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Groundwater Quality of Coastal Aquifer Systems in the Eastern Coast of the Gulf of Aqaba, Saudi Arabia

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ABSTRACT

Groundwater aquifers of the eastern coast of the Gulf of Aqaba, Saudi Arabia, are of critical economic and social significance to the region, where groundwater is the sole source of irrigation and drinking water. Evaluation of groundwater quality of the coastal aquifers revealed that groundwater salinization is widespread. Groundwater samples exceeded the permissible limits for the majority of drinking water parameters tested except for dissolved metals. The occurrence of very low trace element levels probably reflects natural sources. The distributions of total dissolved solids were found to vary spatially. The variability observed within the groundwater samples is primarily related to seawater intrusion, mineral dissolution in the aquifer, distance from the sea, solutes in recharging water, time of year. Wells located in the upper north part of the study area were highly contaminated compared to southern wells. In addition, the occurrence of high salinity in the northern wells may be the result of surface water flow direction, where leaching and runoff flushing through the basin occur. Saline groundwater might occur due to both high evaporation and dissolution of evaporate minerals. Nitrate concentrations are variable but showed elevated levels. Evaluation of usability of groundwater aquifer for irrigation revealed that the majority of wells are generally not suitable for irrigation use under normal conditions but rather for salt-tolerant plants or livestock watering.

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INTRODUCTION

Seawater intrusion is a common problem encountered in coastal aquifers around the globe (Batayneh, 2006; Mondal *et al*., 2010, Mondal *et al*., 2011; Batayneh, 2013). It takes place when saline water displaces or mixes with freshwater in aquifers. This phenomenon can be attributed to a variety of conditions like gentle coastal hydraulic gradients, tidal and estuarine activity, sea level rises, low infiltration, excessive withdrawal, and local hydrogeological conditions (Barrett *et al*., 2002; Saxena *et al*., 2004; Melloul and Collin, 2006; Lee and Song, 2007; Mondal *et al*., 2008; Kim *et al*., 2009). One of the most common methods for assessing seawater intrusion through an aquifer in coastal belts is a periodic analysis of groundwater chemistry (Saxena *et al*., 2003; Beddows *et al*., 2007; Sarwade *et al*., 2007).

The interaction between ground and surface water can be investigated using a variety of approaches, including (i)experimental determination and estimation through numerical modeling (Sakr, 1999; Zhou *et al*., 2000; Sadeg and Karahanolu, 2001; Ghosh Bobba, 2002; Zhang *et al*., 2004; Qahman and Larabi, 2006); (ii)geophysical surveys (Nowroozi *et al*., 1999; Batayneh, 2006; Adepelumi *et al*., 2009; Batayneh *et al*., 2010); (iii) circulation of groundwater using specific electrical conductance and groundwater temperature as tracers (Beddows *et al*., 2007); (iv)pressure data from fresh and saline zones (Kim *et al*., 2007); (v)submarine groundwater discharge and freshwater-saline water interaction (Taniguchi *et al*., 2007); (vi)isotopic signatures like stable isotopes, radiogenic isotopes and 87Sr/86Sr ratios (Bottomley *et al*., 1999; Beaucaire *et al*., 1999; Barth, 2000; Casanova *et al*., 2001; Négrel and Casanova, 2005); (vii)GIS method based on Na^+/Cl^-, Na^+/Ca^{2+}, Mg^{2+}/Ca^{2+}, EC, SAR and mixing ratios (Somay and Gemici, 2009); and (viii)multivariate statistical techniques, such as multiple linear regression, principle component analysis, Q-mode factor analysis and cluster analysis (Edet *et al*., 2003; Papatheodorou *et al*., 2007; Liu *et al*., 2008; Yaouti *et al*., 2009; Batayneh and Zumlot, 2012).

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Saudi Arabia has experienced dramatic population growth, urban expansion and economic development over the last few decades. In a desert country with very limited surface water resources, Saudi Arabia depends largely on groundwater resources to fulfill the growing demand for water. This has created significant pressure on groundwater resources and led to extensive use of groundwater reserve. Groundwater aquifers of the eastern coast of the Gulf of Aqaba, Saudi Arabia, are of critical economic and social significance to the region where groundwater is the sole source of irrigation and drinking water. Excessive withdrawal of groundwater has resulted in decline in water levels and has led to widespread seawater intrusion from the Red Sea. In addition, inappropriate resource use and absence of proper management practices have resulted in quality deterioration of groundwater and has become a source of concern for water management resources authorities. With ever-increasing water demands, management and protection of groundwater resources of Saudi Arabia, particularly in the eastern coast of Gulf of Aqaba, is a crucial issue for the future of the region. Among other uses, irrigation is the largest consumptive use of water in the region, and groundwater sources contribute the majority of water used for irrigation. While coastal groundwater aquifers have been a major natural source of water supply for the eastern Gulf of Aqaba, the quality of water has not been fully investigated.

The objective of the present study is to ascertain the shallow groundwater quality conditions along the coastal region of the Gulf of Aqaba in northwest Saudi Arabia. It also intends to assess the status of saline intrusions, cause of salinization of groundwater aquifers and the potential for contamination from other sources. This aids decision-makers and public authorities manage existing water supplies and satisfy different resource users.

MATERIALS AND METHODS

Description of Study Area:

The Gulf of Aqaba is the eastern deep gulf of the northern tip of the Red Sea. It is a partially-enclosed coastal water body that is connected to the Red Sea by the Strait of Tiran. The Gulf of Aqaba is about 180 km long with a maximum width of 25 km (Fig. 1). It is located in the sub-tropical arid climate with extremely high temperatures and low precipitation. The oceanographic characteristics of this partially-enclosed portion of the Red Sea created a unique biodiversity in the Gulf of Aqaba.

The coastal plain of the Saudi Gulf of Aqaba is approximately 0.5 to 20 km wide and is accessible by one modern highway joining Saudi Arabia in the south with Jordan to the north. The study area is located on the eastern coast of the Gulf of Aqaba which stretches approximately 1 km from the Jordanian border in the north and trends about 50 km south toward the Strait of Tiran (Fig. 1). This portion contains groundwater resources that are important for public water supplies and also for irrigation and livestock farming. For the purpose of comparison, the wells were divided into three groups: group 1 (wells from 1-17), group 2 (18-22) and group 3 (only well 23). Wells of group 1 are located in the southern part of the study area whereas group 2 and 3 in the north (Fig. 1) Surface water flow in the study area is nonexistent or limited solely during rare intense rain storms occurring as flash floods.

Geology and Hydrogeology:

Regional scale geological map (1:250,000 scale) for northwestern Saudi Arabia has been prepared by Clark (1986). Later, some other geological studies have been reported by Wyn Hughes *et al*. (1999) and Wyn Hughes and Johnson (2005). According to these studies, the Late Cretaceous Adaffa Formation (fluviatile in origin) is determined as the oldest sedimentary rocks unit, which unconformably overlie the Proterozoic basement (Fig. 1). The metamorphic basement varies in composition from monzogranite to alkali feldspar granite. The Adaffa Formation is then unconformably overlain by deep marine Early Miocene Burqan Formation, which in turn is overlain by marine mudstones, carbonates and evaporites of the middle Miocene age. The poorly exposed middle Miocene Mansiyah and middle to upper Miocene Ghawwas formations are made of marine evaporites and shallow to marginal marine sediments, respectively. The youngest rocks in the area are the alluvial sands and gravels of the Late Pliocene Lisan Formation.

The area under study is located in an extremely arid zone with annual average precipitation of 20 mm and temperatures in the excess of 47 $^{\circ}$C in summer (Batayneh *et al*., 2012a). Rainfall generally occurs during the winter months; however, some of the years pass without any rainfall at all, whereas others receive heavy rainfall of short duration causing ephemeral flooding. The primary sources of water in Saudi Arabia are aquifers and basins that are fed/recharged from erratic rainfall. The groundwater aquifers occur in two systems: the shallow alluvial aquifers beneath the wadi systems, and deep rock aquifers, usually hosted by sandstone and limestone (Batayneh *et al*., 2012a). The alluvial shallow aquifer is the primary source of water for agriculture, domestic and industrial uses in the region. The recharge to this aquifer takes place either from the elevated areas in the east, or due to local surface water infiltrations. Water levels vary from about 60 m above sea level in the head waters to about 10 m in the coastal plain.

Sampling and Analytical Techniques:

Groundwater samples were collected in March 2012 from twenty-three different wells along the coastal areas of Gulf of Aqaba, Saudi Arabia. Sampling wells are presented in Fig. 1. The majority of wells sampled is privately owned, dug in shallow aquifers and are located in relative close proximity to the east coast, except for well 23 (deep aquifer and located around 40 km further east from the coast). After purging, samples were collected in1-liter precleaned polyethylene containers. Following collection, samples were kept refrigerated at 4°C and transported to the water laboratory for subsequent chemical analyses. In addition to dissolved metals, a variety of physical and chemical parameters were analyzed (Table 1 and Table 2). Total dissolved solids (TDS), pH, redox potential, specific conductance (EC, μS/cm at 25°C) and dissolved oxygen were directly measured in-situ using portable field meters. Trace elements were measured with Inductively Coupled Plasma Mass Spectrometer (ICP-MS): ELAN 9000 (Perkin Elmer Sciex Instrument, Concord, Ontario, Canada). Anion concentrations were measured in the laboratory using ion chromatograph (IC). Potassium and sodium were measured with Atomic Emission Spectrophotometer (AES). In addition, soil and rock samples from the adjacent geologic units were collected to correlate data and verify observed water conditions. The soil samples were ground, sieved through 2 mm sieve and transferred to plastics bags. Samples were prepared by weighing around 200 mg of samples into a dry and clean Teflon digestion beaker, 6 mL of HNO_3, 2 mL HCl and 2 mL HF were added to the Teflon beaker. Samples were digested on the hot plate at 120-150 ˚C for approximately 40 minutes. The resulting digest was not clear, so it was filtered through Whatman filtered paper No.42. The filtered digest was transferred to a 50 mL plastic volumetric flask and made up to mark using deionized water. A blank digest was carried out in the same way. As for the rock samples, 500 mg of rock-powdered samples were placed in a dry and clean Teflon digestion beaker and 2 mL of HNO_3 and 6 mL HCl were added. Samples were digested, filtered and diluted with deionized water similar to soil samples. Dissolved metals contents were measured by ICP-MS.

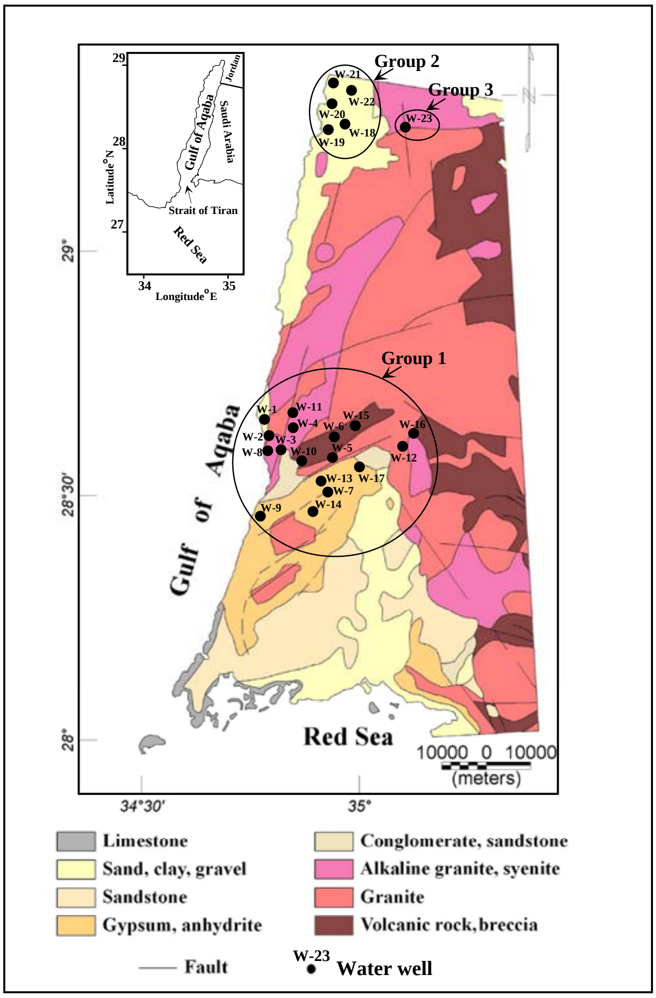

Fig. 1: Geological map for the Gulf of Aqaba-Red Sea region (modified after Clark, 1986). Black circles indicate borehole locations. The inset map shows the Red Sea, the Gulf of Aqaba and the Straits of Tiran.

RESULTS AND DISCUSSION

Groundwater Chemistry:

Results of dissolved metals and physicochemical properties of groundwater samples are presented in Table 1 and Table 2. Metal contents in groundwater samples were low throughout the sampling wells and they are within the range listed for waters suitable for drinking water (WHO, 2008). High concentrations of these metals have been found in the adjacent soil samples and geologic units (Table 3 and Table 4). This suggests that the primary source of dissolved metals to groundwater is not probably metals leached from the surrounding rocks and soils, but rather released from aquifer materials (water-rock interaction). It may also suggest that groundwater aquifer is not significantly recharged from surface runoff or the recharge rate from surface water is low or negligible. This is consistent with the low and erratic annual precipitation rate occurred in the region.

On the other hand, metals may have been released from aquifer sediments and/or leached from soils during events of intense rainfall (occurs as flash flood) but have been either precipitated due to near-neutral pH and oxidizing conditions, or adsorbed onto metal oxides and clays. Metal release from aquifer sediment is affected by pH and salinity, where the lower pH and salinity, the higher the metals released (Gambrell *et al*., 1991; Lau and Chu, 1999). Therefore, the mobilization of the metals from aquifer materials to groundwater is not preferential due to the coupling effect of high pH and salinity of water. In addition, flash rainfall events occur in the region do not favor metal release from rocks as the flow path is rather short. Also, the contact time between water runoff and both soils and rock materials is also short for metals to dissolve due to high water percolation through sandy soils and high rate of evaporation.

Groundwater pH values varied slightly ranging between 7.0 to 7.8 with an average of 7.4 (Table 2). These values are generally consistent with open-system carbonate dissolution (Langmuir, 1971; Batayneh *et al*., 2012b), though, seawater constituents appear to be major contributors to groundwater pH. While there is no much distinct variation of pH among the tested wells, this indicates that the groundwater is probably tapping from aquifers of a single formation. These levels of pH values are within the range listed for waters suitable for drinking water (WHO, 2008).

Elevated levels of TDS in groundwater samples were observed, where the vast majority of wells showed values above 800 and up to 10,018 mg/L (Table 2). Only one borehole (23) exhibits acceptable TDS value for drinking water (406 mg/L). Although drinking water containing more than 500 mg/L is undesirable (WHO, 2008), such water is commonly used in this region as less mineralized water is rare and/or not available. However, groundwater with salinity greater than 3000 mg/L is generally suitable for livestock (sheep farming is common in the area). The TDS values are likely elevated due to dissolution of aquifer materials, leaching soluble salts following irregular rainfall events. In addition, high TDS levels may be due to sea spray, intermittent tidal influences and seawater intrusion. The spatial distribution of TDS in groundwater illustrates that high occurrences of TDS are located further coastward (except for wells 14 and 15). This indicates that dissolved salts are primarily related to saltwater intrusion in the vicinity of the shoreline caused by intensive pumping of groundwater and enhanced probably by evaporative concentration. Besides, dissolving salts from evaporate formation and carbonate layers are contributing factors to high TDS. Additionally, in winter seasons, storms batter the coast and water near shore becomes rough and encroaches towards land. During summer seasons, when the demand of water increases and over-abstraction of groundwater becomes widespread, the saline water finds its way through tidal channels and admixes with shallow coast aquifers. Excessive withdrawal of groundwater coupled by high evaporation and significant decrease in recharge particularly during drought years contributes substantially to increased groundwater contamination by seawater. As for other wells (14, 15) with relatively higher salinity eastward, this is likely related to leaching of nearest localized evaporate outcrops and agricultural discharges following excessive irrigation and over-extraction of groundwater.

TDS data of the upper northern wells (except well 23) exhibited significantly higher TDS values compared to those located in the lower south of the study area. In addition to seawater intrusion, surface drainage pattern in the upper most northern part is directed to the west and northwest, where wells 18-22 are located down-gradient of water drainage. Following intense rainfall, salts and dissolved minerals from the surrounding geologic formations are transported down-gradient following the general flow direction to end up in groundwater. These wells also lie within the beach area and are subjected to regular seawater seepage, particularly during spring tides. We have also observed during groundwater sampling that these wells are extensively abstracted for public use, livestock farming and irrigation as they are located in close proximity to human settlements. Additionally, groundwater wells may have also been enriched in mineral content by irrigation, where inhabitants rely also on agricultural activities for their livelihoods.

On the other hand, surface water runoff is not directed to those wells located in the lower south area and the rate of groundwater extraction is relatively low compared to the northern wells, which is consistent with the lower TDS value observed for the southern wells. However, well 23 exhibited the least TDS level, where it has been probably enriched in mineral content by dissolution of naturally occurring soluble minerals of underground formations, rather than the effects of seawater intrusion. In addition, saline groundwater might occur in well 23 due to both high evaporation and dissolution of evaporate minerals.

Assessment of TDS distribution pattern in groundwater aids public water supplies and regulatory agencies in targeting zones of lower groundwater TDS concentration by relocating wells or by mixing multiple groundwater sources. The artificial recharging of aquifers with fresh groundwater or harvested rainwater can reduce groundwater salinization as the recharge increases the groundwater pressure and reversing the pressure gradient caused by coastal groundwater abstraction. TDS trends also help in quantifying the optimum groundwater abstraction rate without major increase in salinity for sustainable utilization of this water source. Additionally, saltwater intrusion into the shallow groundwater aquifers, particularly those in close proximity to the coast, can be minimized by construction of tidal and subsurface barriers.

Cl^- concentrations in groundwater samples exceed the permissible limit of drinking water set by WHO (250 mg/L) except for well 23 (213 mg/L). Increased concentrations of Cl^- were measured in boreholes nearer the coast, where the highest values were observed in the northern wells. These values indicate a marine source following reverse flow from the sea to the aquifer. Wells located south of the study area showed lower Cl^- concentrations indicating the seawater intrusion occurs but less extensively due to lower rate of groundwater extraction. At some sites close to the coast, Na^+ and Cl^- concentrations are more than 10 times compared to other boreholes located further landward which are indicative of seawater intrusion rather than just the coastal effect of sea spray. In the deep private borehole (23) located further from coast, mineral dissolution is possibly the major source of Cl^- because some evaporate minerals, particularly halite, are common in the area, though seawater intrusion may be additional but a minor contributor to Cl^- content through seawater spray. The concentrations of Na^+ and K^+ varied widely. Na^+ concentrations ranged from 64 mg/L for well number 17 to 3,879 mg/L for borehole 20 (Table 2). K^+ concentrations ranged from 3 mg/L for wells 6 to 39 mg/L for well 15. The average correlation coefficient for both ions is weak (0.37) (Table 5) suggesting different sources for both ions.

On the basis of major ions present in the water, groundwater is dominant by a sequence of Na^+-Ca^{2+}-SO_4^{2-}-Cl^-. There is a positive correlation between Ca^{2+} and Cl^- with correlation coefficient of 0.86 and 0.63 for the northern and southern wells, respectively (Table 5). These values may reflect dissolution of co-occurring halite and gypsum. For the northern wells, the correlation coefficients were 0.98 between Cl^- and TDS concentrations and 0.61 between Ca^{2+} and TDS (Table 5). However, for wells located south, the correlation coefficients between Cl^- and TDS, and Ca^{2+} and TDS became 0.97 and 0.83, respectively (Table 5). These values indicate that seawater intrusion plays a major role in controlling the groundwater chemical composition in the coastal shallow aquifer, particularly in the northern wells.

SO_4^{2-} in the groundwater samples ranged in concentration from 92 to 1402 mg/L. Seventeen of the 23 samples exceed the WHO drinking water limit of 250 mg/L (Table 2). The large concentrations of SO_4^{2-} are mainly from dissolution of evaporite deposits (gypsum and anhydrite).

Total Hardness (TH) of the groundwater samples varied from 646 to 2,478 mg/L with mean and median values of 1,177 mg/L and 811 mg/L, respectively (Table 2). In the northern half of the study area, the average TH concentration is 1098 mg/L where it became 1549 mg/L in the southern groundwater wells. Well 23 showed lower TH value of 646 mg/L. In general, the high values of TH are primarily attributed to the introduction of Ca^{2+} and, to lesser extent, Mg^{2+} into the groundwater system. Ca^{2+} is derived from dissolution of Ca^{2+} bearing minerals from the aquifer material or the adjacent geologic deposits (gypsum and anhydrite). Mg^{2+} is likely derived from intrusion of seawater and dissolution of dolomitic limestone (Batayneh *et al.*, 2012b) which is consistent with high HCO_3^- concentrations in the southern wells. All water samples may be regarded as very hard water (hardness > 300 mg/L) (Radojevic and Bashkin, 1999).

Total Alkalinity (TA) ranged from 90 to 185 mg/L with mean and median values of 132 mg/L and 158 mg/L (Table 2). Relatively higher average TA concentration was observed in the southern wells (138 mg/L) compared to wells located in the north (111 mg/L) which is possibly related to higher HCO_3^- content in wells 1-17 (Table 2). Generally, these values indicate a non carbonate type of groundwater samples, where TH greatly exceeds TA. This is due to the increase in Cl^- and other anions, particularly SO_4^{2-}. Negatively weak correlations were observed between TH and TA (-0.2), (Table 5) suggesting that TH and TA in groundwater aquifers were not derived from the same sources (either leaching/dissolution of minerals, or seawater intrusion) (Batayneh *et al.*, 2012b).

Little variations in dissolved oxygen (DO) levels for groundwater samples were observed (Table 1). DO concentrations varied from 6 mg/L to 7.5 mg/L indicating oxygenated water. Redox (Eh) indicators suggest that the unconfined conditions result in predominantly oxidizing conditions. Eh values of groundwaters ranged between 355 and 394 mV (Table 2); such oxidizing conditions are favorable for immobilization of most elements, which is consistent with low levels of dissolved metals observed in groundwater samples. These values of DO and Eh commonly occur in unconfined shallow aquifer systems as groundwater has not been isolated from the atmosphere for a considerable amount of time.

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Biological oxygen demand (BOD) and chemical oxygen demand (COD) concentrations did not vary systematically ranging from 0.4-2.0 mg/L, and 0.2-1.6 mg/L, respectively. The DO, COD and BOD values indicate the groundwater is relatively not affected by human activities. Nitrates (NO_3^-) are widespread throughout the aquifer and present in all samples, where the concentrations increased in some areas, although not all. NO_3^- concentrations ranged between 7 mg/L and 48 mg/L, with overall mean and median concentrations of 40 and 43 mg/L, respectively. No groundwater samples exceeded the NO_3^- permissible limits for drinking water of 50 mg/L. The relatively high NO_3^- levels found in several samples are probably related to leaching of agricultural nitrogen (especially the use of inorganic fertilizers and manure) with irrigation drainage or during flash floods. Farm livestock also produce nitrogen-containing waste that possibly contributes to groundwater, although BOD values are low. In addition, no reduced nitrogen species (NO_2 and NH_3) were detected because, under oxidizing conditions, nitrate is generally the predominate ion in groundwater due to rapid oxidation of nitrogen species to nitrate.

Suitability for Irrigation Uses:

Water for irrigation use has been evaluated by a variety of water quality parameters, including TDS, pH, metal composition, sodium percentage (Na%), sodium adsorption ratio (SAR), TH and salinity hazard. TDS is an important indicator of the suitability of water for irrigation use. TDS in irrigation water may adversely affect plants directly by the development of high osmotic conditions in the soil solution. Based on Freeze and Cherry (1979) classification, three wells (11, 17 and 23) exhibited freshwater values of less than 1000 mg/L, while the remaining wells present brackish water class which is not suitable for irrigation use under ordinary conditions.

Trace metal composition and pH values of groundwater of the Gulf of Aqaba coast are generally within the permissible limits for irrigation with no restrictions (Ayers and Westcot, 1985).

Sodium affects soils physical properties and high sodium content (SAR) leads to development of alkaline soils. Irrigation with Na-rich water reduces soil permeability as a result of ion exchange between Na^+ and Ca^{2+}/Mg^{2+}. SAR value of greater than 18 indicates a sodium hazard. In this study, SAR values of groundwater samples ranged between 1.03 and 33.92 (Table 6), with the northern wells having the highest SAR values. Groundwater samples from wells 1-17 and 23 showed SAR values below 10 which are rated excellent. Wells 18-22 exhibited elevated SAR value above 10, where two wells (18 and 21) fall under the category of doubtful, well 22 is good and wells 19 and 20 are unsuitable. These high values of SAR indicate that soil sodification/alkalization or reduction of soil infiltration rate is expected, when these waters are used for irrigation. In addition, obvious trends in SAR values have been observed with a relative increase closer to the coast.

Table 1: Statistics for dissolved metals results of groundwater samples.

Borehole Fig. 1	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Pb	Se	Zn
	μg/L														
1	0.2	15.2	7.1	0.3	0.3	0.1	0.5	0.6	93	0.5	0.1	26	2.2	1.5	0.8
2	0.3	9.4	7.5	0.3	0.4	0.1	0.3	0.6	14	18.7	0.3	14	1.9	1.8	0.6
3	0.7	9.6	7.1	0.3	0.3	0.2	0.1	0.7	23	58.3	0.1	17	2.2	0.7	0.5
4	0.2	9.9	6.8	0.4	0.4	0.3	0.4	0.6	2.5	3.9	0.2	24	2.8	1.5	0.3
5	0.7	9.1	8.8	0.4	0.3	0.2	0.5	0.7	3.7	20	0.2	11	2.3	0.9	1.6
6	0.3	9.3	8.7	0.4	0.3	0.1	0.3	0.5	2	3.2	0.2	27	2.2	0.7	3.6
7	0.3	18.5	9.2	0.4	0.3	0.1	0.6	0.5	4	2.3	0.1	13	2.5	2.3	1.6
8	0.6	7	13.9	0.4	0.3	0.1	0.4	0.5	1.2	19.2	0.1	18	2.5	0.9	1.2
9	0.2	8.5	3.3	0.3	0.3	0.1	0.3	0.6	2.7	1.9	0.3	31	3	0.1	0.8
10	0.1	8.6	24.6	0.4	0.3	0.2	0.8	0.5	0.8	21.7	0.1	25	2.1	1.5	1.4
11	0.7	6.6	17.4	0.3	0.3	0.2	0.4	0.5	1.6	4.3	0.2	18	2.1	1.5	0.5
12	0.8	7	10.8	0.4	0.3	0.2	0.6	0.7	1.3	1	0.2	27	2.7	2.8	0.4
13	0.5	7	41.2	0.3	0.1	0.2	0.5	0.5	7.8	0.7	5.2	15	2.9	2.5	6.5
14	1.2	22.8	16.7	0.4	0.3	0.1	2.1	0.7	0.5	2.1	0.3	12	1.3	2.2	0.9
15	2.2	16.4	20.2	0.4	0.3	0.1	0.7	0.6	14.9	0.1	0.7	13	1.7	3	0.4
16	0.4	6.6	43.1	0.5	0.3	0.7	0.7	0.5	2	1.2	0.8	23	2.3	2.3	0.1
17	1	4.9	25.6	0.4	0.3	0.2	0.7	0.6	3.7	0.7	0.3	19	2.4	0.7	1.1
18	0.3	16.4	77.3	0.3	0.3	0.2	1.3	0.8	0.5	0.1	0.8	12	1.1	0.5	1.2
19	0.8	13.2	79.4	0.3	0.3	0.2	0.5	0.6	4.5	28.2	0.1	11	0.1	0.2	2
20	1.5	16.7	100.8	0.2	0.3	0.2	0.4	0.6	0.6	1.8	0.3	22	0.7	0.2	2.1
21	0.9	9.7	44.7	0.4	0.3	0.1	1	0.8	0.6	44.3	0.1	14	1.4	0.4	0.3
22	0.1	12.8	68.5	0.4	0.3	0.1	0.8	0.9	0.7	3.5	0.1	21	2	0.4	3.9
23	0.5	4.4	9.1	0.5	0.3	0.1	1.4	0.6	0.2	10.1	0.1	21	1.9	0.2	3.4
Mean	0.6	10.9	28.3	0.4	0.3	0.2	0.7	0.6	8.1	10.8	0.5	19	2.01	1.3	1.5
Max	2.2	22.8	101	0.5	0.4	0.7	2.1	0.9	93	58.3	5.2	31	3	3	6.5
Min	0.1	4.4	3.3	0.2	0.1	0.1	0.1	0.5	0.2	0.1	0.1	11	0.1	0.1	0.1
Median	12	0.6	9.8	8.1	0.4	0.3	0.1	0.95	0.6	46.6	5.3	0.1	23.5	0.8	4.55
SD	0.5	4.8	28.1	0.1	0.1	0.1	0.4	0.1	19.4	15.5	1.1	6	0.7	0.9	1.5
N	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23

Max: Maximum, Min: Minimum, SD: Standard Deviation and N: Number of Samples

Groundwater samples from the southern wells are classified as follows: C3-S1 (11, 12, 17), C4-S1 (1, 3-6, 8, 9, 13, 16) and C4-S2 (2, 7, 10, 14, 15). None of the northern wells is suitable for irrigation (C4-S4), except well 23 which belong to class C3-S1 (Table 6). Class C3-S1 (high salinity-low sodium hazard) indicates that this water is generally acceptable for irrigation of the majority of soils with little danger of exchangeable sodium. However, for other classes (C4-S1, C4-S2, C4-S4) the use of groundwater for irrigation is unsuitable under ordinary conditions or restricted to special circumstances as it increases soil salinity and affects crop yields. Poor groundwater quality can infrequently be used for irrigation of salt-tolerant crops and under very special circumstances of considerable drainage (on coarse-textured soils).

Sodium percentage (Na%) values ranged between 18.04 and 82.08 with an average value of 42.3% (Table 6). The majority of water samples were not suitable for irrigation and fall under the category of permissible (40-60 Na%) based on Wilcox (1955). Eleven wells with Na% level of less than 35 meq/L were found (3-8, 11-13, 16, 17) indicating that groundwater wells suitable for irrigation purposes are located south of the study area. All wells located in the northern half (18-22) have high sodium percent (above 60%) and are clearly not suitable for irrigation use.

Evaluation of water quality for irrigation according to salinity hazards (Wilcox, 1948) showed that it is obvious that the vast majority of groundwater wells presents high and severe salinity hazard and none belongs to low or medium salinity contamination (C1 and C2 classes, Table 6). Groundwater samples fall in the high salinity hazard class (C3) may pose detrimental effects on sensitive crops and adverse effects on many plants. Such areas require careful management practices. Very high salinity water (C4) is not suitable for irrigation under ordinary conditions but may be used for salt tolerant plants on permeable soils with special management practices.

Table 2: Statistics for physical and chemical parameters of groundwater samples.

Borehole Fig. 1	pH	Eh	TDS	Ca	K	Mg	Na	HCO_3	Cl	SO_4	NO_3	F	PO_4	TH	TA	TS	SS	COD	BOD	DO
		mV	mg/L																	
1	7.5	377	1780	269	19	75	338	226	852	302	42	1.1	0.4	977	185	3320	1540	0.4	1.1	6.7
2	7.4	382	1456	259	20	68	257	183	710	312	41	1.0	0.1	925	150	2946	1490	0.2	1.4	6.5
3	7.4	378	1471	476	35	66	238	189	710	797	40	1.1	0.1	1460	155	2976	1505	0.4	1.9	6.6
4	7.5	382	1578	374	17	60	226	220	745	413	39	1.1	0.1	1180	180	3144	1566	0.8	1.5	6.7
5	7.7	376	1411	291	7	58	191	214	710	178	40	1.1	0.1	966	175	2906	1495	1	1.4	7.0
6	7.8	380	1400	464	3	58	338	159	710	935	40	1.0	0.1	1400	130	2880	1480	0.4	1.9	6.1
7	7.6	374	1683	369	17	83	272	128	781	606	42	1.0	0.1	1261	105	3198	1515	0.8	0.4	6.0
8	7.3	377	1184	330	10	42	132	128	568	341	42	1.0	0.1	998	105	2559	1375	1.2	1.5	7.0
9	7.5	370	1784	311	39	73	352	153	781	634	7	1.0	0.1	1078	125	3240	1456	0.4	1.9	7.5
10	7.4	367	1319	316	8	59	447	134	639	925	45	1.0	0.1	1033	110	2820	1501	1	1.7	7.5
11	7.6	367	985	234	10	35	112	165	497	120	40	1.0	0.1	729	135	2317	1332	0.4	1.7	7.0
12	7.6	386	1048	214	5	37	109	140	426	178	38	1.0	0.1	689	115	2488	1440	1.2	0.5	6.9
13	7.5	382	1878	399	6	72	267	165	1065	202	43	1.0	0.1	1293	135	3463	1585	0.4	1.7	6.8
14	7.4	380	3028	427	10	133	482	159	1562	298	48	1.0	0.1	1615	130	4758	1730	0.8	1.7	7.1
15	7.4	378	2583	456	39	96	400	183	1349	350	46	0.9	0.1	1535	150	4253	1670	1	1.9	7.3
16	7.8	377	1124	262	4	38	109	153	568	92	39	0.9	0.1	812	125	2544	1420	0.4	1.9	7.0
17	7.8	377	800	246	16	26	64	171	426	120	28	1.0	0.1	723	140	2122	1322	0.4	2.0	6.2
Mean	7.5	377	1560	335	16	64	255	169	771	400	39	1.0	0.1	1098	138	3055	1495	0.7	1.5	6.8
Max	7.8	386	3028	476	39	133	482	226	1562	935	48	1.0	0.4	1615	185	4758	1730	1.2	2.0	7.5
Min	7.3	367	800	214	3	26	64	128	426	92	7	0.9	0.1	689	105	2122	1322	0.2	0.4	6.0
SD	0.2	5	561	86	12	26	126	30	304	278	9	0.0	0.1	291	25	662	107	0.3	4.8	0.4
18	7.2	389	3080	506	24	27	1816	110	3408	408	47	0.8	0.1	1376	90	4838	1758	1.2	1.6	6.9
19	7.1	394	6703	461	24	29	2661	128	4686	331	46	0.8	0.1	1272	105	8835	2132	1.2	0.4	6.2
20	7.0	387	10018	900	29	56	3879	116	7455	302	43	0.8	0.3	2478	95	12722	2704	1.2	1.5	6.9
21	7.0	382	2142	290	20	21	1251	153	1349	1402	45	1.0	0.1	811	125	3762	1620	1.6	1.8	7.3
22	7.1	388	5010	677	21	29	1639	110	3408	465	27	1.0	0.2	1810	140	6940	1930	1.2	1.1	6.7
Mean	7.1	388	5391	567	23	32	2249	123	4061	582	41.6	0.9	0.2	1549	111	7419	2029	1.3	1.3	6.8
Max	7.2	394	10018	900	29	56	3879	153	7455	1402	47.0	1.0	0.3	2478	140	12722	2704	1.6	1.8	7.3
Min	7.0	382	2142	290	20	21	1251	110	1349	302	27.0	0.8	0.1	811	90	3762	1620	1.2	0.4	6.2
SD	0.1	4	3129	232	3	13	1047	18	2243	463	8.3	0.1	0.1	629	21	3549	423	0.2	0.5	0.4
23	7.6	355	406	239	5	12	207	159	213	612	44	1.0	0.1	646	130	1698	1292	1.2	1.9	7.3

Max: Maximum, Min: Minimum and SD: Standard Deviation.

Table 3: Statistics for physiochemical parameters and dissolved metal contents of soil samples.

Statistics	μg/g									
	Ca	K	Mg	Na	HCO_3	Cl	NO_3	SO_4	F	Al	As
Mean	21975	430	2613	3447	2029	3904	1127	5204	213	1112	7.4
Max	62483	1560	7168	20812	3050	7455	2557	20885	275	3044	19
Min	4923	104	686	404	1220	2485	665	1118	180	164	2.0
Median	19431	357	2051	1133	1830	3550	877	2722	196	755	5.0
SD	16621	320	1899	5312	492	1376	508	5356	33	824.1	5.5
N	23	23	23	23	23	23	23	23	23	23	23

Tabel 3: Continue

B	Ba	Be	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Pb	Se	Zn
9.1	9.8	0.2	0.2	1.4	8.7	6.1	2260	0.3	102	0.7	11	0.3	20
19	31	1.4	0.6	4.0	15.0	26.0	5511	0.7	347	4.0	33	0.7	49
3.0	2.5	0.1	0.0	0.3	0.3	2.0	486	0.1	7.5	0.2	2.0	0.1	5
7.5	8.0	0.1	0.1	1.0	9.0	5.0	1692	0.3	94.0	0.5	9.0	0.2	17
4.8	6.8	0.3	0.2	1.1	3.7	5.2	1435	0.2	82	0.8	7.0	0.2	12
23	23	23	23	23	23	23	23	23	23	23	23	23	23

Max: Maximum, Min: Minimum, SD: Standard Deviation and N: Number of Samples.

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Table 4: Statistics for physiochemical parameters and dissolved metal contents of rock samples.

Statistics	μg/g										
	Ca	K	Mg	Na	HCO_3	Cl	NO_3	SO_4	F^-	Al	As
Mean	38964	219	5623	2394	1789	4696	1066	22036	240	2021	7
Max	123611	556	38408	20600	3660	10650	2868	71500	300	9442	20
Min	165	67	247	220	305	1775	384	4100	175	129	2
Median	25783	199	2509	537	1830	3550	827	15300	240	979	6.0
SD	40374	117	8273	4510	778	2043	584.8	19555	30.8	2606	3.9
N	25	25	25	25	25	25	25	25	25	25	25

Tabel 4: Continue

B	Ba	Be	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Pb	Se	Zn
15	11	0.3	0.3	1.8	5.7	4.5	3042	0.4	188	0.4	9.9	1.0	25
54	79	0.8	1.5	6	21	16	10746	1.0	980	1.4	68	2.0	112
5	1	0	0	0.1	1.0	0.6	187	0.1	6	0.0	0.9	0.2	2
12.0	7.0	0.2	0.2	0.7	5.0	3.0	1777	0.4	75.0	0.2	3.0	0.9	15
11	16	0.2	0.4	2.0	3.6	4.2	3174	0.2	229	0.3	16	0.4	26
25	25	25	25	25	25	25	25	25	25	25	25	25	25

Max: Maximum, Min: Minimum, SD: Standard Deviation and N: Number of Samples.

Table 5: Correlation matrix of water quality parameters.

	pH	Eh	TDS	Ca	K	Mg	Na	HCO_3	Cl	SO_4
pH	1.00	-0.50	-0.71	-0.60	-0.50	0.10	-0.76	0.46^{**}	-0.72	-0.30
Eh	-0.50	1.00	0.59^{**}	0.52^{**}	0.24	0.00	0.57^{**}	-0.24	0.60^{**}	-0.15
TDS	-0.70	0.59^{**}	1.0	0.86^{**}	0.41	0.01	0.95^{**}	-0.45	0.98^{**}	-0.08
Ca	-0.60	0.52^{*}	0.86^{**}	1.0	0.42^{*}	0.12	0.80^{**}	-0.44	0.86^{**}	0.05
K	-0.50	0.24	0.41	0.42^{*}	1.00	0.20	0.38	-0.01	0.39	0.16
Mg	0.10	0.00	0.01	0.12	0.20	1.00	-0.21	0.32	-0.10	-0.09
Na	-0.76	0.57^{**}	0.95^{**}	0.80^{**}	0.38	-0.21	1.00	-0.54	0.98^{**}	0.06
HCO_3	0.46^{*}	-0.24	-0.45	-0.44	-0.01	0.32	-0.54	1.00	-0.51	-0.13
Cl	-0.72	0.60^{**}	0.98^{**}	0.86^{**}	0.39	-0.10	0.98^{**}	-0.51	1.00	-0.08
SO_4	-0.30	-0.15	-0.08	0.05	0.16	-0.09	0.06	-0.13	-0.08	1.00
NO_3	-0.21	0.14	0.11	0.08	-0.30	0.09	0.16	0.01	0.15	0.03
F	0.44^{*}	-0.42	-0.65	-0.49	-0.24	0.22	-0.72	0.68^{**}	-0.72	0.15
PO_4	-0.27	0.16	0.45^{*}	0.38	0.19	0.09	0.40	0.13	0.43^{*}	-0.14
TH	-0.54	0.48^{*}	0.80^{**}	0.96^{**}	0.45^{*}	0.38	0.69^{**}	-0.32	0.77^{**}	0.02
TA	0.35	-0.16	-0.37	-0.29	0.03	0.26	-0.48	0.92^{**}	-0.44	-0.14
TS	-0.71	0.59^{**}	1.00^{**}	0.86^{**}	0.41	0.01	0.95^{**}	-0.45	0.98^{**}	-0.08
SS	-0.72	0.62^{**}	0.99^{**}	0.87^{**}	0.40	0.06	0.95^{**}	-0.41	0.93^{**}	-0.04
COD	-0.62	0.22	0.39	0.29	0.03	-0.36	0.50^{*}	-0.48	0.43^{*}	0.29
BOD	0.20	-0.43	-0.29	-0.06	0.05	0.03	-0.25	0.24	-0.26	0.20
DO	-0.19	-0.41	-0.11	-0.14	0.08	0.04	-0.07	-0.01	-0.11	0.15

Tabel 5: Continue

NO_3	F	PO_4	TH	TA	TS	SS	COD	BOD	DO
-0.21	0.44^{*}	-0.27	-0.54	0.35	-0.71	-0.72	-0.62	0.20	-0.19
0.14	-0.42	0.16	0.48^{*}	-0.16	0.59^{**}	0.62^{**}	0.22	-0.43	-0.41
0.11	-0.65	0.45^{*}	0.80^{**}	-0.37	1.00^{**}	0.99^{**}	0.39	-0.29	-0.11
0.08	-0.49	0.38	0.96^{**}	-0.29	0.86^{**}	0.88^{**}	0.29	-0.06	-0.14
-0.30	-0.24	0.19	0.45^{*}	0.03	0.41	0.40	0.03	0.05	0.08
0.09	0.22	0.09	0.38	0.26	0.01	0.06	-0.36	0.03	0.04
0.16	-0.72	0.40	0.69^{**}	-0.48	0.95^{**}	0.95^{**}	0.50^{*}	-0.25	-0.07
0.01	0.68^{**}	0.13	-0.32	0.92^{**}	-0.45	-0.41	-0.48	0.24	-0.01
0.15	-0.72	0.43^{*}	0.77^{**}	-0.44	0.98^{**}	0.97^{**}	0.43^{*}	-0.26	-0.11
0.03	0.15	-0.14	0.02	-0.14	-0.08	-0.04	0.29	0.20	0.15
1.00	-0.22	0.01	0.10	-0.12	0.12	0.18	0.32	-0.14	-0.07
-0.22	1.00	0.00	-0.40	0.73^{**}	-0.65	-0.62	-0.35	0.11	0.01
0.01	0.00	1.00	0.37	0.22	0.45^{*}	0.46^{*}	-0.02	-0.20	-0.06
0.10	-0.40	0.37	1.00	-0.21	0.81^{**}	0.83^{**}	0.17	-0.05	-0.12
-0.12	0.73^{**}	0.22	-0.21	1.00	-0.37	-0.34	-0.42	0.18	-0.04
0.12	-0.65	0.45^{*}	0.81^{**}	-0.37	1.00	0.99^{**}	0.39	-0.29	-0.11
0.18	-0.62	0.46^{*}	0.83^{**}	-0.34	0.99^{**}	1.00	0.40	-0.27	-0.09
0.32	-0.35	-0.02	0.17	-0.42	0.39	0.40	1.00	-0.29	0.31
-0.14	0.11	-0.20	-0.05	0.18	-0.29	-0.27	-0.29	1.00	0.45^{*}
-0.07	0.01	-0.06	-0.12	-0.04	-0.11	-0.09	0.30	0.45^{*}	1.00

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

Hardness of water limits its use for irrigation as it causes closure to irrigation systems. In this study, all groundwater samples exceeded the permissible limit (300 mg/L), where hard water is the predominant type in the majority of groundwater wells (Sawyer and McCarty, 1967).

Residual Sodium Carbonate (RSC) value of greater than 2.5 mg/L is not appropriate for irrigation purposes, from 1.25-2.5 mg/L is marginal and less than 1.25 mg/L is suitable. The RSC values ranged between -10.31 and -47.59 meq/L (Table 6) indicating that all water samples are free of residual sodium carbonate. These values are far well below the 1.25meq/L criterion for safe water, therefore, are suitable for irrigation (Ghosh *et al*., 1983).

Table 6: Sodium percentage (Na%), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and classification based on Wilcox (1948) for groundwater wells in the study area.

Sample No.	SAR	Na%	RSC	Classification based on Wilcox (1948)
	meq/L			
1	4.70	43.74	-15.84	C4-S1
2	3.67	38.68	-15.50	C4-S2
3	2.71	27.82	-26.06	C4-S1
4	2.87	30.38	-19.97	C4-S1
5	2.67	30.52	-15.79	C4-S1
6	3.93	34.55	-25.37	C4-S1
7	3.33	32.70	-23.09	C4-S2
8	1.82	23.09	-17.84	C4-S1
9	4.66	43.05	-19.05	C4-S1
10	6.05	48.77	-18.46	C4-S2
11	1.81	26.12	-11.87	C3-S1
12	1.81	26.07	-11.47	C3-S1
13	3.24	31.32	-23.13	C4-S1
14	5.21	39.63	-29.70	C4-S2
15	4.44	37.51	-27.67	C4-S2
16	1.66	22.98	-13.71	C4-S1
17	1.03	18.04	-11.65	C3-S1
Mean	3.3	32.6	-19.2	
Min	1.03	18.04	-29.70	
Max	6.05	48.77	-11.47	
SD	1.42	8.38	5.80	
18	21.31	74.34	-25.68	C4-S4
19	32.48	82.08	-23.31	C4-S4
20	33.92	77.40	-47.59	C4-S4
21	19.13	77.23	-13.68	C4-S4
22	16.77	66.53	-34.33	C4-S4
Mean	24.7	75.5	-28.9	
Min	16.77	66.53	-47.59	
Max	33.92	82.08	-13.68	
SD	7.92	5.74	12.77	
Median	21.31	77.23	-25.68	
23	3.54	41.44	-10.31	C3-S1

Conclusion:

This study has been developed to evaluate groundwater quality, particularly the salinity status and cause, in the costal aquifer systems in the eastern coast of the Gulf of Aqaba, Saudi Arabia. Among other physicochemical parameters, salinity remains the principal concern for the usability of groundwater for drinking or agricultural uses. Of the 23 water samples, water from only one wells had TDS value that is acceptable for drinking purposes, whereas the majority of groundwater wells exhibited brackish water. Moreover, based on all parameters tested, none of these wells is suitable for human consumption. High groundwater salinity is probably related to mineral composition of the aquifer material, geochemical processes, dissolution of evaporites, overexploitation, high evaporation rate and surface water flow direction, particularly the northern wells. In the northern part, groundwater salinity is greater than that of the southern wells. The majority of groundwater wells exhibited salinity levels that are generally not suitable for irrigation use, where special management practices of salinity control including salt-tolerant plant should be considered. In addition, these wells need carefully-controlled withdrawal of groundwater to maintain fresh-saline water equilibrium and sustainable water use.

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