DRINKING WATER QUALITY IN SAUDI ARABIA — AN OVERVIEW

Muhammad Sadiq*

Water Resources and Environment Division, Research Institute
King Fahd University of Petroleum and Minerals
Dhahran, Saudi Arabia

and

Ghulam Hussain

Institute of Natural Resources, KACST
Riyadh, Saudi Arabia

الخلاصـة :

تـمَّتْ مراجعة المعلومات المنشورة عن نوعية مياه الشرب (الجوفية والمحلاة) في المملكة العربية السعودية. فهناك معلومات متوفرة – ولكنها متناثرة – عن ملوحة هذه المياه ومكوناتها من الأيونات السالبة والموجبة. إنَّ غالبية المياه الجوفية، وخاصة في المنطقتين الوسطى والشرقية مرتفعة الملوحة، وتتطلب معالجة لتكون مناسبة للاستهلاك الآدمي، وفي بعض المناطق يتسبَّب الاستهلاك المرتفع للمياه في انخفاض مناسيب المياه الجوفية لعدة أمتار، كما لوحظتْ تغيرات على نوعية تلك المياه.

أما المعلومات عن المعادن الثقيلة النزرة فهي محدودة، سواء في المياه الجوفية أو مياه الشـرب. ولكن تَـمَّ عرض معلومات جديدة عن تأثير شبكة التوزيع على نوعية المياه؛ فقد أدّى تآكل الأنابيب المعدنية والنض الكيميائي من الأنابيب البلاستيكية (بي ڤي سي) إلى رفع تراكيز المعادن في مياه الشرب.

وقد تَـمَّ تحديد مشاكل مياه الشرب في المملكة العربية السعودية، واقترحت توصيات لتحسـين نوعيتها.

*Address for correspondence:
KFUPM Box 417
King Fahd University of Petroleum & Minerals
Dhahran 31261
Saudi Arabia

ABSTRACT

Published literature on the Kingdom of Saudi Arabia's drinking water quality (groundwater and desalted water) are reviewed. Data on general water quality parameters (salinity and major cations and anions), for both groundwater and drinking water, are available, but fragmented. The majority of groundwater aquifers, especially in the central and eastern parts, are highly saline and the water requires desalting to become fit for human consumption. In some areas, over-pumping has lowered the groundwater table by several meters and the water quality has also been changing.

The data on toxic trace metal concentrations, either in the groundwater or drinking water, are limited. However, new data on the effect of the distribution network on water quality have been presented. Corrosion of utility pipes and leaching of chemicals from PVC pipes could elevate metal concentrations in drinking waters supplied to the end users. The problems of drinking water supplies in Saudi Arabia are identified and recommendations are made to improve the drinking water quality in the Kingdom.

DRINKING WATER QUALITY IN SAUDI ARABIA — AN OVERVIEW

1. INTRODUCTION

The Kingdom of Saudi Arabia is an arid desert country extending over an area of 2.1 million km^2 [1]. The scarcity of water has become a serious problem for Saudi Arabia because of limited supplies and ever-growing demand. There are no perennial rivers or freshwater lakes in the Kingdom. However, it has many large reservoirs of geologically trapped groundwater. These reservoirs have been the primary source of water supply in the country [2, 3]. The recharge of aquifers is limited as the country receives scanty and sparsely distributed rains. Faced with the steady and substantial rise in water demand, the Saudi government has spent about 32 billion SR on public water supply projects during 1985–1990 [4].

Water consumption in the year 2000 is expected to reach 16.5 billion m^3 of which 79% is expected to come from groundwater and the remaining from other sources [5]. Since groundwater is the most important water source, its rapid depletion or deterioration may have severe socio-economic implications. Every efforts should be made to conserve and keep groundwater clean. In recent years, several factors have led to the deterioration of the quality and quantity of groundwater. Over-exploitation and excessive pumping caused salt intrusion in the coastal areas [6, 7]. Seepage of sewage from septic tanks and cesspools are responsible for both the deterioration of chemical and biological quality of some well waters [8]. Agricultural related pollution sources, such as irrigation water, pesticides, fertilizers, *etc*., are gradually contaminating groundwater [9]. As a consequence, it is important to monitor the quality of groundwater.

Saudi groundwater is largely saline and excessive salts have to be removed to make it fit for human consumption. Desalination processes are used to reduce dissolved salts from groundwater and/or seawater. The desalted water is pumped through utility pipes to consumers. Corrosion products and leaching of chemicals from the pipes may deteriorate water quality during transportation [10, 11]. The objectives of this paper are to collect information on the drinking water quality in Saudi Arabia, and identify some of the problems that are associated with the water supply systems.

2. SAUDI DRINKING WATER SUPPLIES

It is expected that by the year 2000, about 79% of the water consumed in Saudi Arabia will come from groundwater and the remaining 21% from other sources [5]. The major source of drinking water in Saudi Arabian cities is desalinated water, either groundwater or seawater. In the country side, groundwater as such is used for drinking purposes. The quality of groundwater varies widely whereas the composition of desalinated water is relatively constant. In Saudi Arabia, the drinking water quality can be affected by the composition of the source water, and by the contaminants released from the pipes due to corrosion and leaching.

2.1. Saudi Groundwater Resources

Mainly, there are two types of groundwater aquifers in Saudi Arabia; the shallow alluvial aquifers and confined aquifers. The shallow alluvial aquifers generally occur along wadi systems, and are sometimes underlain by weathered bedrock, which is usually limestone and/or sandstone. The shallow alluvial aquifers are generally unconfined, narrow and long. The water table in these aquifers fluctuates rapidly in response to the local precipitation and season. Most of the alluvial aquifers are found in the western part of the country where these are generally used for domestic and agricultural purposes [12]. The mean annual recharge of the alluvial aquifers is estimated to be 800 million cubic meter (Mm^3). About 80% of the recharge occurs in the western and southwestern region of the country. These are the regions where rainfall is relatively abundant.

There are seven major confined aquifers in Saudi Arabia: Saq, Wijid, Minjur, Dhruma, Wasia, Umm Er Radhuma, and Dammam aquifer [13]. The Ministry of Agriculture and Water [14] identified nine main deep aquifers in the country (Tabuk, Neogene, and the above seven). The Neogene and Umm Er Radhuma are carbonate aquifers while the remainder are mainly sandstone. In addition to the above primary aquifers, the secondary aquifers are Aruma, Jauf, Khuff, Jilh, and Sakaka. The Saq and Tabuk sandstone formations hold the best quality water in Saudi Arabia. A summary of confined groundwater aquifers in Saudi Arabia is given in Table 1.

2.2. Quality of Saudi Groundwater

The quality of groundwater in Saudi Arabia varies from area to area and from season to season; and in only a few areas, is it of an acceptable drinking quality (*i.e.* dissolved salts < 1000 mg l^{-1}). As mentioned earlier (Table 1), most of the groundwater in Saudi Arabia is brackish, and contains dissolved salts over the 1000 mg l^{-1} level. El Din *et al.* [8] and Manwaring *et al.* [15] determined dissolved salts, nitrate, ammonia, and coliforms in 388 groundwater wells in six regions of Saudi Arabia (Riyadh, Qasim, Hail, Western, Northern, and Southern regions). They reported that dissolved salts varied widely (180–9350 mg l^{-1}), and that about 19% of the wells contained salts above the SASO [16] and WHO [17] drinking water limit of 1000 mg l^{-1}. Similarly, nitrate in about 8% wells were higher than the proposed health limit of 45 mg l^{-1} and 21% of the wells tested positive for fecal coliform. The authors concluded that nutrient and fecal coliform contamination of well water was occurring; these data from [8] are summarized in Table 2.

Spatial trends in groundwater quality were also investigated. For example, Al-Faruq *et al.* [18] investigated trends in chemical characteristics of groundwater in the Qasim region. They found that dissolved salts and pH levels of the drinkable groundwater samples were gradually increasing in the Qasim region, where 205 water samples were analyzed between 1978 and 1987 [18]. In another study, El Din *et al.* [9] noted that nitrate contamination of groundwater in the Riyadh region has increased from 1984 to 1989; however, these data were not conclusive. In 302 drinking water samples, 95% contained nitrate below the 45 mg/l limit. The authors suspected agricultural sources for nitrate contamination. In about 3% of well water samples, ammonia levels were more than the accepted limit. This finding was associated with the use of fertilizers. Fecal coliforms were present in about 21% of the well water samples — an indication that human and animal wastes are finding their way into groundwater. This situation, if it remains unchecked, could cause serious groundwater contamination.

The groundwater chemistry of Wadi Al-Yamaniyah has been investigated in 1981 and 1987 [19]. Due to overdraw, the aquifer table has been lowered by 7 meters during this period. Interestingly, however, the groundwater salinity was lower in 1987 water samples as compared with those collected in 1981. This could be due to the removal of some of the easily soluble salts from the aquifer during the early exploitation of the groundwater. A critical evaluation of water quality data indicated that salinity and major components (cations and anions) have been increasing in water samples having low total dissolved salts whereas a reverse trend can be seen in waters of high salinity.

The chemical characteristics of Saudi groundwater are given in Table 3. The groundwater is largely alkaline. The major components of the groundwater are sodium, calcium, magnesium, chloride, sulfate, and carbonates. Data on toxic metal concentrations in Saudi groundwater are not reported — probably not determined at all. In a recent study [20], 12 water samples were collected from Umm Er Radhuma aquifer and analyzed for toxic metal concentrations. These data are summarized in Table 4. Significant (p <0.05) variations in the concentrations of major elements are shown. Concentrations of toxic metals, except nickel and lead, were found to be below the drinking water guidelines of SASO [16] and WHO [17].

Table 1. Summary of Deep Groundwater Reserves in Saudi Arabia.

Aquifers*	Salinity (mg l^{-1})	Annual Recharge (Mm^3)	Groundwater Reserves (Mm^3)		
			Proven	Probable	Possible
Saq	300–3000	310	65000	100000	200000
Wajid	500–1200	104	30000	50000	100000
Minjur and Dhruma	1100–20000	80	17500	35000	85000
Wasia/Biyadh	900–10000	480	120000	180000	290000
Umm Er Radhuma	2500–5000	406	16000	40000	75000
Dammam	2600–6000	200	5000	25000	
Tabuk	250–2500	455	205000		
Neogene	3700–4000	290	120000		
Khuff/Tuwail	3800–6000	132	30000		
Aruma	1600–2000	80	71000		
Jauf/Sakaka	400–5000	95	100000		
Jilh	3800–5000	60	113000		

*Data from Al-Khatib [13]; Abu Rizaiza *et al.* [12]; MAW [14]; Authman [30]; BAAC [31].

Table 2. Chemical Composition of Water in Saudi Arabia. Data from El-Din [8, 9].

Region/City	No. of Samples	Dissolved salts (mg l^{-1})	Nitrate (mg l^{-1})	Fecal coliform (MPN/ml)
Riyadh	249	803±691	23.2±18.8	380±1037
Qasim	66	860±540	18.6±16.4	609±1271
Hail	17	364±231	17.1±5.4	1133±1573
Western	23	455±312	15.2±7.3	711±1368
Northern	16	512±245	7.3±8.1	800±1446
Southern	17	666±227	15.3±22.2	1±5

Table 3. Chemical Composition (mg l^{-1}) of Groundwater Samples.

Parameter	Wasia Aquifer [22]	Minjur Aquifer [22]	Riyadh Shallow Aquifers [22]	Wadi Al-Yamaniyah [19]		Saudi Groundwater [32]*	Al-Qasim Region [18]				Saudi well water [15]**
Year	1995	1995	1995	1981	1987	1983	1978	1983	1984	1987	1980
pH	7.2	7.2	7.15	6.2–7.4	7.6–8.4		6.7–8.32	6.2–8.5	6.6–8.6	6.9–9.0	6.8–7.4
TDS	1172	1611	1267	453–7000	770–5010	550–9100	370–6712	223–6732	292–7010	514–6676	602–2772
Total alkalinity	144	156	214	8–53	14–67		18–231	48–302	80–372	36–243	124–325
Calcium	177	200	161	28–66	28–56	50–780	2–809	44–614	43–605	30–455	94–311
Magnesium	41	53	53	4–30	17–35	30–270	3–114	8–364	3–330	10–144	14–130
Potassium	6	50	18	0.1–3.4	0.3–1.5		1–70	4–133	4–121	4–44	4–20
Sodium	101	118	180	16–60	16.47	70–2200	23–1656	23–1035	46–2001	69–1150	46–368
Chloride	206	332	217	30–74	25–76	70–3200	18–2370	30–1740	30–2120	100–1850	103–811
Sulfate	439	488	478	8–40	10–21	200–2100	73–2552	35–3080	292–7010	50–1400	152–764
Nitrate	11	7	16					4–260	0–330	0–310	

* Groundwater samples that were analyzed at the Regional Agriculture and Water Research Center during 1981–1982 [32]

** Manwaring *et al.* [15] data from six muncipitalities' well water.

About 25% of the water samples contained nickel and lead higher than the permissible limits. However, this water is desalted prior to human consumption. The desalination process, along with other dissolved salts, removed these toxic metals from the feed water (groundwater). Alabdula'aly [21] determined concentrations of aluminum, barium, chromium, copper, iron, manganese, nickel, and zinc in the samples from deep and shallow groundwater wells in Riyadh. The concentrations (μg/l) of these metals ranged as: aluminum 0.7–41.2; Barium 28.5–73.1; chromium 0.0–10.4; copper 0.0–12.0; iron 7.0–2106; manganese 0.3–292; nickel 0.0–3.5; and zinc 1.6–69.0. These limited data [20, 21] suggest that a national survey of toxic metal concentrations in groundwater should be undertaken. This type of study will help to assess groundwater quality for human consumption and agricultural uses.

3. SURFACE WATER

Saudi Arabia has inadequate surface water resources and information on the quality of surface water is limited. It has no perennial river and natural precipitation is extremely low and sparse. Rain in the country varies widely. The southwestern part receives the most (500 mm) and the northern part the least (20 mm). In Saudi Arabia, surface runoff occasionally occurs during storms, mostly during the rainy season. Estimates of the amounts of runoff range between 2000 to 2400 Mm^3 annually [4]. Most of the runoff occurs in the coastal areas and highlands in the southwest, where rainfall is relatively abundant and regular.

4. TREATED WATER QUALITY

4.1. Water Quality at the Treatment Plant

As mentioned above, many groundwater aquifers in the Kingdom are salty and water must be desalted to make it fit for human consumption. It is estimated that about 82% of the groundwater is treated and the most commonly used desalting process is reverse osmosis [22]. By the end of 1991, there were 635 water treatment plants in Saudi Arabia and about 80%

Table 4. Metal Concentrations (mg l^{-1}) in Groundwater Samples from Umm Er Radhuma Aquifer.

Parameters	Mean*	Standard Deviation	Minimum	Maximum	Permissible or recommended upper limits
Arsenic			<0.01	<0.01	0.05
Calcium	304	51	247	391	75.00
Cadmium			<0.001	<0.001	0.01
Cobalt			<0.05	0.07	
Chromium			<0.05	0.09	0.05
Copper	0.004	0.007	0.002	0.021	1.00
Iron	0.042	0.039	0.005	0.119	0.30
Potassium	45	16	28	78	
Magnesium	107	16	84	133	150.00
Manganese			<0.05	0.013	0.05
Mercury			<0.001	<0.001	0.001
Sodium	537	47	485	631	200.00
Nickel			<0.05	0.097	
Phosphorus	5.21	5.86	<0.05	16.77	0.05
Lead			<0.05	0.084	0.05
Strontium	6.04	0.86	4.84	7.52	
Zinc	0.175	0.306	0.016	0.766	5.00

*Mean of 12 Water Samples. All Data from Sadiq *et al.* [11].

of them were desalting groundwater [23]. There are many seawater desalination plants in Saudi Arabia as well. The Kingdom is the largest producer of desalinated water in the world.

In general, performance of the treatment plants have been satisfactory. Alabdula'aly [22] investigated quality of treated water in Riyadh. The product water was within the health guidelines for dissolved salts. The large coastal desalination plants are producing near-distilled water. Alam and Sadiq [10] and Sadiq *et al.* [11] concluded that RO desalination plants in a Dhahran community were satisfactory for removing salts from groundwater. From the foregoing, it can be concluded that in general water quality at treatment plants in the Kingdom is within established health guidelines.

4.2. Water Quality in the Distribution Network

From the desalination plant, the treated water is transported to consumers through various types and sizes of pipes. There are a few studies regarding the water quality in the distribution networks. These studies are summarized in Table 5. Information on the chemicals, especially those that can be released to the water during transportation, are limited. In a survey,

Table 5. Chemical Composition (mg l^{-1}) of Drinking Waters in Saudi Arabia.

Parameter	Riyadh (1)	Dhahran / Dammam (2)	Dhahran (3)	Eastern Province (4)	Permissible or recommended upper limits
pH	7.2–9.1	7.2–8.1	7.1–8.0		6.5–8.5
Dissolved salts	226–580		180–740	<500–4710	1000
Alkalinity	44–92		14–82		500
Chloride	18–194		92–244	<250–2192	250
Sulfate	78–268		10–109	<250–1725	400
Nitrate	3–19		0.1–2.62		10
Arsenic		<0.01	<0.01		0.05
Cadmium		<0.01	<0.01	0.01–0.35	0.01
Calcium	14–54	22–61	3–47		200
Chromium	0.009±0.007	<0.01	<0.05	0.004–0.910	0.05
Cobalt		<0.01	<0.05		
Copper	0.036±0.143	<0.01–6.8	0.02–0.09		1.0
Iron	0.067±0.168	0.01–2.0	0.05–0.50	0.01–0.70	0.3
Lead	0.002±0.002	<0.05	<0.05–0.21	0.000–0.095	0.05
Magnesium	1–24	7–18	1–17		150
Manganese	0.002±0.003		<0.01–0.013	0.00–17.3	0.1
Mercury			<0.001		0.001
Nickel	0.004±0.007	<0.05	<0.05–0.19		0.05
Potassium	1–20	4–9	3–9		
Sodium	11–134	183–223	56–137		200
Titanium		<0.01	<0.05		
Vanadium		<0.05	<0.05		
Zinc	0.018±0.027	0.02–5.5	0.02–0.19		5.0
Coliforms		0–2	0–2	0–2400	

1. Alabdula'aly [21, 22] 2. Alam and Sadiq [10]
3. Sadiq *et al.* [11] 4. Hassan *et al.* [24] and Melha *et al.* [25].

Hassan *et al.* [24] determined Cr and Pb concentrations in the drinking water samples collected from the Eastern Province (Dammam, Khobar, Dhahran, Jubail, Al-Hassa, and Hafr Al-Batin cities). They reported that many of the water samples contained chromium and lead higher than the permissible limits for these elements in drinking water. However, water samples in this study were collected randomly without any consideration to the distribution network. In the same study, Melha *et al.* [25] found that many of these samples were microbiologically contaminated. Since the study, the drinking water situation in the Eastern Province has improved significantly [24].

The treated water quality may deteriorate during transportation due to corrosion and leaching of utility pipes. Alabdula'aly [22] rightly pointed out that future studies should concentrate on the distribution network water quality. Only a few studies have addressed the issue. In a recent study, Sadiq *et al.* [11] investigated the influence of distribution network, consisting of utility pipes made from copper, PVC, and galvanized steel, on water quality. The highest copper concentrations were found in the samples collected from the area served by the copper pipes. Corrosion of the pipes appears to be responsible for the wide variations in copper concentrations in the drinking water samples. Similarly, the highest mean lead concentration was found in the water samples collected from the area supplied with PVC pipes. These PVC pipes contained about 1% lead which gradually leached to the water, thus increasing lead concentrations in the drinking water. The galvanized steel utility pipes might be responsible for the higher concentrations of zinc and iron in the water samples from these pipes. This study demonstrates the effect of distribution network material on the drinking water quality at the consumers end. Some of these data from Sadiq *et al.* [11] are plotted in Figure 1. The effect of utility pipes on drinking water quality was also investigated in another study [10]. Concentrations of copper in drinking water as a function of utility copper pipe length are given in Figure 2. El-Rehaili and Misbahuddin [26] reported that homes with galvanized iron plumbing contained higher concentrations of iron, copper, chromium, lead, zinc, and cadmium in drinking water than those houses with PVC or copper plumbing. The study found that 34, 23, and 3 percent of the water samples exceeded iron, copper, and lead maximum permissible limits, respectively.

The change in water treatment technology may also affect water quality in a distribution network. Water samples were collected from a community in Dhahran during 1986 and 1995. All parameters (personnel, equipment, chemicals, sampling procedure, *etc.*) were similar except that, in 1986 pH fixation and disinfection were achieved by sodium hypochlorite treatment, whereas in 1995 these were obtained by degassing. The results of 1986 and 1995 are compared in Figure 3. It is clear that a change in treatment technology may affect drinking water quality in a distribution network. The treatment technology should be documented at the time of an investigation.

4.3. Water Quality and Consumers Health

The users' end water quality is the most important from the human health point of view. A few studies have investigated drinking water quality with reference to local health implications. Melha *et al.* [25] investigated chemical and microbiological composition of drinking water in the Eastern Province (cities of Alkhobar, Dammam, Dhahran, Al-Hassa, Jubail, and Hafr Al-Batin) and associated the water quality with the local health problems. The study reported positive correlation between cadmium concentrations in local water supplies and the magnitude of cardiovascular related morbidity in the Eastern Province. The study also found a negative correlation between the cardiovascular morbidity and both minimum and maximum levels of zinc in the local drinking water. In contrast to the published above reports, Melha *et al.* [25] observed a positive correlation between water hardness and cardiovascular related morbidity rate. More studies should be conducted to evaluate the effects of drinking water quality on the community health.

5. DRINKING WATER PROBLEMS AND RECOMMENDATIONS

Over-exploitation and inefficient management have led to the decline of groundwater levels in many areas [3, 12, 19]. As a result of this, good quality groundwater is gradually being depleted and the lower level salinity is on the rise. Serious problems of groundwater quality and quantity may arise if this situation is not abated. The government should re-evaluate groundwater resources from both quantity and quality points of view, rates of draw down should be controlled, and a comprehensive national groundwater monitoring program should be developed. A long term national groundwater utilization program should be developed and implemented.

Estimates indicate that a significant portion of water produced and piped is lost in major Saudi Cities. For instance, it is reported that 50% of water supplied to Medinah is lost to leaks [27]. Furthermore this percentage exceeds 50% in Jeddah

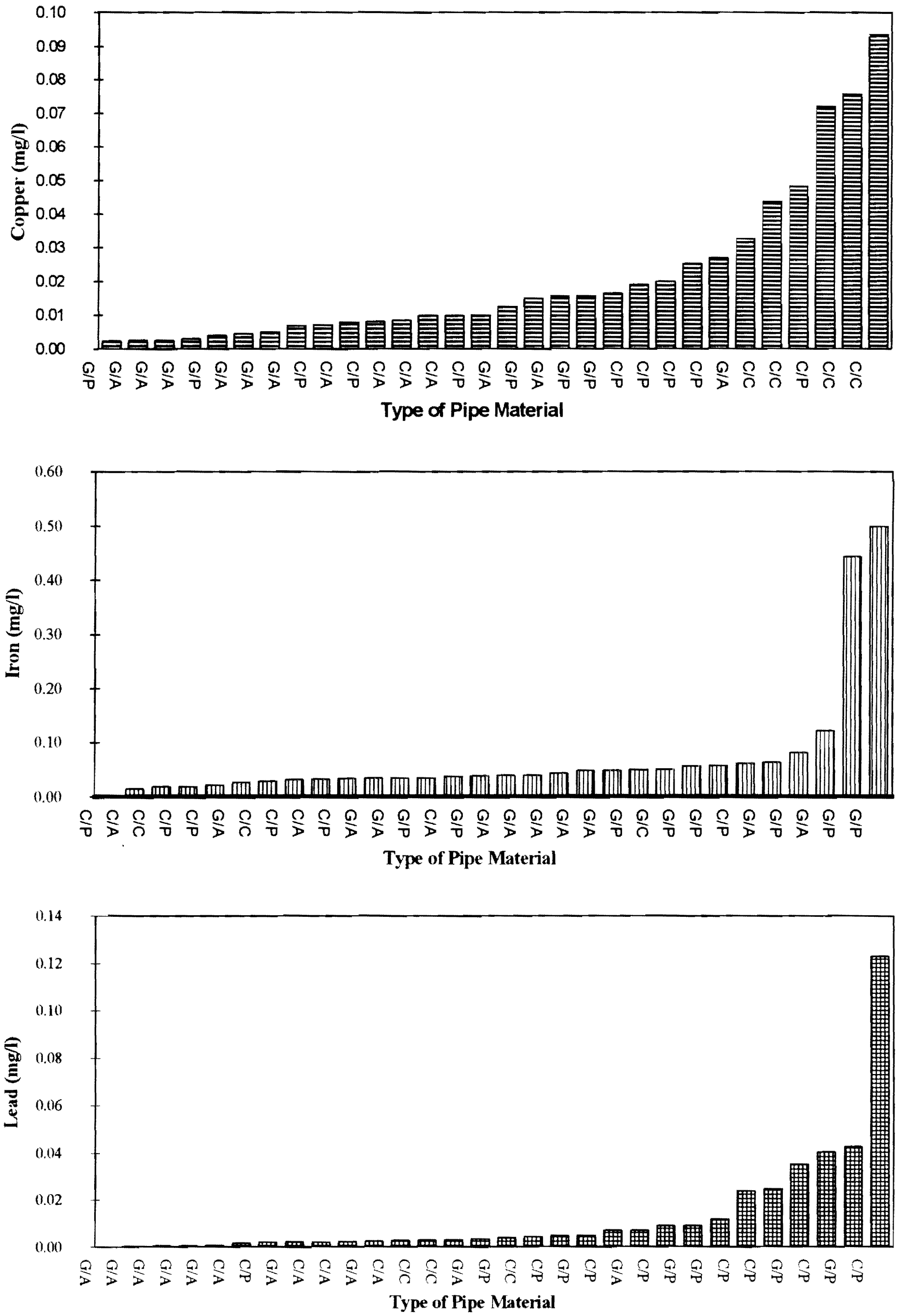

Figure 1. Effect of Pipe Material on Copper, Iron, and Lead Concentrations in Drinking Water.
C: copper pipe; G: galvanized pipe; P: PVC pipe; A: asbestos pipe.
First letter of x-*axis indicates the utility pipe type and the letter after / represents type of main pipe,* e.g., *G/A: main pipe is of asbestos cement and the utility pipe is galvanized.*

and Riyadh [28]. Other studies indicate that gross water leakage in the Riyadh water distribution network varies from 9 to 67% of the total network water supply [29]. Most of the water leakage is attributed to the inefficient design, poor installation, use of wrong types of pipes, and inadequate maintenance of the water pipe system [4]. The municipalities should improve performance in these areas.

In addition to the water loss, leakage may cause chemical and microbiological contamination of drinking water supplies. Many studies have shown the presence of coliform in drinking water supplies [8, 25]. Drinking water should be free from pathogenic organisms. The distribution network leakage and disinfection treatment should be improved to control microbial contamination of drinking water.

Information on toxic trace elements concentrations in groundwater is limited. A comprehensive survey should be conducted to collect these important data. This information will not only be helpful in designing a safer drinking water supply, but also will allow improved agricultural utilization of groundwater.

Corrosion of distribution networks may deteriorate drinking water quality [10, 11]. The future drinking water quality evaluation studies should consider possible deterioration of water quality due to network conditions. Concentrations of toxic metals should be determined along with general quality parameters.

Microbiological contamination of drinking water is occurring in Saudi Arabia [8, 25]. As more and more urban areas are served by septic tanks, the probability of microbiological contamination of both groundwater and drinking water is on the rise. Therefore, in addition to toxic chemicals, microbiological quality of drinking water should be monitored for both

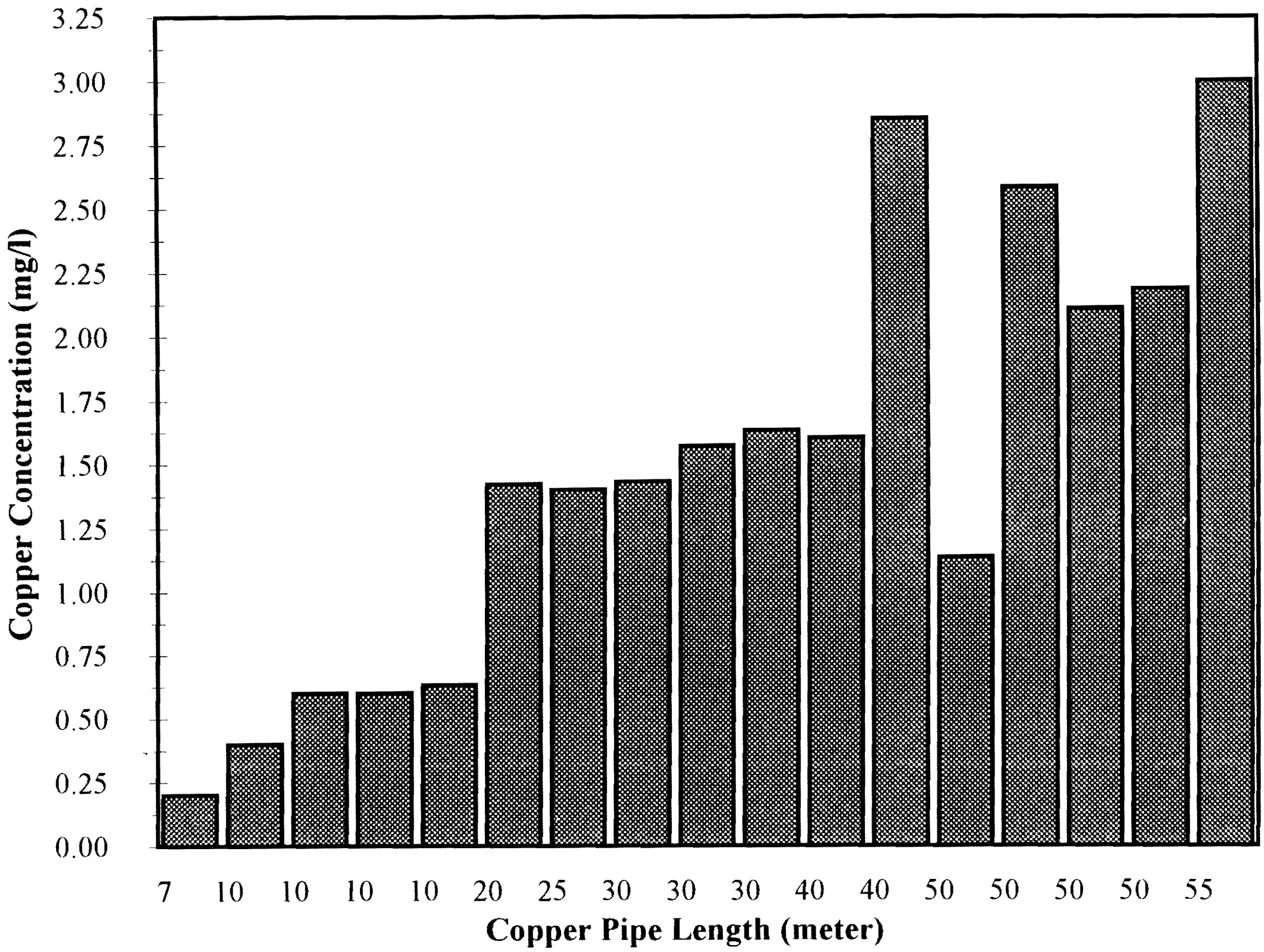

Figure 2. Effect of Corrosion on Copper Concentrations in Drinking Water.

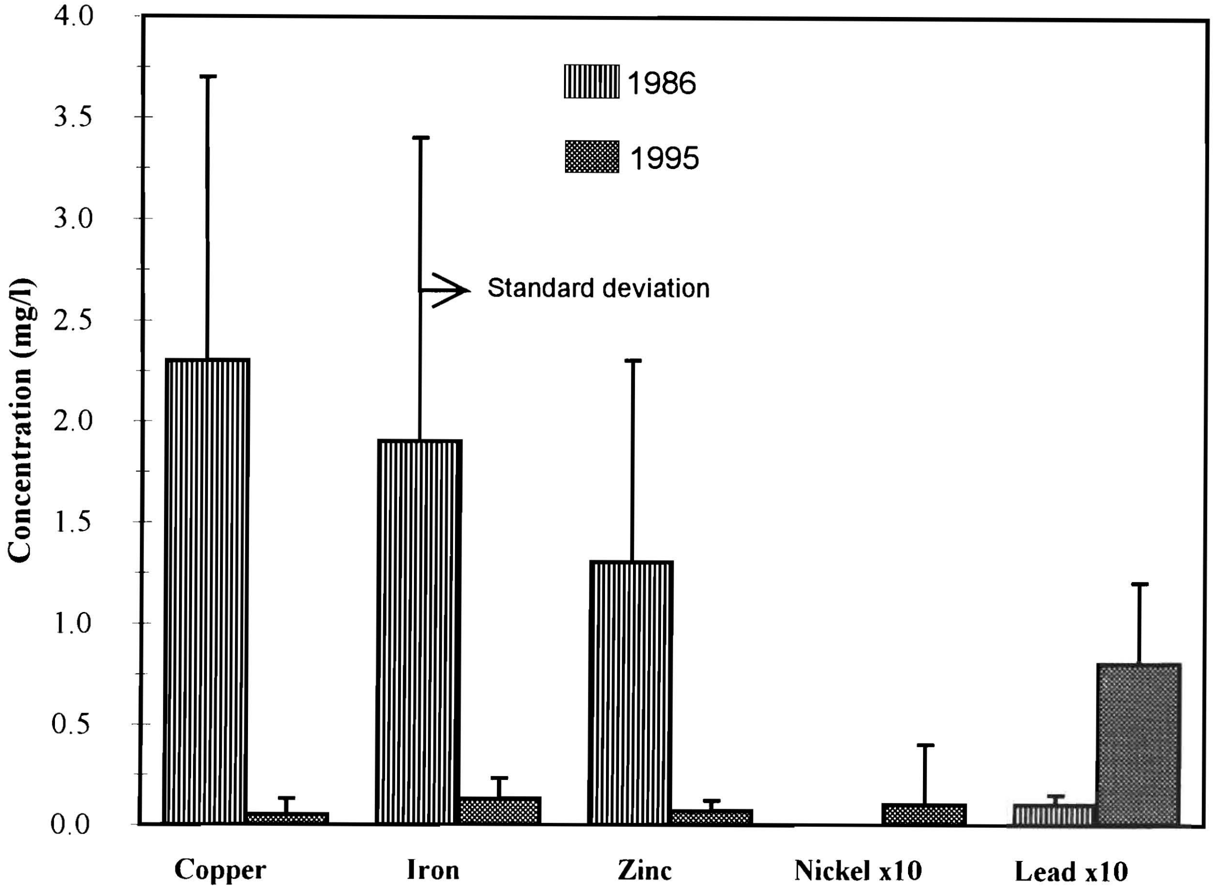

Figure 3. Mean Concentrations of Selected Chemicals in Water Samples Collected in 1986 and 1995 (Values of Nickel and Lead are Multiplied by 10 to be Shown in the Graph).

coliforms and viruses. Counts of coliphages in combination with the standard plate counts of coliform bacteria offer a practical reliable indicator system for the evaluation of bacteriological and virological safety of drinking water supplies.

The main objective of maintaining good quality drinking water is to safeguard consumers' health. We could find only one investigation which correlates drinking water quality with human health problems [25]. More studies should be developed to correlate water quality with human health.

Water is a precious resource and its conservation should be a national goal. The government should introduce water conservation programs, such as water scheduling. Public awareness of water conservation will make a real change.

One question which bothers us very much is the integrity of the reported data. Many investigators have not addressed quality assurance concerns in their investigation. This is particularly true about trace metal data. Sometimes authors have extrapolated instrument readings beyond or very close to the "conceptual detection limits". The use of internal standard or standard reference material has been ignored. Information on sampling procedure and sample preparation is often missing.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Research Institute of King Fahd University of Petroleum and Minerals in carrying out this study.

REFERENCES

[1] F. van der Leeden, *Water Resources of the World.* Water Information Center, Inc., 1975.

[2] S. Farouq and R. I. Al-Layla, "Potential of Water Development in Saudi Arabia", *Water Int.*, **10** (1985), pp. 151–155.

[3] M. A. Al-Saleh, "Declining Groundwater Level of the Minjur Aquifer, Tebrak Area, Saudi Arabia", *Geographical J.*, **158** (1992), pp. 215–222.

[4] A. A. Al-Ibrahim, "Water Use in Saudi Arabia: Problem and Policy Implications", *Water Resource Plann. Manag.*, **116** (1990), pp. 375–388.

[5] R. I. Al-Layla, R. L. Long, and W. J. Selen, "Alternative Strategies in Water Resources Development", *Final Report, Research Grant AR-6-134, King Abdul Aziz City for Science and Technology, Riyadh,* 1991.

[6] A. F. Abdul-Fattah, A. A. Husseiny, and Z. A. Sabri, "Desalting in Saudi Arabia — Demand, Production, Management, Associated Power Generation and Future Plans", *Desalination,* **25** (1978), pp. 9–44.

[7] A. A. Al-Ibrahim, "Excessive Use of Groundwater Resources in Saudi Arabia: Impacts and Policy Options", *Ambio,* **20** (1991), pp. 34–37.

[8] M. N. A. El Din, I. M. Madany, and A. Al Tayaran, "Quality of Water from Some Wells in Saudi Arabia", *Water, Air, and Soil Pollut.*, **66** (1993), pp. 135–143.

[9] M. N. A. El Din, I. M. Madany, A. Al Tayaran, H. A. Al-Jubair, and A. Gomaa, "Trends in Water Quality of Some Wells in Saudi Arabia", *Sci. Total Environ.*, **154** (1993), pp. 110–122.

[10] I. Alam and M. Sadiq, "Metal Contamination of Drinking Water from Corrosion of Distribution Pipes", *Environ. Pollut.*, **57** (1989), pp. 167–178.

[11] M. Sadiq, T. H. Zaidi, H. Al-Muhanna, and A. A. Mian, "Effect of Pipe Material on Metal Concentrations in Drinking Water", *J. Environ. Sci. & Health,* **A32** (1997), pp. 445–454.

[12] O. S. Abu Rizaiza and M. N. Allam, "Water Requirements *versus* Water Availability in Saudi Arabia", *J. Water Resource Plann. & Manag.*, **115** (1989), pp. 64–74.

[13] A. B. Khatib, *Seven Green Spikes.* Riyadh, Kingdom of Saudi Arabia: Ministry of Agriculture and Water, 1974.

[14] MAW, *Water Atlas of Saudi Arabia.* Riyadh, Kingdom of Saudi Arabia: Ministry of Agricultural and Water, 1984.

[15] J. F. Manwaring, R. G. Lee, and J. W. Hoffbuhr, "Quenching the Thirst for Potable Water in Arid Saudi Arabia", *J. Am. Well Water Assoc.*, December 1980, pp. 656–665.

[16] SASO, "Bottled and Unbottled Drinking Water", *Saudi Standard No 409.* Saudi Arabian Standards Organization, The Kingdom of Saudi Arabia, 1984.

[17] WHO, *Guidelines for Drinking Water Quality. Vol. 2. Health Criteria and Other Supporting Information.* Geneva: World Health Organization, 1984.

[18] I. M. Al-Faruq, M. Jhangir, and A. S. Al-Shreef, "Chemical Characteristics of Saudi Groundwater, Al-Qassim", *Biol. Sci.*, **4** (1996), pp. 123–140.

[19] A. S. Buzhair and A. Alkaff, "Evaluation of Groundwater Quality in Wadi Al-Yamaniyah, Saudi Arabia", *Arab Gulf J. Sci. Res.*, **7** (1989), pp. 21–38.

[20] KFUPM, *Drinking Water Quality at the King Fahd University of Petroleum and Minerals, Dhahran,* An Internal Report, 1996.

[21] A. I. Alabdula'aly, "Trace Metals in Riyadh Public Water Supplies", *Arabian Journal for Science and Engineering,* **22:1C** (1997), pp. 165–174.

[22] A. I. Alabdula'aly, "Groundwater Quality and Treatment in Riyadh, Saudi Arabia", *Proc. International Desalination Association (IDA) World Congress on Desalination and Water Science, Abu Dhabi, UAE, November 18–24, 1995.*

[23] K. Wangnick, *IDA Desalting Plant Inventory Report No. 12.* International Desalination Association, 1992.

[24] H. Q. Hassan, H. T. Mustafa, and T. I. Rican, "Lead and Chromium Concentrations in the Potable Water of the Eastern Province of Saudi Arabia", *Bull. Environ. Contam. Toxicol.*, **43** (1989), pp. 529–533.

[25] A. A. Melha, *et al.*, "Relationship Between Chemical and Microbiological Contents of Potable Water and Local Health Problems in the Eastern Province", *Final Report of Research Project AR-3-088, King Abdul Aziz City for Science and Technology, Riyadh,* 1986.

[26] A. El-Rehaili and M. Misbahuddin, "Levels of Trace Metals in Riyadh Drinking Water at the Consumer Tapes", *J. King Saud University, Eng. Sci.*, **7** (1995), pp. 1–23.

[27] SCET International, *Survey of Constraints: Water.* Riyadh, Saudi Arabia: Ministry of Planning, 1975.

[28] British Arabian Advisory Committee, *National Water Plan.* Riyadh, Saudi Arabia: Ministry of Agriculture and Water, 1980.

[29] K. H. Al-Dhowelia and U. K. Shammas, "Leak Detection and Quantification of Losses in a Water Network", *Water Resources Development,* **7** (1991), pp. 30–38.

[30] M. N. Authman, *Water and Development Process in Saudi Arabia.* Jeddah, Saudi Arabia: Tihama Press, 1983, 302 pp.

[31] British Arabian Advisory Committee, *Water Resources of Saudi Arabia. Volume 1.* Prepared for the Ministry of Agriculture and Water, Riyadh, 1980.

[32] J. M. Mee, "Saudi Groundwater Chemistry and Significance", *Arab Gulf J. Scient. Res.*, **1** (1983), pp. 113–120.

Paper Received 23 July 1996; Revised 16 December 1996; Accepted 31 December 1996.