

Characterization and evaluation of the confined limestone aquifer in Kuwait

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Abstract In Kuwait Al-Sulaibiya field is considered as the largest groundwater well field producing brackish water from the Dammam aquifer. The areal distribution of the TDS trend of some wells showed an increase in TDS towards the NE direction and the trend size reached to approx. 65% in the eastern water wells. The groundwater is used for irrigation, domestic purposes and blending with distilled water. The chemical analyses showed that the field is occupied by brackish groundwater whose salinity ranges from 3448 to 9460 mg/L. The groundwater chemical types are Na_2SO_4 , CaSO_4 , NaCl and CaCl_2 . The groundwater exhibited a simple dissolution or mixing process, a reverse ion-exchange process. The groundwater exhibited an over-saturation with respect to calcite and dolomite and under-saturation with respect to anhydrite, gypsum and halite. Moreover, ion-exchange, reverse ion-exchange, dissolution of gypsum, calcite precipitation, and the carbonate weathering are the prevailing geochemical processes in the Dammam aquifer.

Key words trend detection; attribution; circulation types; Europe; temperature; precipitation

LOCATION OF THE STUDY AREA

Kuwait occupies an area of 17 818 km², and is located at the northwestern shore of the Arabian Gulf. It is an arid region, which is marked by very low rainfall, high temperatures and evaporation rates, and a lack of perennial surface waters.

Al-Sulaibiya field, located 20 km south of Kuwait Bay (Fig. 1), is the first groundwater well field used for public water supply: brackish groundwater used mainly for irrigation, domestic purposes and blending with distilled water. The annual field production, which was 3.6 million m³ in 1958 increased to 16.3 million m³ in 2007. The trend analysis of Al-Sulaibiya field production indicates a negative production rate, where a downward trend of 18% is detected. This means that the production from well field has decreased over pumping, and this is because the field is approaching its life expectancy.

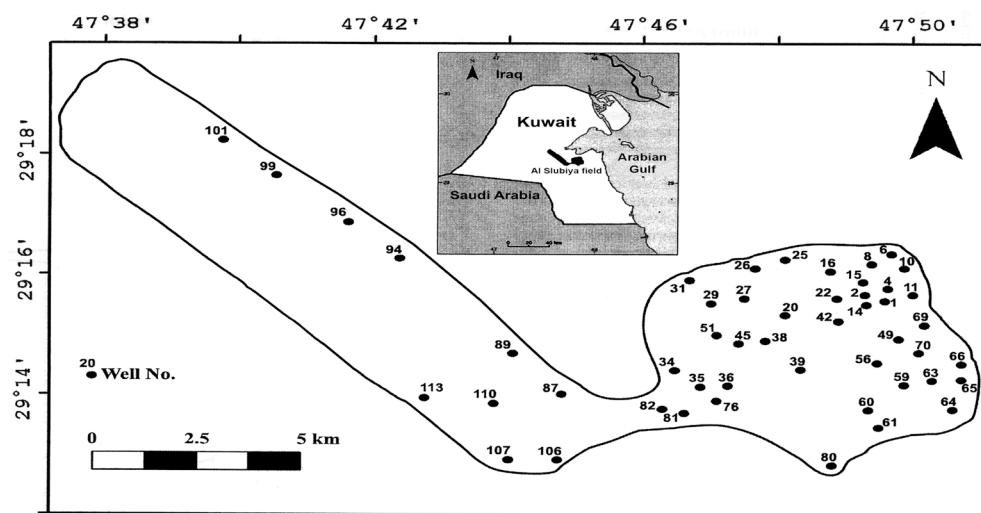


Fig. 1 Location map of selected water wells in Al-Suaibiya field.

The aquifer system in Kuwait

The most significant aquifer in Kuwait is the Tertiary-Quaternary system. These are the upper clastic sediments of the Kuwait Group and the lower Dammam Formation, which are separated by

a confining layer of cherts and/or clay (Al-Ruwaih *et al.*, 2005). Based on lithology, hydraulic properties and karstification, the middle part of the Dammam Formation represents the main aquifer in Kuwait (O'Brein, 1952; Owen & Nasr, 1958; Al-Awadi & Mukhopadhyay, 1995; Qabazared, 2001; Al-Sulaimi & Al-Ruwaih, 2004). The recharge of the Dammam aquifer occurs in the southern Iraqi desert, west of Kuwait and in Saudi Arabia (400 km west of Kuwait), where the exposures of the Dammam aquifer cover 1200 km². However, this aquifer system was recharged mostly during ancient periods, while the modern current recharge is weak. The lateral outflow is directed easterly to the Arabian Gulf and to the north into Iraq (Mukhopadhyay *et al.*, 1994). Discharge is indicated by terrestrial springs, by upward leakage into the overlying aquifer and evaporation through coastal sabkhas (Senay, 1981). The salinity of the Dammam aquifer increases from SW–N–NE from brackish (3000 mg/L) to brine (>150 000 mg/L). This increase in salinity may be attributed to the geometry of recharge and discharge of the aquifer system.

Objectives of the study

The main objective of this study was the investigation and evaluation of the groundwater chemistry of the Dammam aquifer of Al-Sulaibiya field. It was carried out in order to recognize the prevailing geochemical processes in the aquifer and to study the trends of groundwater quality changes during the period 2001–2005. Moreover, the study was to deduce the source-rock, and to assess the chemical equilibrium of groundwater with respect to the minerals of the aquifer matrix and in addition, recognition of groundwater chemical types and genesis.

METHODOLOGY

Well-known graphical methods such as the Piper diagram (Piper, 1953) and DurovDiagram (Durov, 1948) were used to plot the chemical data in order to determine the groundwater chemical types, groundwater genetic types and the prevailing geochemical processes. Several computer programs have been utilized, which include: WATEQ4F program to compute the saturation indices of the minerals with respect to a stated water composition (Ball & Nordstrom, 1992); WATEVAL program (Hounslow, 1995) to deduce the source-rock; Surfer for Windows, to construct contour maps to show the distribution of salinity; SPSS program for statistical analyses of various hydrochemical characteristics; and AQUACHEM package to carry out the graphical and numerical analysis of the geochemical data.

Groundwater chemistry of Al-sulaibiya field

The results of the field and laboratory analyses of 139 groundwater samples from Al-sulaibiya field were interpreted to determine the groundwater chemical types, groundwater genesis and deduction of aquifer source rock in order to identify the dominant geochemical processes operating in the aquifer.

Piper's Trilinear Diagram

The trilinear plotting technique developed by Piper (1953) is used to classify groundwater on the basis of chemistry, and to compare chemical trends among different aquifer systems with a view to getting the picture of water quality at a glance.

The Piper diagram has been utilized to plot the chemical analyses of Al-Sulaibiya field for the period 2001–2005 is presented in Fig. 2. It is clear from the Piper diagrams that most of the groundwater samples of Al-Sulaibiya field during the study periods are located in sub-areas 1, 4 and 6 where the alkaline earths ($\text{Ca}^{2+} + \text{Mg}^{2+}$) exceed alkalis ($\text{Na}^+ + \text{K}^+$), strong acids exceed weak acids and non-carbonate hardness (secondary salinity) exceeds 50%, respectively. A few groundwater samples are located in sub-area 2 and 7, where the alkalis exceed alkaline earths and non-carbonate alkali (primary salinity) exceeds 50%, respectively. Therefore, it is obvious from the chemical analyses that the groundwater chemical properties of the study area are dominated by alkaline earths Ca^{2+} and Mg^{2+} and by strong acids, Cl^- and SO_4^{2-} .

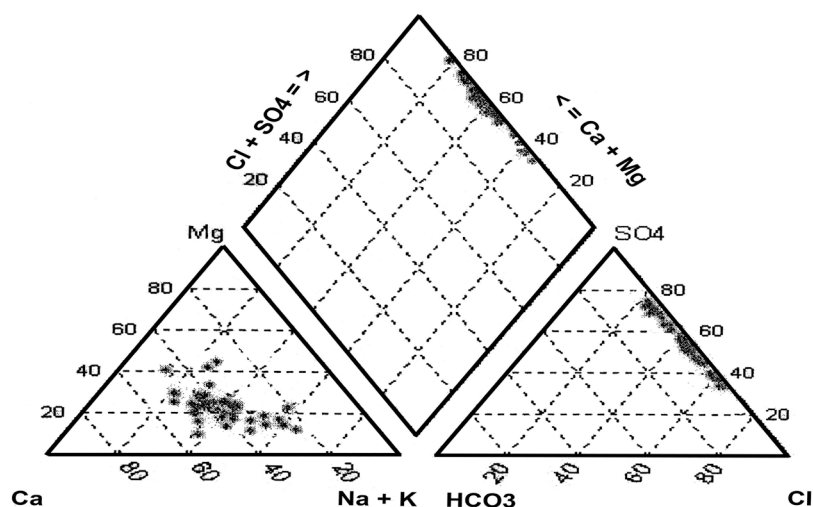


Fig. 2 Piper diagram for the period 2001–2005.

Expanded Durov diagram

The groundwater samples of Al-Sulaibiya field have been plotted on the expanded Durov (1948) diagram for the period 2001–2005. It is clear that some groundwater samples are located in area 5, which indicates that the groundwater exhibits simple dissolution or mixing processes. However, the residual samples are located in area 8, which indicates that the Cl^- ion is the dominant ion and there are no dominant cations. This suggests that reverse ion exchange of $\text{Na}^+ - \text{Cl}^-$ water is a prevailing chemical process (Lloyds & Heathcote, 1985).

GEOCHEMICAL MODELING

In this study, the Inverse speciation model has been applied to determine the thermodynamic speciation calculations of the groundwater of the study area for the period 2001–2005 (Table 1), using WATEQ4F Program (Ball & Nordstrom, 1992), in order to determine the degree of saturation of groundwater with respect to certain minerals. In addition, a mass-balance model using WATEVAL program proposed by Hounslow (1995) has been applied to deduce the source-rock in order to investigate the major geochemical processes that influence the groundwater chemistry of Al-Sulaibiya field.

The degree of saturation or under-saturation of groundwater with respect to some minerals has been calculated for the Dammam aquifer of Al-Sulaibiya field, during the period 2001–2005; and the results are displayed in Table 1. The results of the saturation index of anhydrite, dolomite, gypsum and halite for the period 2001–2005 indicate that the groundwater was under-saturated with respect to these minerals, while the groundwater was oversaturated with respect to calcite, which then might be precipitated.

The average partial pressure of carbon dioxide (P_{CO_2}) of the groundwater for the studied periods ranged between 3.95×10^{-3} atm. and 5.65×10^{-3} atm., i.e. greater than the P_{CO_2} of the Earth's atmosphere ($10^{-3.5}$), and revealed that the aquifer is being charged with carbon dioxide through the soil zone, and suggested a deep closed environmental system (Appelo & Postma, 1994; Stigter *et al.*, 1998; Hadi & Al-Ruwaih, 2005, 2008).

Source-rock deduction

A mass-balance technique using WATEVAL program (Hounslow, 1995) has been utilized to deduce the source-rock of the Dammam aquifer of Al-Sulaibiya field, in order to identify the main geochemical processes that influence the groundwater chemistry. The most common chemical reactions are gypsum dissolution, calcite precipitation, dedolomitization, ion exchange and silicate/carbonate weathering.

RESULTS AND DISCUSSION

Dissolution and precipitation

The ratio of $\text{HCO}_3^-/(\text{sum anions})$ indicates the mineral dissolution rates in the aquifer, which according to Hounslow (1995) if $\text{HCO}_3^-/(\text{sum anions})$ is <0.8 it reveals gypsum dissolution and if the ratio >0.8 it indicates silicate or carbonate weathering. However, it is found that the ratio of

Table 1 Thermodynamic speciation calculations for Al-Sulaibiya Field (2001–2005).

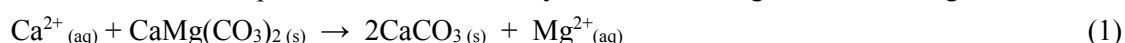
Well No.	Anhydrite	Calcite	Dolomite	Gypsum	Halite	P_{CO_2}
1	-0.204	-0.261	-1.067	0.014	-4.666	1.11E-02
2	-0.129	-0.902	-2.405	0.088	-4.351	2.95E-02
4	-0.207	-0.076	-1.018	0.010	-4.093	7.58E-03
6	-0.205	-0.010	-0.600	0.013	-4.604	5.92E-03
8	-0.146	0.110	-0.459	0.071	-4.482	3.53E-03
10	-0.272	-0.216	-0.988	-0.054	-4.519	1.06E-03
11	-0.055	0.210	-0.212	0.163	-4.700	7.32E-03
14	-0.368	0.290	0.028	-0.150	-4.747	3.11E-03
15	-0.143	-0.141	-0.970	0.075	-4.538	6.72E-03
16	-0.242	0.036	-0.615	-0.024	-4.724	4.34E-03
18	-0.096	0.140	-0.342	0.122	-4.786	4.00E-03
20	-0.284	0.013	-0.672	-0.066	-5.013	5.94E-03
22	-0.475	0.118	-0.481	-0.257	-4.653	3.35E-03
25	-0.632	0.088	-0.456	-0.413	-4.757	3.54E-03
26	-0.333	0.541	0.476	-0.114	-4.864	2.37E-03
27	-0.332	0.101	-0.386	-0.113	-4.808	4.75E-03
30	-0.207	0.140	-0.309	0.011	-5.008	4.92E-03
31	-0.493	-0.089	-0.385	-0.274	-4.772	7.45E-03
34	-0.727	0.097	-0.447	-0.509	-4.643	2.63E-03
35	-0.257	-0.876	-2.465	-0.038	-4.485	9.96E-03
36	-0.740	-0.098	-0.839	-0.522	-4.494	4.25E-03
38	-0.396	0.661	0.870	-0.177	-4.970	1.50E-03
42	-0.219	0.197	-0.362	-0.001	-4.924	3.88E-03
45	-0.121	0.546	0.398	0.097	-4.973	1.50E-03
49	-0.367	-0.078	-0.820	-0.149	-4.418	7.19E-03
51	-0.256	-0.017	-0.672	-0.037	-5.047	7.73E-03
56	-0.237	0.001	-0.765	-0.018	-4.717	7.14E-03
59	-0.410	-0.138	-0.722	-0.192	-4.660	7.73E-03
61	-0.393	-0.316	-1.408	-0.175	-4.766	1.08E-02
63	-0.319	0.288	0.286	-0.101	-4.435	3.40E-03
64	-0.224	0.513	0.439	-0.007	-4.315	2.87E-03
65	-0.427	0.052	-0.493	-0.209	-4.276	5.52E-03
70	-0.217	0.174	-0.502	0.001	-4.151	7.56E-04
80	-0.459	-0.043	-0.960	-0.240	-4.947	8.48E-03
81	-0.811	-0.378	-1.087	-0.592	-4.735	1.12E-03
82	-0.737	0.191	-0.179	-0.518	-4.975	2.01E-03
87	-0.758	0.274	-0.033	-0.539	-5.075	4.57E-04
94	-0.090	0.148	-0.431	0.129	-5.229	7.17E-03
96	-0.309	0.441	-0.021	-0.090	-5.144	3.77E-03
99	-0.209	0.589	0.024	0.010	-5.223	4.61E-03
101	-0.227	0.828	0.948	-0.008	-5.159	3.11E-03
106	-0.376	0.359	0.114	-0.157	-5.124	3.48E-03
107	-0.187	0.341	0.104	0.032	-5.034	4.02E-03
110	-0.252	0.205	-0.287	-0.033	-5.191	3.30E-03
113	-0.250	-0.034	-0.848	-0.031	-5.216	1.06E-02
Mean	-0.329	0.089	-0.467	-0.110	-4.765	5.46E-03

HCO_3^- (sum anions) of all groundwater samples of the study area is <0.8 , which suggests that the gypsum and anhydrite are dissolving minerals in the aquifer of the study area.

Calcite will precipitate when the Ca^{2+} ion concentration increases by dissolution of soluble calcium minerals such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). This process is called dedolomitization. The Langelier index, which is an indication of calcite precipitation, has been computed for all the groundwater samples of the study area and showed positive values ranging from 0 to 1.2, which revealed that the groundwater is oversaturated with respect to calcite, which in turn might be precipitated in the system.

Dedolomitization

Dedolomitization may occur in aquifers containing limestone and dolostone. In its simplest form, dedolomitization is the replacement of dolomite by calcite according to the following reaction:



The ratio $\text{SiO}_2 / [(\text{Na}^+ + \text{K}^+) - \text{Cl}^-] < 1$ indicates the conditions for cation exchange in the aquifer. The results showed that most of the groundwater samples of the study field fall within the range of cation exchange ratios of less than one. It is indicated that the cation exchange is taking place as one of the chemical processes operating within the Dammam aquifer.

CONCLUSIONS AND RECOMMENDATIONS

The aquifer system in Kuwait is mainly divided into two main aquifers: the Kuwait Group and the Dammam aquifers. The groundwater production is mainly derived from Dammam aquifer. The groundwater salinity of the Dammam aquifer ranges from brackish (2500 mg/L) in the southwest to brine ($>150\,000$ mg/L) in the northeast of Kuwait.

The chemical analyses of groundwater samples collected from the Dammam aquifer of the study area showed that the aquifer is occupied by a brackish groundwater with a TDS range between 3448 and 9460 mg/L, which gradually increases towards the north and northeast. The increase in salinity has been attributed to a number of factors, including the dissolution processes, connate water, possible saline intrusion and upwelling of saline water due to over pumping within the well field. The main groundwater chemical types are recognized based on the most dominant cation and anion concentrations are: Na_2SO_4 , CaSO_4 , NaCl and CaCl_2 . Three main groundwater genetic types: NaHCO_3 , MgCl_2 and CaCl_2 are present in the aquifer and exhibit a continental-marine environment interaction.

The computed saturation indices indicated that the groundwater is under-saturated with respect to gypsum and anhydrite, and over-saturated with respect to calcite and dolomite, due to the dissolution and precipitation processes. The calculated mean values of the partial pressure of carbon dioxide (P_{CO_2}) of the groundwater in the Dammam aquifer, ranged between 3.95×10^3 atm. and 5.65×10^{-3} atm, which is greater than the P_{CO_2} of the Earth's atmosphere, suggesting that the Dammam aquifer represents a deep closed environmental system with respect to CO_2 .

The application of the mass-balance technique indicated that ion-exchange, reverse ion-exchange, dissolution of gypsum, calcite precipitation (dedolomitization), limestone-dolomite weathering and the carbonate weathering are the prevailing geochemical processes in the Dammam aquifer of Al-Sulaibiya field.

The spatial distribution of the groundwater salinity indicated an increase in groundwater salinity from SW to NE, where the range of salinity in 1995 was from 3448 to 9084 mg/L, and increased slightly to the range of 3623 to 9460 mg/L in 2005. The trend analysis of Al-Sulaibiya field production indicates a negative production rate of 18%, mainly due to the fact that the field is approaching its life expectancy, and to the increase of TDS in NE wells, and the construction of new emergency water wells. Due to the heavy exploitation of the Dammam aquifer since 1954, the salinity is found to be increasing with time, especially in the NE area, and the water level is also expected to decline. Accordingly, it was recommended to install a regular monitoring system for

groundwater quality, water level measurements and production. It was also recommended to decrease pumping rates in the eastern area of the aquifer of Al-Sulaibiya field to counteract the continuous lowering of piezometric level and deterioration of water quality.

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