

## GEOCHEMICAL PROCESSES AND POLLUTION OF GROUNDWATER BENEATH THE HIGHLY URBANIZED COASTAL AREA OF NORTH JEDDAH, SAUDI ARABIA

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### ABSTRACT

The exponential rise in the urban population of the developing countries during the past few decades, coupled with accelerated urbanization phenomenon, has brought the necessity to develop environmentally sustainable and efficient waste management systems. Rapid urbanization and lack of efficient sewage networks in the City of Jeddah, Saudi Arabia, has led to adverse influences on both groundwater levels and groundwater quality. Groundwater in the coastal aquifer of north Jeddah occurs at shallow depths under unconfined conditions within highly permeable formations. Different sources of recharge have led to a serious problem of groundwater level rise beneath the city (0.10 to 0.12 m/year). Leakage of sewage from septic systems is a prominent source of groundwater pollution. In the present study, groundwater samples for water quality analysis were collected from 56 shallow wells scattered in the city. Results showed variable values for salinity and chemical composition of groundwater. Groundwater salinity ranges from 803 to 74765 mg/l, generally increases northward, where the dominant water type is Na-Cl. It appeared that mixing between groundwater and the Red Sea water could be the main factor for salinization of groundwater. Some samples have Na/Cl molar ratio of 1.00 and very close to one indicating the possibility of halite dissolution in the aquifer matrix or may be possibly due to continuing modification of water chemistry by sewage leakage, where most of these samples were collected from the residential area. The study showed that silicate weathering is not the main source for release of sodium into groundwater. Excess of Ca and Mg in the groundwater revealed that it may be due to the exchange of sodium in the water by calcium and magnesium in clay materials (reverse ion exchange) instead of being derived from the dissolution of carbonate minerals. The saturation index of the most common carbonate minerals showed noticeable variability. It ranges from -0.88 to 0.53 for aragonite, from -0.74 to 0.66 for calcite and from -1.10 to 1.48 for dolomite. Significantly elevated levels of nitrates in most parts of the settlement (up to 1050 mg/l) can be related to nitrification of ammonium-rich municipal wastewater that is disposed just to the east of the study area in an open pond as well as to irrigation by raw wastewater in vegetable farms to the east of the study area. High  $\text{NH}_4$  levels were observed at the southern more densely settled areas, with a higher density of septic tanks. These high levels indicate that continuous input from septic tank is a prominent source of pollution. The general groundwater flow direction, from east towards west, indicates that polluted groundwater of north Jeddah is ultimately discharged into the sea at the coastline. This process will increase the nutrients flux into the sea, which has detrimental effects on the aquatic ecosystem in north Jeddah.

## 1. INTRODUCTION

Jeddah is one of the major cities of Saudi Arabia, which has become highly urbanized with a continued population growth. It is evident that urbanization may modify the underlying groundwater systems. This often leads to adverse hydrological, water quality, geotechnical, and socio-economic effects. Urban environments significantly alter the nature of recharge to underlying aquifers. Direct precipitation is reduced, but additional recharge may result from storm water runoff, water mains supply leakage and sewer leakage. In order to minimize the effects of urbanization, groundwater management is required irrespective of whether the groundwater is to be used or not.

The geochemical properties of groundwater depend on the chemistry of water in the recharge area as well as on different geochemical processes that are taking place in the subsurface. The quality of water along the course of its underground movement is therefore dependent on the chemical and physical properties of surrounding rocks, the quantitative and qualitative properties of through-flowing water bodies, and the products of human activity (Matthess, 1982).

The increase in groundwater salinity, particularly in coastal area of north Jeddah, may be due to influx of natural saline water, such as sea water intrusion or due to dissolution of soluble salts in the unsaturated zone (e.g. Vengosh *et al.*, 1999; Allison *et al.*, 1990; Herczeg *et al.*, 1991). Anthropogenic contamination is another major cause of salinization and water-quality degradation. One of its most apparent impacts is the increase in the nitrate concentration which is derived from infiltration of sewage effluents, industrial wastes and agriculture return flows (Hern and Feltz, 1998; Hao and Change, 2002; Mitchel *et al.*, 2000; Vengosh and Keren, 1996). Irrigation by groundwater from unconfined aquifers enhances recycling of salts and their accumulation in the aquifer. Moreover, irrigation with wastewater, which

is generally more saline than regional groundwater, increases the rate of salinization of shallow groundwater. This problem is more conspicuous in arid and semi-arid zones where potable water is replaced by wastewater for irrigation in order to save the depleting water resources.

In urban area, additional recharge routes include leaking sewers (Lerner *et al.*, 1994; Barrett *et al.*, 1997) and deliberate recharge through septic tanks in unsewered areas. The complex and ever-changing urban environment makes it difficult to identify individual recharge sources and pathways, and to estimate their contributions to the overall groundwater balance.

A factor common to most urbanization is that it results in impermeabilization (through soil compaction, paving and roofing) of a significant proportion of the land surface and major water imports from outside the urban limits. While land surface impermeabilization can significantly reduce normal soil infiltration (especially in the densely built-up areas), water mains leakage, wastewater disposal and excess irrigation of amenity areas, more than compensate for this reduction in most situations, and the net effect is normally one of increased groundwater recharge. Sanitation and drainage arrangements, which are fundamental to consideration of the urban hydrological cycle, generally evolve with time and vary widely with differing patterns of urban development. In the towns and cities of most developing nations, installation of mains sewerage lags considerably behind population growth and water-supply provision (Foster, 2001).

The objective of the present study was to investigate the geochemical processes occurring in the groundwater environment and the impact of urbanization, particularly the effects of leaky septic tanks and sewage pipes and combined sewer overflows, on the groundwater quality in north Jeddah. Therefore, water quality of shallow groundwater in the phreatic aquifer of north Jeddah has been investigated in order to

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identify possible sources of pollution as well as role of natural geochemical processes such as water/rock interactions. Moreover, spatial distributions of sewage-derived pollutants in groundwater samples collected from the highly urbanized areas of North Jeddah are discussed.

### 1.1. Present status of the study area

The majority of Saudi Arabia's cities are characterized by rapid urban growth during the last several decades. Jeddah, the second (after Riyadh) highly urbanized city in Saudi Arabia, exhibits a noticeable population increase (over 3.7 million in 2006). This demographic growth in the past decades has been caused by migration from the rural areas by people in search of a better life. This has led to the growth of mostly uncontrolled settlements lacking primary services of sewage systems and waste collection and has caused an increasingly negative impact on the environment. The provision of adequate water supply and sanitation to the rapidly growing urban population is increasingly becoming a problem in Jeddah. Currently, desalinated water represents the main source of water supply to the majority of Jeddah's more than 3.7 million inhabitants for both their domestic consumption and for industry. Arising from human activities outlined above, impairment of groundwater quality in the north Jeddah aquifer may be difficult to doubt. However, there is no regular quality monitoring of Jeddah's groundwater resources.

Most of the municipal wastewater of Jeddah city is ultimately disposed in an open pond in Wadi Briman to the northeast of the study area. Most of the disposal site has formed by mining activities of the in-filling detrital soils for construction purposes. Waste dumped in this features is totally sewage. Since replenishment/recharge to the groundwater in north Jeddah occurs occasionally via the same channel that is generally filled with municipal liquid wastes, the danger of quality degradation of the groundwater resource by nitrogen species and

pathogens may not be difficult to envisage. Additionally, around 75% of the domestic sewage is disposed mainly through septic tanks. In order to avoid rapid filling-up of these septic tanks, the practice has been to dig them quite deeply (4–6 m). Unfortunately, this facilitates wastewaters to percolate directly to the shallow unprotected groundwater table (typically 0.60–9.15 m below ground surface). Thus, there is a high likelihood of unhindered access of sewage to the groundwater reservoir, thereby posing great threats of aquifer pollution. This study is dealing with the chemical characteristics of groundwater and pollution of groundwater in relation to urbanization in north Jeddah.

### 1.2. Geologic setting

Jeddah is located on the western margin of the Arabian Shield on the flat low relief coastal plain bordering the Red Sea which is called Tihamat Al-Hijaz. The coastal plain has a width ranging from 8 km to the south to 19 km to the north. The land surface is rocky or sandy and is sparsely vegetated. The whole area is underlain by the Kamil suite (Ramsay, 1983) and consists of the Dighbij and Hafnah complexes, granitic intrusive rocks, metagabbro and gabbro, Rumayda granite and Madrasah Formation.

Jeddah is bounded to the east by hills and mountains which are consisting of Precambrian rocks (Fig. 1). These rocks are represented by Samran Group which are composed of metavolcanics and metasediments of felsic to mafic lavas and volcanic clastic rocks capped with thin sedimentary cover. Samran Group is intruded by Dighbij and Al-Hafnath batholiths. Samran rock units which are encountered in Jeddah are Bahrah, Fayidah, and Madrasah formations (B, F, and M.) (Moore and Al-Rehaili, 1989). There are some occurrences of Tertiary rocks encountered as small outcrop called (Ubhur Formation) located to the north of the study area. Ubhur Formation consists of green sandy clay, siltstone and soft white bioclastic limestone. Basaltic flow lies on the top of Ubhur Formation indicating

a previous fluvial filling whose flanks were eroded probably under the effect of the sea (Hacker *et al.*, 1984). The Quaternary deposits cover an extensive part of the study area. There is a general agreement among several authors that the coastal plain (alluvial and marine deposits) belongs to the Quaternary period (Brown *et al.*, 1963; Al-Sayari and Zöhl, 1978; Hacker *et al.*, 1984).

The coastal plain deposits (Recent and Quaternary) are divided into the following units (Moore and Al-Rehaili, 1989; Al-Quahatani, 1998): (a) *Alluvial deposits* comprise the largest Quaternary units in the study area. They are found in the form of alluvial terraced sandy gravel and silty sand which seems that the later one was formed as a deposition from several wash deposits; (b) *Sabkha soils* exist as grey sandy silt, and they are in immediate contact with the sea in the form of a narrow strip of supratidal deposits; (c) *Coralline limestone Formation* crops out along the coast north of Jeddah and having a range of 5-10 km wide, while it is less than 1 km in the area to the south of Jeddah. The reef limestone exists as discontinuous belt along the Red Sea coast. On the land, the limestone raised 3-6 m above sea level, the limestone is massive and very porous. It is composed of corals and mollusks (Basamed, 2001). The limestone is covered by terraced gravels which are characterized by a shallow dendritic drainage; and (d) *Fills* which are used either to make higher lands as in the Al-Balad district, or filling some saline ponds as in south of Jeddah, and/or for health and beautification reasons as in the Cornish road and As-Salamah district (Bayumi *et al.*, 2000).

The Red Sea fault system affects most of the rock units of the Makkah quadrangle. These faults form three main sets trending approximately northwest, northeast, and north. In many cases represent the reactivation of Precambrian faults (Moore and Al-Rehaili, 1989).

### 1.3. Groundwater Occurrence and Flow

Jeddah is characterized by desert climate, which is slightly moderated by the effects of the Red Sea in the west and of high altitude in the east. Rainfall events are scarce and the mean annual rainfall is about 65 mm falling mainly in November, December and January.

Groundwater occurs within the highly permeable formations in the city, such as surficial soil, sandy gravel and coralline limestone. The clay layers act as confining beds, whereas the sandy silt is an aquitard. Shallow water table (ranges in depth from 0.60 to 9.15 m) usually exists above clay beds, which prevent deep percolation of groundwater. The aquifer is mainly unconfined; however, confined conditions may exist wherever shallow clay beds overlie the carbonate aquifer (Bayumi *et al.*, 2000).

Leakage from water supply network and sewage from septic tanks, exfiltration from cesspool (used for disposal of most of wastewater of the Jeddah city), rainfall recharge, excess landscape irrigation and subsurface inflow from the eastern wadis are the main sources that lead to average annual groundwater level rise of about 0.10 to 0.12 m (Basamed, 2001; Al-Sefry and Sen, 2006). The different and complicated sources of recharge exert great influences on the shallow groundwater quality of Jeddah city.

In coastal aquifers, fresh groundwater normally discharges into the sea if a seaward hydraulic gradient exists. The groundwater flow shown on the water table contour map of north Jeddah (Basamed, 2001) is generally from east towards west (Fig. 2). This means that the shallow groundwater of north Jeddah is ultimately discharging at the Red Sea coastline. Since seawater has a larger density than freshwater, it tends to intrude into the aquifer and lie under the less dense freshwater to form a saltwater wedge. A freshwater/saltwater interface is established once the seawater comes into contact with the freshwater. The interface is a diffusion zone, where hydrodynamic dispersion occurs. The thickness of the interface depends upon some physical parameters of the medium and the flow conditions (Volker and Rushton, 1982).

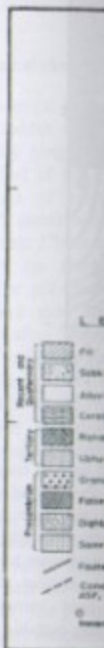


Fig. (1): G

terized by desert climate, moderated by the effects of west and of high altitude events are scarce and the rainfall is about 65 mm falling in December and January. It occurs within the highly urbanized areas in the city, such as gravel and coralline layers act as confining layers. Sandy silt is an aquitard. The aquifer (ranges in depth from 10 to 20 m) usually exists above clay beds. Deep percolation of rainwater into the aquifer is mainly prevented by the overlying shallow clay beds overlying the aquifer (Bayami *et al.*, 2000).

The groundwater supply network and storage tanks, exfiltration from the landfills or disposal of most of the waste (in the Jeddah city), rainfall infiltration, landscape irrigation and runoff from the eastern wadis are the main factors that lead to average annual groundwater rise of about 0.10 to 0.12 m (Al-Sefry and Sen, 2006). The groundwater is a complicated source of various chemical influences on the shallow aquifers of Jeddah city. The fresh groundwater is intruded into the sea if a seaward flow exists. The groundwater table contour map of Jeddah (Al-Sefry, 2001) is generally westward (Fig. 2). This means that the groundwater of north Jeddah is recharging at the Red Sea. Seawater has a larger density than freshwater and tends to intrude into the land under the less dense freshwater. A saltwater wedge is formed under a saltwater wedge. A water table interface is established between the freshwater and the saltwater. The interface is a diffusion zone, where molecular dispersion occurs. The interface depends upon some parameters of the medium and the flow velocity (Volker and Rushton, 1982).



Fig. (1): Geological map of the Jeddah region.

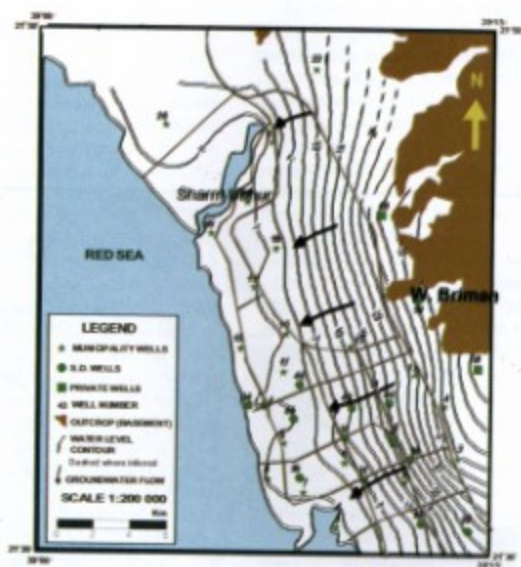


Fig. (2): Groundwater level contour map (1999).

#### 1.4. Groundwater sampling and analysis

In order to understand the general spatial variation in groundwater chemistry over the study area, a well inventory survey was carried out during 2002. Almost all of the wells in the area were monitored for groundwater levels, electrical conductivity (EC) and pH. These data were used to select the representative wells for routine groundwater sampling. Depths to water table in the wells were recorded using a water level indicator. Sampling wells were selected in such a way that they represent different parts of the urbanized areas in north Jeddah. Groundwater samples were collected during 2003 from 56 sampling wells (Jeddah Municipality wells, Sewage Department wells, and private wells). Groundwater samples were collected in clean polyethylene bottles. All sampling bottles were soaked

with 1:1 HNO<sub>3</sub> and washed using detergent. These bottles were then rinsed with double-distilled water. At the time of sampling, sampling bottles were thoroughly rinsed 2–3 times using the groundwater to be sampled. EC and pH of groundwater samples were measured in the field immediately after sample collection using portable EC- and pH-meters. Samples were filtered using 0.45 µm Millipore filter paper and acidified with nitric acid (Ultrapure, Merck) for cation analyses. For anion analyses, these samples were stored below 4 °C. The samples were analyzed for major cations (Ca, Mg, Na, K) and anions (HCO<sub>3</sub>, SO<sub>4</sub>, Cl) as well as for minor constituents (SiO<sub>2</sub>, F, NH<sub>4</sub>, NO<sub>3</sub>, NO<sub>2</sub>, PO<sub>4</sub>, Fe). The chemical analyses were carried out, as per the procedure given in APHA (1998), at the Faculty of Earth Sciences, King Abdulaziz University, Jeddah and at the Saudi Geological Survey, Jeddah, Saudi

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## 2. RESULTS AND DISCUSSION

Results of chemical analysis of the collected groundwater samples are given in Table (1).

### 2.1. Chemical characteristics

The chemical composition of groundwater in north Jeddah is variable, with electrical conductivity ranging from 1340 to 104000  $\mu\text{S}/\text{cm}$ . Most of the groundwater with very high values of electrical conductivity is dominantly distributed in the northern part of the area near Ubhur and close to Dhahban sabkha in the extreme northern part of Jeddah. The pH values range from 6.20 to 7.83, where most of the groundwater is slightly alkaline. The salinity of groundwater is greatly variable and ranging from fresh to highly saline or brine where its value ranges from 0.803 to 74.765 g/l (Fig. 3). The groundwater salinity shows an increasing trend toward the northern part of the study area near Ubhur (e.g. well # 22). Groundwater with low salinity values is encountered in the southern highly urbanized area between Palestine and Heraa streets (well # 31 to the south of Tahlia street) and southeast near the catchment areas (wells # 58, 59, 60). The groundwater salinity in the southern part increases rapidly towards west in the direction of the Red Sea. Exceptionally higher salinity values were recorded in the central part of the area at wells # 13 and 17 to the south of King Abdul Aziz airport. Mixing with seawater is reflected in a high ionic content of groundwater. It is obvious that groundwater quality is degraded seriously in the study area.

Sodium is the dominant cation in most of the analyzed samples where it is followed by Ca or Mg in some samples. Two groundwater samples had Ca as the dominant cation

followed by either Mg or Na (samples # 2 and 45). These two samples were collected from the southern part of the study area. On the other hand, Cl is the most dominant anion in most samples followed by  $\text{SO}_4$  and  $\text{HCO}_3$ . Few samples are characterized by the dominance of  $\text{SO}_4$  over the other anions (e.g. samples # 2, 32, 45, 49, 52, 58 and 60). Only one sample (# 30), collected from the southern part of the area, is characterized by the dominance of  $\text{HCO}_3$  over Cl and  $\text{SO}_4$ . This sample has a salinity value of 894 mg/l which is relatively low compared to other samples. This may be attributed to the effect of recharge water, which is possibly leaking desalinated water mains. Figure (4) shows the Piper plot of the analyzed 56 samples compared to the Red Sea water (using chemical composition of the Red Sea published by Wilson, 1975). This figure indicates that most samples are characterized by the dominance of alkalis (Na + K) over alkaline earths (Ca + Mg) and strong acids (Cl +  $\text{SO}_4$ ) over weak acids ( $\text{HCO}_3$ ) in their hydrochemical facies. Most of these samples are clustered around the plot of the Red Sea water, which indicates possible effect of sea water and/or dissolution of salts derived from sea sprays. At the extreme northern part of the study area, mixing with brine water and dissolution of salts of Dhahban sabkha are most pronounced and reflected in extremely high salinity values (over Red Sea salinity of 42‰). Moreover, a very shallow water level in the study area enhances the effect of evaporation especially in the non-residential areas such as in King Abdul Aziz International Airport. Few samples are characterized by prevalence of Ca + Mg over Na + K and  $\text{SO}_4$  + Cl over  $\text{HCO}_3$ . This may be attributed either to dissolution of Ca-bearing minerals in the aquifer matrix (carbonate minerals and gypsum) or to reverse cation exchange. The diagram also indicates that only one sample (# 30) exhibits dominance of  $\text{HCO}_3$  over Cl and  $\text{SO}_4$ . The ion dominance of this sample may be the result of leakage of fresh desalinated water from water supply mains.

Depending on the most prevalent cation and anion in the groundwater of north Jeddah, the following water types could be distinguished arranged in a decreasing order:

Na-Cl > Na-SO<sub>4</sub> > Ca-SO<sub>4</sub> > Na-HCO<sub>3</sub>.

Salinity values of groundwater samples (eight samples) of the Na-SO<sub>4</sub>, Ca-SO<sub>4</sub>, and

Na-HCO<sub>3</sub> types ranging from 803 to 2585 mg/l. These samples were collected from the southern and extreme eastern parts of the study area. The rest of samples are of Na-Cl type indicating that they reached an advanced state of geochemical evolution, mostly with high to very high salinity values.

Table (1): Chemical data of groundwater from north Jeddah (concentrations in mg/l).

Well No.	T°C	pH	E.C. (µm/cm)	TDS (mg/l)	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	SiO <sub>2</sub>	F	NH <sub>4</sub>	NO <sub>2</sub>	NO <sub>3</sub>	PO <sub>4</sub>	Fe
1	34.2	7.08	34128	21385	715	705	7980	405.3	112	1844	11796	13.0	0.033	0.413	1.200	149	0.105	0.287
2	33.9	7.33	2425	1482	879	276	303	5.1	530	3804	330	43.0	0.031	0.337	0.040	20	0.018	0.030
3	35.2	7.06	15828	8748	355	190	4137	15.0	169	3368	4104	30.0	0.074	0.588	0.031	525	0.280	0.432
4	35.5	7.08	51408	32860	2680	480	10760	26.3	57	2704	18108	23.0	0.111	0.186	0.016	980	0.028	0.426
6	35.6	7.13	7525	4275	95	96	1365	5.4	415	642	1777	32.0	0.043	0.267	0.020	245	0.086	0.071
8	35.6	7.04	14025	7995	104	284	2635	150.3	186	1158	4379	4.3	0.053	0.278	0.032	132	0.030	0.080
9	35.7	6.83	20625	12564	820	410	4032	60.0	116	2732	6275	19.0	0.040	0.249	0.122	136	0.023	0.128
11	35.9	7.28	6300	3382	100	31	1159	4.1	173	968	1587	23.0	0.080	0.295	0.086	41	0.035	0.238
12	34.9	6.97	37308	22568	2617	726	6015	18.6	86	736	14861	20.0	0.055	0.115	0.029	217	0.013	0.273
13	36.1	7.18	75300	52828	2540	1330	15280	19.0	84	2094	21285	16.0	0.079	0.900	0.244	913	0.030	0.907
14	32.9	7.32	5220	2882	81	134	879	55.0	545	384	1220	16.5	0.052	0.200	0.018	16	0.040	0.110
15	33.7	7.05	18960	11859	92	494	3745	208.0	1055	500	6235	16.0	0.042	0.130	0.011	122	0.100	0.047
16	33.7	6.75	30105	18819	1384	458	9025	283.0	96	2540	10187	17.0	0.060	0.200	0.030	201	0.280	0.232
17	32.9	7.02	60105	42174	980	1405	14380	403.0	116	2740	25480	16.4	0.104	0.310	0.030	408	0.030	0.545
18	32.1	7.00	51000	29177	1240	1060	9405	429.0	110	1822	18677	16.9	0.113	0.180	0.014	290	0.070	0.264
19	32.2	7.18	34320	20869	310	602	6810	250.0	143	1740	13025	17.0	0.267	0.200	0.010	238	0.080	0.197
20	33.9	7.06	79025	52885	820	1820	17720	830.0	102	1700	31383	15.4	0.040	0.130	0.018	583	0.180	0.036
21	36.7	7.25	40380	61380	1308	2230	18860	730.0	181	2680	32415	16.4	0.116	0.470	0.027	534	0.080	0.015
22	35.1	6.88	134020	74765	3274	3400	17715	270.0	60	1340	48990	20.0	0.026	1.405	0.018	895	0.180	1.000
23	43.3	7.01	66000	52211	3878	2023	13616	36.0	160	3272	31980	13.0	0.058	0.080	0.012	1060	0.080	0.548
24	32.4	7.02	67905	40278	967	2420	16700	680.0	129	457	36280	13.0	0.026	0.221	0.028	640	0.180	0.087
25	35.5	7.20	41500	25044	218	1802	8115	302.0	152	480	14880	12.9	0.040	0.446	0.019	395	0.070	0.267
26	36.8	7.49	11100	6605	402	138	1846	11.0	152	780	3420	20.0	0.100	0.731	0.043	188	0.080	0.104
28	32.7	7.24	14020	8605	738	289	2515	19.0	182	2234	3775	22.0	0.074	0.182	0.018	75	0.020	0.040
29	35.0	7.28	11040	6251	330	102	2218	6.3	180	1906	2944	15.0	0.063	0.171	0.012	116	0.040	0.020
30	33.0	7.00	1255	684	101	17	171	14.0	447	23	342	42.0	0.007	0.030	0.130	12	0.200	0.005
31	34.0	7.03	1240	686	42	9	228	11.0	265	168	211	34.0	0.015	0.030	0.010	26	0.046	0.012
32	37.8	7.00	3020	1580	96	30	425	15.0	365	878	404	26.0	0.073	0.670	0.013	4	0.016	0.030
33	38.0	7.14	9800	5401	717	115	1740	33.0	70	2764	2135	22.0	0.107	0.218	0.022	160	0.099	0.064
34	35.7	7.00	6900	4040	29	126	1246	60.0	108	714	1820	6.5	0.047	0.171	0.003	20	0.022	0.024
35	37.2	7.28	4910	2280	221	82	728	42.0	112	795	866	26.0	0.033	0.276	0.004	47	0.063	0.028
36	36.3	7.04	18800	6118	94	280	2891	140.0	231	1220	2967	11.6	0.096	0.400	0.008	49	0.027	0.080
37	36.8	6.91	4910	2802	186	91	726	43.0	111	226	1427	26.0	0.006	0.058	0.023	128	0.048	0.040
38	35.9	7.21	8400	4702	117	97	1862	18.7	250	1230	1980	27.0	0.060	0.180	0.026	81	0.017	0.026

Table 1 (Co

39	36.2	7.10																
40	36.0	7.00																
41	36.5	7.08																
42	36.8	7.00																
43	36.5	7.00																
44	36.8	7.00																
45	36.5	7.10																
46	36.5	7.00																
47	36.4	7.00																
48	36.2	7.00																
49	36.2	7.10																
50	36.2	7.10																
51	36.2	7.10																
52	36.2	7.10																
53	36.1	6.90																
54	36.2	7.00																
55	36.2	7.10																
56	36.2	7.10																
57	36.2	7.10																
58	36.1	7.24																
59	36.1	7.07																
60	36.2	7.07																
61	36.2	7.07																

Fig. (3



anging from 803 to 2585  
es were collected from the  
eme eastern parts of the  
st of samples are of Na-Cl  
they reached an advanced  
al evolution, mostly with  
alinity values.

centrations in mg/l).

F	Na <sub>2</sub>	NO <sub>2</sub>	NO <sub>3</sub>	PO <sub>4</sub>	Fe
0.02	0.415	1.208	149	0.105	0.207
0.021	0.237	0.843	20	0.018	0.036
0.074	0.988	0.801	325	0.280	0.432
0.111	0.186	0.016	968	0.028	0.436
0.042	0.237	0.020	245	0.080	0.071
0.051	0.214	0.003	102	0.020	0.060
0.040	0.246	0.122	136	0.023	0.128
0.080	0.226	0.086	41	0.025	0.238
0.080	0.115	0.028	217	0.013	0.273
0.075	0.060	0.264	313	0.026	0.267
0.022	0.200	0.016	18	0.040	0.110
0.042	0.120	0.011	122	0.100	0.047
0.080	0.220	0.020	201	0.280	0.222
0.104	0.310	0.009	488	0.020	0.045
0.113	0.190	0.014	280	0.020	0.204
0.087	0.260	0.010	238	0.080	0.197
0.040	0.120	0.018	820	0.100	0.026
0.118	0.475	0.027	634	0.080	0.015
0.028	1.400	0.018	880	0.180	1.000
0.020	0.080	0.012	1000	0.080	0.048
0.028	0.221	0.028	640	0.100	0.087
0.040	0.446	0.019	260	0.020	0.247
0.108	0.751	0.043	180	0.080	0.104
0.074	0.102	0.016	75	0.020	0.040
0.063	0.171	0.012	118	0.040	0.090
0.027	0.220	0.120	12	0.200	0.020
0.073	0.100	0.010	20	0.040	0.012
0.073	0.4070	0.013	4	0.010	0.080
0.107	0.210	0.022	120	0.080	0.084
0.047	0.171	0.020	70	0.020	0.024
0.022	0.076	0.064	47	0.080	0.020
0.026	0.1400	0.026	40	0.027	0.080
0.028	0.028	0.020	128	0.040	0.040
0.020	0.120	0.020	81	0.027	0.020

Table 1 (Cont.)

38	15.2	7.27	1485	1452	98	28	1910	8.3	301	514	1204	2613	0.020	0.100	0.027	72	0.016	0.140
40	14.6	7.62	1000	1269	201	38	1000	19.2	274	747	1448	2613	0.006	13.880	0.003	81	0.024	0.001
42	15.5	7.54	2045	1588	81	22	495	488.9	320	408	547	1718	0.027	1.260	0.008	81	0.060	0.001
43	16.5	7.40	7000	4120	112	34	1744	18.7	220	1628	1627	2518	0.016	5.260	0.100	108	0.024	0.001
44	14.6	7.65	4400	2627	93	12	784	18.7	472	1148	1847	2613	0.002	87.200	0.008	62	0.002	0.001
45	12.5	7.11	4400	2275	820	100	411	32.2	60	1712	1803	1612	0.000	14.700	0.018	2	0.010	0.004
46	12.5	8.05	1810	1275	194	151	821	40.5	378	817	1002	2518	0.016	75.200	0.002	28	0.010	0.230
47	11.4	7.00	2812	2755	108	148	535	39.2	408	142	720	2218	0.026	0.000	0.011	680	0.000	0.750
48	12.2	7.45	17750	10170	643	213	1880	148.0	67	2780	2001	27.4	0.047	10.000	0.007	1	0.070	0.110
49	10.2	7.10	4000	2240	307	108	530	50.0	270	1380	194	2613	0.016	0.000	0.012	2	0.040	0.100
50	12.2	7.11	4000	3030	307	42	732	13.0	274	204	2613	2613	0.016	0.000	0.000	30	0.014	0.121
51	10.5	7.17	30000	18761	251	121	5820	292.0	320	1300	10720	1818	0.047	0.100	0.012	242	0.000	0.740
52	10.5	7.13	1610	2185	616	100	1225	14.4	242	2710	310	2613	0.012	0.000	0.014	100	0.004	0.008
53	11.1	6.18	27000	12780	1201	450	3210	19.8	148	1124	7020	30.0	0.020	0.042	0.002	174	0.007	0.100
54	10.6	7.10	2742	2274	77	38	886	10.0	388	374	841	2613	0.028	0.000	0.002	62	0.018	0.001
55	12.5	7.10	4000	2427	112	84	740	10.0	320	388	1148	2613	0.013	0.020	0.000	83	0.014	0.001
56	11.7	7.23	7400	4335	162	87	1422	15.0	248	740	2700	3610	0.027	0.120	0.008	144	0.011	0.001
57	11.2	7.05	40000	24248	1424	822	7804	21.4	142	3008	10760	340.0	0.002	0.100	0.010	988	0.012	0.920
58	10.1	7.14	1700	928	40	18	280	24.0	345	312	338	12.0	0.012	84.000	0.004	31	0.010	0.243
59	10.4	7.14	6800	4080	401	121	907	0.0	112	270	1680	41.0	0.020	0.008	0.008	102	0.040	0.001
60	14.7	7.81	4050	2245	142	34	1713	13.0	401	2108	730	463.0	0.078	0.148	0.001	243	0.014	0.001
61	18.0	7.27	25000	14010	1185	282	4880	20.0	281	2138	7380	30.0	0.000	11.500	0.002	760	0.700	0.120

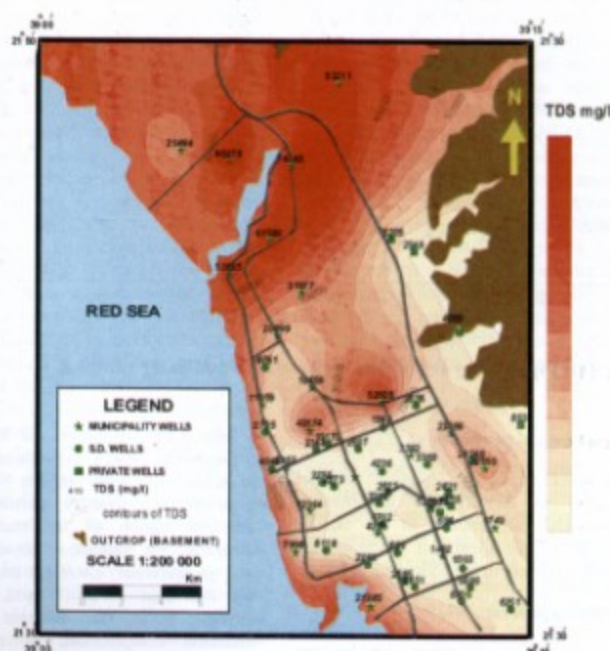


Fig. (3): Spatial distribution of groundwater salinity in north Jeddah.

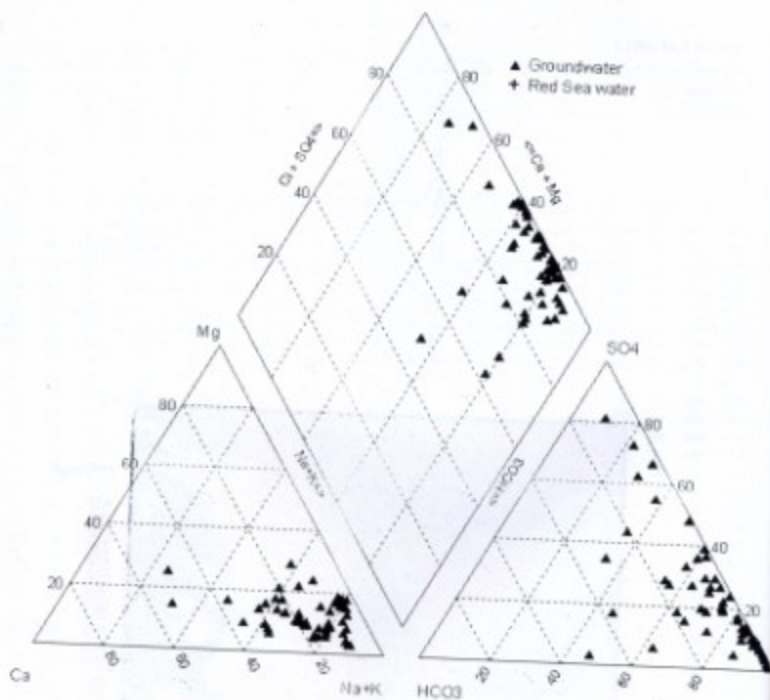


Fig. (4): Piper diagram for the collected groundwater samples.

## 2.2. Geochemical processes

The results from the chemical analyses were used to identify the geochemical processes and mechanisms in the aquifer region. All of the identified processes are explained, in detail, in the following sections.

### 2.2.1. Mixing process

Red Sea and Dhabban sabkha are important features bounding the study area from west and north, respectively and provide

a source of salt water and brine into the groundwater system, as discussed earlier. The presence of this sabkha controls the groundwater chemistry, particularly in the northern region of the study area. To determine the interaction between sea water and groundwater, chemical analysis data of the Red Sea water (Wilson, 1975) were introduced in the different plots. The chemical compositions of most of the groundwater and sea water are similar, which indicates possible mixing with sea water. The

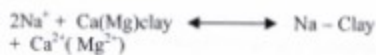
plot of Na and groundwater along lowest salinity of of the study area. Groundwater sample as a single group also shows that the mixing sea water is the mixing taking place in this from the mixing line be attributed to mixing has varying proportions samples were plotted where an extended them indicating evaporation mixing with brine northern part ne Dissolution of halite aragonite and dolomite common minerals in (Kadi, 1988), may be salinity in the north general, it is expected process would cause concentrations of all evaporation process that no mineral species Na/Cl ratio would be and Acworth 1997). Na/Cl versus Cl, as would give a horizontal by evaporation. The (Fig. 6) in the study area the ratio of Na/Cl decreases Cl concentration. As observed at low Cl. Similarly, the Na vs indicates that four salinity plot above whereas only three samples line. This indicates that be the major process of chemistry. Hence, groundwater might have some other processes. responsible for sodium should be approximately whereas a ratio greater

plot of Na and Cl concentrations of groundwater along with mixing line between lowest salinity of groundwater and sea water of the study area is shown in Fig. (5). Groundwater samples of the study area plot as a single group along the mixing line. This shows that the mixing of existing water with sea water is the major mechanism that is taking place in this area. Small deviation from the mixing line can be observed and can be attributed to mixing with wastewater that has varying proportion of Na and Cl. Seven samples were plotted beyond sea water point, where an extended dash line pass through them indicating evaporation process/and or mixing with brine water in the extreme northern part near Dhahban sabkha. Dissolution of halite, gypsum, calcite, aragonite and dolomite, which are the common minerals in the Dhahban sabkha (Kadi, 1988), may be a possible source of salinity in the northern part of the area. In general, it is expected that the evaporation process would cause an increase in concentrations of all species in water. If the evaporation process is dominant, assuming that no mineral species are precipitated, the Na/Cl ratio would be unchanged (Jankowski and Acworth 1997). Therefore, the plot of Na/Cl versus Cl, as an indicator of salinity, would give a horizontal line, which would then be an effective indicator of concentration by evaporation. The Na/Cl versus Cl plot (Fig. 6) in the study area indicates clearly that the ratio of Na/Cl decreases with increasing Cl concentration. A high Na/Cl ratio is observed at low Cl value (<800 mg/l). Similarly, the Na versus Cl plot (Fig. 5) indicates that four samples with maximum salinity plot above the evaporation line whereas only three samples plot along the line. This indicates that evaporation may not be the major process controlling groundwater chemistry. Hence, chloride in the groundwater might have been derived from some other processes. If halite dissolution is responsible for sodium, the Na/Cl molar ratio should be approximately equal to one, whereas a ratio greater than one is typically

interpreted as Na released from a silicate weathering reaction (Mayback 1987). In the present study, the molar ratio of Na/Cl for groundwater samples generally ranges from 0.59–3.33 (Fig. 6). Some samples have Na/Cl molar ratio of 1.00 and very close to one indicating the possibility of halite dissolution in the aquifer matrix or may be due to continuing alteration of water chemistry by sewage, where most of these samples were collected from the residential area. Samples having a Na/Cl ratio greater than one (Fig. 6) indicate excess Na, which might have derived from silicate weathering where the eastern catchment areas are totally made up of igneous rocks. If silicate weathering is a probable source of sodium, the water samples would have  $\text{HCO}_3^-$  as the most abundant anion (Appelo and Postma, 2005). This is because of the reaction of the feldspar minerals with the carbonic acid in the presence of water releases  $\text{HCO}_3^-$  (Elango *et al.*, 2003). In the study area,  $\text{HCO}_3^-$  is not the dominant anion in groundwater indicating that silicate weathering is not the main source for release of sodium into groundwater. This confirms the effect of sewage pollution on the groundwater chemistry where varying concentrations of Na and Cl are characteristic for sewage. However, groundwater samples with a Na/Cl ratio around and less than one indicate the possibility of some other chemical processes, such as ion exchange.

### 2.2.2. Reverse ion exchange

The plot of  $\text{Ca} + \text{Mg}$  versus  $\text{SO}_4 + \text{HCO}_3^-$  will be close to the 1:1 line if the dissolution of calcite, dolomite and gypsum are the dominant reactions in the aquifer system. Ion exchange tends to shift the points to the right due to an excess of  $\text{SO}_4 + \text{HCO}_3^-$  (Fisher and Mulican, 1997; Rajmohan and Elango, 2004). If reverse ion exchange is the process, it will shift the points to the left due to a large excess of  $\text{Ca} + \text{Mg}$  over  $\text{SO}_4 + \text{HCO}_3^-$ , which can be explained by the following reaction:



The plot of Ca + Mg versus  $\text{SO}_4 + \text{HCO}_3$  (Fig. 7) shows that most of the groundwater samples from north Jeddah are clustered around and above the 1:1 line. An excess of Ca and Mg in the groundwater of the coastal plain aquifer of north Jeddah may be due to the exchange of Na in the water by Ca and Mg in clay material. Groundwater samples which are plotted on and below the 1:1 line indicate excess  $\text{SO}_4$  and  $\text{HCO}_3$ . The plot of  $m(\text{Ca} + \text{Mg})$  versus  $m(\text{Cl})$  (Fig. 8) indicates that Ca and Mg increase with increasing salinity. The plots of Na/Cl molar ratio versus Cl (Fig. 6) and  $m(\text{Ca} + \text{Mg})$  versus  $m(\text{Cl})$  (Fig. 8) clearly indicate that salinity increases with the decrease in Na/Cl and increase in Ca + Mg, which may be due to reverse ion exchange in the clay-bearing aquifer materials. During this process, the aquifer matrix may adsorb dissolved Na in exchange for bound Ca and Mg. The sources of Ca and Mg in groundwater can be deduced from the

(Ca + Mg)/ $\text{HCO}_3$  molar ratio. As this ratio increases with salinity (Fig. 9), Mg and Ca are added to solution at a greater rate than  $\text{HCO}_3$ . According to Sami (1992), this ratio would be about 0.5 if Ca and Mg originate solely from the dissolution of carbonates in the aquifer materials and from the weathering of silicate minerals such as pyroxene or amphibole. Figure (9) shows that (Ca + Mg)/ $\text{HCO}_3$  molar ratios of few samples are less than 0.5 that could be the result of either Ca + Mg depletion by cation exchange or  $\text{HCO}_3$  enrichment. However, high ratios cannot be attributed to  $\text{HCO}_3$  depletion; under the existing alkaline conditions,  $\text{HCO}_3$  does not form carbonic acid ( $\text{H}_2\text{CO}_3$ ) (Spears, 1986). High ratios of most samples, therefore, indicate other sources for Ca and Mg, such as reverse ion exchange, which is observed in the coastal plain groundwater of north Jeddah with an increase in salinity (Fig. 9). A ratio less than 0.5 may be due to the exchange of calcium and magnesium in water by sodium bound in the clay.

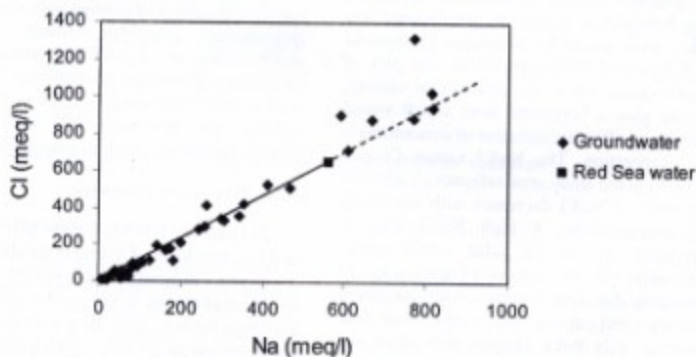


Fig. (5): Plot of Na versus Cl showing mixing and evaporation processes.

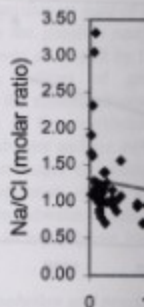


Fig. (6): Plot of

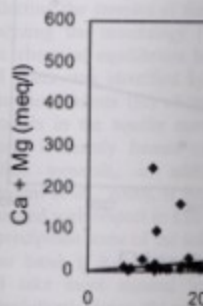


Fig. (7): Relation

molar ratio. As this ratio (Fig. 9), Mg and Ca ion at a greater rate than to Sami (1992), this ratio if Ca and Mg originate from the weathering of carbonates in rocks and from the weathering of silicates such as pyroxene or olivine. Figure 9 shows that (Ca + Mg) ratios of few samples could be the result of either cation exchange or precipitation. However, high ratios of Ca and Mg to  $\text{HCO}_3^-$  depletion; under these conditions,  $\text{HCO}_3^-$  does not precipitate as acid ( $\text{H}_2\text{CO}_3$ ) (Spears, 1992). For most samples, therefore, the high Ca and Mg ratios are due to the exchange of calcium in water by sodium

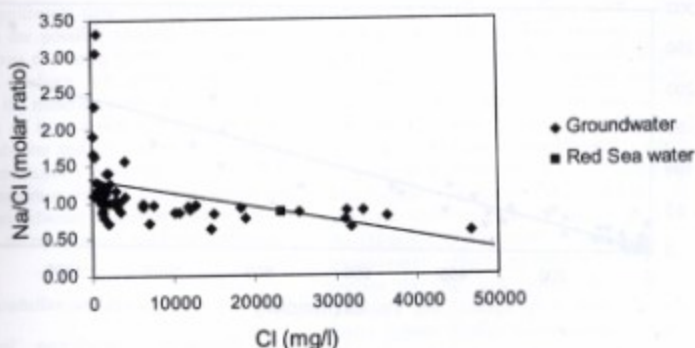


Fig. (6): Plot of Na/Cl molar ratio versus Cl.

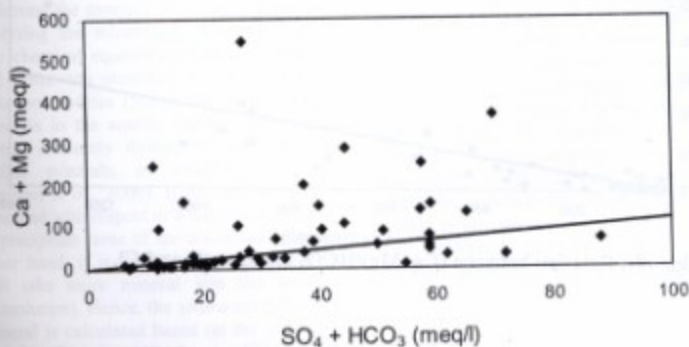


Fig. (7): Relation between Ca+Mg and  $\text{SO}_4 + \text{HCO}_3$ .

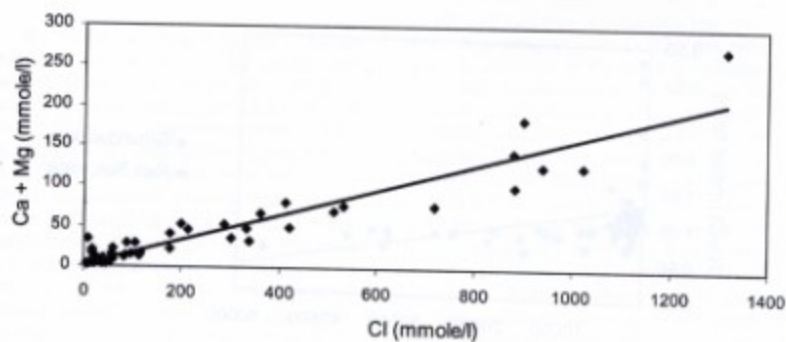
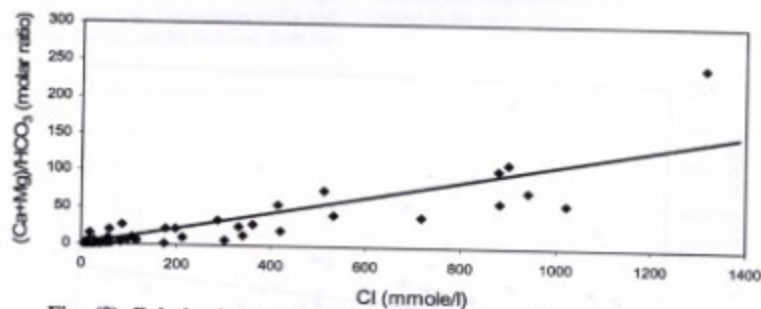


Fig. (8): Relation between Ca+Mg and Cl.

Fig. (9): Relation between (Ca+Mg)/HCO<sub>3</sub> molar ratio and Cl.

### 2.2.3. Geochem

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### 2.2.4. Dissolutio

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### 2.2.3. Geochemical equilibria and reaction

The equilibrium state of groundwater with respect to the possible reactant and product minerals was evaluated by the calculation of saturation indices of groundwater with respect to the mineral phases, providing some indication of the equilibrium state between the groundwater and the surrounding mineral rock assemblages (Njitchoua *et al.*, 1997). The investigation of the mineral equilibria state of groundwater of this area has revealed that it is in equilibrium with the carbonate minerals.

### 2.2.4. Dissolution and precipitation

Mineral equilibrium calculations for groundwater are useful in predicting the presence of reactive minerals in the groundwater system and estimating mineral reactivity (Deutsch, 1997). By using the saturation index approach, it is possible to predict the reactive mineralogy of the subsurface from groundwater data without collecting the samples of the solid phase and analyzing the mineralogy (Deutsch, 1997). The chemical equilibrium between minerals and water was identified by calculating the saturation indices (SI) of the most common minerals in the aquifer matrix. The aquifer matrix is mainly formed of carbonate and sulfate minerals, in addition to quartz (Bayumi *et al.*, 2000). If the groundwater is saturated with respect to a mineral, it is prone to precipitate some of the solute load. On the other hand, if it is undersaturated (SI < 0) it will take more mineral into the solution (dissolution). Hence, the saturation index of a mineral is calculated based on the following equation (Lloyd and Heathcote, 1985):

$$SI = \log \frac{IAP}{K_{sp}}$$

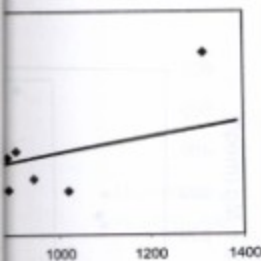
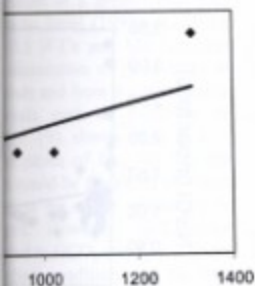
where IAP is the ion activity product and  $K_{sp}$  is the solubility product of the mineral.

PHREEQC (Parkhurst and Appelo, 1999) was used to determine saturation indices (SI)

for associated minerals in the groundwater of north Jeddah. The SI of the most common carbonate minerals varies from -0.88 to 0.53 for aragonite, from -0.74 to 0.66 for calcite and from -1.10 to 1.48 for dolomite. Figure (10) shows that most groundwater samples varies from near equilibrium to oversaturation with respect to calcite and dolomite, whereas groundwater varies between undersaturation and oversaturation with respect to aragonite. Oversaturation with respect to these minerals may be attributed to the influence of evaporation of the shallow groundwater, which concentrates dissolved species in the soil zone. Recharge of rainwater and leakage of sewage from the septic system flushes concentrated solutions from the soil zone into groundwater as well as dissolves the precipitated minerals, which increases the SI of groundwater. However, as sewage leakage continues, the saturation levels go down due to dilution.

The study of the Ca/Mg ratio of groundwater from this area also supports the dissolution of calcite and dolomite present in the alluvium. That is, if Ca/Mg molar ratio equals 1, dissolution of dolomite should occur, whereas a higher ratio is indicative of greater calcite contribution (Maya and Loucks, 1995). Higher Ca/Mg molar ratio (>2) indicates the dissolution of silicate minerals, which contribute calcium and magnesium to groundwater (Katz *et al.*, 1998). The groundwater of north Jeddah have Ca/Mg molar ratio varying between 0.12 and 4.56 reflecting probable contribution of calcite, dolomite and silicate minerals (plagioclase, amphiboles and pyroxenes) which are derived from the eastern part of the study area.

On the other hand, groundwater samples are mostly undersaturated with respect to gypsum indicating dissolution of gypsum in the aquifer matrix, which leads to an increase of both Ca and  $SO_4$  concentrations in groundwater (Fig. 10). Furthermore, groundwater is oversaturated with respect to quartz indicating its precipitation (Fig. 10).



Ca/Mg ratio and Cl.

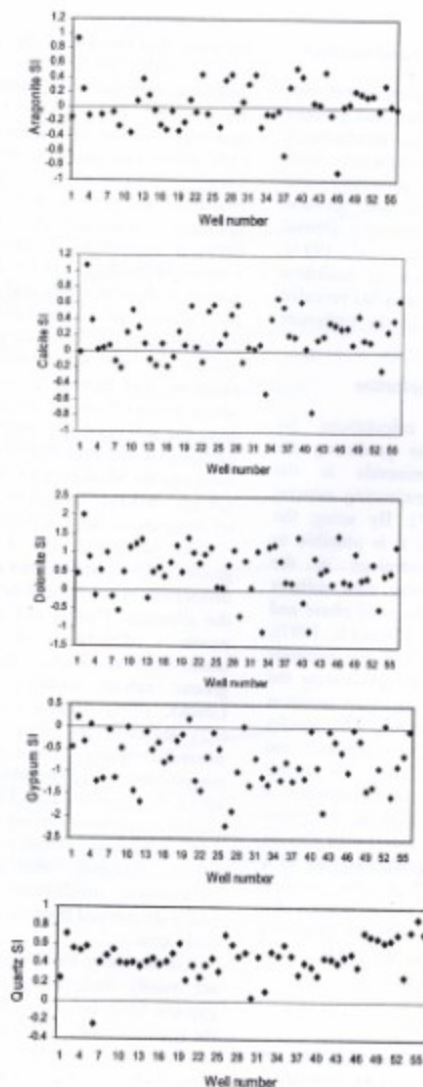
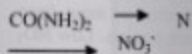


Fig. (10): Saturation indices (SI) of aragonite, calcite, dolomite, gypsum and quartz.

### 2.3. Groundwater pollution

Nitrogen is one of the major elements. The major sources of nitrogen into bodies of water are agricultural and industrial wastewater discharges, animal manure, and emissions from car exhausts. Bacteria can convert nitrites ( $\text{NO}_2^-$ ) to nitrate ( $\text{NO}_3^-$ ). Nitrogen compounds are considered as contaminants in subsurface water, mainly originating from point agricultural sources (Rodvang and Schilling, 2002). In non-constructed septic tanks, wastewater disposal is considered as multi-point groundwater pollution.

Nitrate ( $\text{NO}_3^-$ ) is one of the major levels by anthropogenic activities, such as nitrogenous compounds from fertilizer and by-products from agricultural compounds from agriculture and poultry or cattle manure (Williams *et al.*, 1998; Williams *et al.*, 1998). excreted waste is mainly nitrogenous, which is hydrolyzed to nitrate ( $\text{NO}_3^-$ ) in the soil zone (W



The hydrolysis of urea leads to a temporary rise in pH and the formation of ammonia, which is volatilized into the atmosphere.

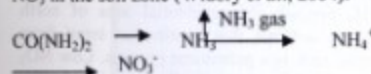
The level of nitrate in groundwater samples varies and fluctuate between a few mg/L to 1 to 1050 mg/L, with a maximum of 239.5 mg/L. Nitrate values in 75% of the samples exceed the allowable concentration for consumption (50 mg/L). Furthermore, about 36% of the samples have values greater than 200 mg/L. Figure 10 shows the spatial distribution of



### 2.3. Groundwater pollution by nutrients

Nitrogen is one of the most abundant elements. The major routes of entry of nitrogen into bodies of water are municipal and industrial wastewater, septic tanks, feed lot discharges, animal wastes and discharges from car exhausts. Bacteria in water quickly convert nitrites ( $\text{NO}_2^-$ ) to nitrates ( $\text{NO}_3^-$ ). Nitrogen compounds are the most widespread contaminants in subsurface environments, mainly originating from non-point and multi-point agricultural sources (Freeze and Cherry, 1979; Rodvang and Simpkins, 2001; Schilling, 2002). In north Jeddah, improperly constructed septic tanks and the unlined wastewater disposal pond (Wadi Briman) are considered as multi-point sources for groundwater pollution with nutrients.

Nitrate ( $\text{NO}_3^-$ ) is often enriched to high levels by anthropogenic activities involving nitrogenous compounds such as mineral fertilizer and by-products of organic compounds from agriculture, septic systems, and poultry or cattle manure (Ostrom *et al.*, 1998; Williams *et al.*, 1998). Nitrogen in excreted waste is mainly in the form of urea, which is hydrolyzed to  $\text{NH}_3$  and converted to  $\text{NO}_3^-$  in the soil zone (Widory *et al.*, 2004):



The hydrolysis of urea produces a temporary rise in pH. This favors the formation of ammonia, which is easily lost to the atmosphere.

The level of nitrate ( $\text{NO}_3^-$ ) in the collected groundwater samples was significantly high and fluctuate between a very wide range from 1 to 1050 mg/L, with an average value of 239.5 mg/l. Nitrate values in the majority of samples (75%) exceeded the maximum allowable concentration for human consumption (50 mg/L), set by WHO (2004). Furthermore, about 36% of the samples have values greater than 200 mg/L. Figure (11) shows the spatial distribution of  $\text{NO}_3^-$  in

groundwater in north Jeddah. It indicates that  $\text{NO}_3^-$  contents are highly variable throughout the study area. The northern and eastern parts of the area have the highest  $\text{NO}_3^-$  concentrations (wells # 20, 21, 22, 23, 24 surrounding Sharm Ubhur and wells # 3, 4, 57 and 61 in the eastern part of the study area). In the eastern part of the area, agricultural activity consists mainly of vegetable productions for which municipal untreated wastewater are used for irrigation. Some wells in the central part exhibited high  $\text{NO}_3^-$  levels (e.g. wells # 13, 17, and 47), where the main source of  $\text{NO}_3^-$  pollution of groundwater is due to poorly constructed septic tanks and private sewage disposal systems. It is very likely that there is a significant contribution from leaking sewers. However, the concentrations of nitrate were low in the some wells in the central and southern parts of the area.

#### 2.3.1. Transformation of nitrogen species

Most of the untreated municipal wastewater of Jeddah city is collected by means of trucks and carried to a dumping site in Wadi Briman to the east of Makkah-Madinah Expressway at the northern part of the study area. This exposed dumping site allows oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  to become a major source of nitrate pollution in the northern part of the study area. Similarly, irrigation by untreated wastewater in the eastern part of the area contributes high  $\text{NO}_3^-$  concentration in groundwater originated mostly from oxidation of ammonium in the unsaturated zone. The source of ammonium was from leakage of effluents from sewers and improperly constructed septic tanks, in which urea and  $\text{NH}_4^+$  prevail over other nitrogen compounds (Jacks *et al.*, 1999; Canter and Knox, 1985). It could have been produced in the unsaturated zone either by relatively fast hydration of urea (Burt *et al.*, 1993) or by slow mineralization of soil organic matter.

ite, dolomite, gypsum and quartz.

Under aerobic conditions,  $\text{NH}_4$  is oxidized easily to  $\text{NO}_3$  within a few hours to a few days and within distances of a few tens of centimeters (Barrett *et al.*, 1999; Leenhouts *et al.*, 1998; Robertson and Blowes, 1995). According to Stumm and Morgan (1996) nitrification (microbial oxidation of ammonium) in the unsaturated zone is described by the equation:



This equation illustrates the reaction that decreases the pH of groundwater (Robertson and Blowes, 1995), which may be reflected in association with low pH and high  $\text{NO}_3$  in samples collected from wells adjacent to the downstream of Wadi Briman, where dumping of sewage is currently occur in the upstream part of the wadi.

In cases where vadose zone residence time is relatively short (hours or <1 week), the oxidation process may remain incomplete. Short residence times may result in greater  $\text{NH}_4$  and lower  $\text{NO}_3$  concentrations than when residency in the unsaturated zone is relatively long (>7 days) (Robertson *et al.*, 1991). Short residence times may occur at some wells (such as short distances between septic tanks and domestic well and a shallow water table) sampled during this work. Positive correlation between  $\text{NO}_3$  and Ca concentrations ( $r = 0.75$ ) in groundwater of north Jeddah (Fig. 12) provides evidence for the development of this process. Increased acidity during nitrification leads to carbonate dissolution, which results in Ca enrichment of groundwater. Furthermore, dissolution of carbonate minerals tends to increase pH, which is reflected in the neutral to slightly alkaline nature of groundwater in the study area.

Ammonia concentration might also decrease as a result of ammonia volatilization and sorption on clay particles (Jacks *et al.*, 1999). The potential for ammonium sorption in soil is limited, and this pathway is not likely to be important in the long-term nitrogen budget of the soil system

(Venhuizen, 1999). In the sandy unsaturated zone with a clay content of less than 0.5%, the sorption of ammonium has to be negligible.

Denitrification (microbial reduction of nitrate) in groundwater under anoxic conditions, reaches its final stage where  $\text{NO}_3$  is transformed to  $\text{N}_2$  gas following the reaction (Stumm and Morgan, 1996):



Contrary to nitrification, denitrification is a process with relatively slow kinetics (Stumm, 1990). Anaerobic conditions may result in the formation and persistence of nitrite. The formation of nitrite is as a consequence of microbial activity and may be intermittent. Nitrification can increase nitrite levels (WHO, 2004). High  $\text{NO}_3$  concentration was encountered at the northeastern part of the area (well # 61) near the downstream part of Wadi Briman, where untreated wastewater is dumped. On the other hand, spatial distribution of  $\text{NH}_4$  shows that high levels were observed at the southern part of the study area which is a highly urbanized area as well as at well # 61 (Fig. 13). This area has also low  $\text{NO}_3$  levels. These high levels of  $\text{NH}_4$  beneath the residential area of north Jeddah indicate that continuous input from septic tank is a prominent process. Low  $\text{NO}_3$  levels reflect that nitrification is not the controlling process due to lack of contact between shallow groundwater and the atmospheric oxygen because most of the land surface in this dense residential area is covered by buildings and paved roads. Moreover, anaerobic conditions can develop if substantial amounts of labile organic carbon, possibly derived from septic waste, are present in the aquifer media (Verstraeten *et al.*, 2005).

The general groundwater flow direction from east towards west (Fig. 2) indicates that polluted groundwater of north Jeddah is ultimately discharged into the sea at the coastline. This process will increase the

nutrient flux into the sea which impacts on the aquatic life in Jeddah.

Fluoride (0.006-0.01 mg/l) and phosphate (0.002-25.0 mg/l) were determined, but were not found to be problematically high. A high concentration of  $\text{PO}_4$  (25 mg/l) was recorded in the southeastern part of the study area and may be attributed to phosphorus fertilizers used in the vegetable farms near the coast.

### 2.3.2. Iron

Iron in groundwater is present in the ferrous form ( $\text{Fe}^{2+}$ ) state. It is easily oxidized to the ferric form ( $\text{Fe}^{3+}$ ) or insoluble iron (iron hydroxide) upon exposure to air. High concentrations in the coastal aquifer were observed in samples from north Jeddah and reached up to 1.0 mg/l.



Fig. (11): Spatial di

in the sandy unsaturated zone of less than 0.5%, ammonium has to be

microbial reduction of nitrate under anoxic conditions at its final stage where  $\text{NO}_2^-$  and  $\text{N}_2$  gas following the reaction (Morgan, 1996):



denitrification is a relatively slow kinetics process. Anaerobic conditions may lead to the reduction and persistence of nitrite as a result of microbial activity and may be enhanced as nitrification can increase nitrite levels. High  $\text{NO}_2^-$  concentration is observed in the northeastern part of the study area near the downstream part where untreated wastewater is discharged. On the other hand, spatial distribution of  $\text{NO}_3^-$  shows that high levels are observed in the southern part of the study area, which is a highly urbanized area as shown in Fig. 13. This area has high population levels. These high levels of  $\text{NO}_3^-$  are due to residential area of north Jeddah and the continuous input from the urban area is a dominant process. Low  $\text{NO}_3^-$  concentration is observed due to lack of contact with groundwater and the reason is because most of the land in the dense residential area is covered by buildings and paved roads. Anaerobic conditions can develop in the aquifer because of labile organic matter derived from septic waste, which is a common aquifer media (Verstraeten

and Verstraeten, 1990). Groundwater flow direction is generally west (Fig. 2) and this indicates that groundwater of north Jeddah is discharged into the sea at the coast. This process will increase the

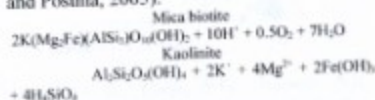
nutrient flux into the sea, which has negative impacts on the aquatic ecosystem in north Jeddah.

Fluoride (0.006-0.116 mg/l) and phosphate (0.002-25.0 mg/l) levels were also determined, but were not found to be problematically high. Anomalous value of  $\text{PO}_4$  (25 mg/l) was recorded at well # 58 at the southeastern part of the area, which may be attributed to phosphate fertilizers applied in the vegetable farms scattered in this area.

### 2.3.2. Iron

Iron in groundwater is normally present in the ferrous form ( $\text{Fe}^{2+}$ ) which is a soluble state. It is easily oxidized to ferric iron ( $\text{Fe}^{3+}$ ) or insoluble iron (iron hydroxyl complex) upon exposure to air. Total iron (Fe) concentrations in the collected groundwater samples from north Jeddah were significantly low and reached up to 1.0 mg/l. The sources

from anthropogenic activities appear to be unlikely because of the low concentrations of Fe. Fe content may be related to the weathering of mineral grains (such as biotite) composing the igneous rocks covering the elevated catchment areas in eastern part of the study area. The primary reaction through which  $\text{Fe}^{3+}$  oxides are formed is the hydrolytic and oxidative decomposition of  $\text{Fe}^{2+}$  containing primary minerals (mainly  $\text{Fe}^{2+}$  silicates) through the reaction (Appelo and Postma, 2005):



Once formed, the  $\text{Fe}^{3+}$  oxides can be dissolved either through (microbial) reduction to  $\text{Fe}^{2+}$  or through complexation by organic ligands (Awoleye, 1991).

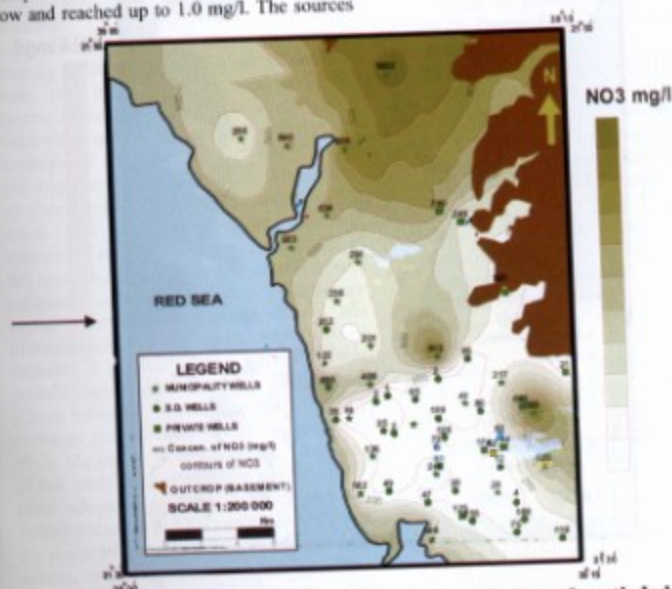


Fig. (11): Spatial distribution of  $\text{NO}_3^-$  in groundwater of north Jeddah.

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## العمليات الجيوكيميائية وتلوث المياه الجوفية تحت المنطفة الساحلية الحضرية المزدحمة في شمال جدة - المملكة العربية السعودية

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ادت الزيادة السكانية المضطردة في الدول النامية في العقود القليلة الماضية وما نتج عنها من ظاهرة التحضر السريع الى ضرورة تنمية الانظمة البيئية المستدامة ونظمة ادارة المخلفات ذات الكفاءة. وقد ادت عملية التحضر السريع ونقص شبكة تجميع مياه الصرف ذات الكفاءة في مدينة جدة بالمملكة العربية السعودية الى تأثيرات ضارة على كل من منسوب المياه الجوفية وجودتها. وتوجد المياه الجوفية في المتكون المائي الساحلي بشمال جدة تحت الظروف غير المحصورة في المتكونات عالية النفاذية وعلى عمق ضحل. وقد ادت المصادر المختلفة للتغذية الى مشكلة خطيرة وهي ارتفاع منسوب المياه الجوفية تحت المدينة (10% - 12% متر/سنة). ويعتبر تسرب مياه الصرف من الخزانات من ابرز مصادر تلوث المياه الجوفية. وقد تم في هذه الدراسة جمع عينات مياه جوفية لتحليل جودتها من 56 بئر ضحل منتشرة في المدينة. وقد اوضحت النتائج وجود تغيرات كبيرة في ملوحة والتركيب الكيميائي للمياه الجوفية. وتتراوح ملوحة المياه الجوفية من 803 الى 74765 مج/لتر. وتزداد بصفة عامة في اتجاه الشمال حيث يكون نوع المياه السائد هو Na-Cl. ومن الظاهر ان عملية الاختلاط بين المياه الجوفية ومياه البحر الاحمر هي اهم عامل لزيادة ملوحة المياه الجوفية. وبعض العينات كانت فيها قيمة نسبة Na/Cl 1.00 وبالقرب من 1.00 مما يدل على احتمال ذوبان الهاليت في المتكون المائي او ربما نتيجة التغير المستمر لكيماوية المياه نتيجة تسرب مياه الصرف حيث تم جمع معظم هذه العينات من المنطقة السكنية. وعلاوة على ذلك فان عسبة تجوية معادن السيليكات ليست المصدر الاساسي لخروج الصوديوم الى المياه الجوفية. واثبتت الزيادة في الكالسيوم والماغنسيوم في المياه الجوفية احتمالية تبادل الصوديوم الموجود في الماء بالكالسيوم والماغنسيوم في معادن الطين (تبادل ايوني معكوس) وليس نتيجة ذوبان معادن الكربونات. ويتراوح معامل التشبع لمعظم معادن الكربونات الشائعة من -0.88 الى 0.53 للاحاديث ومن -0.74 الى 0.66 للكالسيت ومن -1.10 الى 1.48 للذولوميت. وتم الربط بين المستويات المرتفعة للنترات في معظم اجزاء المدينة (بصل حتى 1050 مج/لتر) و عملية تحول مياه الصرف المسدني الغني بالامونيوم الى نترات حيث يتم التخلص منها في شرق منطقة الدراسة في بركة مكشوفة وكذلك نتيجة الري بمياه الصرف غير المعالجة في مزارع الخضروات شرق منطقة الدراسة. ولوحظ وجود مستويات مرتفعة من  $NH_4$  في المنطقة الجنوبية ذات الكثافة السكانية المرتفعة وكذلك خزانات الصرف الصحي. وتدل هذه المستويات المرتفعة على النخول المستمر لمياه الصرف من هذه الخزانات وهو من ابرز مصادر التلوث. ويدل الاتجاه العام لسريان المياه الجوفية من الشرق للغرب على ان المياه الجوفية الملوثة في شمال جدة تصرف في النهاية في البحر عند خط الساحل. وتسودي هذه العملية الى زيادة تنفق المغذيات في البحر مما يكون له تأثيرات ضارة على البيئة الساحلية لشمال جدة.