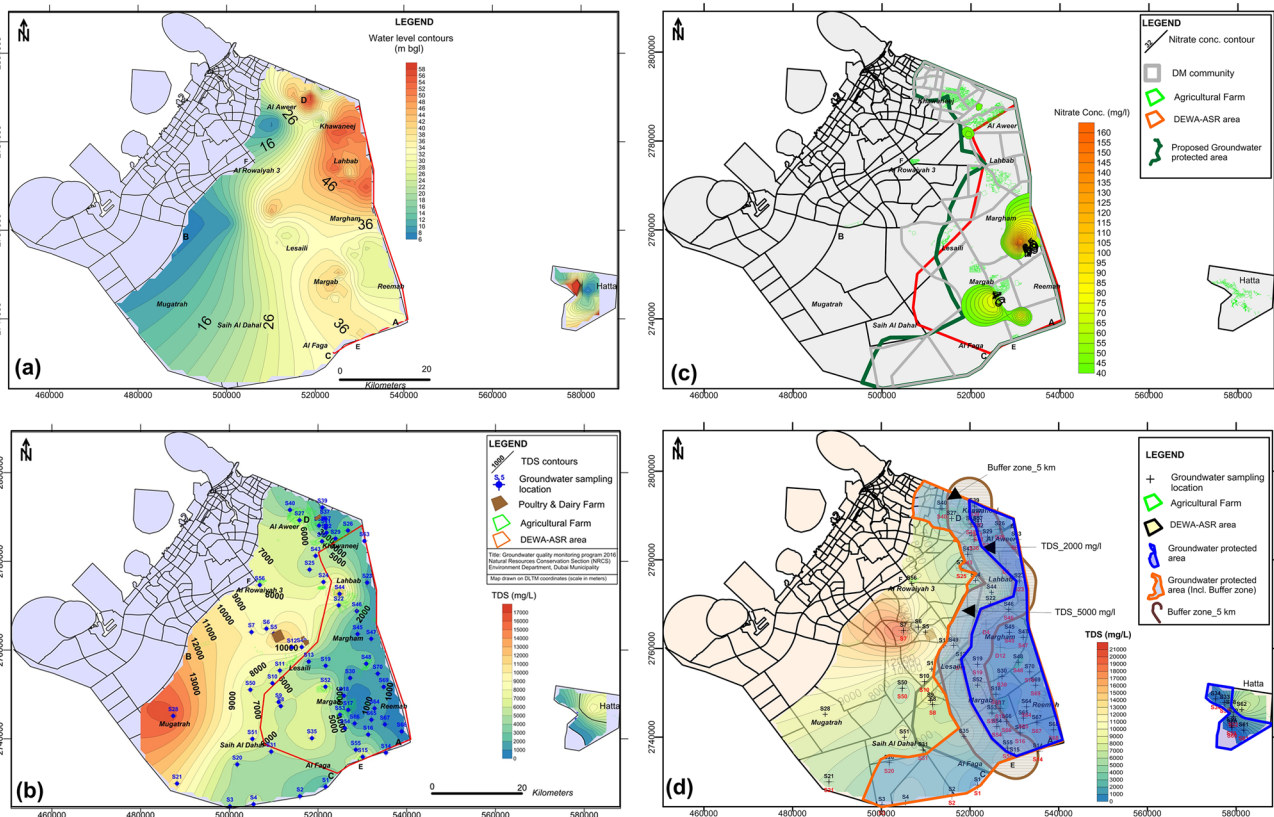
(USDH 2010) and land use compatibility policy (DoW 2016) to protect groundwater resources from inappropriate land uses. The hydrogeological analysis carried out for this study has shown large variations in groundwater quality occur in the emirate, indicating that various processes involved in introducing unique chemical signatures to the groundwater chemistry. Recharge zones are located in the Hatta enclave and in the far eastern and southeastern parts of the emirate where fresh groundwater occurs as indicated by TDS levels. Fresh water usually has TDS levels between 0 and 1000 mg/L, depending on the climate and geology of the region that affects sources of dissolved material and its transport to a water system. In the absence of other source of drinking water or during emergency times, a TDS of 2000 mg/L can be considered for drinking use (BIS 2012).

In the absence of a natural catchment boundary, the groundwater protection area was demarcated using the 2000 mg/L TDS contour. A 5-km buffer zone around the 2000 mg/l TDS contour was also drawn around this area which also follows 5000 mg/l TDS contour. Furthermore, these areas were superimposed on a water table contour map to observe groundwater movement direction. Though the integration of the TDS map, a map of an aquifer storage

recovery (ASR) area, water table maps and farm, and drinking water supply well location maps, it was concluded that a 5-km buffer zone could serve as the boundary to the groundwater protection area (Fig. 7). Separate inspection plans should be developed for the protected groundwater basin and buffer zones focusing on vulnerable (micro-zone) areas that could be sources of groundwater pollution.

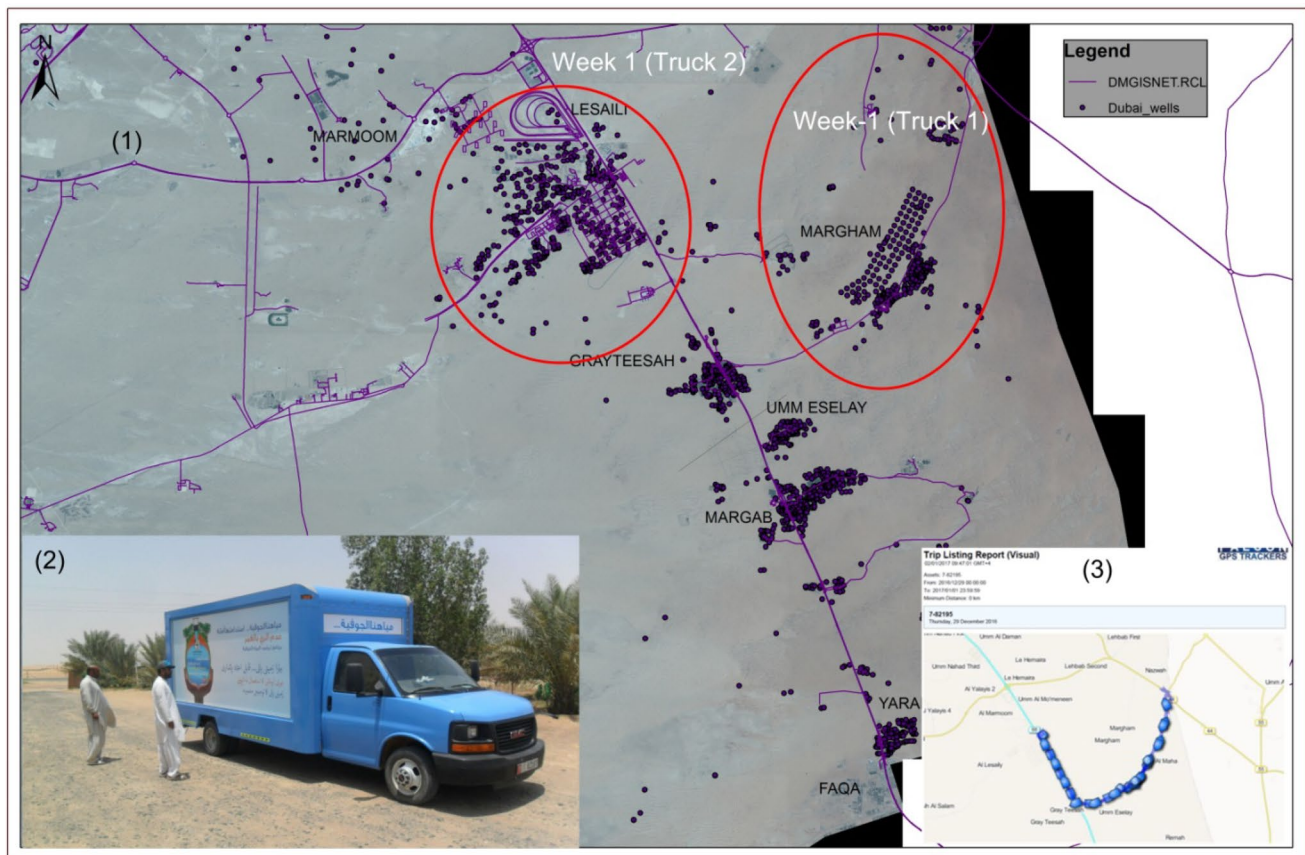
### Groundwater awareness programs

Groundwater awareness programs can be carried out using different media including audio–video messages, social media posts, truck campaigns and gift distribution. These programs are aimed at educating the general public about the importance of groundwater resources and to cooperate with government initiatives in the protection of the groundwater resources. To run such a program and get maximum benefits, proper planning is vital. For truck routes and gift distribution, the selection of target areas and people, maximum area coverage, and route selection are key elements which in Dubai were performed effectively using GIS techniques. In a unique style of raising awareness within the farming community, specially designed trucks were used for advertisement. These trucks were given the target areas, i.e.



**Fig. 7** Conceptualization map including **a** depth to water level **b** TDS concentrations **c** NO<sub>3</sub> conc. Contour and **d** criteria for groundwater protection zone





**Fig. 8** Showing **a** selection of target area. **b** Articulated advertisement truck and **c** real-time GPS tracker route information

agricultural areas (Fig. 8a). The specially designed trucks (Fig. 8b) travelled along selected routes and the travel was monitored through real-time GPS tracking (Fig. 8c).

## Conclusions and recommendations

Groundwater samples from 70 wells from an unconfined sandy aquifer in the Emirate of Dubai were chemically analysed and were statistically assessed to determine the minimum, maximum, average and standard deviations of results for each parameter. A comparison of groundwater quality against existing water quality standards shows that most of the samples are unsuitable for some specific uses. Chemical classification of groundwater samples was carried out using a Piper trilinear diagram which indicated that most samples are classified as being of a Na–Cl facies type. This assessment was further validated by the use of a Na/Cl versus EC plot and a Parson’s plot. A Gibb’s plot suggested that evaporation is the dominant factor that influences the chemical composition of groundwater in the emirate.

Various  $x$ – $y$  plots also indicated that ion-exchange and reverse ion-exchange processes influence groundwater

quality. The presence of elevated Ca and Mg concentrations in groundwater suggests water–rock reactions either from deep basinal source and/or from recent carbonate rocks have also influenced groundwater quality in the unconfined aquifer. It is also likely that basement rocks are the source of the elevated chromium concentrations that are present in the unconfined aquifer in the emirate.

Elevated concentrations of nitrate, potassium, sulfate and iodine in groundwater indicate contaminated by land use activities in the area as these chemical constituents are common components of manure and fertilizers. The suitability of groundwater for agricultural uses was determined through the sodium adsorption ratio (SAR), Kelley’s ratio and the magnesium hazard. This assessment indicated that most of the groundwater samples fell into the “medium-” to “high-salinity” categories, indicating that the groundwater may be unsuitable for irrigating some salt-sensitive crops.

Hydrogeological and water quality information in a GIS environment for the unconfined aquifer was compiled in a GIS together with information about the overlying land use and distribution of water supply wells. This indicated that groundwater of a suitable quality for potable use would need to be managed through the implementation of a groundwater

protection area to ensure future water security for the emirate. This protection area was defined on the basis of existing groundwater salinity contours and a public awareness campaign was developed to inform the community about the need to protect groundwater quality and to manage the risk of excessive abstraction through the implementation of appropriate regulatory measures.

The information collected in this study will be used to help implement the groundwater policy for the Emirate of Dubai water which forms part of the Sustainable Development Goals (SDG) for the emirate. The key aims of the groundwater policy are as follows:

1. Determine the groundwater budget: appropriate methodologies will be developed to determine the groundwater budget for the region using existing hydrogeological data.
2. Understand trans-boundary aquifer flows: appropriate studies will be undertaken to determine trans-boundary groundwater flow into neighbouring countries.
3. Raise public awareness of the importance of groundwater management: communication and public participation programs will be developed to inform the community of the importance of sustainable groundwater use, particularly for the agricultural sector in the emirate.
4. Improve groundwater monitoring and data management programs: the existing groundwater sampling program should be to better represent seasonal impacts, existing threats and stress conditions. Additionally, information from drilling and sampling programs should be housed in publicly accessible databases to ensure that up-to-date information on the state of groundwater resources in the emirate is readily available to a wide range of stakeholders.
5. Update groundwater management methodologies: a program of ongoing regulatory reform, and on-the-ground sampling and metering practices will be required to ensure that groundwater and waste disposal in the emirate will employ best international practices.
6. Groundwater modeling: develop a groundwater flow model to help and manage groundwater resources in the emirate with respect to current and projected groundwater demands in the emirate.
7. Development of groundwater protection plans: groundwater in the emirate should be classified based on its quality and protection plan for the fresh and usable groundwater resources which should be developed with the assistance of planning regulatory tools.

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## Compliance with ethical standards

**Conflict of interest** The author declares no conflict of interest.

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