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Impact of land disposal of reject brine from desalination plants on soil and groundwater

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Abstract

The impact of reject brine chemical composition and disposal from inland desalination plants on soil and groundwater in the eastern region of Abu Dhabi Emirate, namely Al Wagan, Al Quaa and Um Al Zumool, was evaluated. Twenty five inland BWRO desalination plants (11 at Al Wagan, 12 at Al Quaa, and 2 at Um Al Zumool) have been investigated. The study indicated that average capacity of these plants varied between 26,400 G/d (99.93 m^3/d) to 61,000 G/d (230.91 m^3/d). The recovery rate varied from 60 to 70% and the reject brine accounted for about 30–40% of the total water production. The electrical conductivity of feed water and rejects brine varied from 4.61 to 14.70 and 12.90–30.30 (mS/cm), respectively. The reject brine is disposed directly into surface impoundment (unlined pits) in a permeable soil with low clay content, cation exchange capacity and organic matter content. The groundwater table 1ies at a depth of 100–150 m. The average distance between feed water intake and the disposal site is approximately 5 km. A survey has been conducted to gather basic information, determine the type of chemicals used, and determine if there is any current and previous monitoring program. The chemical compositions of the feed, product, reject, and pond water have been analyzed for major, minor and trace constituents. Most of the water samples (feed, product, reject and pond water) showed the presence of major, minor and trace constituents. Some of these constituents are above the Gulf Cooperation Council (GCC) and Abu-Dhabi National Oil Company (ADNOC) Standards for drinking water and effluents discharged into the desert. Total Petroleum Hydrocarbon (TPH) was also analyzed and found to be present, even in product water samples, in amount that exceed the GCC standards for organic chemical constituents in drinking water (0.01 mg/l).

Keywords: Feed; Product; Reject; Sandy soils; Land disposal; Cations; anions; Heavy metals; Pertroleum hydrocarbons

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1. Introduction

Given the importance of water to human and ecosystem survival, water quantity and quality represent important environmental elements. Evidences indicate that the world is facing a growing challenge in maintaining water quality and meeting the rapidly growing demand for water resources [20]. However, many regions of the world that are subjected to critical water shortages and contamination are facing famine, economic breakdown, and a potential warfare [24]. Within the Middle East, the Gulf Region is suffering water scarcity. Water shortages problems in the United Arab Emirates (UAE) are aggravating by the rapidly growing population, and the expansion of industrial and agricultural activities. The struggle of UAE to meet present and future demands for water resources has shifted attention to the role of desalination technology in alleviating water shortages using sea and brackish water as feed. Desalinated water accounts for approximately 98% of domestic supplies, with a total production of 701.6 mcm/year [25]. Between 1999 and 2001, the production of the desalination water in the UAE has increased by 30%, due to the remarkable economic and demographic development. Currently, desalination plants produce about 98% of the total drinking water supplies in the UAE [21].

The degradation of groundwater resources in terms of quality in the eastern region of Abu Dhabi Emirate (Al Wagan, Al Qua'a and Um Al Zumool) is due to the increase of the total dissolved solids (TDS) in the groundwater. Salinity problems, however, are likely to increase in the future both quantitatively and qualitatively due to brackish groundwater intrusion and low recharge rate. For the aforementioned reasons the reliance on unconventional water resources such as the water produced by brackish water reverse osmosis (BWRO). Desalination Technology has increased to meet the demographic and economic developments and to fulfill one of the requirements for the settlement of nomadic citizens. Since 1980s the BWRO has gradually increased and become a prime method for solving the pressing water supply problem. The current daily output of inland desalination plants in eastern region is 95,992 G/d (3,633 m^3/d) with an 30–40% reject brine.

All desalination method have always been limited by the disposal costs of the concentrated waste brines produced and the adverse impact of brine compositions on the environment, particularly in large-scale plants. In coastal regions, disposal of brine water can be accomplished by discharging into the neighboring body of seawater. However, in the eastern part of Abu Dhabi Emirate brine concentrate cannot be discharged to the distant sea. But in some special cases, particularly for small capacity plants, the brine water discharged over the land surface. In the inland desalination plants brackish water is the feed source and the rejected water is disposed of into a surface impoundment (unlined pits).

The major constituents of reject brine are inorganic salts. The brine also contains small quantities of anti-scale additives, corrosion products, and other reaction products. Early desalination plants practices emphasized water production with little consideration for environmental impact. One of the impacts of inland plants is water pollution that results when concentrated brine is discharged back into the feed water source from unlined ponds or pits. Over the last 23 years, reject brine in the eastern region has not been utilized and the environmental implications associated with that have not been adequately considered from the higher authorities.

Technical, economical and environmental issues of the rejected water have not been addressed properly. Therefore, this study is aimed at the determination of the composition of feed or raw water, product, reject brine, and pond water, characterization of the inland soil at the disposal site in view of its physical, chemical and mineralogical composition, and evaluation of the status of inland BWRO in the Eastern Parts of Abu Dhabi.

2. Scope and boundaries of the study

The study is limited to inland desalination plants located in the eastern region of Abu Dhabi Emirates. Inland desalination plants in other regions of Abu Dhabi Emirate (i.e. Liwa), and in the Northern Emirates have not been surveyed. A questionnaire was distributed among the surveyed plants to obtain data about the quality and quantity of feed or groundwater, product, brine and pond water. Furthermore, water samples were analyzed for the three investigated plants. Soil samples were collected from Al Qua'a disposal site and from two nearby locations. No other soil samples were collected from the other two inland disposal sites. Water samples were analyzed for physical, chemical and total petroleum hydrocarbons (TPH), whereas soil samples were analyzed for physical, chemical and mineralogical composition. No groundwater samples from surrounding areas were collected. Impact of reject brine on soil and groundwater was evaluated using the above-analyzed parameters.

3. Water resources in the study region

The Abu Dhabi Emirate (Fig. 1) is located in a dry arid to semi-Arid region with an

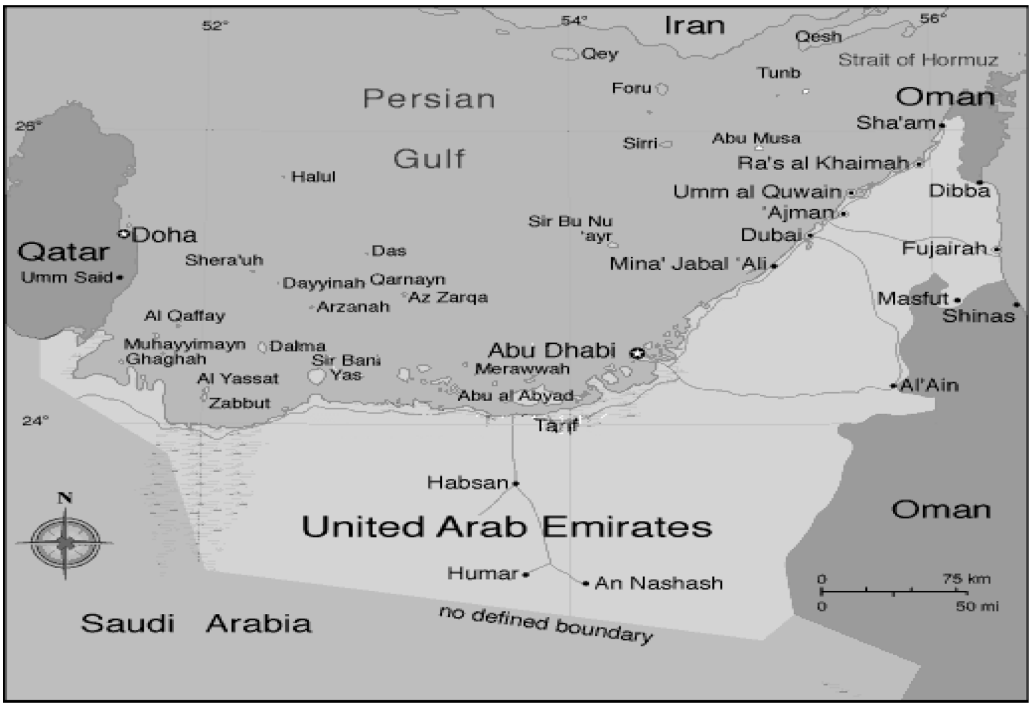

Fig. 1. Map of United Arab Emirates (UAE).

average rainfall of less than 100 mm/y [16]. Abu Dhabi Emirate has a population of 1.3 million and has the highest GCC growth rate of +10% per annum [22]. The Emirate has a low groundwater recharge rate and a very high evaporation rate (2,000–3,000 mm/y) with no reliable perennial surface water resources, and with a summer shade temperature frequently exceeding 40°C [22]. Strong persistent winds are normally encountered in many areas of Abu Dhabi Emirate.

Table 1 shows the renewable water resources availability in the UAE and the GCC Countries [7]. Total conventional freshwater resources available in UAE are 315 Mm^3/y while the total water demand was 2,180 Mm^3 in the year 2000. The forecasted demand for the year of 2025 is 3,200 Mm^3/y [21].

Conventional water resources available in the UAE include groundwater from single wells and central well fields, storage dams, Aflaj, Wadi flow and springs. Unconventional water resources include desalination and recycled treated wastewater. The contribution of each source to the total water demand for year 2000 is 35% from desalination, 3% from surface water, 53% from groundwater, and 9% from recycled treated wastewater [13]. In analyzing the water demand in UAE, there are three major sectors, which are domestic sector (households and drinking demands), the industry and commerce sector and the agricultural, forestry and landscaping sector [1]. The distribution of water uses by sector is 24, 67, and 9% for domestic, agriculture, and industry, respectively. The percentage water consumption by different sectors is shown in Fig. 2.

In the Eastern Region of Abu Dhabi Emirate the groundwater statistics indicate a total abstraction of approximately 880 Mm^3/y [22]. For agricultural development, there are about 24,000 wells on 9,100 registered farms. There are about 130 drilling rigs. About 124 wells are used to support six Aflaj in Al-Ain City [13]. It's worth mentioning that no Aflaj are presently working. Over the last two decades the forestry sector has grown dramatically due to the greening program adopted by the government of Abu Dhabi. There are about 71 plantations and 7.1 million trees occupying an area of 50,000 ha and consume 97 Mm^3/y of drinkable water abstracted from 2,600 wells [13]. To satisfy the domestic water demands, there are about 25,000 wells including municipal supplies.

4. Role of desalination

The Gulf countries, by necessity, have become the world leader in desalination of sea and brackish water, and currently have more than 65% of the total world's capacity [9]. The UAE is

Table 1
Renewable water resources (Mm^3/y) in the UAE and GCC countries [7]

Country	Total renewable water resources (TR)	Total demand (TD)		TD/TR (%)	
		2000	2025	2000	2025
Saudi Arabia	6,080	17,765	24,200	292	398
UAE	315	2180	3200	692	1,016
Oman	1,468	1,847	2,430	126	169
Kuwait	160.1	590	1,400	369	874
Bahrain	100.1	282	609	282	608
Qatar	51.4	347	485	670	943

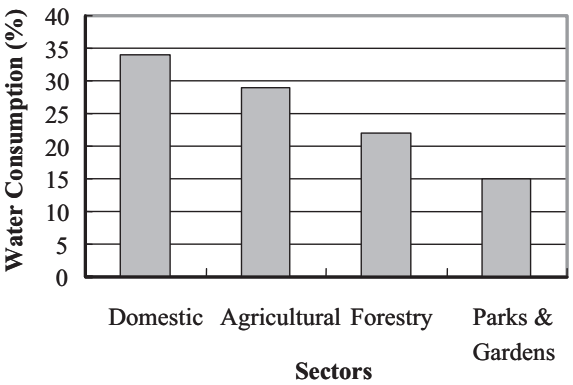

Fig. 2. Percentage water consumption by different sectors.

considered as the second largest producer of desalinated water in the Gulf countries, with a production of 5,465,784 Mm^3/y (Table 2).

Abu Dhabi has the highest per capita domestic consumption rate 500 l/d in the GCC, and is ranked worldwide after the USA [25]. Further development in the UAE can't be satisfied without reliance on unconventional water resources such as desalination of sea and brackish water, which currently account for about 98% of the water supply for drinking purposes. The total production of desalinated water in the different Emirates for year 2000 is shown in Fig. 3. Abu Dhabi Emirate has the highest production among the other Emirates. Desalination requirements in

Table 2
Desalination Units in the six GCC countries in 2000 [9]

Country	Number of units	Total capacity (Mm^3/y)
Saudi Arabia	2,074	11,656,043
UAE	382	5,465,784
Kuwait	178	3,129,588
Qatar	94	1,223,000
Bahrain	156	1,151,204
Oman	102	845,507
Total	2,986	23,471,126

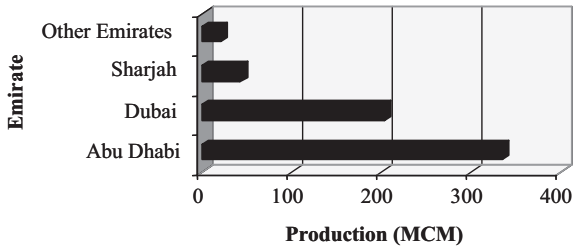

Fig. 3. Total production of desalinated water (MCM) in UAE in 2000 [1].

UAE will continue to grow. Between 1999 and 2001 the desalinated water production increased by 30% due to the startup of new desalination projects [21].

5. Reject brine

Reject brine, also referred in the literature as concentrate or wastewater, is a by product of the desalination processes. Brine discharged is more concentrated than brackish water or seawater and contains chemicals like antiscalent, used in the pretreatment of the feed water, washing solutions, rejected backwash slurries from the feed water, and other substances.

5.1. Concentrate chemical composition of reject brine

The chemical composition of BWRO (Table 3) concentrate has a profound effect on the disposal method. The chemical characteristics reflect feed water quality, desalination technology used, the chemicals used for pre- and post treatment, and percent recovery [14]. Alabddul'al and Saati [6] and Khordagui [11] presented the chemical composition of reject brine from some inland desalination plants in the GCC countries. Concentrate quality from some membrane drinking water plants in Florida has been reported by [14] where the concentrations of 40 different inorganic chemicals were

Table 3
Chemical composition of reject brine from inland desalination plants in GCC countries (after Ahmed [2], Ahmed et al. [4] and Alabdul'aly and Khan [5])

Parameter	Alssadanat Oman	UmmAl Quwain, UAE	Hamriyah, Sharjah, UAE	Saja'a Sharjah, UAE	Buwaib, Saudi Arabia	Salboukh, Saudi Arabia
Ca^{++}, mg/l	923	202	173	188	573	404
Mg^{++}, mg/l	413	510	311	207	373	257
Na^{+}, mg/l	2780	3190	1930	4,800	2327	1433
K^{+}, mg/l	81.5	84.5	50.7	60	NA	NA
Sr^{++}, mg/l	28.2	21.10	14.20	40	NA	NA
Σ cation meq/l	203.06	192.98	119.48	NA	NA	NA
pH	7.21	7.54	7.66	7.95	4.1	4.5
Electrical conductivity, mS/cm	16.8	14.96	127.41	NA	NA	NA
TDS, mg/l	10553	10923	7350	12,239	10800	6920
NO_3, mg/l	7.2	27.4	15.9	NA	143	142
F^{-}, mg/l	—	1.6	1.3	8.0	NA	NA
Cl^{-}, mg/l	4532	4108	2933	4,860	2798	1457
SO_4, mg/l	1552	2444	1537	2,400	4101	2840
SiO_2, mg/l	NA	164.09	133.71	120	NA	NA
Carbonate (CO_3^{-})	NA	NA	NA	NA	NA	NA
Bicarbonates (HCO_3^{-})	466	656	753	NA	NA	NA
N^{-}	1.6	6.2	3.6	NA	NA	NA
Σ anions maq/l	167.88	198.05	127.41	NA	NA	NA
Ion balance	9.48	4.02	−3.21	NA	NA	NA
SAR	19.12	27.20	20.30	NA	NA	NA
SER	59.55	71.91	70.27	NA	NA	NA
L.I	1.24	1.04	1.26	NA	NA	NA
R.I	4.73	5.46	5.14	NA	NA	NA
Total ion, mg/l	10781	11245	7719	NA	NA	NA
Total alkalinity	380	538	617	945	NA	NA
Total hardness	4041	2630	1730	NA	2968	2066
Fe, mg/l	0.06	0.08	0.05	NA	65.5	NA
Mn, mg/l	0.05	0.05	0.05	NA	22.6	NA
Cu, mg/l	0.05	0.05	0.05	NA	10.8	NA
Zn, mg/l	0.05	0.05	0.05	NA	NA	NA
Cr, mg/l	0.02	0.12	0.05	NA	NA	NA
Al, mg/l	NA	NA	NA	NA	182	NA
Ba, mg/l	NA	NA	NA	NA	68	NA
As, mg/l	NA	NA	NA	NA	23.2	NA
Pb, mg/l	NA	NA	NA	NA	5.2	NA
Se, mg/l	NA	NA	NA	NA	7.7	NA

reported. Alabdula'aly and Khan [5] analyzed the feed, permeate and brine water of four groundwater RO plants in the central region of Saudi Arabia for 9 metals, namely Al, As, Cd, Fe, Mn, Ni, Pb, Se and Zn. Ni and Cu were found to be absent in all samples. All other metals were observed within the drinking water limit set by World Health Organization (WHO).

Another important issue of concern is the presence of corrosion products. Studies conducted in a large scale plants use seawater as feed, and acid dosing as anti-scalent can further aggravate the corrosion problem [17]. RO system recovery can influence concentrate characteristics. The system volume recovery is the volume of permeates produced from the feed water expressed as a percentage. High recovery leads to a concentrating effect of dissolved species in the feed water.

The dilution of concentrate (blended) results in a final discharged effluent that is rarely more than 15% higher in salinity than the receiving water. Concerns over the potential adverse effects are tempered by the total volume of brine being released, the constituents of the brine discharged (i.e. heavy metals, organic and inorganic compounds and also by products from pre-and post-chemical treatment which might include antiscalent, antifoaming agents, polyphosphates, coagulant aids, residual chlorine, and acid).

Also, it is possible to find corrosion products in brine water resulting from the effect of water flow, dissolved gases and treatment chemicals (acids) on the alloys utilized in the construction of desalination pipes and equipments. The corrosion products may include harmful heavy metals such as nickel (Ni), copper (Cu), molybdenum (Mo), and other less toxic metals such as iron (Fe) and zinc (Zn). The amount of these metal ions is directly related to redox potential, pH and the material in contact with water during the desalination process.

5.2. Reverse osmosis concentrate disposal

There are many options for concentrate disposal from inland desalination plants [11]. Some of these are: (1) discharge into well-engineered solar evaporation pond; (2) disposal to wastewater system; (3) land application (includes spray irrigation and percolation ponds); (4) injection into deep saline aquifers (non-drinking water aquifers); (5) disposal into land surface, and (6) disposal into the sea through a pipeline.

A survey was conducted by Ahmed et al. [3,4] on the current status of brine disposal techniques of 23 inland desalination plants in Oman, Jordan, and the UAE. The survey concluded that the disposal practices in the above countries range from evaporation ponds to the utilization of saline water in irrigation after dilution as well as disposal in boreholes, shoreline, wadi beds, and the ocean. Another survey was conducted in the USA at membrane drinking water facilities of size greater than 95 m^3/d [23]. About 73% of the plants were brackish water RO, 11% were nano-filtration (NF), 11% electrodialysis (ED) and the remaining 5% seawater RO plants. Table 4 summarizes the different methods for disposal of concentrate in the USA.

The necessity for a special disposal technique could make the system very costly.

Table 4
Methods of concentrate disposal in USA

Method of disposal	(%)
Surface water	48
Discharged to wastewater treatment plants	23
Land application	13
Deep well injection	10
Evaporation ponds	6

A report published by [25] outlined that the cost plays an important role in selecting a method of reject brine disposal. The cost could range from 5 to 33% of the total cost of desalination [11]. Evaporation ponds are the most appropriate for relatively worm, dry climates with high evaporation rates. It should be noted that with all types of land disposal procedures, there would always be a potential risk of groundwater contamination.

5.3. Impact of reject brine on soil and groundwater

Disposal of reject brine into unlined pond or pits from inland desalination plants has a significant environmental consideration. Improper disposal has the potential for polluting the groundwater resources and can have a profound impact on subsurface soil properties if it's discharged by land application. A case study in India indicated that seepage from brine caused groundwater contamination of the source well and resulted in an increase in hardness of the groundwater [18]. High salt contents in reject effluent with elevated levels of sodium, chloride, and boron can reduce plants and soil productivity and increase the risk of soil salinization [12]. It can also alter the electrical conductivity of soil, changing the sodium adsorption ratio (SAR), and induce specific ion toxicity. SAR defines the influence of sodium on soil properties by calculating the relative concentration of sodium, calcium, and magnesium [15]. Higher SAR values can lead to lower permeability [19]. Although sodium does not reduce the intake of water by plants, it changes soil structure and impairs the infiltration of water, affecting plant growth [10,12]. Additional impacts include increased irrigation and rainwater runoff, poor aeration, and reduce leaching of salts from root zone because of poor permeability. Heavy metals and inorganic compounds build up in the soil and groundwater sources and may cause long-term health problems.

Assessing the extent and rate of pollutant movement through the soil profile from the disposed brine on inland desalination plants is of great importance. It provides means for addressing the water quality issues associated with the deep percolation of reject brine when this by-product of desalination is discharged in improper way. In addition, understanding the movement of the concentrated brine along with heavy metals is essential in evaluating their negative impacts on the environment and addressing the policies and the regulatory aspects of brine reject discharge. Models that describe the physical, chemical, and biological processes associated with the movement of solutes in the soil profile have been developed and investigated by many researchers [8,27,15].

6. Assessment of the study area

The study area (Fig. 4) is located at the eastern region of Abu Dhabi Emirate, about 100 km from Al-Ain City, where a hot arid

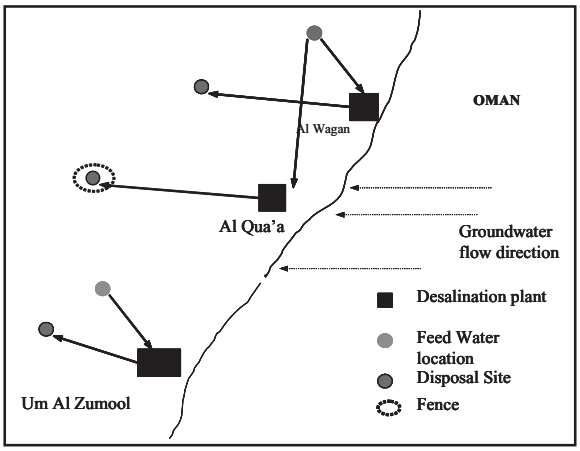

Fig. 4. Study area.

climate prevails and evaporation greatly exceeds precipitation. The average annual rainfall may only be a few centimeters, which usually occurs seasonally and sometimes only from a single cloudburst. The summer shade temperature is frequently above 40°C. Strong persistent winds are normally experienced. The geological features of the area consist mainly of sand dunes with marine sand and silt. The principal transporting agents of the environment is wind. The superficial deposits overlie interbeded sandstone, limestone, conglomerates, calcites, gypsum, plagioclase and siltstones. The raw water originates from Sayh Al Raheel, Um Al Ash and from Aslab wells with a water table of 100–150 m below the ground surface. The average brackish water conductivity ranges between 6.5 and 15.0 mS/cm.

6.1. Desalination plants visited

Al Wagan, Al Qua'a and Umm Al Zumool BWRO desalination plants were visited. A survey was conducted and the results obtained are summarized in Table 5.

6.2. Feed, product and reject brine water production

The reject brine production and total desalinated and rejected water in 1999 and 2002 along with the monthly feed, desalinated, and reject water are shown in Table 6 and Figs 5–9. The figures show an increase in feed, product, and reject water over the last four years due to increase in water demands for both domestic and livestock use. The ranges of brine production in 2002 from Al Wagan, Al Qua'a and Um Al Zumool as compared to the 1999 are illustrated in Table 6. The data show a dramatic increase in both product and reject water with a brine recovery rate of 30–40%.

6.3. Methods of brine disposal

The existing method of brine disposal in the study area is surface impoundment (unlined pond). The size of the pond at Al Wagan is (65 m by 100 m by 50 m by 120 m), and at Al Qua'a is (45 m by 75 m by 40 m by 55 m) with a depth of 17 m. The photographs of the sites are shown in Figs 10 and 11.

7. Sampling and analysis

7.1. Water samples

Representative discharge effluents from three inland desalination plants along with feed, products and pond water were collected and analyzed. Temperature and pH were analyzed in the field whereas, electrical conductivity, TDS, major cations (Ca, Mg, Na, K), major anions (HCO_3, SO_4, Cl, NO_3), major metals (Al, As, Cu, Fe, Zn, Cd, Cr, Pb, Se, Mn, Sr, V, B and Ba), and TPH were analyzed at the Central Laboratory Unit (CLU), UAE University, using ICP-OES-VISTA-MPX CCD, HACH DR4000U Spectrophotometer, and MAGNA-IR (560), ESP spectrometer, respectively. The water samples analyzed for TPH were collected in 1000 ml; acid washed, and kept in dark brown glass bottles. The samples for trace elements and TPH were acidified at the time of collection with spectroscopy grade nitric acid until the pH was less than 2, brought to the laboratory in ice boxes, and stored at 4°C until analyzed.

7.2. Soil samples

Soil samples were collected from Al Qua'a disposal site (Fig. 12) at each location (i.e. A1, A2, A3, B1, B2, and B3). Five samples were collected from each point. Soil samples were air-dried and sieved using 2 mm sieve

Table 5
Basic Information on the Inland BWRO Desalination Plants

Item	Al-Wagan	Al Quaa	Um Al Zumool
Number of plants	11 plants (4 mobile and 7 Stationary)	12 plants (6 mobile and 6 stationary)	2 Stationary
Year of operation	3 plants start operation 1980, 1 in 1991, 1 plant in 1992, 4 plants in 1996 and 2 in 1997	3 plants operated in 1980, 3 in 1991, 3 in 1996, 2 in 1997	1992
Purposes	Domestic and livestock supply	Domestic and livestock supply	Domestic
Feed method	Brackish groundwater	Brackish groundwater	Brackish
Total capacity, G/d	25,000–50,000	25,000–60,000	25,000
Recovery rate, %	70	70	60
Disposal methods	Unlined pit	Unlined pit	Unlined pit
No. of feeding well	13	15	8
Feed salinity and pre-treatment, mS/cm	6,500	6,000 9,000	17,000
Pre-treatment	Sand filtration Cartridges filtration	Sand filtration Carbon filtration Cartridge filt.	Sand filtration Carbon and
Chemical treatment	Anti-scalent, sulphuric acid	Anti-scalent, H_2SO_4	anti-scalent sulphuric acid
Post treatment	1μ–5μ filters	UV System	—
RO membrane cleaning frequency	every 2,000 hs 22 working h/d	every 2,000 hrs 20 working hrs/day	every 2,000 h 16 h/d
Chemical used for cleaning	Citric acid, Bioclean L607, RO clean L607 Bioclean 511	Citric acid, and Fouling (115,807)	—
Membrane manufactures and type	Fluid System, FilmTech Hydromatrix. spiral wound and seawater membranes are used	Fluid System, Dupont spiral wound, seawater membrane 4(SW4040), 8 inch	FilmTech Spril wound 8 inch, SW8040
Membrane life time	9 ys. for Fluid System 5–6 ys for FilmTech 3 ys. for Hydromatrix		

Table 6
Reject brine water production (MG/y) at the studied plants

Plants (BWRO)	Year	
	1999	2002
Al Wagan	25,425	49,627
Al Qua'a	33,129	49,749
Um Al Zumool	9,675	10,584

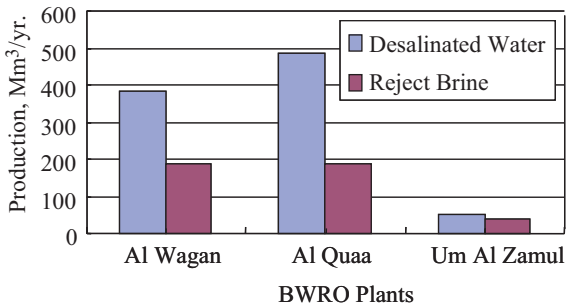

Fig. 5. Total desalinated and reject water produced in the year 2002 (Mm^3).

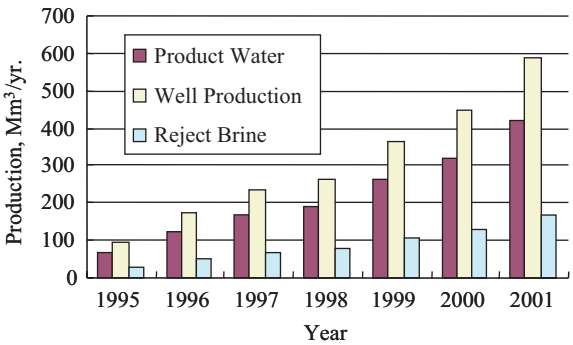

Fig. 6. Rate of change of water production, Al Qua'a desalination plant.

and analyzed for the followings physical and chemical parameters.

Physical parameters: A soil specific gravity and grain size distribution has been analyzed using pycnometer and dry sieve analysis, respectively.

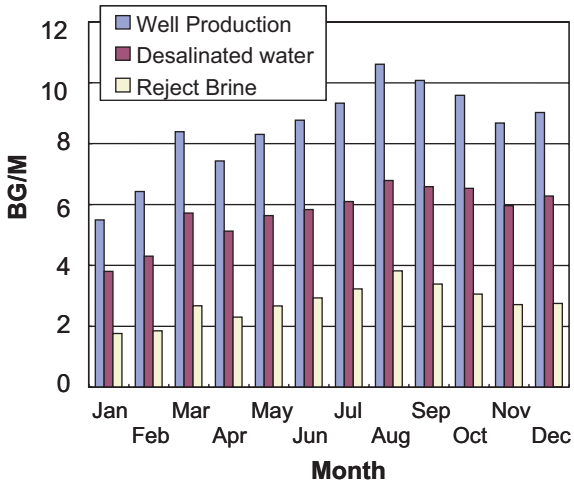

Fig. 7. Monthly feed, product, and brine production, Al Qua'a desalination plant.

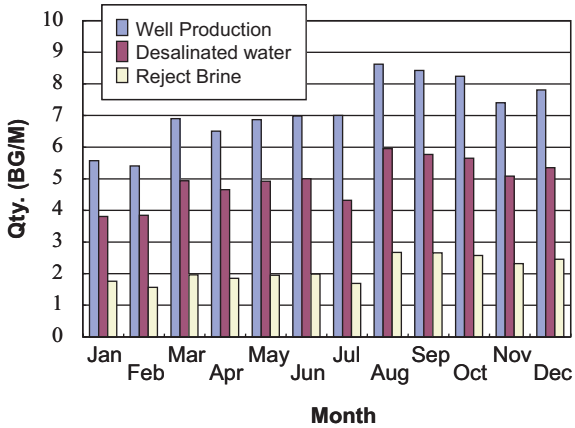

Fig. 8. Monthly desalinated and rejects water produced from Al Wagan desalination plant.

Chemical analysis: Cation exchange capacity (CEC) was determined by using ammonium acetate method. Cations were then analyzed using atomic absorption spectrophotometer. The electrical conductivity (EC), TDS, and pH in the 1:2.5 ratio were measured using a Jenway 4020 EC/TDS and Jenway 3020–pH meter respectively. Readings were taken in the suspension before extraction. Major cations, anions and heavy metals in a suspension of

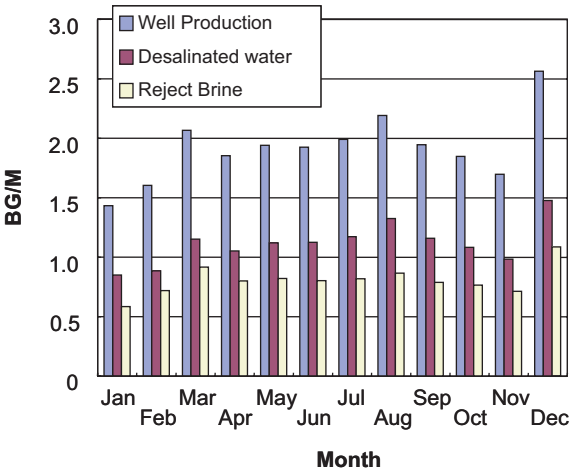

Fig. 9. Monthly desalinated and rejects water produced from Um Al Zumool desalination plant.

Fig. 10. Brine disposal site, Al Wagan.

Fig. 11. Brine disposal site, *Al Qua'a*.

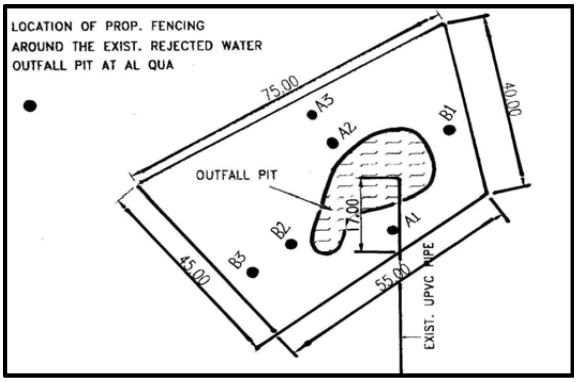

Fig. 12. Soil sampling location at Al Qua'a disposal site.

1:2.5 soils to water ratio were analyzed. Samples were placed in a receptacle shaker for over night and extracted using filter paper. Chloride, carbonate, and bicarbonates were determined by titration method. Nitrate was determined by using HACH DR4000 U spectrophotometer. For the determination of heavy metals, 1.0 g of <2 mm air dry soil was digested in an Aqua Regia solution 1:3 ratio (HNO_3:HCL). Heavy metals and some anions have been analyzed using ICP-OES-VISTA-MPX CCD simultaneous. Note that the results were reported as an average value for the five samples with its related standard of deviations.

Mineralogical analysis: X-Ray diffraction analysis (XRD) was used to determine the mineralogical composition of the samples. Fifteen gram (15 g) of air dried soil passed a No. 200 sieve (75 μm) was placed into a glass slide (2.6 × 2.3 cm), and then analyzed using A Philips X-ray diffractometer model PW/1840, with Ni filter, Cu-Kα radiation (λ = 1.542 Å) at 40 kV, 30 mA and scanning speed of 0.02°/S was used. The diffraction peaks between

$2\theta = 2°$ and $2\theta = 60°$ were recorded. The corresponding spacing (d in Å) and the relative intensities (I/I°) were calculated and compared with the standard data.

7.3. In-place soil samples

Two soil samples were collected, the first one was taken about 100 m from the Al Qua'a disposal site, and the other was taken about 1.5 km away from the disposal site. It is important to mention that samples were collected from two sites. At the first site, samples were taken from sand dune deposition where the disposal site is located. At the other site, samples were taken from the in-place (original) soil of the area (virgin soil). Soils were characterized for hydraulic conductivity, using constant head hydraulic conductivity test (ASTM) standard method. This method is generally used for sands that contain little silt or fines. The hydraulic conductivity cell was used and the soil specimen was compacted inside the cell. Water flows from a reservoir through the compacted specimens that remains under a constant head. Soil samples were also characterized for Specific gravity, particle size distribution using standard ASTM D 2487–92, CEC, pH, EC, TDS, cation, anions using 1:2.5 soil to water ratio and heavy metals by using wet digestion method. Cations, anions and heavy trace metals were analyzed using ICP.

8. Results and discussion

8.1. Variations of pH, Ec, and major cations

Analyses of the feed, product reject brine, and pond water are summarized in Table 7. The table shows the pH and EC at Al-Wagan, Al Qua'a, and Um Al Zumool desalination plants. The pH values ranged from 5.64 to 7.02, 6.76–7.46, 7.03–8.41 for Al-Wagan, Al-Qua'a and Um Al-Zomool, respectively. Whilst, EC ranged from 0.83 to 30.30, 0.22–16.90, and 0.34–14.00 mS/cm, for the same areas, respectively. The concentration Na^+, Ca^{2+} and Mg^{2+} are higher than the allowable limits set by the GCC countries in all water samples.

8.2. Variations of major anions

The major anions of feed, product, reject and pond water are shown in Table 8. The results show that these samples were not

Table 7
pH, EC and major cations of water samples from the desalination plants

Plant	Water sample name	pH	EC (mS/cm)	Cations (mg/l)			
				Na	Ca	Mg	K
Al Wagan	Feed	7.02	14.7	741.59	146.31	112	8.46
	Product	7.02	0.82	55.25	140.00	0.94	1.30
	Reject	5.64	30.3	2,248	367.96	282	68.49
	Pond	6.76	26.6	1,985	393.25	300	56.60
Al Qua'a	Feed	6.67	4.61	451.13	162.36	104	27.24
	Product	7.46	0.22	39.20	1.80	1.16	0.90
	Reject	6.67	16.9	2,880	518.86	337	94.64
	Pond	7.14	14.6	1,994	366.86	252	61.67
Um Al – Zumool	Feed	7.57	5.05	2,482	456.40	194	110.1
	Product	7.40	0.34	151.0	18.23	7.75	4.64
	Reject	7.03	12.9	6,206	846.78	361	264.0
	Pond	8.41	14.0	5,517	782.75	336	245.0

Table 8
Major anions of water samples from the desalination plants

Plant	Water Sample Name	Anions (mg/l)			
		Cl^-	P	NO_3^-	SO_4^{2-}
Al Wagan	Feed	3,827	ND	8.99	539.22
	Product	398.0	ND	1.69	5.36
	Reject	8,946	0.40	7.11	1,540
	Pond	9,943	0.30	10.60	1,436
Al Qua'a	Feed	6,213	0.14	1.57	394.38
	Product	1,143	ND	0.85	5.62
	Reject	7,212	0.42	5.30	1,979
	Pond	10,437	0.40	5.61	1,456
Um Al-Zumool	Feed	9,443	ND	12.70	1,746
	Product	1,243	0.01	1.58	55.56
	Reject	23,856	0.28	17.2	4,179
	Pond	19,880	0.20	14.1	3,622

contaminated with nitrate (NO_3^-) and phosphorus (P), whereas the concentrations of sulfate (SO_4^-) and chloride (Cl^-) were exceeding the allowable limits. The higher SO_4^- concentration in feed water is attributed to the geological nature of the area, which is classified as gypsy-ferrous soil; this has been confirmed by the mineralogical analysis.

8.3. Variations of heavy metals

All water samples collected from the three aforementioned desalination plants were analyzed for the presence of 13 heavy metals. These heavy metals include Al, Ba, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Sr, V, Zn and B as shown in Table 9. The concentrations of vanadium (V), chromium (Cr), and

Table 9
Heavy metals in water samples

Plant	Water sample name	Heavy metals concentration (mg/l)												
		Al	Ba	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Sr	V	Zn	B
Al Wagan	Feed	0.10	0.03	0.01	0.23	ND	0.01	0.01	0.01	ND	5.60	0.04	0.01	1.10
	Product	ND	0.01	0.01	0.01	0.01	0.01	ND	ND	ND	0.05	ND	0.01	0.80
	Reject	0.02	0.10	ND	0.70	ND	ND	0.01	0.01	ND	21.63	0.11	6.02	1.40
	Pond	0.02	0.08	ND	0.63	ND	0.01	0.01	0.01	ND	16.70	0.12	0.01	1.20
Al Qua'a	Feed	0.01	0.03	0.01	0.18	ND	ND	0.01	0.01	ND	5.40	0.03	0.01	0.80
	Product	ND	0.01	0.01	0.01	ND	0.01	ND	0.01	ND	0.07	0.01	0.01	0.60
	Reject	0.03	0.10	ND	0.63	ND	ND	0.01	0.01	ND	24.22	0.11	0.01	1.92
	Pond	0.02	0.07	ND	0.62	ND	ND	0.01	0.01	ND	17.24	0.10	0.01	1.62
Um Al Zumool	Feed	0.02	0.02	ND	0.05	ND	0.01	0.01	0.03	ND	9.96	0.02	0.02	2.86
	Product	ND	0.10	0.01	0.01	ND	0.01	0.01	0.01	ND	0.51	0.01	0.01	1.00
	Reject	ND	0.32	ND	ND	0.09	0.01	0.01	0.01	0.01	30.10	0.04	0.10	5.40
	Pond	ND	0.03	ND	0.09	ND	0.01	0.01	0.01	0.01	30.16	0.04	0.10	4.92

strontium (Sr), have been compared with the GCC drinking water standards of the above three metals, and regulations for effluents discharges. The concentrations were found to be higher in the feed, reject and pond waters. Heavy metals such as Al, Ba, Cd Cu, Fe, Mn, and Ni were found to be within the allowable limits. The concentration of most of the heavy metals which were analyzed in feed water was below the allowable limits set by the GCC standards except for Sr and B which were found to be above the allowable limits for drinking water. Other metals such Cd, Pb, Fe, Cu were not detected in some water samples as shown in Table 9.

8.4. Variations of total petroleum hydrocarbons (TPH)

It can be seen from Fig. 13 that TPH is present in feed, product, reject, and pond water. In some plants the concentration exceeds the standard limits set by the GCC countries, which is 0.01 mg/l for drinking water. The results should be considered as indicative of TPH presence in water samples. A fingerprint study is required to determine the source of hydrocarbons.

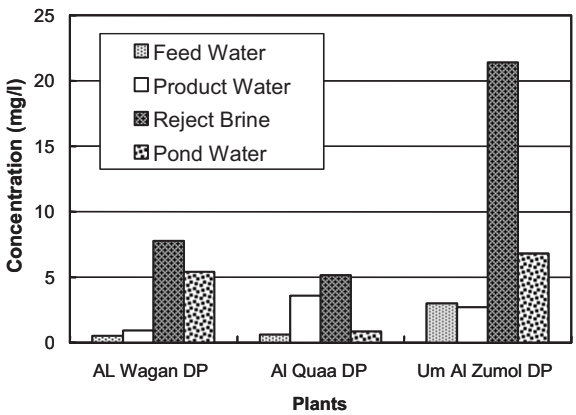

Fig. 13. The level of TPH in water samples.

8.5. Performance of reject brine pits

Table 10 indicates that the reject brine from Al Qua'a and Um Al Zumool has higher concentrations compared to reject brine from the Al Wagan plant. Table 11 indicates that the desalination plants have led to the enrichment of reject brine with major ions as indicated from the calculated rations (reject water: feed water). The concentration factor (CF) calculated as the ratio between the concentrations of species in the pond water to that in the reject brine is shown in Table 12. This may indicate that there is a leakage problem. Further investigations are needed. Usually ponds have much higher concentrations than wastewater depending on age of pond, size, and possible dilution. However, these assumptions are made based on one sampling only. For precise conclusions a series of water samples with constant or different time intervals should be conducted, and results can be reported based on the average sample number and standard of deviation.

8.6. Subsurface pollutant distribution at Al-Qua'a disposal site

Grain size and silt analysis: The size of the mineral particles profoundly affects the physical properties of the soil, leaching, and the ability to hold water and other constituents. Dry sieve analysis has been performed to determine soil texture. The textures of soil samples are fine to very fine sand. The grain size distributions for both soils are illustrated in Fig. 14. The figure shows very clearly that the soil contained negligible fines (soil particles that will pass a 0.25–0.05 mm sieve and retained on a <0.05 mm pan). The unified soil classification system has been used to confirm the soil texture by calculating the C_u and C_c, where C_u is the coefficient of uniformity, and C_c is the coefficient of curvature. The C_u

Table 10
Characteristics of reject brine from desalination plants

Parameter	Al Wagan	Al Qua'a	Um Al zumool
Temperature (°C)	35	35	35
pH	7.03	6.67	5.62
Electrical conductivity (mS/cm)	12.9	16.9	30.3
TDS	7.77	10.2	18.3
Ca (mg/l)	367.96	518.86	846.78
Mg	282.02	337.26	361.68
Na	2,248	2,880	6,206
K	68.44	94.64	264.05
SO_4	1,540	1,979	4,179
Cl	8,946	7,212	2,385
NO_3	7.11	5.30	17.1
F	ND	ND	ND
Al	0.02	0.03	ND
Mn	0.01	0.01	0.01
P	0.40	0.42	0.28
Cu	ND	ND	ND
Zn	0.02	0.01	0.01
Ni	0.01	0.01	0.01
Cr	0.70	0.63	0.09
Cd	ND	ND	ND
Ba	0.10	0.10	0.32
B	1.40	1.92	3.40
V	0.11	0.11	0.04
Se	ND	ND	ND
Pb	ND	ND	0.01
Sr	21.63	30.10	30.10

Table 11
Ratio of major ions of feed water and reject brine of the plants

Location	Constituents (mg/l)				
	Na	Ca	Mg	K	EC
Al Wagan					
Feed water	741.59	146.31	112.41	28.46	5.05
Reject water	2,248	367.96	282.02	66.49	12.90
Ratio	3.03	2.51	2.50	2.34	2.55
Al Qua'a					
Feed water	451.13	162.36	103.64	27.24	4.61
Reject water	2,880	518.86	337.26	94.64	16.90
Ratio	6.83	3.19	3.25	3.47	3.66
Um Al Zumool					
Feed water	2,481	456.40	194.50	110.29	14.70
Reject water	6,206	846.78	361.68	264.05	30.30
Ratio	2.50	1.85	1.86	2.40	2.06

Table 12
Concentration factor in disposal ponds

Location	Constituents (mg/l)				
	Na	Ca	Mg	K	EC
Al Wagan					
Reject rine	2,248	367.96	282.02	68.49	12.90
Pond water	1,985	393.25	300.95	56.60	14.00
Conc. factor (CF)[a]	0.88	1.07	1.07	0.82	1.85
AlQua'a					
Reject brine	2,880	518.86	337.26	94.64	16.90
Pond water	1,994	366.86	252.75	61.60	14.60
Conc. factor (CF)[a]	0.70	0.70	0.75	0.65	0.86
Um Al Zumool					
Reject brine	6,206	846.78	361.68	264.05	30.30
Pond water	5,516	782.75	336.42	245.42	26.60
Conc. Factor (CF)[a]	0.88	0.92	0.93	0.93	0.87

[a]CF Pond Water/Reject water

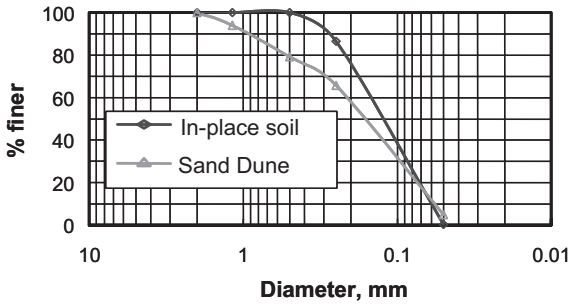

Fig. 14. Grain size distribution of the in-place and sand dune soils from Al Qua'a disposal site.

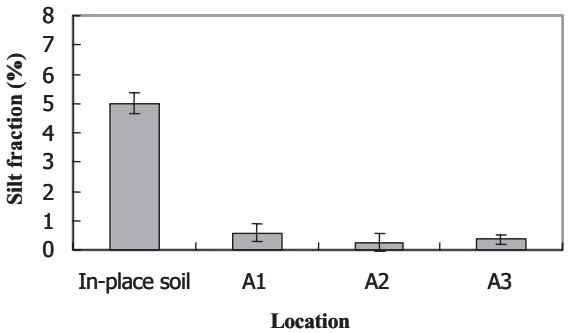

Fig. 15. Variation in silt content among sampling locations.

Table 13
Calculated coefficient of uniformity (C_u), coefficient of curvature (C_c) and hydraulic conductivity (K) for soils from Al Qua'a disposal site

Soil type	C_u	C_c	k (m/s)
In-place soil	0.363	0.817	3.6 E-07
Sand dune soil	2.5	0.9	3.36 E-07

and C_c and the hydraulic conductivity (k) values for in-place and sand dune soil are given in Table 13.

Fig. 15 indicates that there are great variations in silt contents between the original soil (in-place soil) and samples collected from the disposal site. This could be due to the transportation nature of the residual soil (sand dune) that is present in the study area.

Cation exchange capacity (CEC): Fig. 16 indicates clearly the variation in CEC contents between the original (in-place) soil and the soil collected from Al Qua'a disposal site (A1, A2, and A3). The variation in CEC content is attributed to high fine silt content in the original soil.

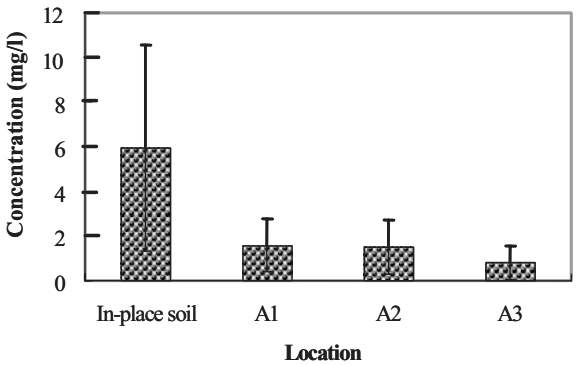

Fig. 16. Variation in soil cation exchange capacity (cmol/kg dry soil).

Mineralogical analysis: XRD analysis for soil samples collected from disposal site and original soil of Al Qua'a area, are analyzed using A Philip XR model PW/1840, with Ni Filter, CU-Kα radiates. Results are summarized in Table 14. The dominants minerals near the disposal site A1, A2, A3, and B1, B2, B3, and sand dune soil are quartz, calcite and plagioclase, and gypsum whereas the in-place soil collected, about 1.5 km down stream contains high amount of gypsum. This finding corresponds to the geological formation and the soil classification of the area (Gyps-ferrous soil) [26].

Pore fluid analysis: Interpolation technique (Kriging) has been used to generate contour lines using Surfer, version 8.02. The program has been used to illustrate the variation in cations, anion and trace metals distribution as well as flow direction.

Anion distribution: Fig. 17 shows that the concentration of chloride is higher at sampling points A1, A2, B1, B2, and B3, whereas the concentration at point A3 is very low. This indicates that the flow direction is from A1 and B1 to A3 and the chloride migration is mainly in vertical direction. Nitrate concentration was lower than the maximum allowable limits by GCC standards. The Nitrate graph shows also that point A3 has the lowest concentration among the other points. Sulfate is concentrated mainly at point A1 and propagates toward A3. The concentration of bicarbonate is high at point A3.

Cation distribution: Fig. 18 illustrate that the concentration of K, Na, Mg, and Ca. All cation concentrations are higher at sampling point numbers A1, A2, B1, B2, B3 than at that at A3.

Heavy metals distribution: Strontium concentration was found to be high at points A1 and A3. Also it was found to be higher than the maximum allowable limits (0.05 mg/l) set by the GCC countries for drinking water (Fig. 19).

In conclusion the graphs suggest that the concentration of the reject brine water decreases by distance from the center of the pond. However, the horizontal movement is

Table 14
Soil minerals

Sample ID	Major minerals	Subordinate minerals	Minor minerals
A1	Quartz, Plagioclase	Plagioclase, calcite	Calcite
A2	Quartz	Plagioclase, calcite	Calcite
A3	Quartz, Calcite	Plagioclase	Gypsum
B1	Plagioclase	Plagioclase, calcite	Plagioclase, calcite
B2	Quartz	Plagioclase	Plagioclase, calcite
B3	Quartz	Calcite	Plagioclase, calcite
Sand dune soil	Plagioclase, calcite	Calcite	Gypsum
In-place soil	Quartz, Calcite, Gypsum	Calcite	Plagioclase, calcite

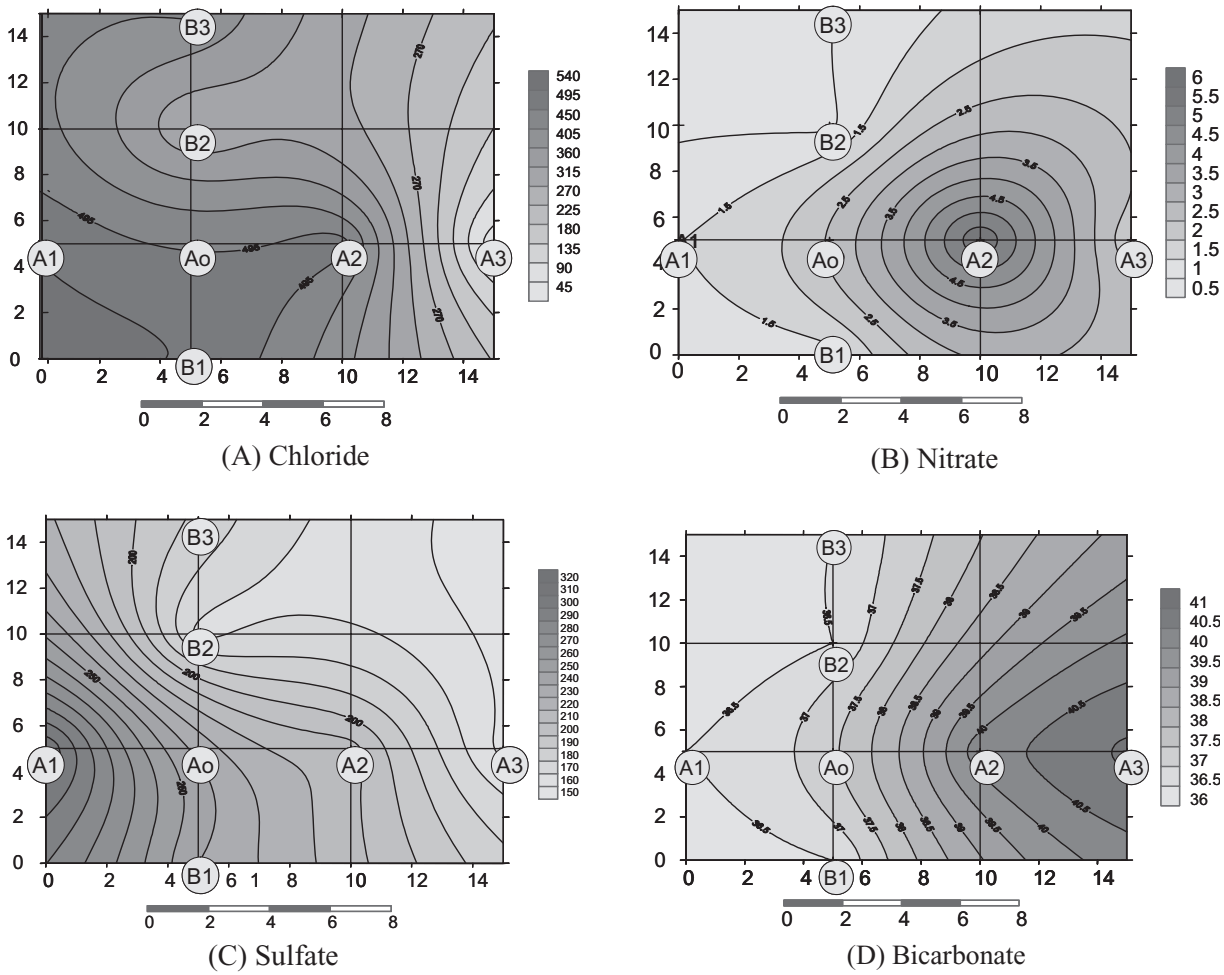

Fig. 17. Anion distribution in subsurface soil below the disposal site at an average depth of 1.0 m.

very limited suggesting that the main direction for transport is the vertical direction. The concentration of these ions are found to be higher than the maximum allowable limits set by the GCC Drinking Water Standards and also higher than the maximum limits set by ADNOC for the disposal of effluents into the desert.

9. Conclusions

The following points could be drawn from the study:

1. Seawater and brackish groundwater are considered as strategic alternatives to provide fresh water resources in the UAE and the Gulf countries.

2. Almost 98% of water supplies in the UAE are currently satisfied by seawater and brackish water desalination.

3. Considering the increase in desalination technology, attention must be given to evaluate desalination from environmental, technical and economical prospective.

4. Considering the geological nature of the study area, concentrate disposal to

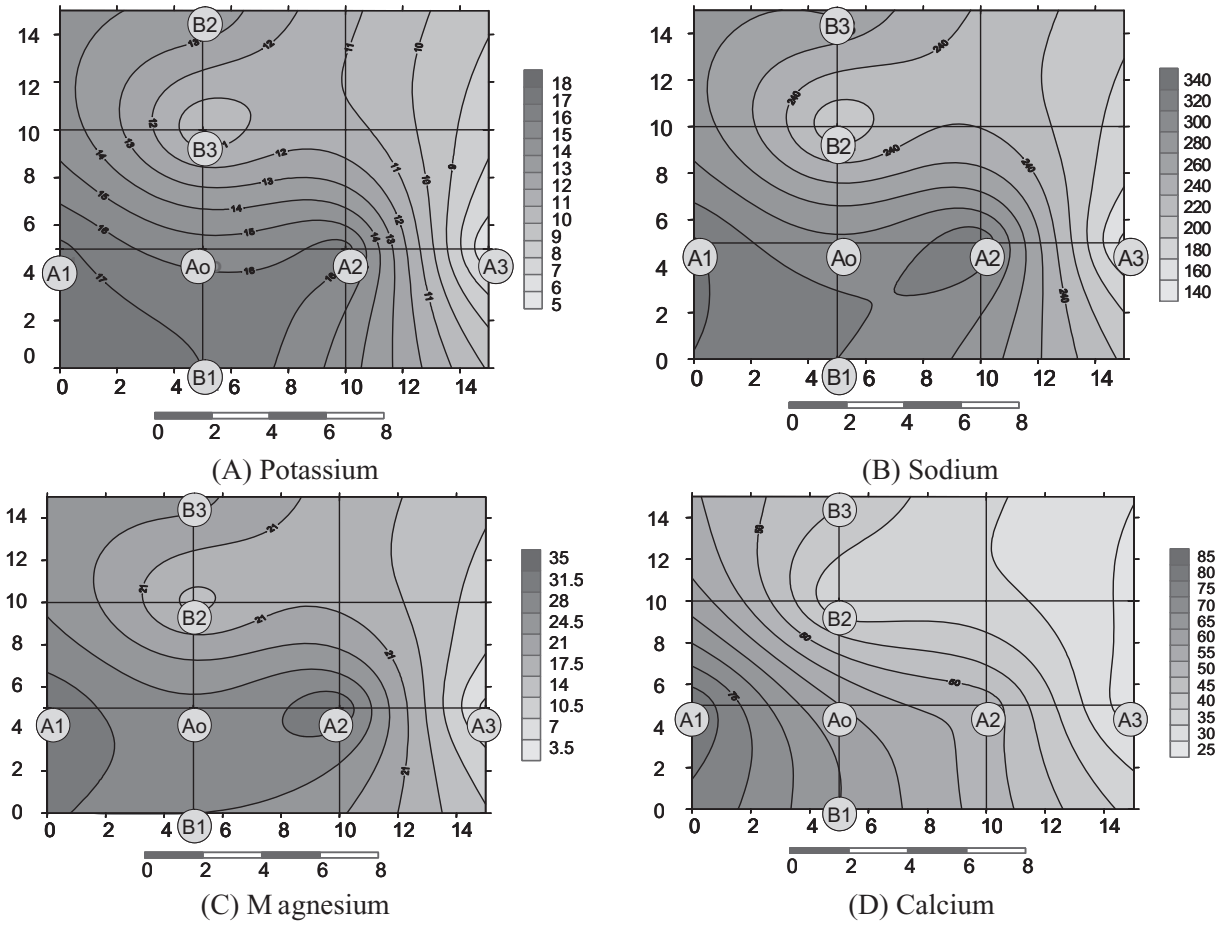

Fig. 18. Cation distribution in subsurface soil below the disposal site at an average depth of 1.0 m.

unlined pond or pits can pose a significant problem to soil and feed water. It can increase the risk of saline brackish water intrusion into fresh water.

5. The percentages of reject brine from the three investigated plants varied between 30 and 40%. The surveyed plants used unlined disposal pits for disposal of reject brine. Chemical analysis showed a slight increase in the concentration of various salts and EC level indicating that concentrate is easily reaching the groundwater.

6. The TDS of reject brine showed a low degree of variability ranging from (7.77–18.3 mS/cm). Heavy metals (Cr, P, Sr, V, and B) and TPH were detected in all water samples. Water samples collected from reject brine at Um Al Zumool RO plant showed the highest increase in TPH and electrical conductivity, where as the highest level of TPH in feed water was observed at the Al Qua'a plant.

7. Increase in TPH in desalinated water can pose a significant health risk. The origin of TPH, types of hydrocarbons should be investigated. A fingerprint study could be useful to define the source of such organic compound.

8. XRD analysis indicated that the dominants minerals near the disposal site are

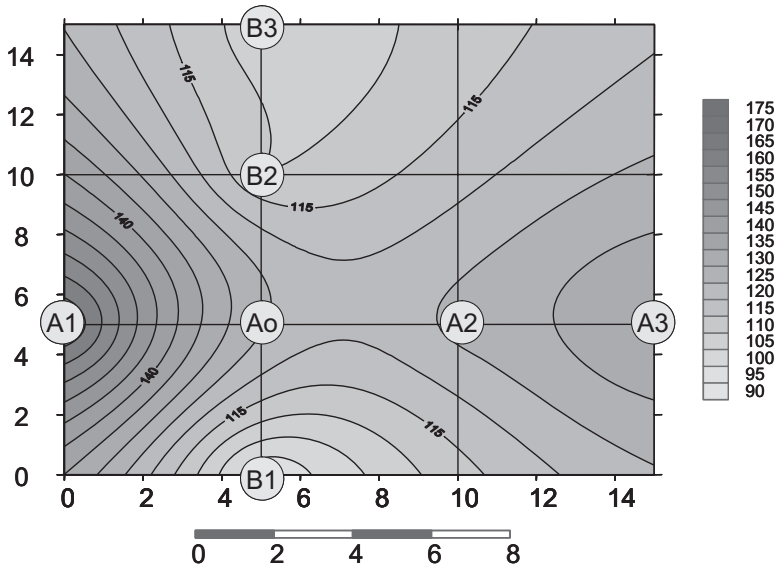

Fig. 19. Strontium distribution in subsurface soil below the disposal site at an average depth of 1.0 m.

quartz, calcite and plagioclase, whereas samples collected, about 1.5 km (original soil) from the disposal site contained high amount of gypsum. This finding corresponds to the geological formation and the soil classification of the area, which is classified as gyps-gyps-ferrous soil. Feed water analysis confirms also, that the soil contains SO_4^-, Ca, Mg, and Na.

The overall study indicates that effluents discharge to the desert can have an adverse effect to the feed water or/underground aquifers. The RO concentrate released has a TDS concentration about two fold higher than the feed water supply. The mechanism for this increase may be attributed to saline intrusion to the feeding aquifers, salts from the reject brine might precipitate out of solution as the discharge water infiltrate to the water table. The salt may be then taken into solution at a new concentration. The re-solution of salts during transport to the water table and enrichments of the soil in the area with gypsum as has been concluded from XRD results may explain the increase in water hardness and SO_4 concentrations. With regards to the impacts on soil quality, the outcomes of this project can give a preliminary findings, further research is required to confirm conclusions reached.

10. Recommendations

The following recommendations can be considered to reduce the impact of concentrate disposal from inland desalination plants. Proactive approaches must be considered to protect groundwater from further deterioration (i.e. lining systems, long term monitoring program, field research, etc.). Regulations and polices related to reject brine chemical composition and concentrate disposal must be implemented and enforced. Private companies have to be encouraged by government to play a role in research, education and training in the field of desalination. Options that can be adopted by the UAE and the Gulf countries are highlighted below:

1. *Zero-discharge of brines from desalination plants*: Industries should apply pollution

reduction programs including, recycling and reusing water, and developing alternative technology. The zero discharged concepts deal with the reduction in waste volume.

2. *Use of reject in solar pond for electricity*: Saline effluents from large desalination plants are increasing dramatically, especially in the Arabian Gulf region. Solar ponds can be used for the production of heat and electricity.

3. *Enhanced evaporation mechanism*: The size of the evaporation pond affect the rate at which reject brine is evaporated from it. Different methods such as spraying of brine, creating turbulence in the pond, and creating airflow over the pond could be adopted.

4. Use of reject brine from desalination plants as a growth medium for spirulina, fish, and shrimp culture: Treated reject brine water from desalination plants with high alkalinity and salinity, and the availability of solar radiation and high temperature can provide an ideal growth medium for spirulina, i.e. arthospira platensis and tilapia, which are of high commercial value. Adopting such project can contribute to the decrease of the cost of waste disposal, and reduce the impact on the environment.

5. *Chemical conversions of salt concentrate from desalination plants*: There is a possibility of producing some chemicals from the salt concentrate. The preliminary results indicate the chance of converting NaCl to producing Na_2CO_3, $NaHCO_3$ and NH_4Cl using a series of batch gas bubbler, and

6. *Mineral Extraction from desalination reject brine*: Extraction of minerals from desalination reject brine can represent a potential important source of minerals, minimize disposal cost and reduce the stress on the environment.

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