

Occurrence of hydrogen sulfide in the ground water of Kuwait

A. Mukhopadhyay · A. Al-Haddad ·
M. Al-Otaibi · M. Al-Senafy

Received: 12 August 2006 / Accepted: 4 October 2006 / Published online: 16 November 2006
© Springer-Verlag 2006

Abstract Hydrogen sulfide occurs in high concentration (10–200 mg/l) in different parts of Kuwait City and its suburbs at relatively shallow depths (15–40 m from the surface). This was revealed by drilling through the aquifer system underlying the city and sampling and analyzing the ground water at the drilled locations. The near-absence of coliform bacteria in the sulfide-rich zones, the presence of sulfur-reducing bacteria in the deep (>80 m) Dammam Formation aquifer and a linear positive relation between the concentration of hydrogen sulfide and the total dissolved solids content suggested non-anthropogenic origin of the sulfide in the ground water of Kuwait. The upward movement of sulfide-rich water from depth and its differential flushing by surface recharge through outcrops of the aquifers appear to have given rise to the present distribution of hydrogen sulfide in the aquifers underlying the Kuwait City.

Keywords Hydrogen sulfide · Ground water · Biogenic source · Anthropogenic source · Kuwait

Introduction

Hydrogen sulfide (H₂S) is present in significant concentrations in the ground water of Kuwait in areas and at depths where the total dissolved solids (TDS) con-

centration often exceeds 10,000 mg/l. During investigations into the causes of the rise of the ground water table in the residential areas of Kuwait (Senay et al. 1987) and applicable remedial measures (Mossaad et al. 1997) carried out by the Kuwait Institute for Scientific Research (KISR) under the sponsorship of Kuwait's Ministry of Energy, hydrogen sulfide was detected in the areas of Sabah AlSalem, Mishref and Salwa at depths of 15–40 m (Fig. 1). In the Sabah AlSalem area, it was detected at a depth as shallow as 8 m near a wastewater lifting station. Possibly some leakage of wastewater from the station was the source of the hydrogen sulfide in this particular case.

Hydrogen sulfide concentrations of 0.1–7 mg/l were detected in shallow wells (depth 5–10 m) drilled in Andalus, Ardiya, Shamiya, Shuwaikh, Kuwait City, Beneid Al-Ghar, Mansouriya, Daiyah, Khaldiyah, Qadisiyah, Hawalli, Shaab, Salmiya, Jabariyah and Rumaithiya in 1985–1986. At Rawdah, the concentration reached a level of 35 mg/l. In the year 2002, hydrogen sulfide (H₂S) at about 200 mg/l was detected in the water pumped from a depth of about 15 m at the construction site of the Al-Awadi Tower in Kuwait City. The water was being discharged to the storm-water network with its ultimate destination being the sea. High (>10 mg/l) concentrations of hydrogen sulfide in pumped water was also encountered in the same year at a construction site for the Ministry of Public Works in the Mishref area.

Kuwait's Environment Public Authority (EPA) instituted a hydrogeological study through KISR in early 2003 to determine the distribution of hydrogen sulfide in the ground water in the Kuwait City area, its mode of occurrence and sources so that effective steps could be taken to minimize the impact on human

A. Mukhopadhyay (✉) · A. Al-Haddad ·
M. Al-Otaibi · M. Al-Senafy
Water Resources Division, Kuwait Institute for Scientific
Research, P.O. Box 24885, 13109 Safat, Kuwait
e-mail: amukhop@safat.kisr.edu.kw

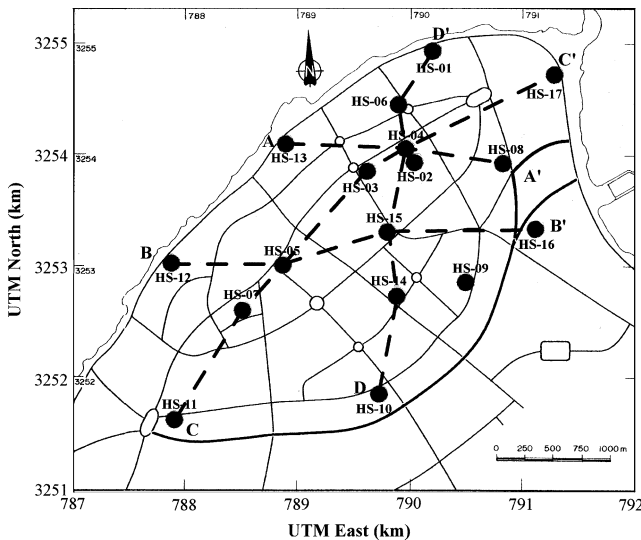


Fig. 2 The study area and the locations of the wells drilled

marine clastic sediments of the Kuwait Group. Five types of sediments were identified based on proportions of the gravel, sand and mud fractions, and categorized as green mud, silty sand, sand, gravelly sand and sandy gravel. Gravelly sand was the most dominant. Different stages of cementation by carbonate precipitation were identified within the gravelly sand, ranging from slight to moderate. Fossils (mostly mollusks) were present within the upper 8 m in the gravelly and the sandy sediments in the wells HS-01, HS-13 and HS-17. Green mud was encountered below a depth of 30 m in the drilled sequence of most of the wells, with thicknesses ranging between 1 and 20 m. Well HS-04 was drilled to a depth of 100 m. A chert-rich carbonate horizon representing the upper Dammam Formation was encountered between 83 and 94 m in this well, with a dolomitic horizon underneath.

Occurrence of hydrogen sulfide in the study area

The data obtained from the 17 wells drilled in the study area plus data from other wells previously drilled in the study zone and adjacent areas were utilized to define the hydrogeology with reference to distribution of H₂S in the ground water. Contour maps of the tops of the Dammam Formation, the water table, high-salinity (>10,000 mg/l) and high-hydrogen-sulfide (concentration >10 mg/l) zones were prepared (Fig. 3). A structural high with a roughly north–south axis exists on the top of the Dammam Formation in the study area. The water table roughly parallels the structural high with a diverging lateral hydraulic gradient towards Kuwait Bay to the west and north, and the Arabian Gulf to the

east. This is possibly somewhat modified by local dewatering activities and infiltration of irrigation water. The tops of the high-salinity (>10,000 mg/l TDS) and high-sulfide-concentration (>10 mg/l) surfaces are shallowest around wells HS-02 and HS-04 and are deeper in the western parts of Kuwait City (Fig. 4).

Possible sources of hydrogen sulfide in the study area

Theoretical considerations

Sources of hydrogen sulfide in ground water can be natural (i.e., biochemical or inorganic reactions) or anthropogenic (e.g., leakage from sewage networks, contamination from waste disposal sites, etc.). Hydrogen sulfide is formed naturally in low temperature–low pressure environments when sulfate ions in the aquifer are reduced to hydrogen sulfide by sulfate-reducing bacteria (SRB), and/or in the absence of bacteria, by reactions of sulfate ions with carbonic acid derived from the decay of organic matter (Dunsmore 1973).

Most natural occurrences of hydrogen sulfide are end products of microbial activities. Chapelle (1993) described in detail the sulfur cycle in nature. Sulfur in the reduced (-2) state is an important component of many proteins. Most microorganisms derive their supply of this sulfur by reducing the sulfate to sulfide. Reduction can take place under both aerobic and anaerobic conditions. The reduced sulfur in proteins is returned to the sulfur cycle as hydrogen sulfide through decaying plants and animals (putrification). Under anaerobic conditions, the reduction of sulfate to sulfide occurs when sulfate acts as the electron receptor in the oxidation of organic carbon or elemental hydrogen. In marine and estuarine environments, sulfate reduction is often the most important process leading to the oxidation of plant debris and the consequent production of carbon dioxide.

A part of the hydrogen sulfide produced through microbial reactions is fixed in the sediments through reaction with metals, especially iron, to form sulfide minerals, and is temporarily removed from the sulfur cycle. Some fraction diffuses to the aerobic zone and is oxidized to sulfate through microorganisms like *Thiobacillus*. Jorgenson (1990) has shown that much of the H₂S produced under anaerobic conditions is also re-oxidized anaerobically, in tandem with the reduction of Fe(III) compounds present in the sediments. Thiosulfate (S₂O₃²⁻), a partially oxidized compound, is the intermediate product that later breaks down into sulfate and sulfide.

Table 1 Chemical parameters measured for water samples collected from test wells in Kuwait City

Wellname	Screen zone	TDS (mg/l)	H ₂ S (mg/l)	pH	Eh (mV)	DO (mg/l)	Measurement date
HS-01	A (11–16 m)	14,640	0.0	7.4	-103	0.01	04-Apr-04
HS-01	B (20–25 m)	10,860	2.1	6.71	14	0.01	06-Apr-04
HS-01	C (32–37 m)	93,000	200.0	6.05	-42	0.41	07-Apr-04
HS-01	D (43–48 m)	85,000	213.0	6.09	-46	0.18	10-Apr-04
HS-02	A (11–16 m)	16,680	12.8	6.87	-649	0.18	03-Apr-04
HS-02	B (20–25 m)	84,800	244.0	6.94	-385	0.02	05-Apr-04
HS-02	C (30–35 m)	98,500	223.1	5.92	-38	3.11	07-Apr-04
HS-02	D (40–45 m)	92,000	213.0	5.94	-47	1.21	10-Apr-04
HS-03	A (6–11 m)	10,860	0.0	7.16	229	7.35	06-Apr-04
HS-03	B (20–25 m)	11,530	5.3.0	7.07	7	0.02	07-Apr-04
HS-03	D (46–51 m)	34,800	138.0	6.43	-48	0.09	14-Apr-04
HS-04	DM (96–100 m)	114,400	213.0	5.94	-40	0.04	25-Apr-04
HS-05	A (11–16 m)	4,100	0.0	7.01	278	0.00	17-Apr-04
HS-05	B (21–24 m)	9,980	0.0	6.92	336	0.04	18-Apr-04
HS-05	D (45–50 m)	15,616	43.0	6.81	-32	0.00	24-Apr-04
HS-06	A (9–14 m)	9,500	12.8	6.78	303	0.13	24-Apr-04
HS-06	B (20–25 m)	75,600	206.0	6.08	-50	0.13	25-Apr-04
HS-06	C (30–35 m)	97,800	223.1	6.03	-48	0.02	25-Apr-04
HS-06	D (40–45 m)	105,320	244.4	6.01	-45	0.05	26-Apr-04
HS-07	A (11–16 m)	4,180	0.0	7.30	137	0.17	17-Apr-04
HS-07	B (20–25 m)	6,650	0.0	7.45	241	1.20	19-Apr-04
HS-07	C (29–34 m)	15,509	0.0	6.97	281	1.04	20-Apr-04
HS-07	D (49–54 m)	11,049	36.1	6.79	-72	0.15	24-Apr-04
HS-08	A (11–16 m)	9,460	0.0	7.41	243	0.00	25-Apr-04
HS-08	B (20–25 m)	30,040	17.0	6.67	-27	0.12	26-Apr-04
HS-08	C (30–35 m)	64,618	170.0	6.19	-53	0.14	27-Apr-04
HS-08	D (55–60 m)	84,800	226.0	6.06	-49	0.00	28-Apr-04
HS-09	A (11–16 m)	9,100	0.0	7.12	265	0.13	25-Apr-04
HS-09	B (19–24 m)	8,740	0.0	7.22	222	0.13	26-Apr-04
HS-09	C (30–34 m)	18,210	2.1	6.88	20	0.00	27-Apr-04
HS-09	D (40–45 m)	27,100	116.8	6.52	-60	0.05	28-Apr-04
HS-10	A (11–16 m)	13,280	0.0	6.93	20	3.28	02-May-04
HS-10	B (21–26 m)	9,010	0.0	7.45	30	0.57	03-May-04
HS-10	C (30–35 m)	15,120	0.0	7.22	-13	1.20	04-May-04
HS-10	D (41–46 m)	15,800	53.1	6.85	-393	0.62	05-May-04
HS-11	A (10–15 m)	8,240	0.0	6.82	34	0.01	28-Apr-04
HS-11	B (20–25 m)	8,550	0.0	7.31	24	2.10	29-Apr-04
HS-11	C (32–37 m)	13,520	0.0	7.19	55	5.45	01-May-04
HS-11	D (55–60 m)	11,400	31.8	6.98	-380	0.10	02-May-04
HS-12	B (20–25 m)	9,500	0.0	6.94	20	2.01	01-May-04
HS-12	C (30–35 m)	29,600	0.0	6.82	-14	0.00	03-May-04
HS-12	D (50–55 m)	15,620	53.1	6.83	-397	0.05	04-May-04
HS-13	B (20–25 m)	23,200	9.6	6.55	-381	0.18	07-May-04
HS-13	D (50–55 m)	87,300	223.1	6.33	-385	0.71	08-May-04
HS-14	B (20–25 m)	17,020	0.0	7.09	-57	0.49	06-May-04
HS-14	C (30–35 m)	19,300	0.0	6.87	38	0.41	08-May-04
HS-14	D (50–55 m)	18,200	64.0	6.85	-339	3.01	09-May-04
HS-15	A (8–14 m)	7,618	0.0	7.18	-27	0.01	11-May-04
HS-15	B (19–25 m)	11,326	0.0	7.11	-200	0.01	11-May-04
HS-15	C (31–35 m)	18,357	0.0	7.08	-60	0.00	12-May-04
HS-15	D (40–44 m)	19,522	68.0	6.87	-400	0.00	13-May-04
HS-16	A (10–16 m)	6,882	0.0	7.27	-273	0.06	11-May-04
HS-16	B (20–26 m)	14,110	0.0	7.22	-299	0.00	11-May-04
HS-16	D (50–56 m)	81,244	233.8	6.28	-406	0.71	13-May-04
HS-17	A (11–16 m)	5,200	0.0	8.58	-105	0.83	08-May-04
HS-17	B (21–26 m)	46,200	2.1	6.97	-316	2.50	08-May-04
HS-17	C (31–36 m)	79,462	233.8	6.28	-387	0.40	09-May-04
HS-17	D (41–46 m)	78,260	218.8	6.22	-387	1.97	11-May-04

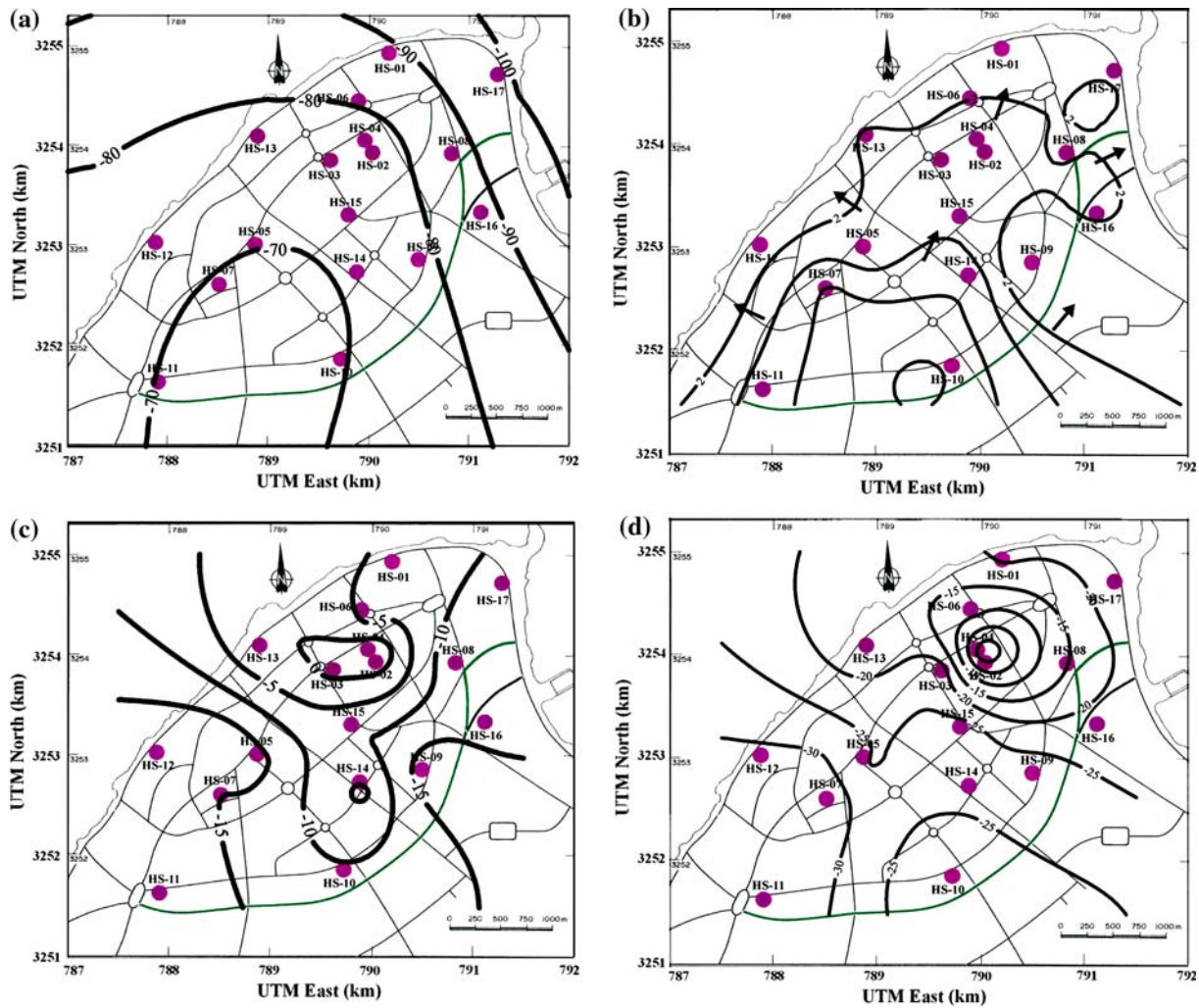


Fig. 3 Structure contour maps (in meters above mean sea level) of surfaces of interest in the Kuwait City area. **a** The top of the Dammam Formation. **b** The water table; the *arrows* indicate the

general movement pattern of ground water in the area. **c** The top of the saline ground water (salinity >10,000 mg/l). **d** The top of the high sulfide zone (sulfide >10 mg/l)

In an oxygenated aquifer in the presence of sulfide minerals like pyrite, sulfides are first oxidized to sulfates. The sulfates are later reduced to produce hydrogen sulfide. The sulfur cycle, however, may not run its full course if interrupted by other processes like iron reduction initiated by consumption of dissolved oxygen. The sulfates accumulate in solution while iron reduction is going on. Once Fe(III) reduction ceases, sulfate reduction is expected to resume.

The sulfur cycle is often important in aquifers that lack sulfate or sulfide minerals and contain low levels of sulfate in solution. Clastic sediments, deposited under humid or temperate fluvial and marine environments, are examples of such situations. As explained by Chapelle (1993), the confining beds associated with such aquifers, specifically if they are of marine origin, often contain relatively high concen-

trations of sulfates in the pore waters and large amounts of sulfide minerals in their matrix. SRB can be recovered from aquifers using culturing techniques, but not from the confining beds. The concentration gradient between the confining bed and the aquifer helps supply sulfate to the aquifer through diffusion, where it is reduced to sulfide through microbial activity. The oxidation of sulfide minerals by Fe(III)-bearing minerals helps to maintain the sulfate concentration in the confining beds. Sulfides produced by sulfate reduction readily form iron sulfide if enough Fe(III)-bearing minerals like glauconite are present in the aquifer. Otherwise, they accumulate in the aquifer and may be responsible for hydrogen sulfide problems. In anaerobic parts of the aquifers that contain sulfate minerals like gypsum, hydrogen sulfide is generated through sulfate reduction. Gypsum dissolution maintains the

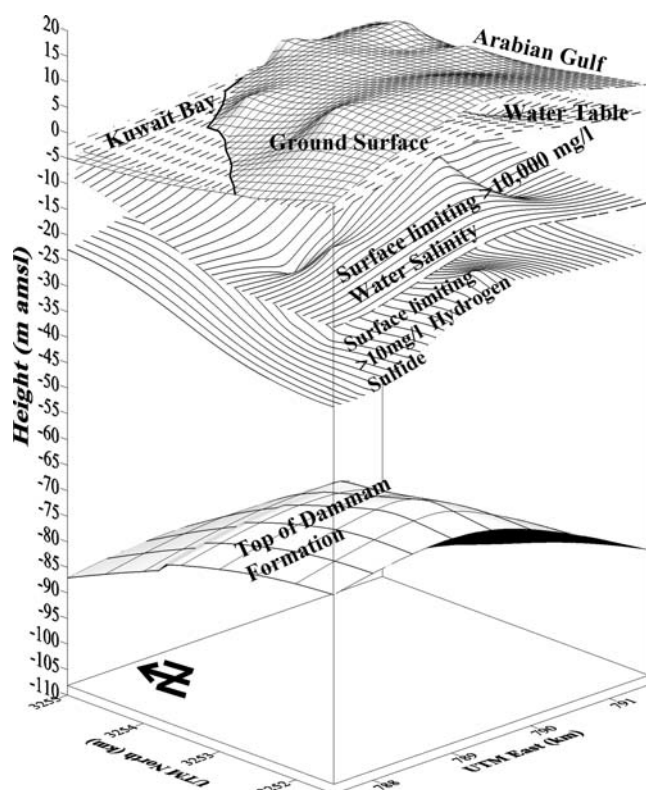


Fig. 4 Three-dimensional orthographic projection of the hydrogeological surfaces of interest in the Kuwait City area

level of sulfate in the aquifer. Again, if iron-bearing minerals are in short supply in these aquifers, water quality problems associated with hydrogen sulfide will be encountered.

Hydrogen sulfide from sewage pollution can occur in some surface waters, in poorly constructed wells or in shallow wells close to sewer lines or septic systems. Wells drilled in shale or sandstone, or near coal or oil fields often have hydrogen sulfide present in the water.

Hydrogeology of the study area and sulfide occurrence

The generalized Tertiary hydrostratigraphy of Kuwait and the surrounding region is presented in Fig. 5. A conceptual model of the hydrogeology (Fig. 6) shows highly saline (>50,000 mg/l TDS) ground water containing hydrogen sulfide in solution in the Dammam Formation and Kuwait Group sequence. During the last pluvial period, which prevailed in the area about 20,000 years ago, rainwater infiltrated into the exposed outcrops of the Dammam Formation and older sequence in the highlands of Saudi Arabia and flowed towards the discharge zone bordering the Arabian Gulf and the Shatt Al-Arab basin. Ground water flow in

permeable aquifer zones and semi-permeable aquitard zones gave rise to an upward movement causing water to flow from the Dammam Formation to the Kuwait Group, especially near the coastal discharge zone. As water flowed down the hydraulic gradient, it flushed out the original saline water from these aquifers and interaction with the minerals in the aquifer increased the dissolved mineral content. Mixing with the older saline water created a transition zone of varying salinity between the older more saline and younger fresher water. Flow became slower and flushing efficiency declined as ground water spread over a wider area and approached the discharge zone, especially while crossing the regional anticlinal axis, the Ahmadi structure near the coast, passing through the Greater Burgan, Sabriya and Raudhatain oilfields of Kuwait (Fig. 7). Near the coastal areas bordering the Arabian Gulf, very little flushing of the original connate water has occurred, except for a thin zone near the water table through which the discharge to the Gulf takes place. This explains the existence of highly saline ground water with high hydrogen sulfide contents near ground surface in the zone bordering the Arabian Gulf, where Kuwait City is located.

Figure 8 presents the water table, the top of high salinity (>10,000 mg/l) water, the zone containing hydrogen sulfide in significant concentration (>10 mg/l) and the structure at the top of the Dammam Formation. The conceptual model (Fig. 6) is confirmed by these cross-sections. Around well HS-04, both the high salinity zone (TDS >10,000 mg/l) and the high H₂S zone rise almost to the water table very near the surface, creating convex upward surfaces that are also seen in the contour maps of salinity and H₂S concentration (Fig. 3c, d). This salinity and H₂S high may be explained by an upward hydraulic gradient and fractures near the axial trend of the anticline that provide an easier path for the highly saline and sulfide-rich water to flow from the deeper horizons to shallower depths; depression of the deeper contact zone between the highly saline, sulfide-rich ground water below and the brackish, low-sulfide water above due to recharge of fresher water from man-made sources (irrigation of public and private gardens) in adjacent areas; differential flushing of the older water due to variations in hydraulic conductivity; or a combination of the above. Numerical modeling of the ground water flow in the Kuwait City area indicated that under steady-state condition, upward flux of 0.6 mm/day (150 m³/day/500 m × 500 m grid block) from the Dammam Limestone to the Kuwait Group aquifer along the extension of the Ahmadi Ridge was essential to maintain observed potentiometric heads in the Kuwait Group

Fig. 5 Generalized hydrostratigraphy of Kuwait and the neighboring region

GENERALIZED STRATIGRAPHY		HYDROGEOLOGICAL UNITS
Quaternary sediments (<30 m)	Unconsolidated sands and gravels, gypsiferous and calcareous silts and clays	Localized Aquifers
Unconformity		
Kuwait Group		
Mio-Pliocene sediments of Hadruk, Dam and Hofuf Formations in Saudi Arabia; Ghar, Fars and Dibdibba Formations of Kuwait and southern Iraq (200–300 m)	Gravelly sand, sandy gravel, calcareous and gypsiferous sand, calcareous silty sandstone, sandy limestone, marl and shale; locally cherty	Aquifer
Unconformity		
	Localized shale, clay and calcareous silty sandstone	Aquitard
	Cherty limestone	
Dammam Formation (60–200 m)	Chalky, marly, dolomitic and calcarenitic limestone	Aquifer
Unconformity		
	Nummulitic limestone with lignites and shales	Aquitard; locally aquiclude where Rus Formation is predominantly anhydritic
Rus Formation (20–200 m)	Anhydrite and limestone	
Umm Er Radhuma (UER) Formation (300–600 m)	Limestone and dolomite (calcarenitic in the middle) with localized anhydrite layers	Aquifer
Disconformity		
	Shales and marls	Aquitard
Aruma Group (400–600 m)	Limestone and shaly limestone	Aquifer

aquifer before the large-scale urbanization of the area (Hamdan and Mukhopadhyay 1991).

Natural versus anthropogenic origin of hydrogen sulfide in Kuwait

Several parameters were selected to determine the source of hydrogen sulfide in the ground water of Kuwait City. Indicators for the natural generation of hydrogen sulfide include the presence of SRB in the ground water, and the location and depth of occurrence of hydrogen sulfide. An anthropogenic source should be characterized by significant concentrations of nutrients like ammonia (NH₃), high total organic carbon (TOC) and biological oxygen demand (BOD) with the simultaneous presence of biological indicators

like total coliform bacteria, fecal coliform bacteria and streptococci.

A total coliform bacteria content of 117 cfu/100 ml and a fecal streptococci content of 20 cfu/100 ml were measured in the sample from well HS-02A only. Other samples of ground water were free from these bacteria. The near absence of coliform bacteria in the water samples collected from the sulfide-rich zones in the aquifers underneath Kuwait City suggests that sewage contamination is localized in a small area around well HS-02, and is not the primary source of sulfide.

The Dammam Limestone Formation is of shallow marine origin and is rich in organics, as demonstrated by the abundance of marine fossils and localized concentrations of lignite and bitumen (Al-Awadi et al. 1998). The lower parts of the Kuwait Group aquifer

Fig. 6 Conceptual model of ground water flow in the aquifers of Kuwait

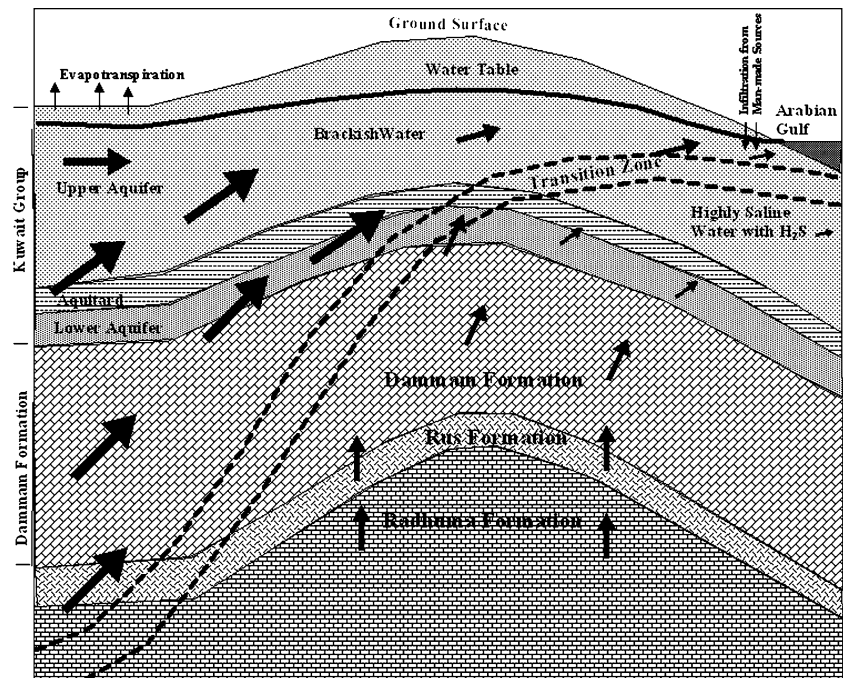
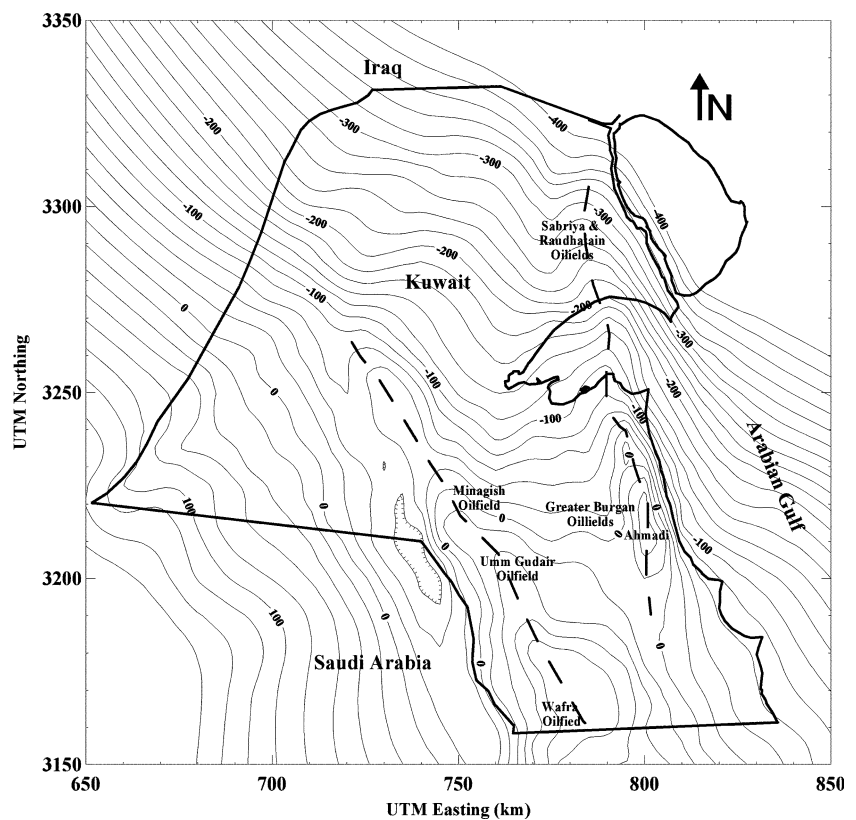


Fig. 7 Structure contours of the top of the Dammam Formation with reference to the locations of the oilfields in Kuwait



were also deposited under partly marine conditions in localized areas, as demonstrated by the presence of green clays rich in glauconite. The ground water in these aquifers is also rich in sulfate (>1,000 mg/l).

These conditions are suitable for the generation of hydrogen sulfide in aquifers under natural conditions.

The good correlation between sulfide concentrations above 40 mg/l and TOC (Fig. 9) suggests that bio-

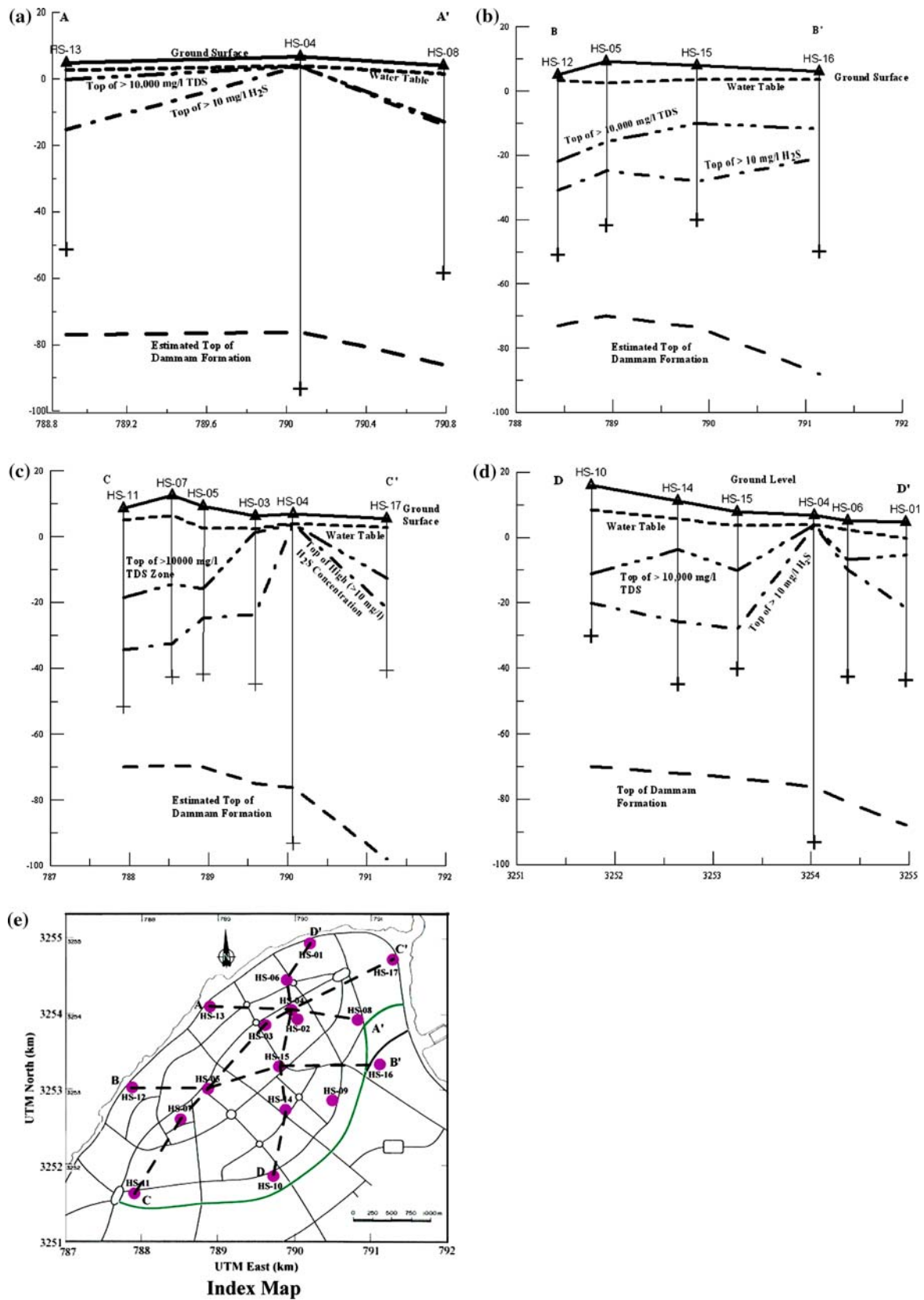


Fig. 8 Cross-sections of Kuwait City: **a** The cross-section A–A’; **b** The cross-section B–B’; **c** The cross-section C–C’; **d** The cross-section D–D’; **e** Index Map

chemical processes may be responsible for the generation of H_2S in the aquifer. SRB were detected in the Dammam Limestone aquifer at 100 m in well HS-04 with a count of 6 cfu/100 ml, giving further credence to the hypothesis that the sulfide in the ground water is natural in origin.

The differential flushing by recharged rainwater originating in the highlands of Saudi Arabia, combined with the structure of the aquifers, modified distribution of hydrogen sulfide in the ground water. When depth distribution of sulfide concentrations at the time of drilling and that of TDS in the ground water are juxtaposed in three dimensions (Fig. 4) and in cross-sections (Fig. 8), the association of high (>10 mg/l) sulfide concentrations with highly saline water (TDS >10,000 mg/l) is apparent. An almost linear relation between the two parameters is revealed by the cross-plot of sulfide concentration against TDS (Fig. 10).

Given the ground water flow conditions and quality variation in Kuwait, and the data and information provided by the wells in the study area and adjacent neighborhoods, the presence of saline ground water in association with hydrogen sulfide at depths ranging from 15 to 40 m in the Kuwait City area and the coastal areas to the south is to be expected. The presence of hydrogen sulfide at high concentrations (>100 mg/l) at relatively shallow depths (8–20 m) in the Mishref and Abdullah Al-Salem areas (Al-Haddad et al. 2003;

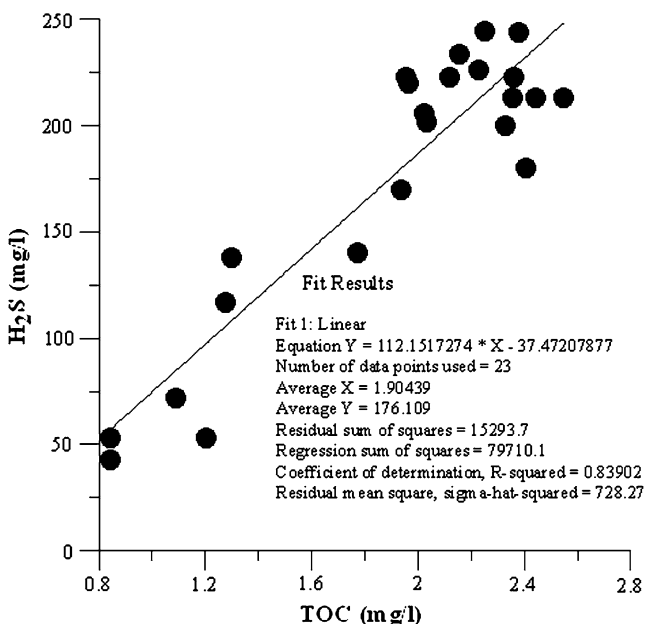


Fig. 9 Cross-plot of sulfide concentrations in the ground water of Kuwait City versus total organic carbon (TOC) concentrations

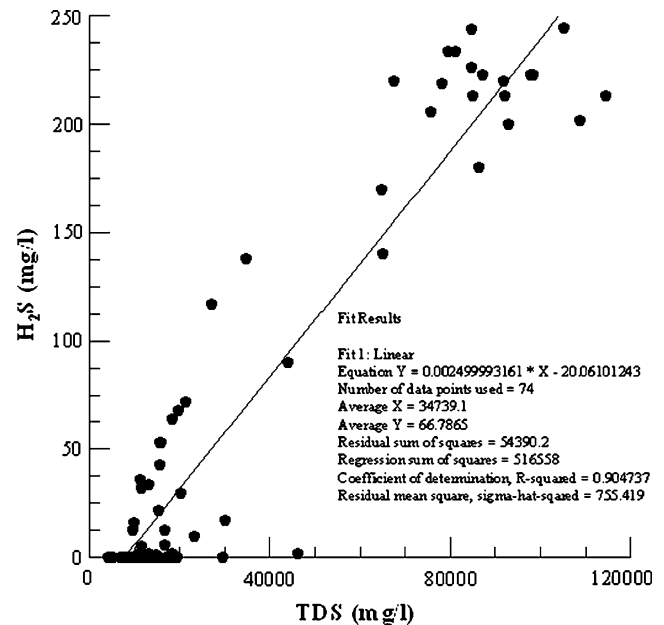


Fig. 10 Cross-plot of sulfide concentrations in the ground water of Kuwait City versus the total dissolved solids (TDS) content

Mossad et al. 1997), in addition to that observed in Kuwait City, supports this idea.

Conclusions and recommendations

Hydrogen sulfide in high concentrations (up to 200 mg/l) has been encountered in the ground water of Kuwait City and its suburbs at relatively shallow depths (15–40 m from the surface). High hydrogen sulfide levels create environmental problems when construction sites are dewatered and the ground water is disposed of on the ground surface or in the stormwater network. Kuwait's EPA retained KISR to study the occurrence and distribution of hydrogen sulfide to determine the source of the contamination in the ground water and to recommend steps to combat the problem. From the data and information collected from 17 wells, the following conclusions were drawn:

- Hydrogen sulfide in the ground water of Kuwait is natural in origin. The near-absence of coliform bacteria associated with the sulfide-rich ground water and a significant correlation of the sulfide concentration with the TDS in the ground water support this conclusion.
- Bacterial reduction of sulfate in the deeper saline (TDS >10,000 mg/l) ground water to sulfide is the most probable cause of the formation of hydrogen sulfide in this area.

- The movement of hydrogen-sulfide-rich saline ground water from the deeper Dammam Limestone Formation to the overlying Kuwait Group clastic sediments along the prevailing upward hydraulic gradient in the coastal discharge zone of Kuwait brings the chemical near the surface. The possible presence of tension fractures and faults, associated with the anticlinal structure represented by the Ahmadi Ridge may help in this upward transfer of water. The deeper occurrence of hydrogen sulfide away from the anticlinal axis may also be related to this structural association.

Care should be taken in locating high-rise constructions that require intensive dewatering in areas with relatively shallow sulfide-rich ground water in and around Kuwait City. These areas should fall predominantly near the coastal zones of Kuwait and adjacent to the axis of the anticline passing through Ahmadi. If such constructions in these locations are absolutely necessary, prior preventive measures should be taken to decontaminate the water withdrawn from the aquifer before its disposal through near-surface facilities or to the sea.

Acknowledgment Kuwait's Environment Public Authority funded the study, while Kuwait's Ministry of Public Works provided material and field support. The comments and the suggestions of Dr. Yildir Senay, the then Senior Hydrogeologist in Kuwait's Ministry of Energy, have enriched the work. The work was carried out at the Hydrology Department of the Water Resources Division of the Kuwait Institute for Scientific Research (KISR). The support of Dr. Muhammad Al-Rashed,

Director of the Water Resources Division, throughout the duration of the work is gratefully acknowledged. The authors are grateful for the permission of KISR's management for the publication of the article (Publication No.: KISR8303).

References

- Al-Awadi E, Mukhopadhyay A, Al-Senafy MN (1998) Geology and hydrogeology of the Dammam Formation in Kuwait. *Hydrogeol J* 6(2):302–314
- Al-Haddad AJ, Al-Qallaf H, Al-Salman B, Ghoneim H, Bhandary H (2003) Investigations on hydrogen sulfide in ground water of Mishref area, Kuwait. Kuwait Institute for Scientific Research, Report No. KISR6914, Kuwait
- Chapelle F (1993) Ground-water microbiology and geochemistry. Wiley, New York
- Dunsmore E (1973) Diagenetic processes of lead-zinc emplacements in carbonates. *Trans Inst Mining Metallurgy Section B* 82:B168–B173
- Hamdan L, Mukhopadhyay A (1991) Numerical simulation of subsurface water rise in Kuwait City. *Ground Water* 29(1):93–104
- Jorgenson BB (1990) A thiosulfate shunt in the sulfur cycle of marine sediments. *Science* 249:152–154
- Mossad M, Sayed SAS, Szekely F, Mukhopadhyay A, Ghoneim H, Al-Murad M, Golder Associates (1997) Study, design and construction supervision of a pilot ground water drainage project: study and design of a ground water drainage project in the Sabah Al-Salem area. Kuwait Institute for Scientific Research, Report No. KISR5053, Kuwait
- Senay Y, Hamdan L, Yaqubi A (1987) Study of subsurface water rise in the residential areas of Kuwait, vol 3A. Methodology and results of hydrological and water quality testing. Kuwait Institute for Scientific Research, Report No. KISR2227, Kuwait