CHEMISTRY OF GROUNDWATER IN THE DAMMAM AQUIFER, KUWAIT

by

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ABSTRACT: Groundwater of the Dammam carbonate aquifer in Kuwait is strongly undersaturated with respect to halite and is weakly undersaturated with respect to anhydrite and gypsum. In addition, the groundwater is oversaturated with respect to calcite and dolomite. Generally, the saturation indices of most minerals increase in the direction of flow. The salinity of the Dammam aquifer ranges from 2,500 to 10,000 mg/l, but locally a maximum of 150,000 mg/l occurs in the direction of groundwater movement toward the north-northeast. The increase in salinity is attributed to dissolution processes, as indicated by the increases of Cl, SO_4, Ca, and Na ions in the direction of flow. The major hydrochemical water types are Na_2SO_4, $CaSO_4$, and NaCl. Lenses of fresh groundwater, in which the salinity ranges from 200 to 1,400 mg/l, occur in the depression of Al-Rawdhatain and Umm Al-Aish fields, in the Upper Dibdibba Formation of the Kuwait Group aquifer. The aquifers are directly recharged by local precipitation, and fresh groundwater is slightly mixed with brackish waters. These aquifers contain $Ca(HCO_3)_2$ and $NaHCO_3$ type water, in which $HCO_3 > SO_4 > Cl$.

RÉSUMÉ: Les eaux souterraines de l'aquifère carbonaté de Dammam au Koweit sont sous-saturées fortement par rapport à la halite et faiblement par rapport à l'anhydrite et au gypse. En outre, ces eaux sont sursaturées par rapport à la calcite et à la dolomite. En général, les indices de saturation de la plupart des minéraux augmentent dans le sens de l'écoulement. La salinité de l'aquifère de Dammam est comprise entre 2.500 et 10.000 mg/l, mais elle peut localement atteindre 150.000 mg/l dans la direction d'un écoulement vers le nord-nord-est. L'accroissement de la salinité est attribuée aux processus de dissolution, mis en évidence par l'augmentation des teneurs en Cl, SO_4, Ca et Na dans la direction de l'écoulement. Les principaux faciès hydrochimiques sont sulfaté sodique, sulfaté calcique et chloruré sodique. Il existe des lentilles d'eau douce, de salinité comprise entre 200 et 1.400 mg/l, dans la dépression d'Al-Rawdhatam et les plaines d'Umm Al-Aish, dans la formation supérieure de Dibdibba de l'aquifère du groupe du Koweit. Les aquifères sont directement rechargés par des précipitations locales et l'eau douce se mélange progressivement aux eaux salées. Ces aquifères présentent des eaux à faciès bicarbonaté calcique et bicarbonaté sodique, dans lesquelles $HCO_3 > SO_4 > Cl$.

RESUMEN: Las aguas subterráneas del acuífero carbonatado Dammam, en Kuwait, se encuentran fuertemente subsaturadas respecto a la halita, y débilmente subsaturadas respecto a anhidrita y yeso. Además, se encuentran sobresaturadas con respecto a calcita y dolomita. En general, los índices de saturación de muchos minerales crecen en la dirección del flujo. La salinidad del acuífero Dammam varía ente los 2,500 y los 10,000 mg/l, con un máximo local de 150,000 mg/l en la dirección del movimiento del agua, hacia el nor-noreste. El incremento de salinidad se atribuye a procesos de disolución, como indica el aumento en la concentración de iones Cl^-, SO_4^{2-}, Ca^{2+} y Na^+ en la dirección del flujo. Las aguas presentes son básicamente sulfatado-sódicas, sulfatado-cálcicas y clorurado-sódicas. Lentejones de agua dulce, con una salinidad entre 200 y 1,400 mg/l aparecen en las depresiones de los campos de Al-Rawdhatain y Umm Al-Aish, en la Formación Dibdibba Superior del acuífero Kuwait. La recarga en los acuíferos se produce por la precipitación local, lo que supone mezcla entre aguas dulce y salobre. Estos acuíferos contienen aguas de los tipos $Ca(HCO_3)_2$ y $NaHCO_3$, donde se verifica la siguiente relación entre concentraciones: $HCO_3^- > SO_4^{2-} > Cl^-$.

INTRODUCTION

The Dammam aquifer is the most potential and productive reservoir of brackish groundwater in the State of Kuwait and in other Gulf areas, such as Saudi Arabia, Bahrain, and Qatar. Since 1950, the hydrochemistry and hydrogeology of this unit have been studied extensively by the Kuwait Ministry of Electricity and Water and by various researchers (Abuhijleh, 1988; Al-Haddad, 1992; Al-Hajji, 1976; Al-Rashed, 1993; Al-Ruwaih, 1980; Al-Ruwaih, 1993; Al-Yaqubi, 1977; Omar et al., 1981). Useable groundwater occurs in the central and southwestern parts of the country. Therefore, these regions were selected for groundwater exploration. The study areas are Al-Sulaibiya well field; Al-Shagaya area, which includes well fields B, C, and D; Al-Wafra, an agricultural farm area; and the Umm-Gudair area (fig. 1).

The Dammam aquifer is the main natural groundwater reservoir that supplies Kuwait State with brackish water from numerous water-well fields. The salinity of the aquifer generally is 2,500 to 10,000 mg/l, but it increases to 150,000 mg/L toward the northeast (fig. 2). The produced brackish water is blended with distilled water from various distillation plants in a ratio of 10-90, respectively, to make the water suitable for drinking. In addition, the water is used to meet the demands of the agricultural and domestic sectors in Kuwait.

The objectives of this investigation are to identify 1) the water origin, 2) water chemical types of the aquifer and their areal distributions, and 3) trends in water quality over the time. In addition, a determination was made of the degree of saturation of groundwater with respect to some minerals. The results are expected to improve understanding of the extent and availability of groundwater resources of the Dammam aquifer in Kuwait State.

Results of chemical analyses of groundwater samples were analyzed by the computer program WATEQ4 (Ball and Nordstorm, 1992) to calculate the distribution of aqueous species, ion activities, and mineral saturation index, S.I., for each groundwater sample. The main purpose of speciation modeling is to calculate mineral saturation indices, which are indicators of the saturation state of a mineral with respect to a given water composition. Undersaturation means that the minerals could be dissolving, which could lead to the enlargement of cavities and pore spaces in the Dammam aquifer, resulting in increased permeability; when water is oversaturated, minerals could be precipitating, resulting in reduced permeability.

HYDROGEOLOGIC FRAMEWORK

Stratigraphy

The State of Kuwait is located in the western side of the Arabian Gulf and has an area of about 17,600 km^2. Generally, the topography is of low relief and mostly gentle. The ground surface slopes gradually from the southwest toward the shore of the Arabian Gulf. The main topographic features are the Jal-Az-Zor escarpment, Al-Ahmadi ridge and Wadi Al-Batin (fig. 1).

According to Owen and Nasr (1958), the sedimentary rocks underlying Kuwait are divided into five groups; in descending order they are the Kuwait Group (Oligocene-Miocene), Hasa Group (Paleocene-Eocene), Aruma Group (Upper Cretaceous), Wasia Group (Middle and Lower Cretaceous), and Thamama Group (Lower Cretaceous).

Pleistocene deposits are overlain by Recent sedimentary deposits. The Kuwait Group and the Dammam Formation of the Hasa Group are the main productive aquifers of brackish water in Kuwait; fresh-water well fields occur in the northern part of the country (Al-Rawdhatain and Umm Al-Aish). The Dammam Formation crops out in the northern desert of Iraq, 400 km west of Kuwait, where it underlies about 300 km^2 (Miletic, 1963). The Dammam Formation also crops out in the eastern part of Saudi Arabia, about 400 km east of Kuwait, where the outcrop underlies about 1,200 km^2. The area between these two exposures is underlain by beds of Neogene age, which are sufficiently permeable to permit water infiltration into the underlying Dammam Formation.

Aquifer System

In Kuwait, the principal aquifer system consists of the Kuwait Group and the Dammam Formation of the Hasa Group. In general, the saturated part of the Kuwait Group and the Dammam Formation are hydraulically connected. The aquifers in Kuwait are replenished by infiltration at the outcrop area of the Hasa Group at the eastern-northeastern part of Saudi Arabia, and groundwater is discharged in Shatt Al-Arab and the Arabian Gulf (fig. 3). According to Omar et al. (1981), the amount of underflow that originates from Saudi

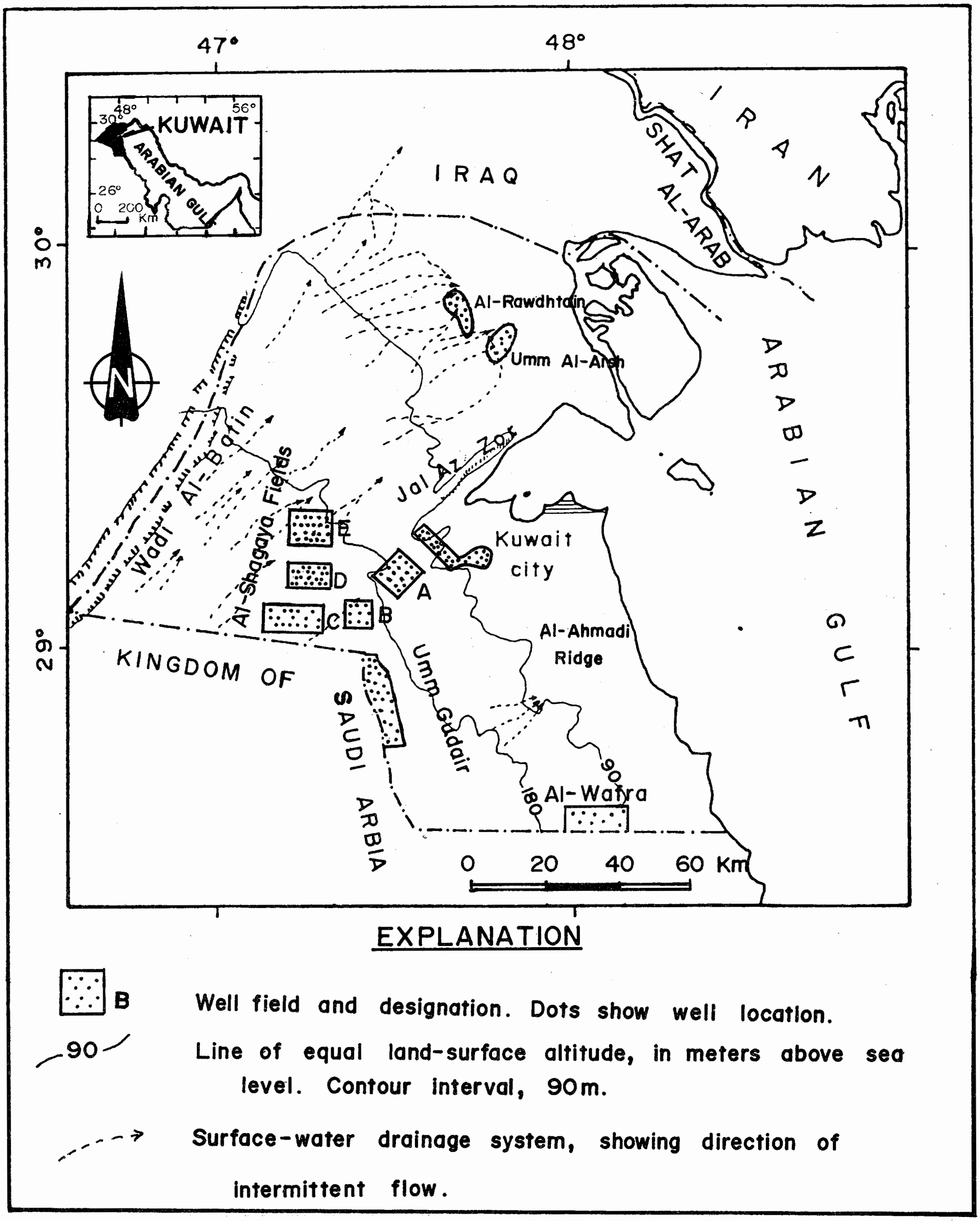

Figure 1. Location of study areas, Kuwait.

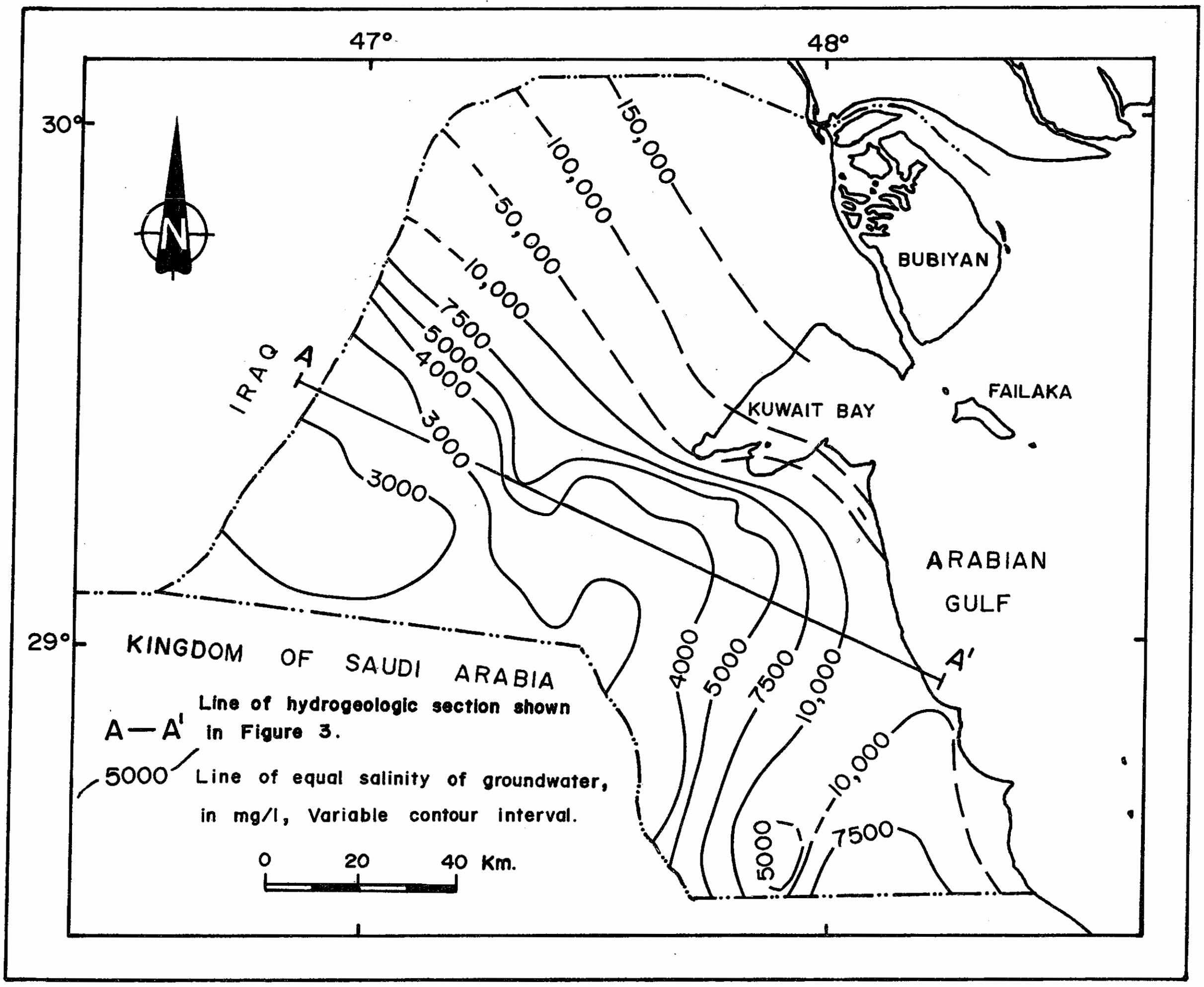

Figure 2. Distribution of salinity of groundwater, Dammam aquifer (Omar et al., 1981).

Arabia through the saturated part of the aquifer, which represents the main part of the natural recharge in Kuwait, is about 22.3×10^3 to 67.7×10^3 m^3/day at the border with the Kingdom of the Saudi Arabia through the Dammam Formation. Carbon-14 is practically absent in the groundwater of the Dammam Formation, which indicates that the groundwater age is not less than 40,000 years (Abusada, 1982). Groundwater salinity increases gradually in the downgradient flow direction toward the discharge area and becomes brackish before reaching Kuwait.

The Dammam aquifer is potentially the most productive aquifer in Kuwait. It is penetrated by all the production wells of the brackish-water well fields in Kuwait. The unit consists of marine limestone whose thickness ranges from 200 to 300 m; saturated thickness increases toward the northeast. The Dammam aquifer acts as a semi-confined aquifer. The calculated transmissivity and storativity values of the aquifer range from 22.36 to 2236.5 m^2/day and 1×10^{-4} to 8×10^{-4}, respectively (Abu-Khamsin, 1987).

CHEMISTRY OF GROUNDWATER

Groundwater Sampling

During 1989-90, the Kuwait Ministry of Electricity and Water made chemical analyses on 200 groundwater samples from well fields B, C, and D of the Al-Sulaibiya field; Umm-Gudair field; and Al-Wafra field. In all wells from which groundwater samples were collected, the total thickness of the Kuwait Group is cased off and cemented, and groundwater was collected exclusively from open holes penetrating the underlying

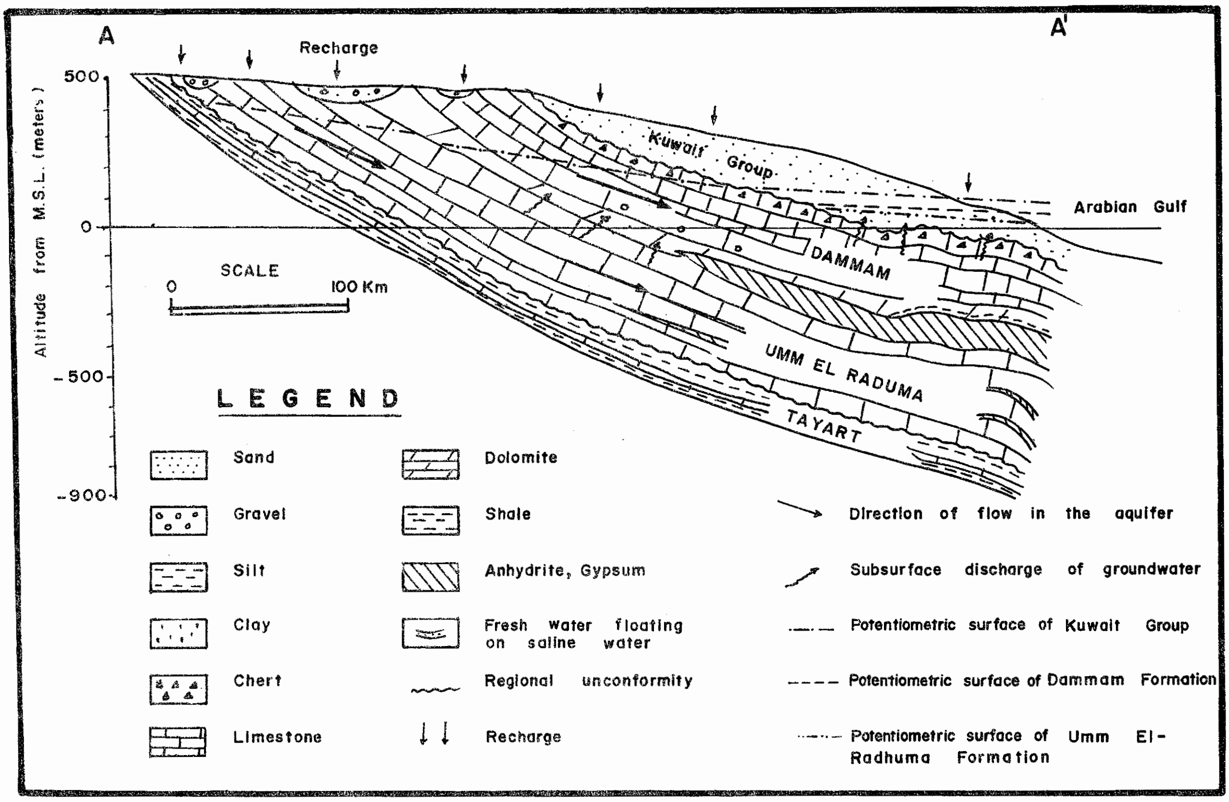

Figure 3. Hydrogeologic section showing recharge, discharge, and directions of groundwater flow (Abu Sada, 1980). Location of line of section shown in figure 2.

the Dammam aquifer. Figure 4 shows the well design of a typical test well in the Dammam aquifer. Open-hole diameters range from 20 to 31 cm, and total well depths range from 335 to 426 m. Each well was pumped 12 hours before collecting the sample; thus, it is assumed that each sample is representative of the groundwater. Field analyses were usually carried out for temperature, pH, electrical conductivity and O_2, which were measured by electrode.

Results of chemical analyses of selected groundwater samples are shown in table 1. Groundwater temperature ranges from 22° to 31° C; most of the samples were within two degrees of 25°C. Total alkalinity of the Dammam aquifer ranges from 114 to 119 mg/l.

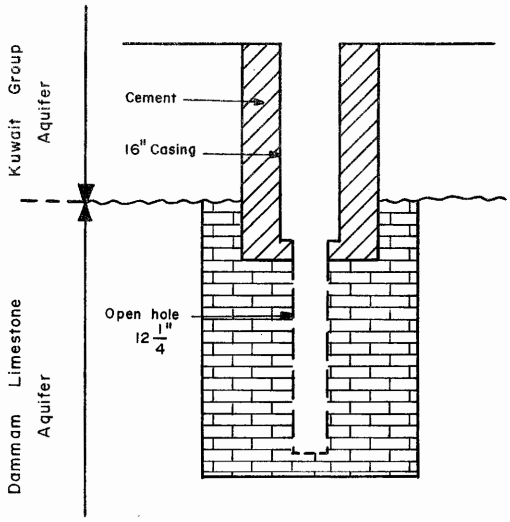

Figure 4. Typical test well for sampling groundwater from the Dammam aquifer.

Table 1. Chemical analyses of groundwater from the Dammam aquifer.

Well Field	Well number	Alkal-inity	pH	Constituent, mg/l											
				TDS	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	NO_3	F	B
Al-Shagaya Field B	B-35	68	7.8	4062	470	138	635	15.2	1241	1189	77	23.0	7.7	2.1	1.5
	B-113	140	7.7	3122	327	144	456	14.5	600	1305	171	19.0	0.7	2.4	1.4
	B-116	128	7.5	3218	357	138	476	15.6	693	1276	156	20.0	8.1	2.4	1.4
	B-117	128	7.5	2872	320	123	420	13.4	531	1204	156	21.0	2.6	2.4	1.3
Al-Shagaya Field C	C-1	103	7.4	2644	338	113	360	12.0	476	1247	126	25.2	32.0	2.0	1.2
	C-4	119	7.5	2869	338	128	470	13.0	489	1363	125	25.6	12.5	2.8	1.6
	C-14	115	7.3	2773	330	143	295	11.0	451	1247	140	23.0	19.0	2.4	1.4
	C-30	122	7.4	2756	330	113	395	12.0	467	1276	148	25.6	15.0	1.9	1.2
Al-Shagaya Field D	D-1	125	7.4	2648	435	128	365	10.5	657	1305	152	24.0	11.0	1.9	1.4
	D-6	139	7.4	2858	454	135	400	11.5	720	1363	170	24.0	0.8	1.9	1.2
	D-13	139	7.7	2744	308	120	355	13.0	421	1334	169	23.4	0.5	1.8	1.1
	D-17	-	7.6	2754	315	135	385	13.0	465	1363	164	23.4	1.4	1.9	1.2
Al-Sulibiya Field	SU-4	105	7.5	7420	833	308	1213	26.0	2730	2088	128	12.5	0.8	-	-
	SU-14	117	7.5	4672	531	210	630	20.0	1180	1595	143	31.2	1.0	-	1.3
	SU-31	131	7.6	4030	495	173	570	17.0	1140	1450	146	30.4	8.0	2.2	1.2
	SU-34	98.4	7.5	4704	540	210	713	20.5	1520	1247	120	26.2	0.7	-	1.1
	SU-65	139	7.4	4920	518	210	763	26.0	1423	1450	169	28.4	2.4	-	1.1
	SU-80	122	7.3	4096	465	188	565	20.0	1040	1653	149	31.0	10.0	2.1	1.2
	SU-91	141	7.7	3612	443	143	485	15.0	970	1363	172	29.2	1.0	-	1.2
	SU-101	148	7.4	4902	630	135	540	18.0	713	2581	180	29.0	2.8	-	1.2
	SU-109	115	7.6	3735	533	165	610	18.0	1162	1463	140	27.0	2.0	-	1.8
	SU-117	134	7.4	3908	548	150	475	16.0	905	1682	163	26.0	1.0	-	1.2
	SU-135	94.7	7.6	3763	428	135	650	15.0	1107	1189	116	30.0	38.0	-	2.0
Umm Gudair Field	UG-1	-	8.0	2945	293	105	440	15.0	588	1260	136	24.7	6.5	2.3	1.3
	UG-9	-	7.6	2881	309	120	380	14.0	560	1212	157	24.0	7.0	2.3	1.2
	UG-17	-	7.8	3127	341	131	430	14.0	640	1230	147	26.0	17.6	2.1	1.2
	UG-39	-	8.2	5107	623	210	550	18.0	1671	1020	124	24.5	58.4	2.2	2.6
Al-Wafra Field	W-1	138	7.5	5390	440	116	940	26.5	2085	946	168	18.8	7.7	1.7	1.4
	W-3	134	7.3	4993	418	121	890	23.5	1860	946	163	18.0	5.2	1.9	1.4

Table 2. Average saturation indices of groundwater in the Dammam aquifer.

Phase	Saturation index					
	Al-Shagaya area			Al-Sulibiya	Umm-Gudair	Al-Wafra
	Field B	Field C	Field D			
Anhydrite	- 0.57	- 0.57	- 0.55	- 0.37	- 0.63	- 0.69
Calcite	.39	.38	.473	.26	.48	- .63
Dolomite (d)	.17	.30	.35	.40	.31	--
Dolomite (c)	.72	.87	.858	.73	.86	--
Gypsum	- .350	.357	- .31	- .00	- .09	--
Halite	- 5.15	- 5.47	- 5.37	- 4.72	- 5.08	--

Saturation Indices

Saturation indices for 200 groundwater samples from the aquifer from various well fields were calculated by using the speciation code WATEQ4. Results are shown in table 2. The Dammam aquifer is saturated with respect to calcite and dolomite and undersaturated with respect to gypsum, anhydrite and halite (NaCl). The saturation index for calcite ranges from 0.26 in the Al-Sulaibiya field to 0.48 in the Umm Gudair area. Groundwater of the Al-Wafra field has a saturation index of -0.63.

The degree of saturation of groundwater with respect to calcite was determined by using the saturation percentage, defined by:

$$\text{Saturation Percentage} = \frac{IAP}{K_{sp}} \times 100 \text{ percent}$$

(Lloyd and Heathcote, 1985), where *IAP* is the ion-activity product, and K_{sp} is the solubility product constant for the mineral. This ratio is the same as the ratio of analyzed calcium from the chemical analysis to the calculated calcium, expressed in mg/l (Back, 1963).

The distribution of saturation with respect to calcite is mapped in figure 5. An equilibrium condition would be represented by a 100-percent line, and supersaturation by percentages greater than 100. Calcite is precipitating in those areas where groundwater is supersaturated; in figure 5, the saturation percentage ranges from 114 to 154. Plummer et al. (1990) attributed supersaturation to dedolomitization, to pressure effects on the activity species, and to variations in calcite stability caused by the incorporation of sulphate into the mineral structure. The dolomite mineral is near oversaturation. Anhydrite should be slightly more stable than gypsum; the saturation indices of anhydrite in the study areas range from -0.37 to -0.69. Because the mineral saturation indices are less than zero, anhydrite cannot precipitate from the groundwater. Thus, the saturation indices suggest that anhydrite is dissolving, dolomite is reacting reversibly, and calcite is precipitating in the Dammam aquifer. However, the saturation indices only provide thermo-dynamic information about which minerals could or could not be dissolving or precipitating in the groundwater system. The hydrochemical cross section of mineral saturation indices (fig. 6) indicates that the saturation indices increase along the direction of groundwater flow, due to the interaction of the groundwater with aquifer materials.

Cation Exchange Process

When sea water intrudes a fresh-water aquifer, an exchange of cations occurs. Sodium is taken up by the exchanger, and Ca^{2+} is released. Water quality thus changes from a NaCl to a $CaCl_2$ water type. The reverse process takes place when fresh water flushes salt water from an aquifer; Ca^{2+} is taken up from water and Na+ is retained, with $NaHCO_3$ type water as a result (Appelo and Postma, 1994).

The effects of cation exchange and reverse cation reactions in the Dammam aquifer are shown in the Piper diagram of figure 7. All the brackish groundwater samples are located in the right vertex of the diamond shape, indicating an intrusion and the formation of

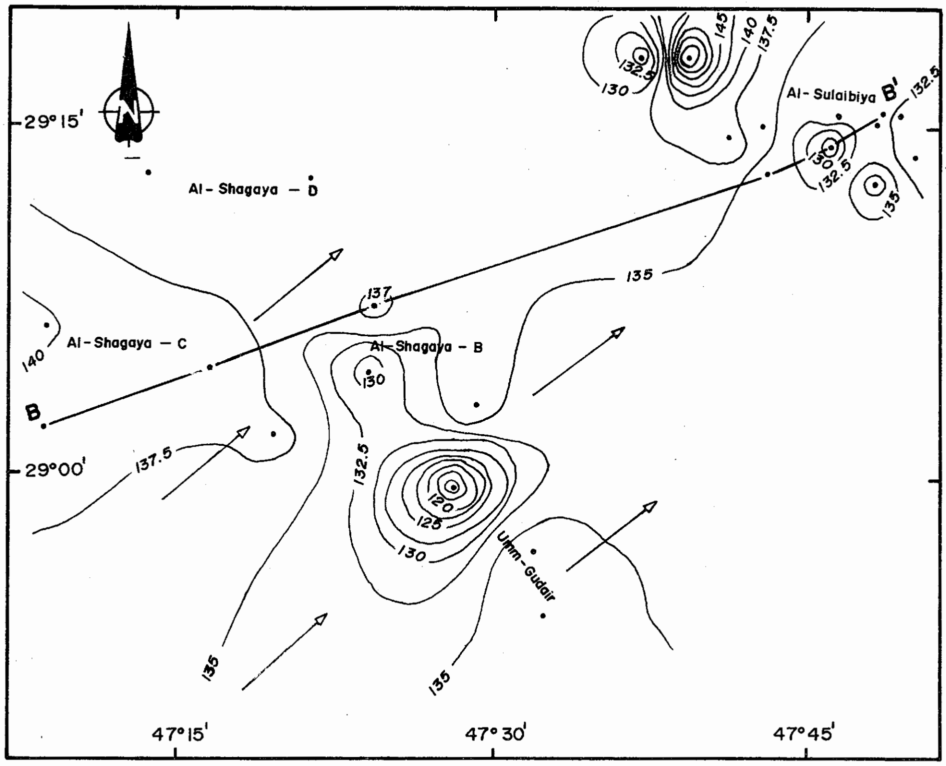

Figure 5. Saturation with respect to calcite, groundwater samples from the Dammam aquifer.

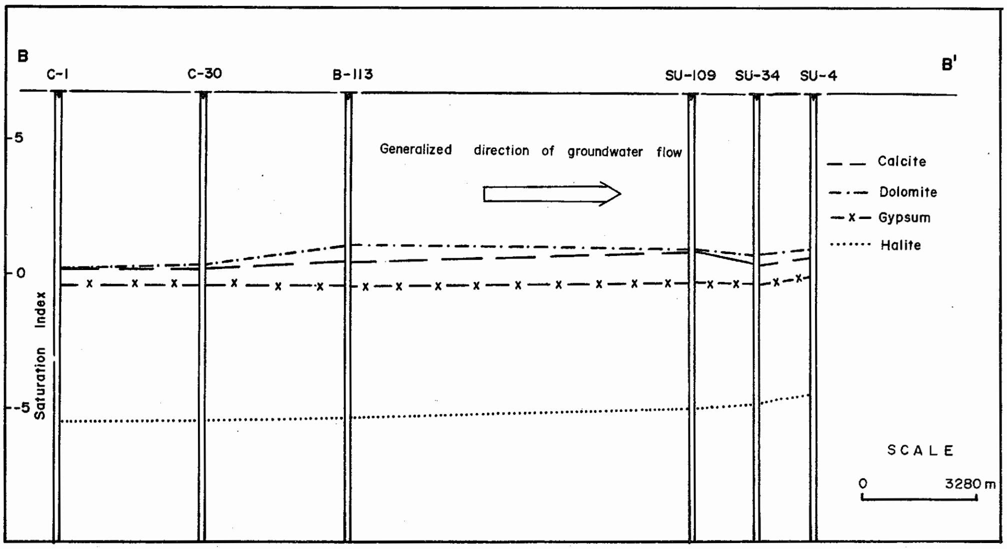

Figure 6. Hydrochemical section of mineral saturation indices of the Dammam aquifer. Line of section shown in figure 5.

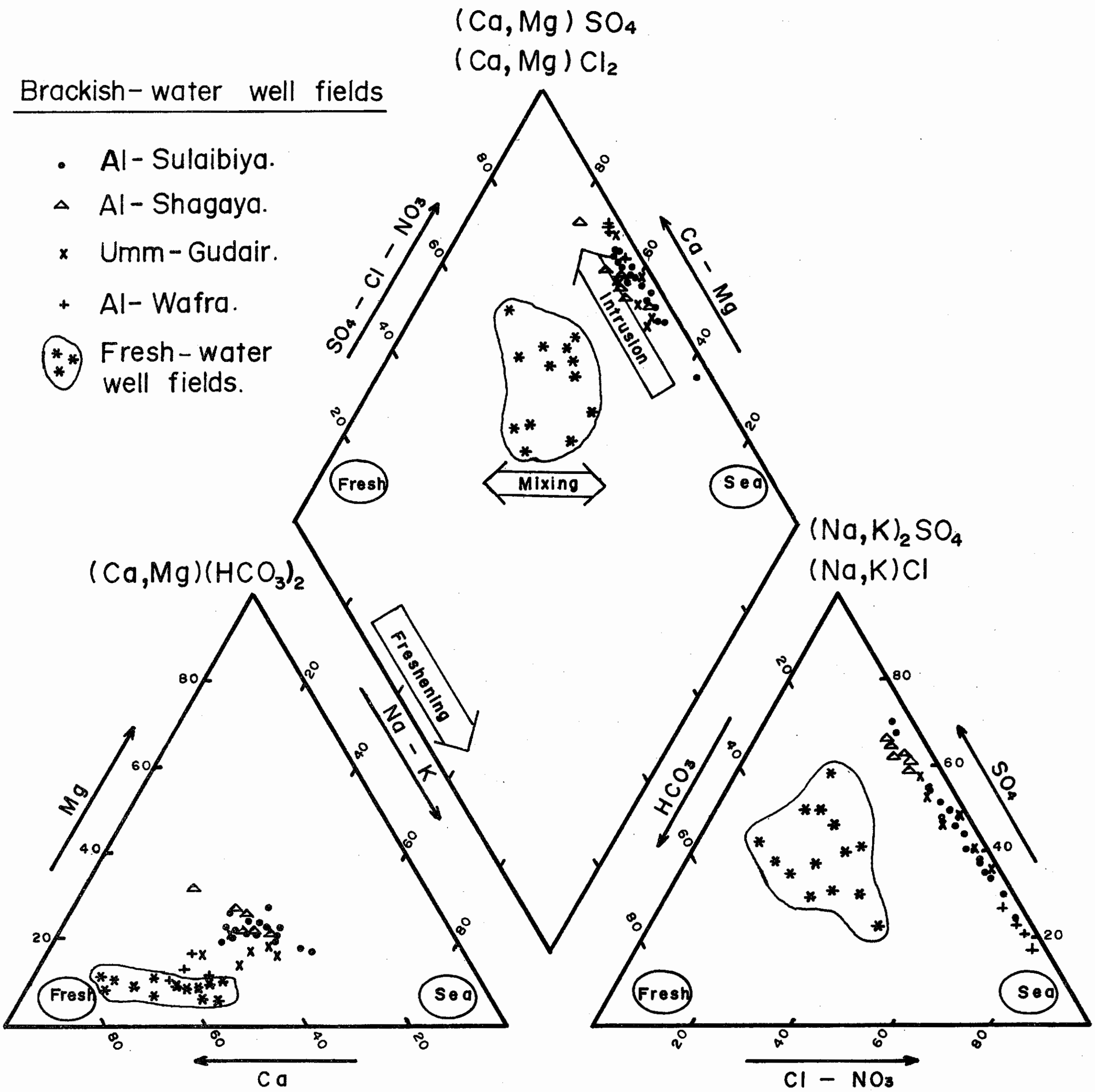

Figure 7. Composition of groundwater from well fields in Kuwait.

$CaCl_2$ - $CaSO_4$ water type. Groundwater samples from the fresh-water well fields, in which the salinity ranges from 200 to 1,400 mg/l (Al-Ruwaih, 1985, 1987) are in the middle of the diamond shape of the piper diagram, indicating that the aquifers are directly replenished by local precipitation and that slight mixing with brackish water occurs. Thus, a reverse cation exchange occurs, and $Ca(HCO_3)_2$ and $NaHCO_3$ type waters result.

Groundwater salinity also increases with flow and aquifer residence time, chiefly because of dissolution processes producing groundwater in which calcium is the dominant cation and sulphate is the dominant anion, as illustrated in figures 8 and 9. In addition, groundwater of Al-Wafra shows high concentrations of Cl and Na, indicating an old brackish water.

The chemical data were also analysed using the Sulin classification method (Collins, 1975). The

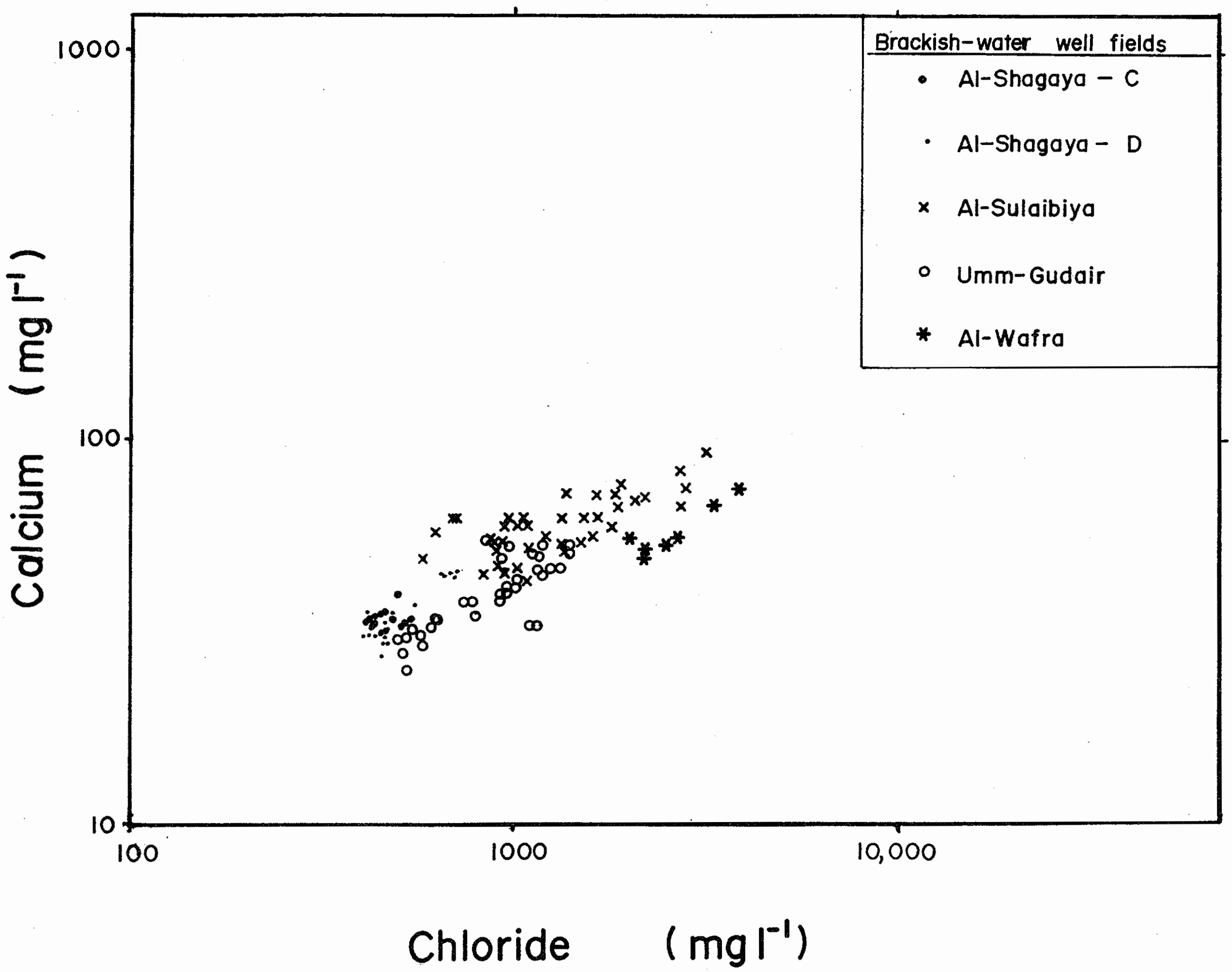

Figure 8. The concentration of Cl in relation to the concentration of Ca, groundwater samples from brackish-water well fields.

resulting chemical and genetic water types are $CaSO_4$, Na_2SO_4, $CaCl_2$, and NaCl, as shown in figure 10 and table 3. The NaCl type is present northeast of the Al-Sulaibiya field.

CONCLUSIONS

The Dammam aquifer of Paleocene-Eocene age has the most potential as a source of brackish groundwater in the State of Kuwait. The aquifer ranges in thickness from 200 to 300 m. Salinity increases toward the northeast, from 2,500 to 10,000 mg/l in the central part of the State of Kuwait, to 10,000 to 150,000 mg/l in the northeastern part.

Saturation indices were computed to assess the tendency of the Dammam groundwater to be in equilibrium with certain minerals. The saturation indices indicate that the groundwater of the Dammam limestone aquifer is strongly undersaturated with halite; this mineral would dissolve if it is present in the aquifer. The groundwater also exhibits weak undersaturation with respect to anhydrite and gypsum.

The minerals calcite and dolomite have slightly positive S.I. values. Thus, these minerals are potentially capable of being precipitated from the groundwater. The results indicate that dedolomitization is occurring, in which an anhydrite dissolves and causes the dissolution of dolomite and precipitation of calcite. Generally, the saturation indices of all minerals increase in the direction of flow, due to the interaction between the groundwater and the aquifer material.

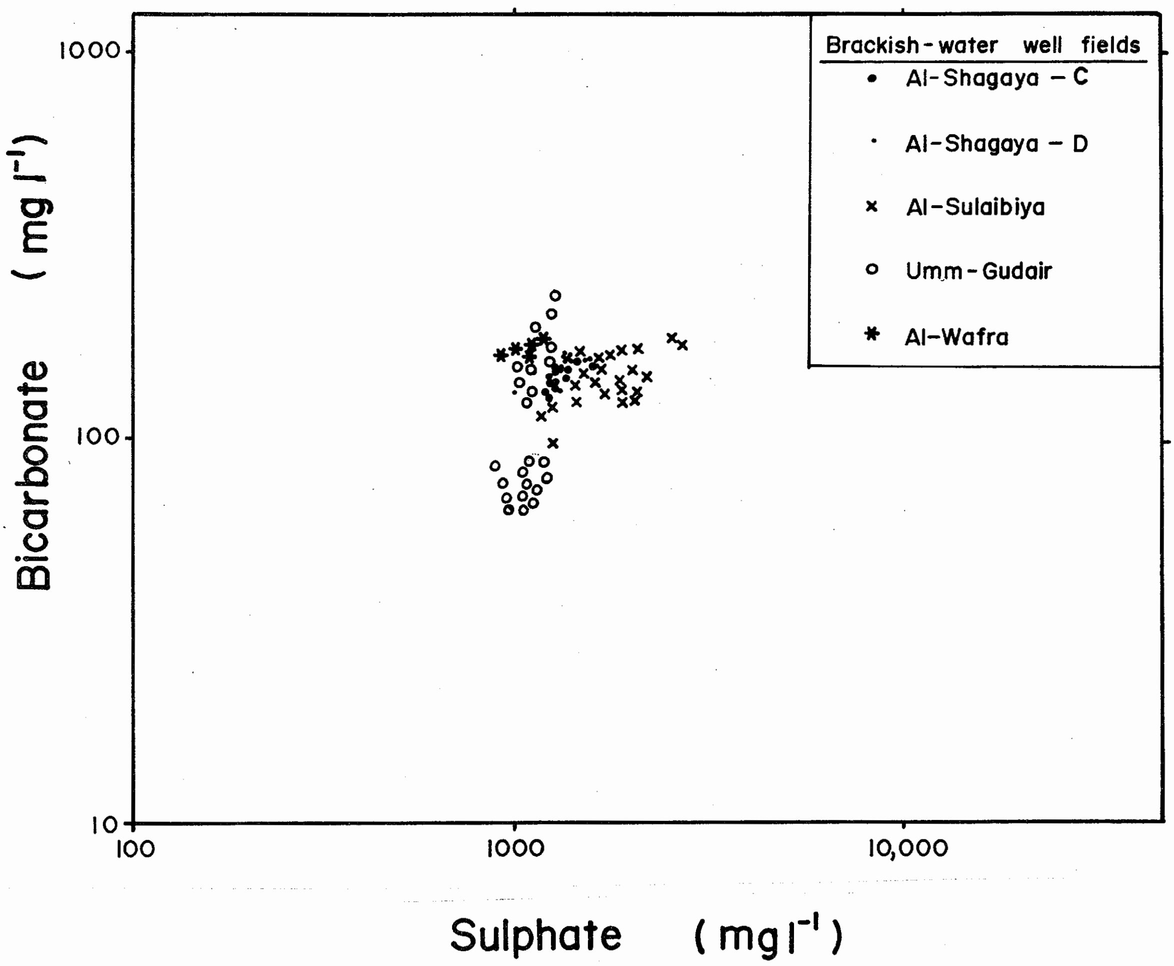

Figure 9. The concentration of SO_4 in relation to the concentration of HCO_3.

The salinity of the groundwater results from a simple dissolution process; Cl, SO_4, Na, and Ca are the dominant ions, and they increase in the direction of flow. Along the border with the Saudi Arabia, most of the marine $MgCl_2$ water type has been replaced by Na_2SO_4 water type of continental meteoric origin, as a result of recharge. The major hydrochemical water types are $CaSO_4$, Na_2SO_4, NaCl, and $CaCl_2$; their presence is mainly due to cation exchange reactions.

The analyses indicate that calcium-rich recharge water originated from infiltration to the Dammam Formation from the outcrops of the Hasa Group in Saudi Arabia and interacted with groundwater of marine origin containing sodium. The result is a mixed zone of Na_2SO_4 and $CaSO_4$ water type that occurs in the southwestern part of the area along the border with Saudi Arabia, as represented by the Al-Shagaya and Umm Gudair areas.

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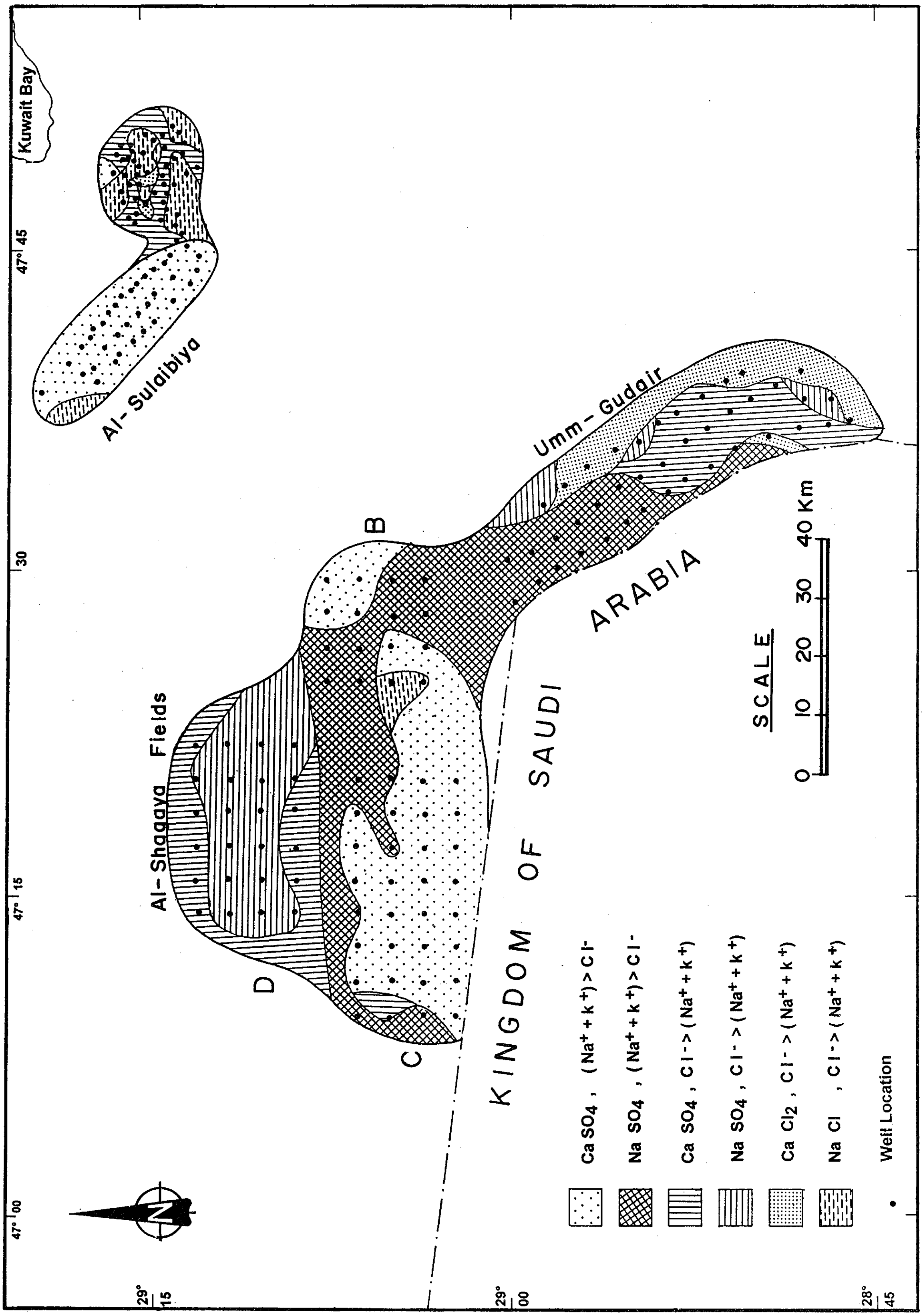

Figure 10. Distribution of hydrochemical water types.

Table 3. Chemical and genetic types of brackish groundwater, Dammam aquifer.

Well field	Range of salinity, mg/1	Groundwater chemical types	Genetic water types
Al-Shagaya B	2,830 - 5,400	$CaSO_4$ Na>Cl NaCl Cl>Na Na_2SO_4	SO_4 - Na Cl - Mg
Al-Shagaya C	2,630 - 2,900	$CaSO_4$ Na>Cl Na_2SO_4 Na>Cl $CaSO_4$ Cl>Na	SO_4 - Na Cl - Mg
Al-Shagaya D	2,648 - 2,980	Na_2SO_4 $CaSO_4$	SO_4-Na Cl-Mg
Al-Sulaibiya Field	3,500 - 8,000	$CaSO_4$ NaCl Na_2SO_4 $CaCl_2$	Cl-Mg SO_4-Na
Umm Gudair Area	2,700 - 3,500	Na_2SO_4 Na>Cl NaCl Cl>Na	Cl-Mg SO_4-Na
Al-Wafra	5,000 - 6,000	NaCl $Cl>SO_4 > HCO_3$ $(Na+K^+)>Ca^{2-}>Mg^{2+}$	Cl-Mg

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