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Original Article

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Abstract

Hydrogeological, hydrochemical and electric logging data of 24 groundwater wells of the D- field of the Shigaya, SW of Kuwait, were used to evaluate the Middle Eocene Dammam carbonate aquifer and to recognize the major geochemical processes that controlling the groundwater quality. The results indicate that the Dammam aquifer has a heterogeneous lithological nature, that composed of limestone, dolomitized at the top, with dispersed argillaceous materials ranges from 0 to 21% and total matrix porosity ranges from 4 to 35 %. The highest matrix porosity is recorded at the top of the formation, that was enhanced by dolomitization, fracturing, and dissolution. Interpretation of the hydrochemical data indicate that the groundwater type is Na_2SO_4 that enriched with Na^+ and Ca^{++} and strong acids (SO_4^{--} and Cl^-) than the weak acids (CO_3^{--}+ HCO_3^-). This indicates a simple dissolution or mixing nature of the groundwater and a reverse ion-exchange between sodium ions of the meteoric water and the magnesium and calcium ions of the groundwater. The sulphate and chloride ranging from 1046 to 1345 ppm and 420 to 647 ppm, respectively. The sodium concentration ranges from 282 to 456 ppm and the calcium ranges from 225 to 387 ppm, while magnesium has the lowest concentration of between 118 and 137 ppm. A rapid decrease of the Dammam water salinity was detected after 1977, as a result of groundwater exchanges that took place between the overlying, relatively lower salinity, Kuwait Group aquifer through the wellbores whenever the wells are not being pumped.

1. Introduction

Kuwait covers an area of 18,000 km2 of the northeastern corner of the Arabian Peninsula, west of the Arabian Gulf. The climate is extremely hot, dry in summer and mild too cold in winter. The rainfall is scarce with an annual average precipitation of 115 mm. The average evaporation is equal 17 mm/day. Location of the state of Kuwait within the arid region gives groundwater great importance. The groundwater is abstracted in Kuwait from two main aquifers, the Kuwait Group aquifer, which is leaky to water-table aquifer, and the Dammam aquifer is confined to semi-confined aquifer. The brackish groundwater in Kuwait is used in agriculture, gardening and domestic purposes. Moreover, it is blend with the fresh water produced by desalination plants to make potable drinking water.

The Shigaya area is located SW of Kuwait, and includes five water-well fields denoted “A, B, C, D and E” that were put in use in the 1970’s. These fields supply Kuwait with brackish groundwater produced mainly from the Dammam aquifer at a peak rate of 60 MIGD from a total of 115 production wells distributed over the five fields. Groundwater is extracted from the Dammam aquifer in Al-Shigaya water field -D to meet the industrial and domestic purposes. The extracted groundwater is of brackish quality with total dissolved solids (TDS) more than 2500 mg/l.

The Middle Eocene Dammam carbonate aquifer in Kuwait is a part of the most extensive artesian limestone aquifer in the Arabian Gulf States. It is represented by a sequence of soft, porous chalky limestone and hard crystalline dolomitic limestone of Middle Eocene age (Lutetian) **(Parson Corporation 1963; Bergstrom and Aten 1964; Burdon and Al Sharhan 1968, Alsharhan and Nairn 1997).** It varies in thickness from 150 m in the southeast to 275 m in the northeast **(Al-Awadi et al. 1998; AL-Sulaimi and Ruwaih 2004).** The

Dammam Formation is overlain unconformably by the Mio-Pleistocene Kuwait Group clastic sequence and is underlain conformably by the anhydritic Rus Formation **(Owen and Nasr 1958)**.

The Dammam Formation was deposited in a shallow coastal environment ranging from mostly tidal flat to backshore lagoons. Vertical variation in facies was related to fluctuation in sea level. Recent study by **Tanoli and Al-Bloushi (2017)** indicated showed that the formation displays two transgressive-regressive depositional sequences.

The Dammam Formation and the overlying Kuwait Group are the two aquifers that provide useable groundwater (salinity<5000 mg/l) in Kuwait. These aquifers extend beyond the political limits of the country to Saudi Arabia and Iraq **(Omar et al. 1981; Al-Awadi et al.,1998).** The Kuwait Group (KG) ranges in thickness from about 30 to 400 m with the greatest thickness occurring in the north of Kuwait, near the Iraqi border. It consists of a lithologically diverse sequence of undifferentiated fluviatile clastics (gravelly sands and sandy gravels), calcareous sandstones, sandy limestones and less permeable marls and shales. The Dammam Formation has a total thickness mostly in the 60–200 m range and consists mostly of limestones and dolomitic limestones. A major unconformity separates the Dammam Formation, which is deposited in a marine environment, from Kuwait Group sediments that are deposited in a continental environment **(Hadi et al., 2016).**

The aquifers in the Kuwait Group appear to be layered semi-confined system with a free water table in the uppermost horizon, and the Dammam Formation acts as a semi-confined to confined aquifer **(Senay et al. 1987, Hamdan and Mukhopadhyay 1991; Mukhopadhyay et al. 1994b; Mukhapadhyay 1995)**. Both the Kuwait Group and Dammam Formation are locally divided into an upper and lower aquifer unit. The generalized stratigraphy of the tertiary sediments in Kuwait and surrounding areas is given in figure (1).

The groundwater flows from the southwest toward the north and east, and it reaches the discharge zone along the coast of the Arabian Gulf **(Hamdan and Mukhopadhyay 1991; Al-Sulaimi and El-Rabaa 1994; Al-Ruwaih 1994; Mukhopadhyay et al. 1994a)**.

The recharge in these aquifers from rainfall mainly takes place outside the territory of Kuwait in Saudi Arabia and Iraq. With very low precipitation, there is practically no direct recharge to the aquifers within the territory of Kuwait **(Mukhopadhyay et al. 1994b)**.

Based on the pumping tests, the estimated transmissivity values of the Dammam Formation are ranged from 160 to 300 m2/d for the shallow wells and from 480 to 1180 m2 /d for the deep wells **(Al-Senafy, 2001)**.

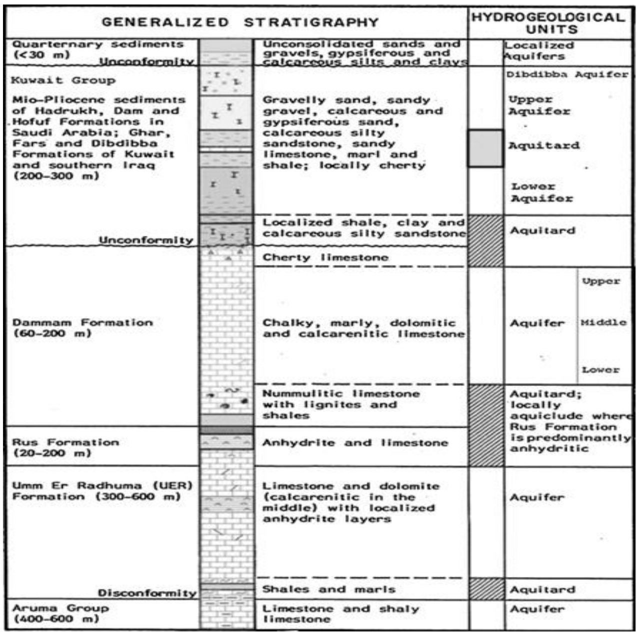

Figure 1: Stratigraphy and hydrogeological subdivisions of the aquifer system in Kuwait **(Mukhopadhyay et al., 1996).**

The subsurface hydrostratigraphy and aquifer system

The territory of Kuwait extends over the discharge section of a hydrological system in which groundwater is replenished by infiltration mostly through the outcropping area of the Hasa group rocks at the north-northeastern part of Saudi Arabia and discharged into the Arabian Gulf and Shatt Al-Arab. In the natural course of the hydrological events, groundwater salinity increases gradually in the lateral flow direction towards the discharge area and becomes relatively brackish with a TDS value ranging between 2500 and 5000 ppm before reaching the State of Kuwait **(Mukhopadhyay et al., 1998).**

The subsurface Tertiary sequence in Kuwait is divided into two major groups: the Kuwait Group that comprises the Dibdibah, Lower Fars and Ghar formations and Hasa Group that comprises the Dammam, Rus and Um Radhuma formations. The Dibdibah Formation, consisting of a sequence of cross-bedded sands and gravel with subordinate sandy clay, sandstone conglomerates and silt stones, is encountered at the northern part of Kuwait. This formation also contains unique freshwater lenses beneath the Raudhatain, Umm Al-Aish and Umm Nigga depressions. The underlying lower Fars Formation is composed of fine sediments, conglomeratic sandstone, shale and thin fossiliferous limestone. The Ghar Formation consists mainly of marine to terrestrial sands, silts and gravel. The sands are generally coarse and unconsolidated. Few sandy limestone, clay and anhydrite streaks also occur in the sequence **(Hadi and Al-Senafy, 2002)**.

This sandy sequence of the Kuwait Group was subjected to varying degrees of diagenetic cementation, resulting in partly to completely cemented calcareous and occasionally gypsiferous and dolomitic layers. The hydraulic conductivity of the aquifer depends on the grain size distribution and degree of cementation (**Al-Senafy and Al-Fahad, 2000)**. It is high in well-sorted gravel and sand and decreases with the increase of the clay fraction and degree of cementation. The groundwater occurs under unconfined conditions in the upper horizons of the group and under semi-confined conditions in the lower horizons. The degree of confinement increases with depth.

However, the Kuwait Group aquifer is subdivided into numerous hydrostratigraphic units of different permeability (Fig. 1). Relatively high permeability values in the direction parallel to the bedding, particularly in the well sorted sandy-gravelly zones have the most bearing on the rate of groundwater movement in the aquifer. This Group provides also a continuous flow system. Most of the groundwater in the aquifer system originates in Saudi Arabia. The other part of the natural recharge is the infiltration through wadis and depressions scattered over the region. Groundwater flows from SW to NE and discharges into the Shatt Al-Arab and Arabian Gulf through the uppermost part of the Kuwait Group aquifer **(Naseeb et al., 2006)**.

On the other hand, the significant decrease in permeability value in the clayey and/or in the densely cemented zones as well as in the direction perpendicular to the bedding is one of the key factors controlling the pattern of groundwater flow and, consequently, hydraulic dispersion of polluted water in the aquifer, if any **(Hadi and Al-Senafy, 2002).**

By contrast, the Dammam Formation is one of the most productive aquifers and is therefore penetrated by nearly all the production wells extracting brackish water. The formation is mostly consisting of stratified marine limestone deposits and is separated from the Kuwait Group by a cherty layer of varying thicknesses and low effective primary porosity.

The effective secondary porosity resulting from faults, fractures, solution channels, etc. (generally known as 'karstification'), appears to be the prime factor controls the hydraulic conductivity and, hence, the productivity of the aquifer **(Al-Senafy et al, 2006)**. Related to the nature of groundwater flow, the effective secondary porosity and the transmissivity of the Dammam Limestone aquifer decreases in the main flow direction of SW-NE, excluding the areas where the formation is locally uplifted and fractured.

2. Materials and Methods

This study was based on hydrogeological, hydrochemical and electric logging data collected from 24 groundwater wells, penetrated the Dammam aquifer of the Shigaya-D field (Fig. 2).

Analysis and interpretation of the hydrochemical was done utilizing the AquaChem V.5.1 of **Schlumberger (2007)**, to determine the groundwater chemical type.

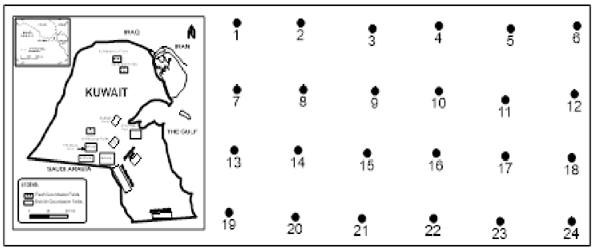

Figure 2: Location of the study wells, the Shigaya-D field, Kuwait.

The electrical logs were quantitatively interpreted to evaluate the petrophysical parameters of the study aquifer utilizing a FORTRAN software of **Shaaban and Mohammed (2000)**. The flow chart of this program is illustrated in figure (3).

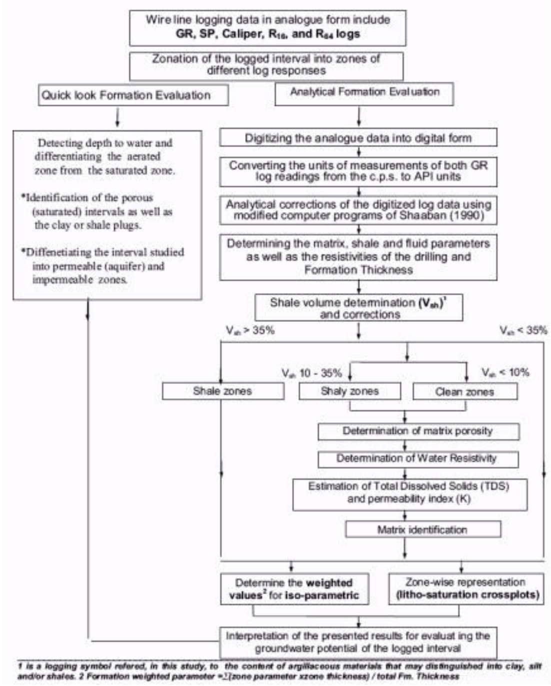

Figure 3: Flow Chart of the well logs interpretation program **(Shaaban and Mohammed, 2000).**

3. Results and Discussion

The results of the present study are presented and discussed in the following items, as follows:

I- The hydrogeology of the Aquifer

A preliminary qualitative interpretation has been done on the available well logs to differentiate between the Kuwait Group (clastic) and the Dammam Formation (carbonate) rocks, identification of the lithological characteristics, locating permeable, impermeable zones and clay plugs within the aquifers. These targets have been reached through correlation of the different types of logs, depending on the physical characteristics of the examined interval. The following are the principles of qualitative interpretation used in interpretation:

- **The Resistivity logs** record the apparent resistivity, which are affected by geometrical dimensions of all the media surrounding the device. For quantitative calculation and interpretation of Rt, bed thickness must be 3 to 4 times the tool spacing **(Brocks, 1984).** Therefore, normal logs have been used, in this study, for detecting resistivity of zone close to the borehole (invaded zone) and beyond the influence of drilling fluids (uninvaded zone), respectively. Lateral devices were not used because they have very widely spaced electrodes, therefore they will not pick out thin beds of different resistivities.

The resistivity logs are marked by sharp and wide fluctuating pattern at the top of the wells, indicating dry unsaturated sands and gravels with medium to high cementation. These fluctuations decrease downwards in the saturated zone of the Kuwait Group. At deeper depths the resistivity values tend to be relatively higher at the Dammam carbonates.

However, the groundwater level can be easily detected by the abrupt decrease of both invaded zone resistivity (R_{16}) and SP logs from the unsaturated to the saturated zone. The resistivity values of the saturated zone vary from 6 to 62 ohm-m all over the field, indicating a brackish to saline groundwater conditions, taking into consideration the variation of lithology and the salinity of the drilling fluids effects.

- Self-Potential (SP) Log measures the natural potential that develops between the formation and the borehole fluids; therefore, it cannot operate properly above the water table (Dirks, 1985). It can be used for determining permeable beds, bed thickness, and formation water resistivity and for correlation purposes. The SP pattern shows relatively high values opposite the permeable zones, while it is of low magnitude at the clay or shale layers

- The Gamma Ray (GR) log is the most used nuclear logging in hydrogeology. It can be used for determining the volume of shale and identifying lithology, especially detritus sediments, based on differences in radiation intensity. While clays and clayey sands are higher in radioactivity, clean sands and carbonates exhibit low levels of radiation. The available gamma logs show a low fluctuating pattern, which increases with increasing the clay content.

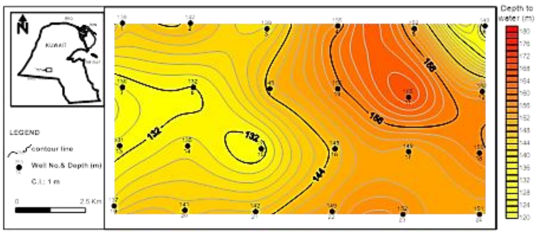

Figure 4: A contour map showing the depth to the Dammam Formation (b.G.L), based on interpretation of the well logs.

Based on the qualitative interpretation of the well logs, the depth to the Dammam Formation was determined and represented by the distribution map of figure (4). This map shows that the depth of the Dammam Formation ranges from 244 m to 261m below the ground surface (b.G.S) of the Shigaya-D field, with a tendency to increase NE-ward and decrease W and SW-ward.

By the beginning of the 1970s, individual wells were completed in both the Dammam Formation and the Kuwait Group in the Shigaya-D field. These well bores provided open hydraulic connections between the two aquifers. Exchanges of groundwater take place between the aquifers through the well bores whenever the wells are not being pumped. Figure (5) confirmed the evidence of this phenomenon, from the rapid decrease of the Dammam water salinity due to the dilution from the relatively lower salinity of the overlying Kuwait Group.

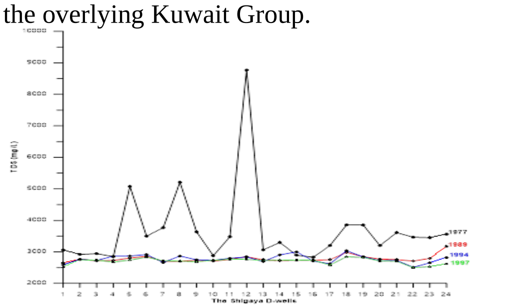

Figure 5: The total dissolved solids (TDS) of the Shigaya -D field's wells from 1977 to 1997.

The field development began in September 1977, and the wells were dually completed in the Dammam Formation and Kuwait Group. A potentiometric-head difference exists between the Dammam Formation and the unconformably overlying Kuwait Group; this difference is maintained by the presence of an intervening aquitard. An upward hydraulic gradient from the Dammam Formation to the overlying Kuwait Group existed before the intense exploitation of the groundwater resources started in Kuwait in the 1960s **(Mukhopadhyay et al.,1994)**. By the 1980s, however, the gradient had reversed throughout most of Kuwait, as a result of the high extraction rate from the confined Dammam Formation **(Al-Awadi et al., 1998)**. Fractures and solution cavities are the primary controlling factors in determining the overall transmissivity of the formation **(Mukhopadhyay, 1995)**, not the porosity and permeability of the matrix as measured in the laboratory.

II- The petrophysics of the Aquifer

The quantitative interpretation of the geophysical logs was conducted to evaluate the petrophysical parameters of the Dammam aquifer utilizing the formation evaluation program of **Shaaban and Mohammed (2000)**. The results are presented, zone wise, in the form of litho-porosity crossplots, that was represented by the D1 well (Fig. 6). Inspection of these crossplots reveals the following:

The Kuwait Group is mainly composed of clastic sediments (sands and gravels) with varying percentages of clay intercalations, ranging from 0 % to 35 %. The calculated total matrix (primary) porosity is variable and ranged from 0 % at the clay or shale levels to about 30 % at the clean (shale or clay free) lithology. These porosities are totally saturated with water below the water table.

By contrast, the Dammam Formation is mainly composed of limestone, silicified at the top with varying percentages of clay intercalations. Apart from the paleokarst zone at the top, that is composed of cherty limestone, the formation consists of chalky dolomitized limestone. It is subdivided by **Al-Awadi et al. (1998)** into three members, based on lithology and biofacies. The upper member consists of friable chalky dolomicrite and dolomite. The middle member is mainly laminated biomicrite and biodolomicrite. The lower member is nummulitic limestone with interlayered shale toward the base. The electric logs conform to this subdivision and that the upper member is the most porous of the three units.

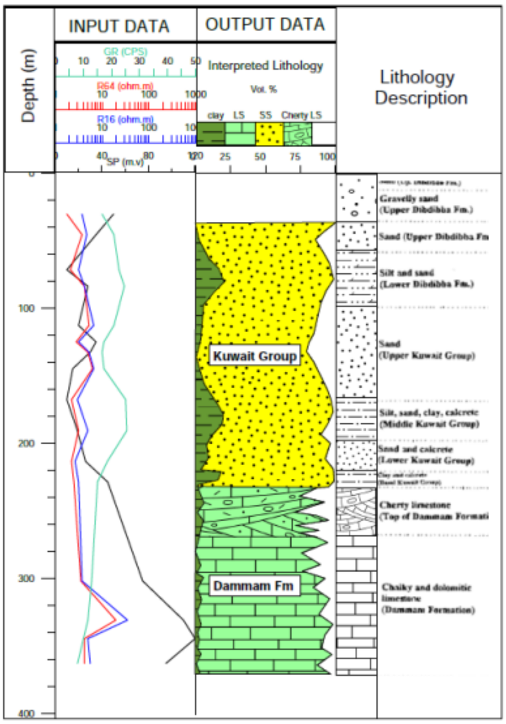

Figure 6: Lithosaturation crossplot of the D1 well.

The calculated total matrix (secondary) porosity is extremely variable along the studied interval and ranged from 4 % at the clay or dense carbonate levels to about 35% at the clean (shale or clay free lithology) levels. The porosity values that recorded at the top of the formation are higher than its middle and the lower parts (Fig. 6). **Al-Awadi et al. (1998)** stated that, the upper member of the Dammam Formation (chalky dolomite - cherty limestone) has the highest matrix porosity, that was enhanced by dolomitization, fracturing, and dissolution. The middle and lower parts are of low porosity. Subsequent fracturing and karstification increased both the porosity and permeability of these members locally.

The top of the Dammam Formation consists mostly of chertified dolomite. Vugs, moulds and intergranular porosity are the main types of porosity of this member (Mukhopadhyayw, et al., 1998). Later diagenetic activities have sometimes dissolved the crystal cores, giving rise to intragranular porosity.

Worthy to mention that the zones of clay or shale content greater than 35 % are discarded from the calculation of the porosity index. The calculated matrix porosity is considerably influenced by the percentage of the encountered shale content, which indicates that the shale content is of dispersed habit. The middle member is mainly composed of vuggy, bioturbated and highly calcitized laminated dolomite and limestone. Remnants of the original dolomicritic host can be observed in the form of nodules within sparry calcite. Vugs, moulds and intergranular porosity are the main porosity types in this range (Mukhopadhyayw, et al., 1998). The lower member consists of nummulitic limestone with vuggy and moldic porosity.

The weighted porosity and shale values of the Dammam Formation were used to construct distribution maps to illustrate the lateral variations of these parameters all over the study field. Interpretation of these maps reveals the following:

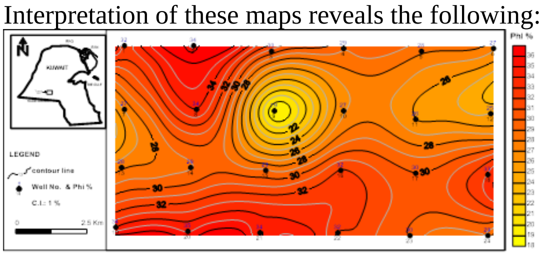

Figure 7: The total porosity (wt %) distribution map of the Dammam Formation.

The weighted porosity distribution map of the Dammam aquifer (Fig. 7) shows values ranging from 19 to 35 (wt %) with a tendency to decrease at the central and the eastern parts of the field, while increase N, S and SE wards. The weighted shale materials (Vsh wt%) distribution map of the Dammam aquifer (Fig. 8) show values ranging from 0 to 21 (wt %) with a tendency to increase at the central and the eastern parts of the field, while decrease N, S and SE wards. This varying content of the argillaceous sediments within the aquifer reflect its heterogeneous lithological nature. The reverse distribution pattern of the shale volume and porosity reflect the partial impact of the shale sediments in decreasing the matrix porosity.

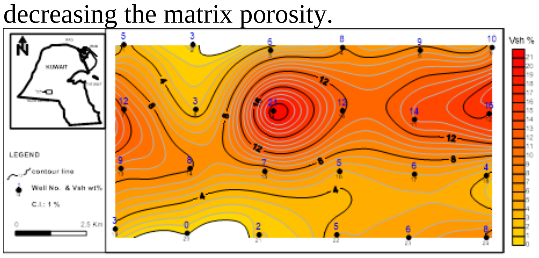

Figure 8: The volume of shale (wt %) distribution map of the Dammam Formation.

The laboratory core-based measured porosity and permeability of the Dammam Formation reflect the influence of only the smaller voids in the matrix, and thus they are not representative of the bulk porosity or permeability of the unit, which contains fractures and karstified features. The dolomite petrography in the upper member is mainly chalky, whereas that in the middle and lower members has a saccharhoidal texture **(Al-Awadi et al., 1998).**

III- The hydrochemistry and Water Quality of the aquifer

Interpretation of the hydrochemical data (Table 1) of the Dammam aquifer, utilizing several specialized charts and plots (Figs. 9 to 15), indicate the following:

Table 1: The chemical analysis data of the Shigaya-D wells

	TDS (mg/L)				Cations and Anions (ppm)											
Well No	1977	1989	1994	1997	Na	K	Ca	Mg	Cl	SO4	HCO3	CO3	NO3	SiO2	T alk	T.Hard
1	3057	2648	2590	2520	362	15.8	225	120	432	1226	161	0	10	26	132	1054
2	2917	2768	2760	2748	391	16.1	255	135	571	1261	178	0	2.5	27	146	1191
3	2944	2716	2730	2736	374	16.3	240	135	545	1259	177	2	0.9	26	149	1153
4	2849	2728	2860	2676	424	16.3	303	123	521	1251	166	2	0.8	7.5	136	1262
5	5078	2806	2868	2740	453	16.6	327	127	553	1263	165	1.5	0.8	7.8	136	1198
6	3500	2858	2916	2828	456	16.9	326	104	579	1296	169	0.6	0.8	8	139	1243
7	3768	2702	2664	2722	399	14.5	284	118	450	1155	155	0.8	3	13	125	1194
8	5210	2704	2868	2708	415	16.3	302	122	513	1284	155	0.7	4.5	8.1	127	1255
9	3635	2730	2748	2684	387	15.7	387	122	460	1345	155	0	1.6	6	127	1238
10	2879	2708	2732	2732	282	15.1	289	137	464	1194	163	0	0	23	134	1284
11	3480	2760	2796	2768	416	15.5	294	126	474	1246	161	4.3	2.5	13	139	1251
12	8770	2850	2840	2764	420	15.8	289	123	453	1210	160	0.6	0	12	132	1226
13	3064	2744	2692	2724	371	15.1	315	138	425	1263	159	0	0	12	130	1353
14	3299	2722	2904	2740	340	14.2	301	132	420	1238	147	0	1.5	12	121	1293
15	2894	2738	3000	2736	409	15.5	298	125	654	1046	158	0	9.4	23	130	1257
16	2830	2730	2712	2736	356	14.8	297	126	450	1282	160	0.6	0.8	12	132	1259
17	3200	2754	2620	2580	390	13	258	137	623	1250	160	0.6	1	12	127	1210
18	3856	2981	3036	2848	447	17.1	294	129	647	1256	161	0	0.8	24	132	1264
19	3851	2848	2840	2820	409	14	301	137	623	1282	158	0.6	0.7	14	130	1259
20	3200	2771	2720	2710	339	13	312	126	420	1263	160	0.5	0.6	12	133	1264
21	3611	2755	2730	2700	386	12	298	139	450	1240	147	0.3	0.7	24	138	1242
22	3465	2710	2510	2500	390	16	269	125	474	1246	160	0.6	1	16	134	1282
23	3451	2793	2654	2530	371	18	298	137	442	1275	161	0	1.2	18	133	1264
24	3560	3172	2820	2620	365	15	289	129	450	1266	147	0	0.9	16	130	1239

- The Na^+ and SO_4^{2-} are the dominant ions and no one pairs of any anion and cation exceeds 50% as indicated from the Pie and Stiff diagrams of the D1 and D11 wells (Figs. 9 to 10). These indicate a simple dissolution or mixing nature of the groundwater.

- The dominant cation is sodium with a concentration ranges from 282 to 456 ppm. Calcium is the second dominant cation with a concentration ranges from 225 to 387 ppm, while magnesium has the lowest concentration of between 118 and 137 ppm. The presence of calcium and magnesium causes the water to be very hard.

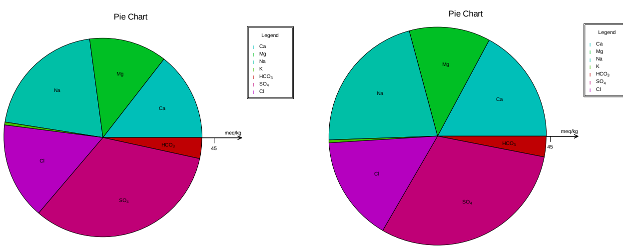

Figure 9: Pie chart of the groundwater chemistry of the D1 and D11 wells.

- The sulphate is the dominant anion with a concentration ranging from 1155 to 1345 ppm. The second most dominant anion is chloride with a concentration ranging from 420 to 647 ppm. The bicarbonate concentration is relatively low compared to chloride and sulphate and ranging from 147 to 178 ppm.

- The dominance of Cl^- anion indicates that the groundwater may be related to reverse ion-exchange between sodium ions of the meteoric water and the magnesium and calcium ions of the groundwater, which give rise to Na^+- Cl^- waters.

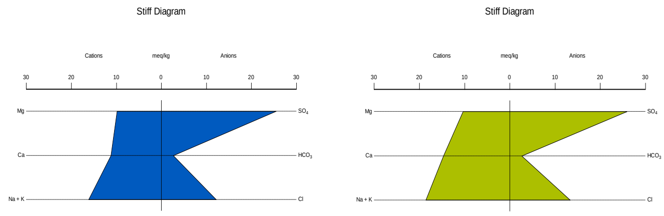

Figure 10: Stiff diagram of the groundwater chemistry of the D1 and D11 wells.

- The groundwater samples are enriched with Na+ and Ca++ and strong acids (SO4—and Cl-) than the weak acids (CO3--+ HCO3-). This can be related in part to the mineralogical composition of the Dammam aquifer (Figs. 11 to 14). The Na2SO4 is the main water type.

The main geochemical processes controlling groundwater chemistry in the study area are due to dissolution/ precipitation process along the path flow. The major ions composition in groundwater of the study area indicated that the water is not suitable for drinking **(Al-Ruwaih and Shehata, 1998).**

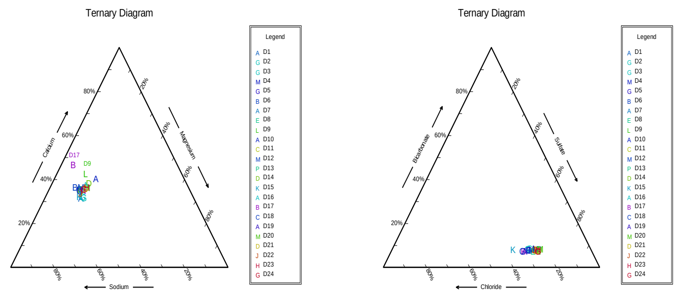

Figure 11: Ternary plots of the groundwater samples of the wells studied.

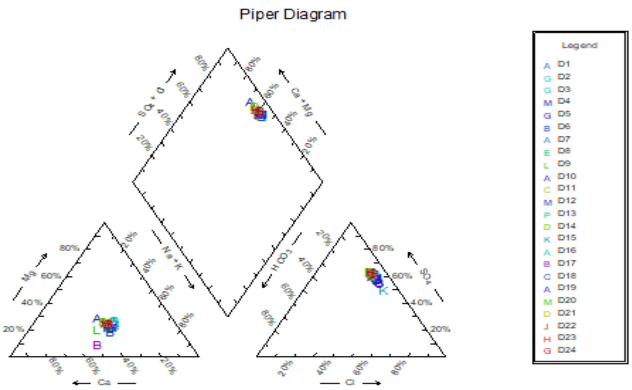

Figure 12: Piper diagram of the groundwater samples of the wells studied.

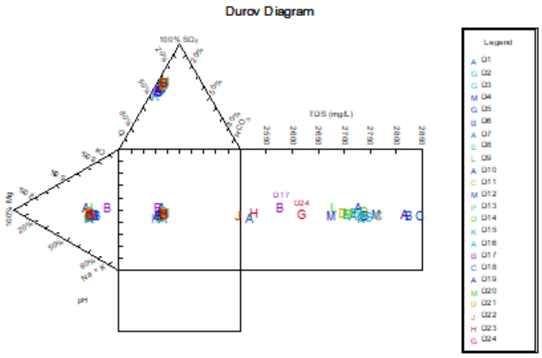

Figure 13: Durov diagram of the groundwater samples of the wells studied.

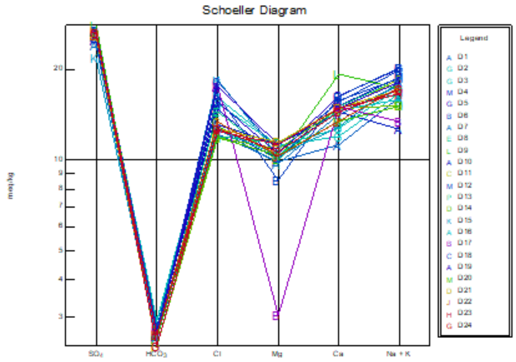

Figure 14: Schoeller diagram of the groundwater samples of the wells studied.

Gibbs (1970) suggested a diagram to study the relationship between the water chemistry and the aquifer lithology. This diagram represents the ratio of dominant anions, $Na^+/(Na+Ca^{2+})$, and cations, Cl^- / $(Cl^- + HCO_3^-)$, plotted against the value of TDS. This diagram is widely used to evaluate the functional sources of dissolved constituents such as precipitation-dominance, rock-dominance, and evaporation-dominance. The chemical analyses of the Shigaya wells were plotted in the Gibbs's diagram (Fig. 15) and showed that the samples fall, totally, into the category of rock-water interaction field. This revealed that the chemical weathering of rock forming minerals are influencing the groundwater quality by dissolution of rock through which there is circulation.

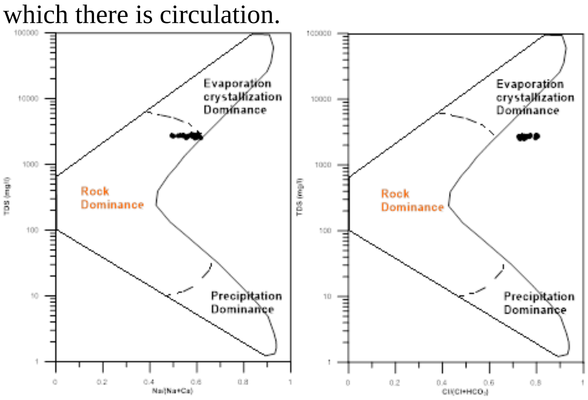

Figure 15: Gibbs's diagram of the Dammam aquifer, the Shigaya-D field.

The total dissolved solids (TDS in mg/l) distribution map (Fig. 16) reveals regular salinity patterns increase generally N and NE wards with the direction of groundwater flow with TDS values range from 2500 mg/l at the D3 well S-ward to 2828 mg/l at the D6 well NE ward during the study period, with an average value of 2700 mg/l and the water is exceedingly very hard. Local high salinity is also recorded NW of the field. Well-defined trends are observed in ion composition, as the groundwater exhibits high concentrations of Na^+, Ca^{++}, SO_4^{--}, and Cl^-.

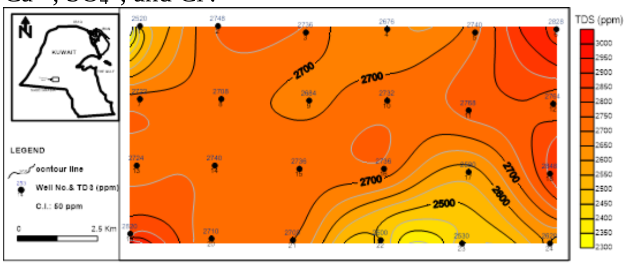

Figure 16: Iso-salinity map of the Dammam aquifer, the Shigaya-D field.

The total hardness (mg/l) distribution map (Fig. 17) reveals regular pattern increase generally S and SW wards with values range from 1054 mg/l at the D1 well NW-ward to 1353 mg/l at the D13 well SW ward during the study period, with an average value of 2500 mg/l.

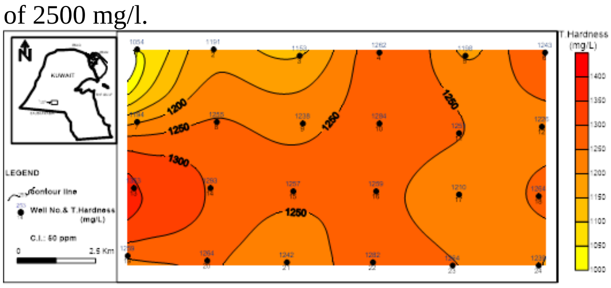

Figure 17: Total Hardness map of the Dammam aquifer, the Shigaya-D field.

CONCLUSIONS

Hydrogeophysical data from 24 groundwater wells of the Shigaya D-field, SW of Kuwait, were used to evaluate the Middle Eocene Dammam carbonate aquifer and to recognize the major geochemical processes that controlling the groundwater quality. The depth to the Dammam aquifer ranges from 244 m to 261m (b.G.S), based on the electric logs. The quantitative interpretation of the well logs indicates that the Dammam aquifer composed of limestone, dolomitized at the top, with dispersed argillaceous materials ranges from 0 to 21% and total matrix porosity ranges from 4 to 35 %. The highest matrix porosity is recorded at the top of the formation, that was enhanced by dolomitization, fracturing, and dissolution. Interpretation of the hydrochemical data indicates that the groundwater is enriched with Na^+ and Ca^{++} and strong acids (SO_4^{--} and Cl^-), with Na_2SO_4 water type. This indicates a simple dissolution or mixing nature of the groundwater and a reverse ion-exchange between sodium ions of the meteoric water and the magnesium and calcium ions of the groundwater. A rapid decrease of the Dammam water salinity was detected after 1977, as a result of groundwater exchanges that took place between the aquifer and the overlying, relatively lower salinity Kuwait Group aquifers through the wellbores whenever the wells are not being pumped.

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