Transient Behavior of the Brackish Rus-Umm Er Radhuma Aquifer in Bahrain

* Dr. Waleed K. Al-Zubari

Abstract

Bahrain brackish water resources occur in the form of a lens of a finite lateral extent, with a salinity range between 8 and 15 g/L, developed in the Rus and Umm Er Radhuma formations. The lens has been exploited since 1984 by a wellfield at an average production rate of 24 Mm 3/y in feeding a desalination plant as an alternative to seawater. The purpose of using the lens is to reduce the upward migration of brackish water into the relatively upper fresh water aquifer and to minimize the risk of shutting down the country desalination plants in the case of accidental oil spills in the Arabian Gulf waters. Examination of the response of the brackish water system to the wellfild pumping over the past nine years shows that the aquifer is undergoing a uniform depletion and no major salinity changes in the produced wellfield water yet have taken place. This is attributed to that flow towards the wellfield occurs in the highly transmissive fractured zones present in the middle of the aquifer. However, geophysical logging indicates that the higher salinity zone underlying the brackish lens has moved into the lower end of the wellfield interval, which

* Assistant Professor, Hydrogeology - Desert and Arid Zones Sciences Program - College of Post-Graduate Studies - Arabian Gulf University

implies that the salinity of the produced water will increase in the coming years. In order to maximize the lens future availability desalination plant, this movement should be delayed.

Modification of the present wellfield design and artificial recharge are proposed as control measures to achieve that. Simulation modeling of the aquifer system to predict the response of the proposed measures is a pre-requisite to aid future management of the aquifer.

Introduction

Although more than 80% of the groundwater resources of the Arabian Gulf countries are classified as brackish, these waters have been adopted within the national water augmentation policies of these countries and are developed to alleviate stresses on their scarce fresh water resources. For example, sultanate of Oman uses brackish water with a total dissolved solids (TDS) in the range from10 to 16 grams/liter (g/L) in oil field operations and development; Kuwait uses waters ranging from 2.5 to 6 g/L TDS for non-drinking domestic purposes through a special domestic network; Saudi Arabia and United Arab Emirates use water exceeding 2 g/L and reaching 6 g/L TDS in irrigation (Saker, 1988).

In Bahrain, brackish groundwater, ranging between 8 and 15g/L, and occurring in the form of a large lens in the Rus and Umm Er Radhuma formations, is utilized for desalination purposes. Since 1984, about 24 Million cubic meters per year (Mm^3/y) is being abstracted from this brackish water reservoir by a wellfield, located at Abu-Jarjur area at the east coast of Bahrain (Figure 1), to feed a reverse osmosis (R0) desalination plant with a maximum output capacity of about $17Mm^3/y$.

The development of the brackish lens is conceived with the objectives of:1) lowering its potentiometric surface in order to reduce its upward migration and pollution to the upper fresh water aquifers; and 2) reducing the risk of shutting down the country desalination plants in the case of accidental oil spills in the Arabian Gulf waters (as was the case in the first and second Gulf wars). Furthermore, this process appears to be more economical compared to the traditional desalination of seawater (Dannish and Al-Ansari, 1991).

The pre-development evaluation and utilization feasibility studies of the brackish groundwater system were made in the period from 1979 to 1983 (GDC, 1980; 1983), when the system was in a rather undisturbed natural equilibrium. These studies indicated that the brackish ground water is a limited non-renewable resource with an estimated reserve of about 10,000 Mm^3 (TDS 8-15g/L), and with continued abstraction it will eventually reach seawater salinity. After about nine years of development and monitoring of the aquifer potentiometric head levels and the wellfield salinity, a new assessment is needed to evaluate and understand the transient behavior of the system.

The aim of this paper is to examine the response of the brackish aquifer system under the past nine years (1984-1993) of continuous abstraction in order to assess the transient behavior of the system. Based on this assessment, future utilization of the brackish groundwater and its potential to continue feeding the desalination plant with raw water are also discussed.

Hydrogeology

Brackish water resources in Bahrain are present in the form of a large lens located in Bahrain main island, which is an anticlinal structure, and is underlain everywhere by hyper-saline brines (GDC, 1983), as shown in Figure 2. The brackish water lens is developed in the Rus (Lower Eocene) and Umm Er Radhuma (Paleocene to Lower Eocene) formations. The aquifer is denoted by the letter "C" to distinguish it from the upper relatively freshwater zones of the Alat and Khobar of the Dammam Formation (Middle Eocene), termed "A": and "B", respectively. The Umm Er Radhuma Formation (UER) is underlain by the shales of the Aruma Formation (upper Cretaceous).

The Rus Formation is composed of chalky dolomitic limestone with subsidiary shale and anhydrite intercalation. Its thickness ranges from about 60 m at the crest of the anticline, where it outcrops, to about 150 m at its margins. The Rus Formation section in the central and eastern areas of Bahrain has undergone extensive solution of anhydrite, which led to the collapse of overlying rocks and has produced very large cavities. The UER Formation is composed of dolomitic limestones containing enlarged joints, cracks and vugy intergranular porosity. Its thickness ranges from about 115 m, at the crestal areas of the anticline to over 300 m at its edges. The Rus Formation was conformably deposited over the UER Formation, and the boundary between the two is difficult to detect lithologically; the upper UER section appears hydraulically and chemically continuous with the Rus section.

In Western Bahrain, the Rus Formation contains thick and extensive evaporite deposits. It thus forms a tight aquitard separating aquifers "B" and "C" and forming the upper confining boundary of the latter. In central and eastern Bahrain however, most of the evaporites section has been removed by solution. The residual Rus section is composed of chalky limestones, dolomitic limestones and marls, and have a significant transmissivity. Therefore, in central and eastern Bahrain, aquifer C is developed in the rocks of the Rus Formation as well as the UER Formation.

In the core of the anticline where the Rus Formation outcrops and its upper section is eroded, the aquifer is unconfined and its upper boundary is limited by the free water table in the Rus Formation. To The east, the aquifer is confined as the upper Rus is predominated by shales, marls and claystones and together with the shales of the lower member of the Dammam Formation, forms an aquitard marking the upper boundary of the aquifer. The lower boundary of the aquifer is usually taken at a salinity limit of 15 g/L delineating the base of the brackish water lens, as shown in Figure 2. The lateral extension of the C aquifer (salinity limit of 15 g/L) to the east offshore areas of Bahrain Island is not completely defined.

The salinity of the C aquifer displays a systematic increase with depth. In the central core area, the salinity of the brackish water lens increases gradually from less 8 g/L at the water table, at about 5 m elevation above sea level (s1), to about 15 g/L at about 180 m below sl (Figure3). The thickness of the brackish water zone ranger from 0 m at the flanks of the anticline, where it is intersected by the dip of the overlying aquitard, and reaches a maximum of about 190 m at its crest. The brackish water zone is underlain by a mixing zone between the underlying brine and the overlying brackish water. The salinity of the mixing zone increases with depth from about 15g/L at the interface to about 100 g/L. The thickness of mixing zone varies from one area to another. Under the Abu-Jarjur wellfield and the core area, it is about 40 m thick (180-220 m below s1.). To the north -east of the wellfield, the thickness of this zone is observed at greater than 150 m. The mixing zone is underlain by brines with a salinity greater than 100 g/L, with a relatively sharp interface, as shown in Figure3.

Pumping tests analyses and specific capacity tests compiled from previous studies (GDC, 1980; 1983) and aquifer C drilled well records showed great variation in the C aquifer transmissivity; it ranges from 110 to 50,000 m^2/d. This extreme variation in the transmissivity reflects the fractured nature of the aquifer rocks, especially the karst zones located in the middle of the UER Fromation, as shown in Figure2. Typically, the hydraulic conductivity of the Rus section (about 40 m thick) is about 25 m/d, the upper UER (about 35 m thick) ranges from 40 to 200 m/d, the middle UER (about 30 m thick) is about 2,500 m/d, while the lower UER (150 m thick) has an hydraulic conductivity of less than 1 m/d (GDC, 1983).

Little data exist on the storage coefficient of the C aquifer. Pumping tests and a tidal efficiency test (4 measurements) have indicated that the storage coefficient of the aquifer ranges from $1.5x10^{-4}$ to $3x10^{-4}$ (dimensionless) in its confined parts (GDC, 1980; 1983). The specific yield of the aquifer is calculated at about 0.2 (dimensionless) using change in head per change in volume analysis for the unconfined parts of the aquifer. The Rus rocks average porosity is about 37.5%, while the average UER porosity is about 27%, obtained from the available core analysis.

Aquifer Discharge

Apart from some localized utilization, the C aquifer main discharge is from the east coast Abu-Jarjur wellfield (Figure 1), which started in the fourth quarter of 1984, at an average rate of about 24 Mm^3/y (Table 1).

The salinity of the produced water from the wellfield averages about 12.8 g/L. The wellfield consists of 15 production wells. The intake zone of the wells was designed to produce from the upper and middle UER zones located at a depth between 75-145m below sl (Figure 2). Abstraction rates from the wellfield are a function of the RO plant recovery and the salinity of the pumped water (GDC, 1983). Therefore, production rate from the wellfield is expected to increase due to anticipated salinity increases in the produced water to maintain the plant production capacity of desalinated water.

Natural discharge from the C aquifer is also occurring due to its vertical leakage to the B aquifer through the Rus aquitard. This phenomenon evidently occurs in the north-central and eastern parts of Bahrain, where the anhydrite section of the upper Rue is absent, and where the B aquifer salinity has reached greater than 10.0 g/L (Zubari et al., 1993). The leakage rate from the C aquifer to the B aquifer is assumed to be negligible during steady state conditions when the heads in the two aquifers are thought to be approximately equal. Due to the sharp decrease in the B aquifer potentiometric levels as a direct result of its over-exploitation, the potentiometric head differential between the two aquifers has increased significantly in favor of the C aquifer. Numerical modeling studies estimated this leakage rate at about 40 Mm^3/y in 1983 (GDC, 1983). Presently with the lowering of the C aquifer heads due to abstraction by the wellfield, the leakage rate to the B aquifer is expected to be declining.

Potentiometric Head Levels Changes

Aquifer C potentiometric head levels have been monitored in an observation network consisting of 19 observation wells, all equipped with continuous recorders and their levels are reported on a monthly basis (Figure 4). Most of the observation wells are monitoring the brackish zone in the middle to upper UER Formation. Fifteen of the 19 observed wells started recording water levels in the aquifer prior to 1985, while the other four wells were added in the period from 1987 to 1989.

Figure 5 displays the observed potentiometric levels in the twenty observation wells of the C aquifer. Prior to the wellfield production in the fourth quarter of 1984, there has been little local abstraction from aquifer C and no significant head decline observed. Differences in the observed potentiometric levels in most of the wells were very small and the potentiometric surface was approximating a flat surface; prior to 1984 production, most of the observation wells illustrated potentiometric levels ranging between 5.0 and 5.3 m above s1.

Figure 5 displays three important features in the observed hydrographs. The first is that although these wells differ in location from the producing wellfield, their drop in head has occurred almost at the same time with a lag of less than two months from the beginning of production by the wellfield. The second feature is that the rate of head drop and pattern in most of the wells hydrographs is almost the same, regradless of their location from the wellfield. These two observations suggest strongly that flow in the C aquifer towards the wellifeld occurs in very high transmissivity zones. These are probably the fractured karstic zones present in the middle of the UER, which possesses transmissivities greater than 50,000 m^2/d. The third observed feature, which might have strong impacts on the future utilization of the aquifer, is that, except for one well, there are no signs of stabilization or reduction in the magnitude of the present drawdown rate in the C aqufer, which confirms the limited lateral extent of the aquifer. The average rate of head decline is estimated at 0.325m/y.

Figures 6a and 6b are two drawdown maps prepared to illustrate the potentiometric levels changes and pattern in the C aquifer for the periods from 1984 to 1988 and from 1984to 1993, respectively. The two maps indicate the absence of major potentiometric head coning under the wellfield, and that the cone of depression in the brackish water lens extends to all areas of Bahrain. In other words, the aquifer water is collected from all areas of Bahrain by the fractured zones. The observed potentiometric levels of the aquifer have dropped within a range of 2.0 m at the edges of the brackish water lens, to about 3.3 m at the producing wellfield. The relatively large drawdowns observed in the north-central area are due to aquifer leakage to the upper Dammam aquifer, in addition to local abstraction. By comparing the two maps, it can be seen that while they differ in values, the observed drawdown patterns at the end of 1988 and 1993 are more or less the same, suggesting a uniform depletion of the brackish water lens.

Aquifer C Salinity Changes

Aquifer C salinity was measured at the wellfield output line (RO plant intake), being the main factor in determining the life of the wellfield, and at the individual production wells. A full chemical analyses (TDS and major anions and cations) were determined every month for the wellfield pumped water since its commencement to present.The production wells monitoring started in 1988 and is conducted on semi-annual basis. In addition, aquifer salinity monitoring was measured in three selected wells penetrating the aquifer using geophysical logging and are used for comparison with those conducted prior to the aquifer development. The wells salinity survey constituted of conducting an Electrical Conductivity (E.C.) and Temperature (T°C) wireline logs for the full section of the wells in the period 1992-93. In these surveys, grab samples at selected intervals in the eight wells were obtained an analyzed chemically, and were used for E.C./T log calibration, and in one case to reproduce a TDS log.

Table 2 displays the yearly average levels of TDS and major anions (Cl-, SO_4^{2-}, HCO_3) and cations (Na+, Ca2+, Mg2+, K+) of the wellfield produced water measured from 1984 to 1993, while Figure 7 displays the monthly measurements graphically. As can be seen from the table and the graph, there were no major concentration changes in the produced waters by Abu-Jarjur wellfield since its commencement; the average TDS in 1985 and 1993 were about the same at about 12.80 g/L. However, within this period, the average TDS showed a variation between a low of 11.40 g/L in June, 1988 and a high of 13.90 g/L in December, 1991 (Figure 7). These fluctuation could be attributed to the variation in the abstraction levels of the wellfield (Table I and Table II).

Table 3 displays the available chemical analyses results for the TDS of the 15 producing wells of the wellfield for the period from October, 1988 to August, 1993 (5 measurements).The data support the previous observation made on the TDS of the plant intake water, as there are no major changes in the TDS of the water produced by each well from 1988 to 1993. However, it can be seen from the table that the TDS takes its highest values in the central wells. This is due to well interference where the maximum drawdown would be in the central wells, and subsequently where the maximum component of upward flow from the underlying saline mixing zones occurs.

Geophysical logging conducted in the three surveyed wells supports the above observation and shows an upward movement from the mixing zone to the brackish water lene is occurring. The new survey displayed a general salinity increase in the brackish water zone in the period from 1984 to 1992/93 as direct result of the general potentiometric level decline. Figure 8 displays a comparison between the results of the salinity survey conducted in the period from 1992to 1993 to those conducted prior to the aquifer development for three wells pentrating the mixing zone. These wells are: well 1116, located within the wellfield and penetrates the full thickness of the mixing zone and about 150 m of the brine zone; well 1012, located to the west of the wellfield by about 7 km and penetrates about 45 m of the mixing zone; and well 1125, located to the north of the wellfield by about 6.6 km and penetrates about 150 m of the mixing zone. The three wells indicate an upward movement for the mixing zone into the brackish water zone in the period from 1984 to 1992/93. This movement is observed to be higher under the wellfield (well 1116) where the maximum drawdown takes place (fig. 6b). The mixing zone upward movement in the brackish water is estimated at about 35m. To the west (well 1012) and north (well 1125) of the wellfield by a distance of about 7 km, the movement is estimated to be less than 10m.

It should be noted that rise in the mixing zone under the wellfield has placed the mixing zone at the same level of the lower end of the production wells opened interval, which is from 75 to 145 m below s1. (Figure 2). This suggests that the salinity of the produced water will show an increase over the coming years, as water from the mixing zone starts to contribute to the water pumped from the wellfield. With continued pumping and decline of the potentiometric heads, the upward advancement is expected to increase and its contribution to the wellfield will increase with time.

Conclusion and Recommendations

Examination of the response of the brackish aquifer system to continuous pumping over the past nine years by the wellfield at Abu-Jarjur desalination plant shows that the aquifer is undergoing a uniform depletion and no major salinity changes in the produced water have taken place. However, geophysical logging reveals that the higher salinity mixing zone underlying the brackish water lens moved into the lower end of the production wells open interval. This implies that the salinity of the produced water will increase in the coming years as water from the mixing zone is expected to contribute to the pumped water by the wellfield.

Therefore, in order to maximize the aquifer future availability in feeding the desalination plant, the upward movement of the saline zone into the brackish water lens should be delayed. This can be achieved by introducing a number of control measures on the current utilization practice, such as modification of the present wellfield design in terms of depth, spacing and pumping intensity in space and time. on the other hand, artificial recharge of the aquifer with excess secondary treated sewage effluent, presently discharged to the sea at about 37 Mm^3/y (Mubarak, 1993), is a promising option that should be considered (Treweek, 1985; Idelovitch et al., 1980, Williams and Wesner, 1979). Technical and economic feasibility for each proposed control measure should be researched. For the last option of artificial recharge by secondary treated sewage effluent a health risk assessment should also be conducted (Nellor et al., 1985; Roberts, 1985). Simulation modeling of the aquifer system to predict the response to the proposed measures is a pre-requisite to aid future management of the aquifer.

Monitoring and evaluation of the C aquifer brackish system in terms of potentiometric head levels and salinity should be continued on a routine basis. However, there are large areas of the C aquifer that do not have control points, especially in the south-western parts of Bahrain. It is recommended that a modification of the existing observation network be made by adding more wells at specific locations to monitor the changes in the brackish water lens. The optimum location of the new observation wells can be determined with the aid of geostatistical methods. Moreover, the eastern lateral extent of the brackish water lens is not fully defined, especially in the north -eastern offshore areas of the wellfield. An exploration program for these areas should be initiated to aid in calculating the brackish water reserves and its future potential for utilization.

Acknowledgment

This study was funded by the Bahrain Center for Studies and Research (BCSR). The author thank the Water Production Directorate, Bahrain Ministry of Works, Power and Water, for providing all data relating to the wellfield salinity and abstraction, and the Water Resources Directorate, Bahrain Ministry of Commerce and Agriculture, for providing the observation wells data, conducting the geophysical survey.

References

Al-Noaimi, M.A. 1993 Assessment of available water resources and their utilization trends in the state of Bahrain. Unpublished, Bahrain Center for Studies and Research, State of Bahrain, 292 p. (in Arabic).

Dannish, S.A. and M. Al- Ansari. 1991. MSF vs. Ro-An Economical Comparison Study. Proceedings of the IDA World Conference on Deslination and Water Reuse, August 25-29, 1991, Washington, DC, USA.

GDC (Groundwater Development Consultants). 1980. Umm Er Radhuma Study, Bahrain Assignment, Ministry of Commerce and Agriculture, State of Bahrain.

GDC. 1983. Project 25/81, Reverse Osmosis Desalination. Unpublished, Ministry of Works, Power and Water, State of Bahrain.

Idelovitch, Terkeltoub, R., and M. Michail. 1980. The role of ground water recharge in wastewater reuse; Israel's Dan Region Project, Journal of American Water works Association, Vol. 72,no.7,pp.319-400.

Nellor, M.H., Baird, R.B., and J.R. Smyth. 1985. Health aspects of groundwater recharge: in Artificial Recharge of Groundwater, II. Groundwater Recharge by Reclaimed Wastewater, Edited by Takashi Asano, Butterworth Publishers, Boston, pp. 329-356.

Roberts, P.V. 1985. Field observations of organic contaminant behavior in the Palo Alto

Baylands: in Artificial Recharge of Groundwater, IV. Fate of Micropollutants during Groundwater Recharge, Edited by Takashi Asano, Butterworth Publishers, Boston, pp. 647-679.

Saker, I.M. 1988. An Introduction to the Geology of Groundwater Resources in the Gulf Cooperation Council Countries. Al-Ain Publishing

Company, Al-Ain, United Arab Emirates, 445 p. (in Arabic).

Treweek, G.p. 1985. Pretreatment processes for groundwater recharge: in Artificial Recharge of Groundwater, II Groundwater Recharge with Reclaimed Wastewater, Edited by Takashi Asano, Butterworth Publishers, Boston, pp. 205-248.

Williams, R., and Wesner, G. 1979, Water reuse and recycling, an assessment of the potential, Consulting Engineer, Vol. 53, no. 3, pp. 103-117.

Zubari, W.K. Mubarak, M.A. and I. Madani. 1993. Development impacts on groundwater resources in Bahrain. Water Resources Development, Vol. 9, no.3, pp. 263-279.

Table 1. Abu-Jarjur wellfield production rates in Mmz/y, 1984-1993

Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Q	2.90	27.10	24.50	23.71	22.56	21,67	22,61	23.64	27.02	25.08

Source: Water Production Directorate, Ministry of Works, Powers and Water, Bahrain.

Table 2. Chemical analysis of the Abu-Jarjur wellfield pumped water in g/L, 1985-1993.

Year	TDS	Na+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-
1985	12.80	3.24	0.62	0.30	0.14	6.73	0.60	0.18
1986	12.64	3.12	0.61	0.29	0.13	6.57	0.65	0.19
1987	13.06	3.16	0.62	0.28	0.13	6.52	0.61	0.19
1988	12.35	3.21	0.61	0.29	0.14	6.51	0.60	0.19
1989	12.62	3.25	0.64	0.30	0.14	6.66	0.59	0.19
1990	12.67	3.06	0.63	0.30	0.14	6.71	0.58	0.20
1991	12.96	3.34	0.64	0.30	0.15	6.86	0.55	0.21
1992	13.08	3.35	0.65	0.29	0.14	6.79	0.54	0.22
1993	12.87	3.28	0.65	0.28	0.14	6.65	0.56	0.21

Source: Water Production Directorate, Ministry of Works, Powers and Water, Bahrain.

Table 3. Measured TDS in the wellfield production wells in g/L

	Survey date, month/year				
Well	Oct/1988	Oct/1990	Dec/1991	Jan/1993	Aug/1993
p1*	11.34	12.06	11.51	11.15	11.39
p2	11.74	12.40	12.34	12.03	12.16
p3	12.31	12.68	12.91	12.80	12.61
p4	12.10	13.13	12.82	12.53	12.64
p5	13.14	13.93	13.80	13.48	13.17
p6	13.18	13.56	13.57	13.50	13.34
p7	13.55	13.21	13.74	12.46	12.67
p8	13.56	12.98	14.00	12.64	12.80
p9	13.05	12.75	13.30	12.27	12.63
p10	13.33	13.00	13.68	12.80	12.66
p11	12.84	13.04	13.77	12.83	12.90
p12	13.07	13.32	13.85	13.15	13.07
p13	12.95	13.43	13.71	13.30	12.66
p14	12.23	12.12	13.10	12.80	12.30
p15**	11.88	12.30	12.92	12.40	12.10

Source: Water Production Directorate. Ministry of Works. Powers and Water, Bahrain.
*north most well; * * south most well.

List of Figures

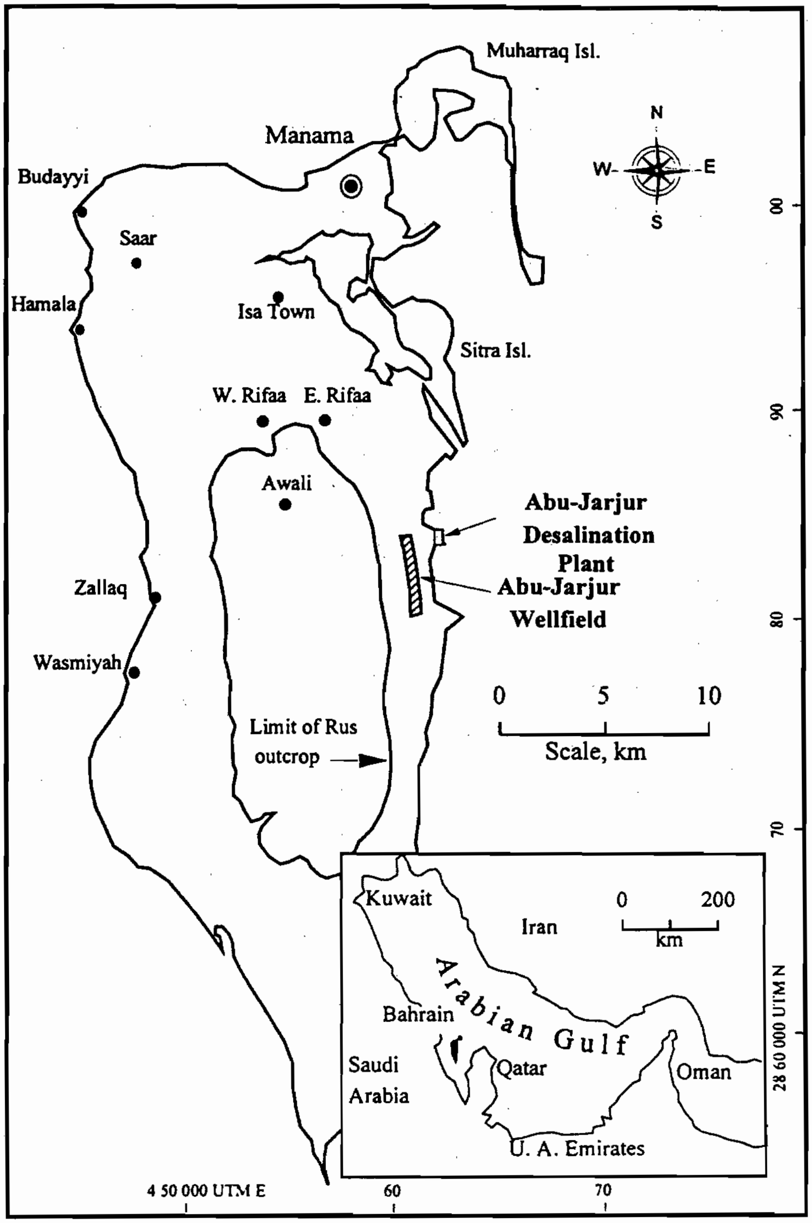

Fig. 1. Location map of Bahrain showing the location of Abu-Jarjur well-field and desalination plant.

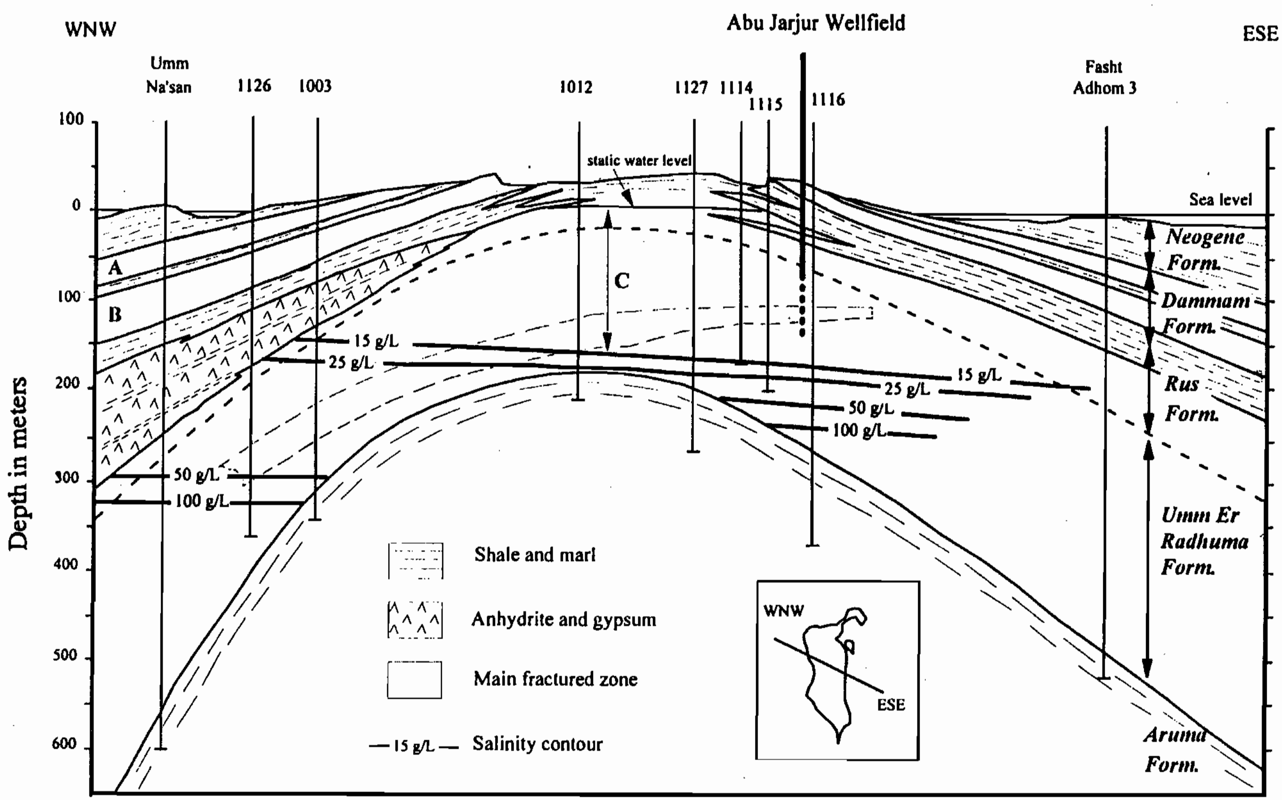

Fig. 2. Hydrogeological cross section showing the C aquifer geometry (modified after GDC, 1983).

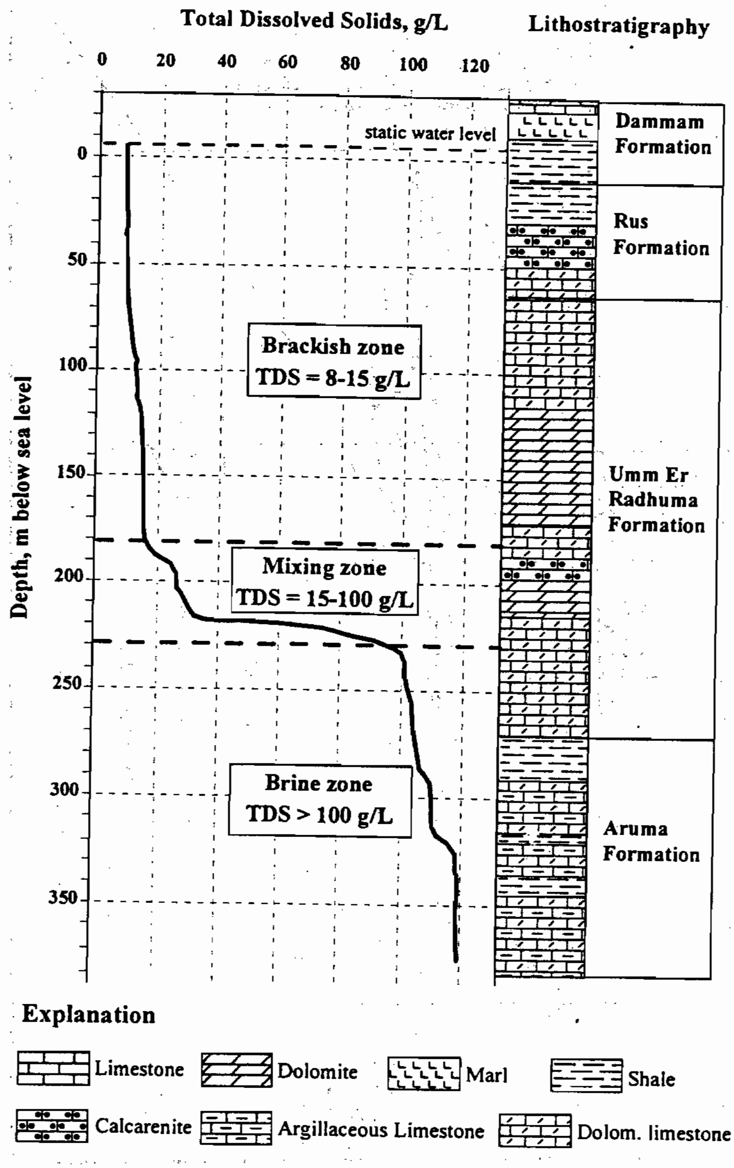

Fig. 3. Salinity profile of the C aquifer at Abu-Jarjur wellfield (modified after GDC, 1983).

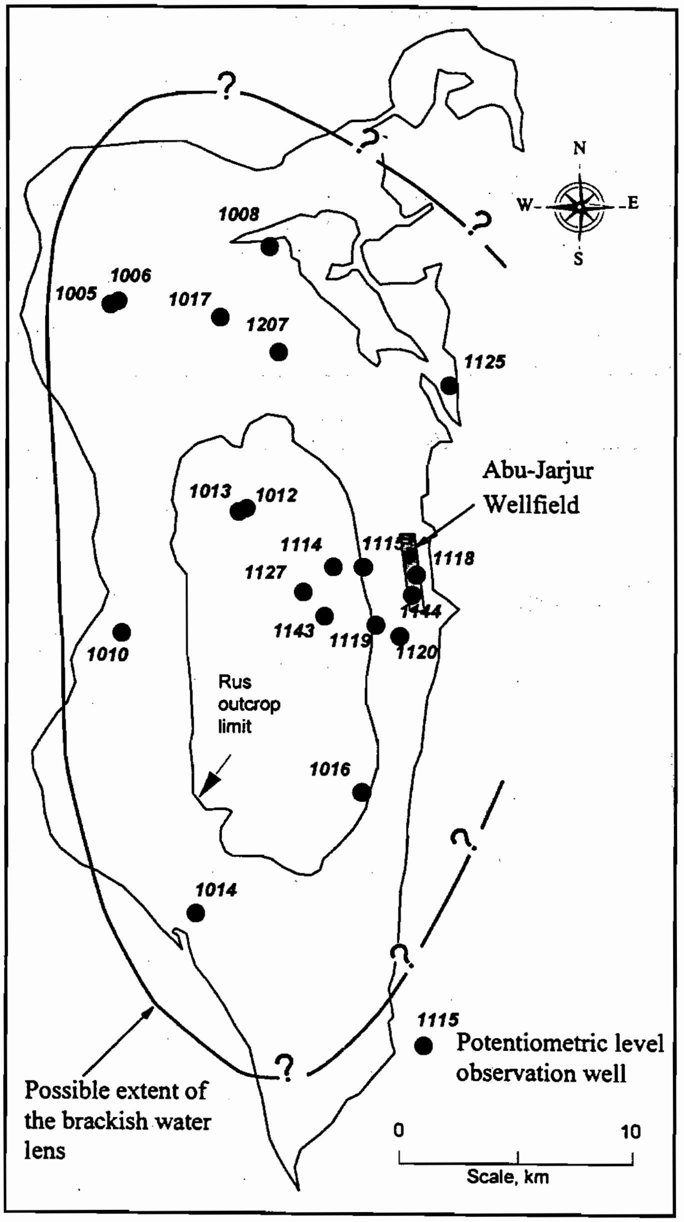

Fig. 4. Aquifer C potentiometric head levels observation network.

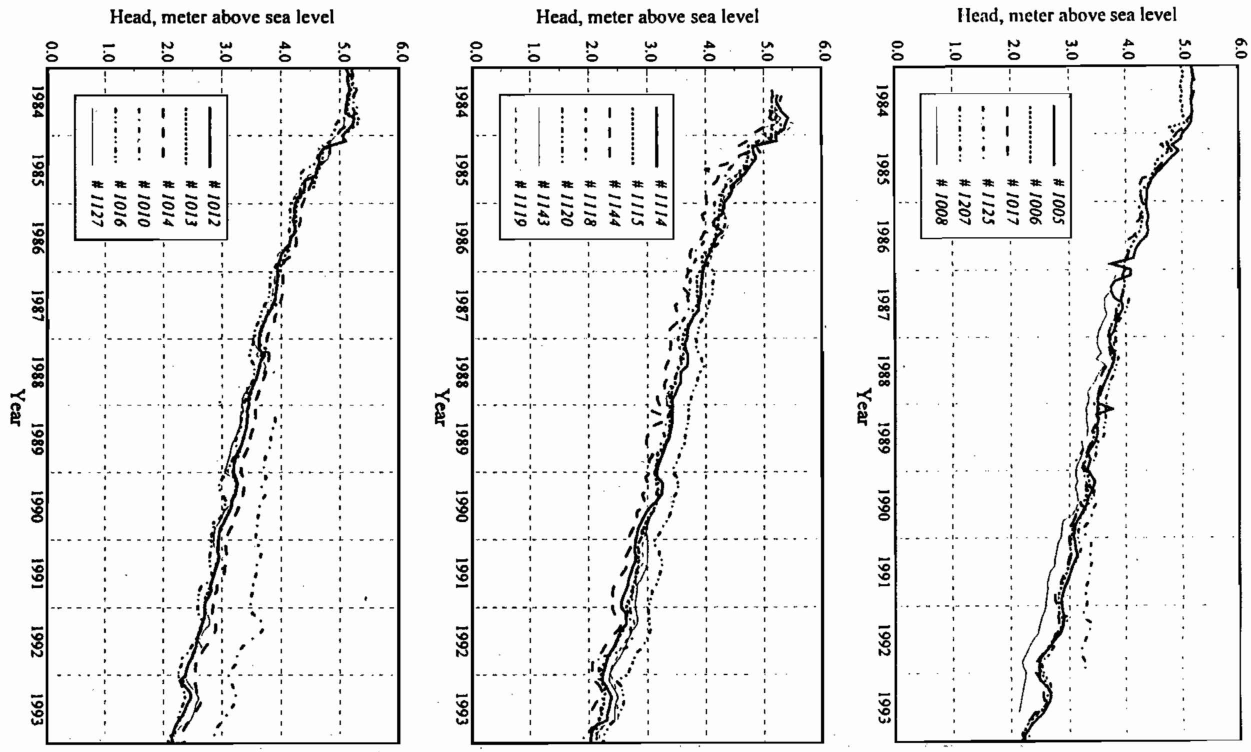

Fig. 5. Observed potentiometric head levels in the C aquifer, 1984-1993.

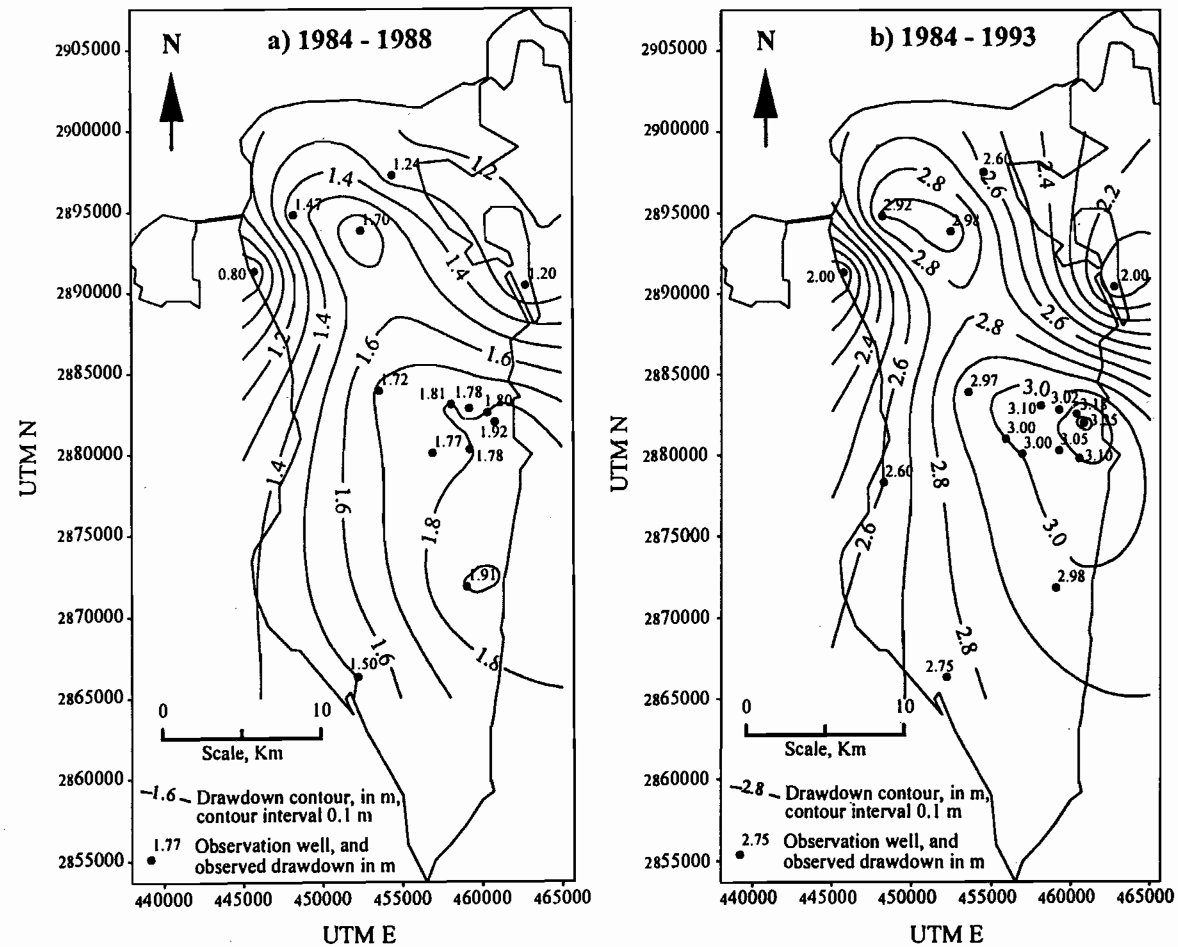

Fig. 6. Drawdown contour maps for the C aquifer. a) 1984-1988.b) 1984-1993.

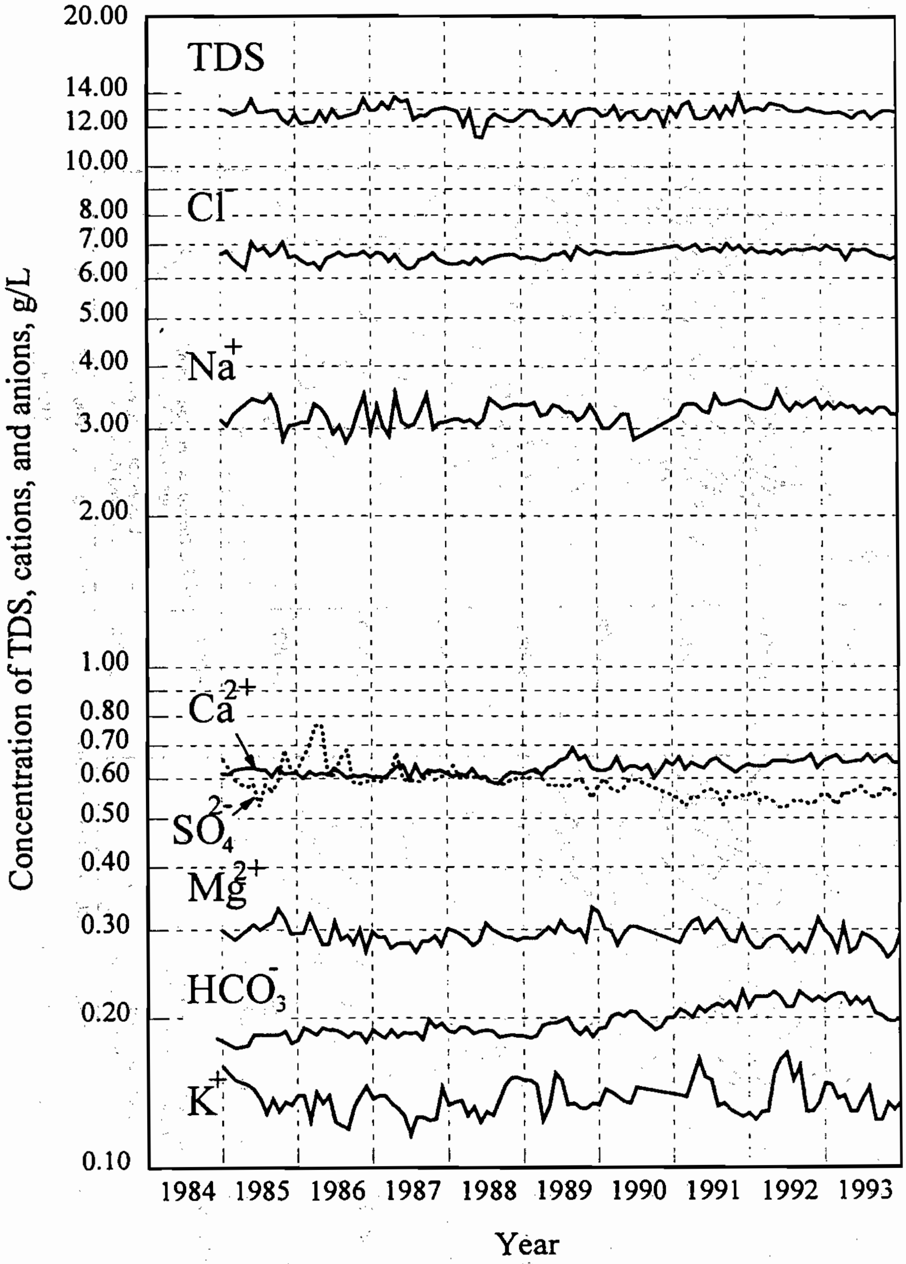

Fig. 7. Measured monthly TDS and major ions concentrations in Abu-Jarjur wellfield produced water, 1984-1993, g/L.

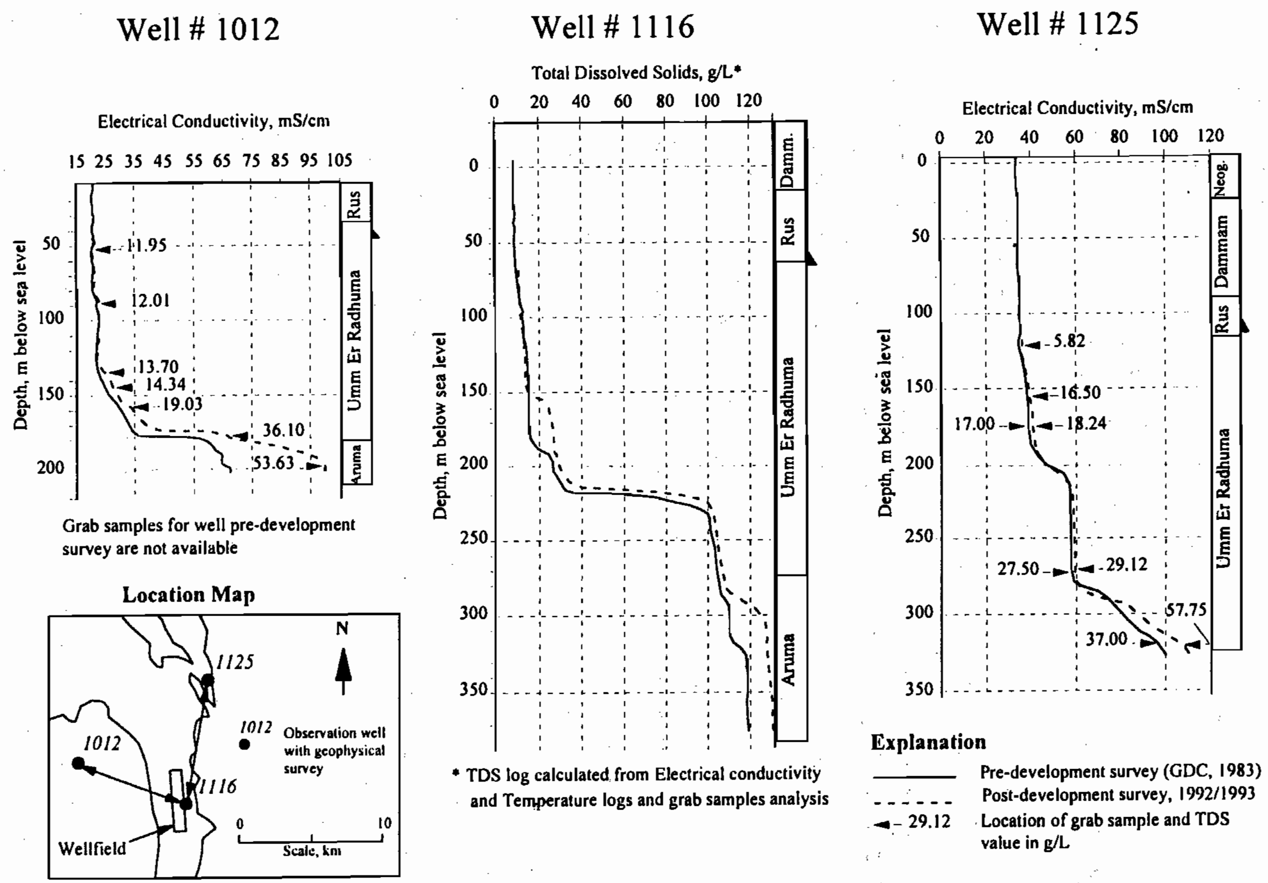

Fig. 8. Geophysical logging comparisons between the pre-development conditions (pre-1984) and the present conditions (1992/93) for three wells penetrating the full section of C aquifer.