Kuwait J. Sci. & Eng. **23**, 1996

Hydrogeology and ground water modeling of the carbonate aquifer of Al-Sulaibiya, Kuwait

F. M. AL-RUWAIH

Geology Department, Faculty of Science, Kuwait University, P.O. Box 5969, 13060 Kuwait

ABSTRACT

Al-Sulaibiya field comprises the old brackish ground water reservoir in Kuwait. The field where 136 water wells were drilled, has been under production since 1954. Hydrogeological investigations reveal that the carbonate aquifer shows a confined to semi-confined character. The aquifer transmissitivity ranges between 1500 and 5500 Igpd/ft and shows an increase in a NNE direction, while the average aquifer storativity is 2×10^{-4}. The records of yearly production of brackish water show an annual increase in the abstraction rate for irrigation and domestic purposes, and the maximum seasonal abstraction is currently 500 million Imp.gal/month. The 28-year mean precipitation was recorded to be 105 mm and the mean evaporation for the same period was 213 mm/day. These low values of rainfall and high potential evaporation in an arid region like Kuwait precludes the rainfall as a source of replenishment to the aquifer. The objective of this study is to identify the water-bearing formation type and its hydrogeologic properties, such as transmissivity, storage coefficient, secular variation of ground water level and the prediction of the ground water storage response to the heavy exploitation of the aquifer in the next 10 years from 1990 to 2000. The fluctuation of the piezometric levels showed a definite response to the production rate. The prediction of the future piezometric level using computer techniques reveals a continuous decline of the piezometric level to −300 ft (MSL) in the eastern part of the field by 1990. Moreover, the ground water level is expected to decline to about −380 ft (MSL) by the year 2000. The total dissolved solid (TDS) of the carbonate aquifer does not show a significant seasonal variation, and the salinity, which ranges between 4000 and 8000 mg/l, increases and concentrates along the eastern part of the field.

INTRODUCTION

The State of Kuwait is located at the western side of the Arabian Gulf and has an area of about 6.8×10^3 miles^2. It is bordered by Iraq to the north and by Saudi Arabia to the west. The average temperature in summer is about 45°C. The water resources in Kuwait are limited to the brackish ground water fields of Al-Shagaya, Al-Sulaibiya, Al-Wafra and Umm-Gudair. The study area, Al-Sulaibiya field, is located to the southwest of Kuwait City and occupies an area of about 53.8 miles^2 (Fig. 1). It is among the water well fields which supply the Kuwait City with brackish water, which is mainly used for irrigation of private and public gardens and domestic use. In addition, it is blended with distilled water from the desalination plants to make the water potable. The seasonal abstraction is currently 6 billion Imp.gal/year and the piezometric level shows a clear correspondence to pumpage (Yildir 1981).

The aquifer pumping tests data were compiled and analysed by analytical methods to establish the time-drawdown curves and to determine aquifer properties (Kruseman & De-Ridder 1970).

GEOLOGY AND STRATIGRAPHY

The territory of Kuwait extends over an area of 6.8×10^3 miles^2 of desert and flat islands. The topographic relief is generally flat. The ground surface decreases gradually from the southwest of the State toward the shore of the Arabian Gulf, with an altitude ranging from 100 ft in the eastern part to about 900 ft above sea level at the southwest corner. The northern and western part of the country has a comparatively dense drainage pattern of small and shallow wadi systems, draining northeast toward the Iraqi border and toward a shallow depression near Al-Rawdhatain, east of the Basra road, and the runoff is toward the coast of Khor Al-Sabiyah. The drainage pattern becomes more obscure in the southwestern section of Kuwait. Only around Al-Dibdibba can the northeastern drainage trend to be recognized in poorly-developed wadis. As per Owen & Nasr (1958) part of the

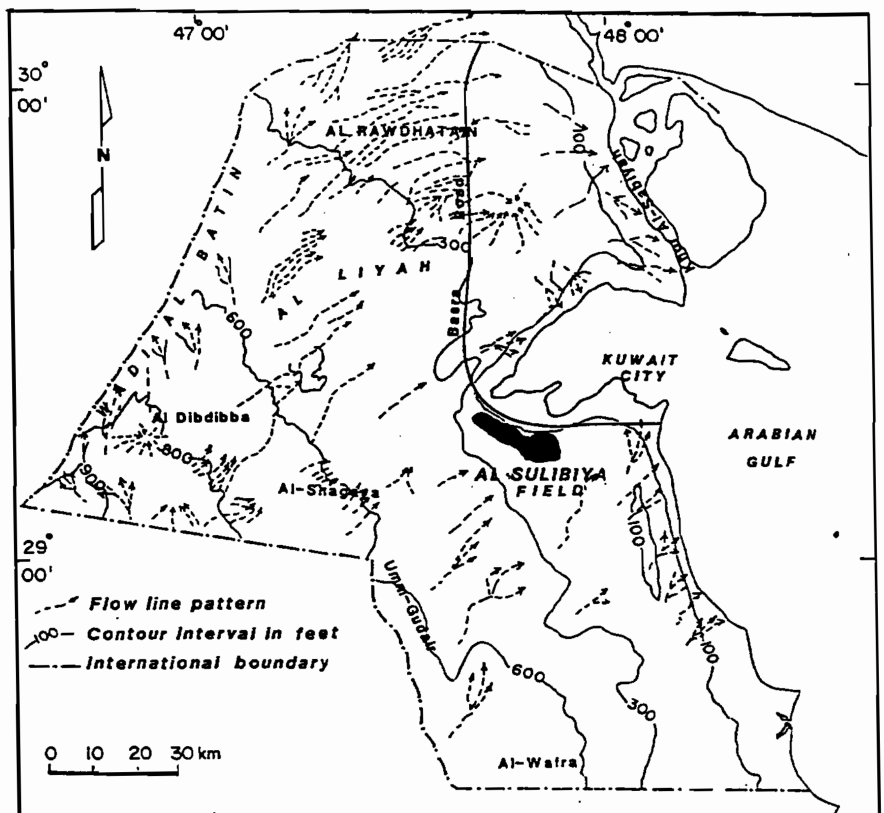

Fig. 1. The location map of Al-Sulaibiya field in Kuwait. Also shown are dominant northeast drainage patterns.

Table 1. General cenozoic stratigraphic sequence of Kuwait (Owen and Nasr 1958).

Age	Group	Formation	Lithology	Range of thickness
Recent			Beach sands and limestone, wind blown sand, playas, silts and clays and Wadi Alluvium	
Pleistocene		Dibdibba Formation	Sands, gravels, silt, mainly conglomerate sandstone	Up to 350 ft.
Pliocene	Kuwait group	Lower fars Formation	Anhydrite, gypsum, marls, and shallow water limestone	350 ft.
Miocene Oliocene		Ghar Formation	Sands with subordinate gravel and clay	Up to 900 ft.
Eocene		Dammam Formation	Recrystallized and dolomitized limestone, dolomite, capped by chert	500–700 ft.
	Hasa group	Rus Formation	Anhydrite, limestone, marl	250–400 ft.
Paleocene		El-Radhuma Formation	Marly limestone, dolomite, anhydrite	500–1 400 ft.

sedimentary successions in Kuwait are shown in Table 1. The Pleistocene deposits are overlain by recent sedimentary deposits. The Eocene aquifer system consists of two limestone formations of El-Radhuma and Dammam, which are separated by the Rus Anhydrite Formation. The Dammam Formation is considered to be vast and infinite in its areal extent. It dips in a northerly direction to reach a depth of 100 ft below sea level. The Dammam Formation has been locally subdivided on the basis of lithology into 3 units from bottom to top (O'Brien 1952). Unit 1 is made up of dense dolomitic limestone, with lower fossiliferous limestone, thin anhydrite beds and green shale in the lower part. Unit 2 is a chalky, shelly limestone with thin siliceous limestone at the top and siliceous limestone with sand beds at the base. Unit 3 is a shelly, chalky to granular, porous limestone with siliceous limestone on top. Chert is present as a discontinuous bed which measures 20 ft in thickness or as frequent chert nodules and concretion. It covers the Dammam Formation and acts as an impermeable layer. Figure 2 represents the NW–SE subsurface geology of some water wells in the study area.

DECLINING WATER LEVEL

In any reservoir storing water, rising water levels indicate an increase in storage and falling levels indicate a decrease in it. In the Al-Sulaibiya area, it was recorded that the piezometric level of the Dammam limestone aquifer ranged from +50 ft to +100 ft (MSL) in 1950 (Al-Hajji 1976). Overpumping due to the heavy exploitation to meet the demands for brackish water produced a great influence on the amount of ground water storage as indicated by a decrease of the piezometric level from +75 ft to −20 ft (MSL) in 1963 (Al-Ruwaih 1980). In addition, the available data of the piezometric levels measured in December 1975, were used to construct the flow net in Fig. 3. The calculated total flow rate of the aquifer was 2.58×10^6 Imp. gal/day as calculated from the equation $Q = T * dh * nf$ (Todd 1980). In this equation, T is the average field transmissivity and is equal to 3000 Igpd/ft. dh is the contour difference between

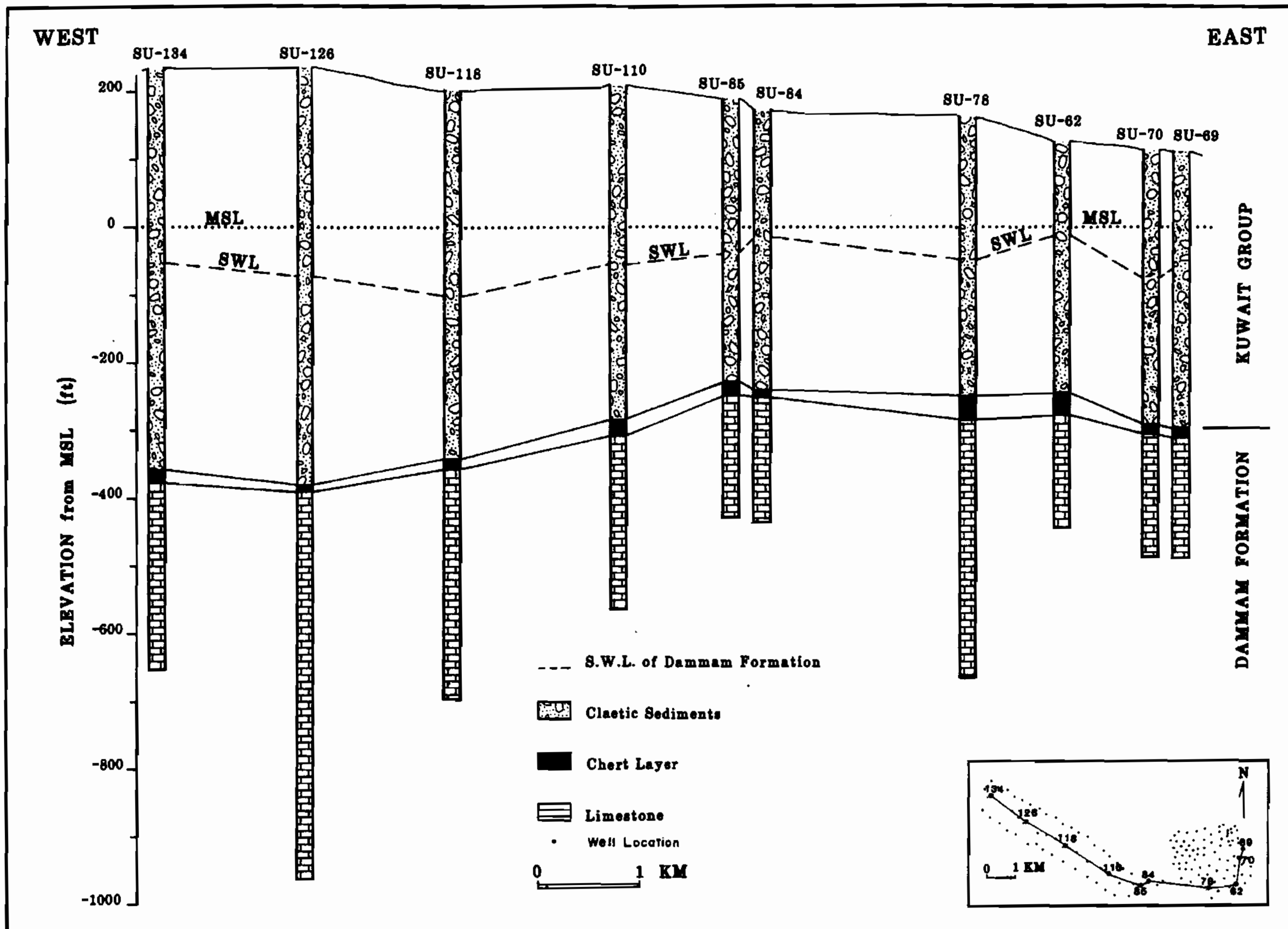

Fig. 2. A well correlation diagram in Al-Sulaibiya field. Inset shows location of correlated wells and field limits.

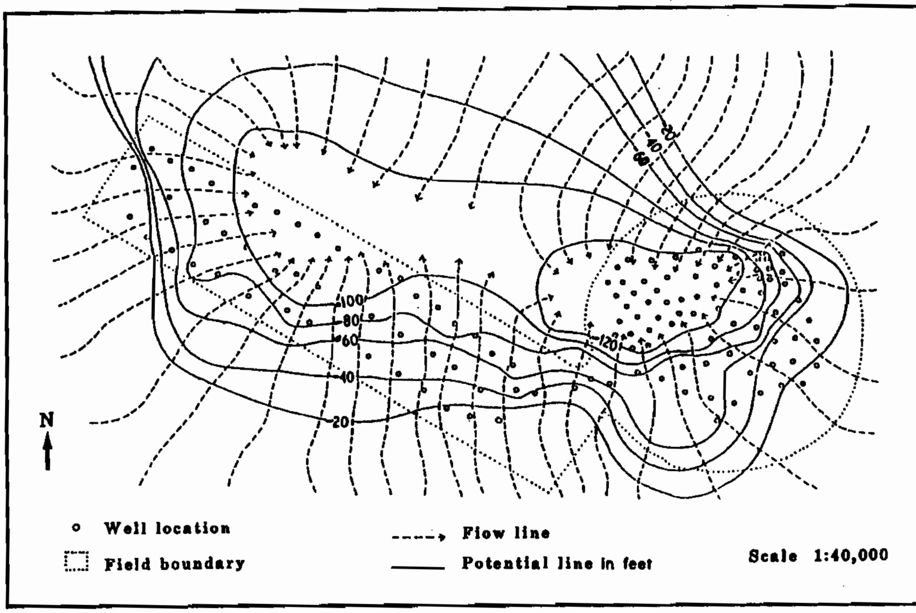

Fig. 3. Flow net analysis pattern of Al-Sulaibiya field as shown by the piezometric level in December 1975.

two equipotential lines and equals 20 ft, and nf is the number of flow channels. In addition, the flow net shows that the ground water flows from SW to NE. It is clear from Fig. 3 that the piezometric level has declined over the period from 1963 to 1975 by about 100 ft in the eastern part of the field and that production is higher than the natural replenishment. To maintain the ground water resources indefinitely, recharge must balance discharge in a steady-state condition, but this is not the case in the study area.

GROUND WATER ABSTRACTION AND AQUIFER RECHARGE

The study area has been under production since 1954. The production of ground water shows an annual increase and seasonal fluctuation in response to population demand, which increases in summer. A plot of the smoothed water level measurements of SU-OW-5, located for monitoring purposes outside the developed field, and the total production of the field between 1984 and 1989 are displayed in Fig. 4. It is obvious that there is a close correspondence between water level fluctuation and ground water abstraction. The water level in 1987–1988 showed a noticeable increase which may be attributed to the fissure flow affected by the karstification effect of the carbonate aquifer. Correlation was attempted between the fluctuation of water level and rainfall; the plot shows that the causes of water level fluctuation are influenced directly and primarily by the ground water abstraction.

However, rainfall is not an accurate indicator of ground water recharge because of the surface and subsurface water losses as well as travel time for vertical percolation. Moreover, in arid and semi-arid regions recharge from rainfall is essentially zero. The amount of rainfall in Kuwait is not expected to make a significant contribution to recharging the aquifers. Historically, the main source of recharge is the direct precipitation on the intake area in Saudi Arabia, where water percolates downdip

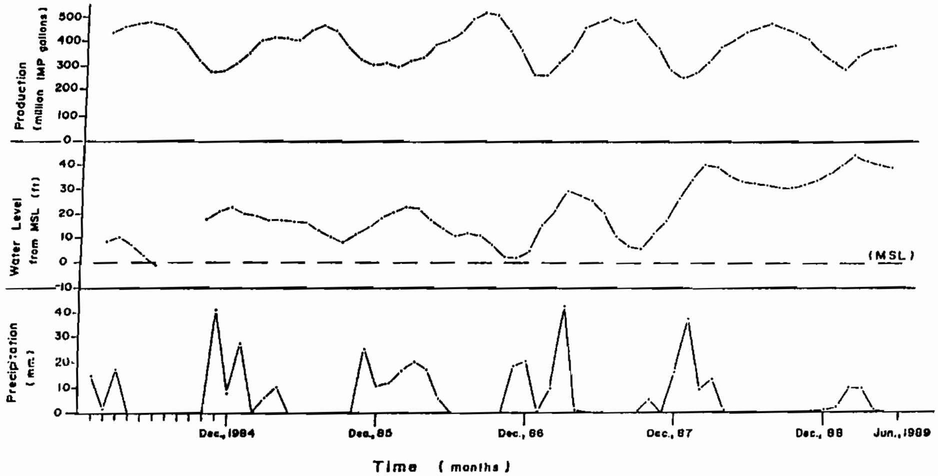

Fig. 4. A plot of the precipitation, smoothed water levels and total production of the Al-Sulaibiyah field in the interval 1984–1989 for well SU-OW-5.

toward the discharge area. This amount of recharge is extremely difficult to determine. Hantush (1971) recommended that ground water exploitation in Kuwait should be based on the notion of mining, since the magnitude of recharge could not be readily determined.

STATISTICAL APPROACH

The regression equation and correlation coefficient concepts (Davis 1973) were applied to find the relation between the static water level (SWL) and pumping rate (Imp.g/m) of well SU-OW-5 in the Al-Sulaibiya field in 1990 (Fig. 5). The equation of

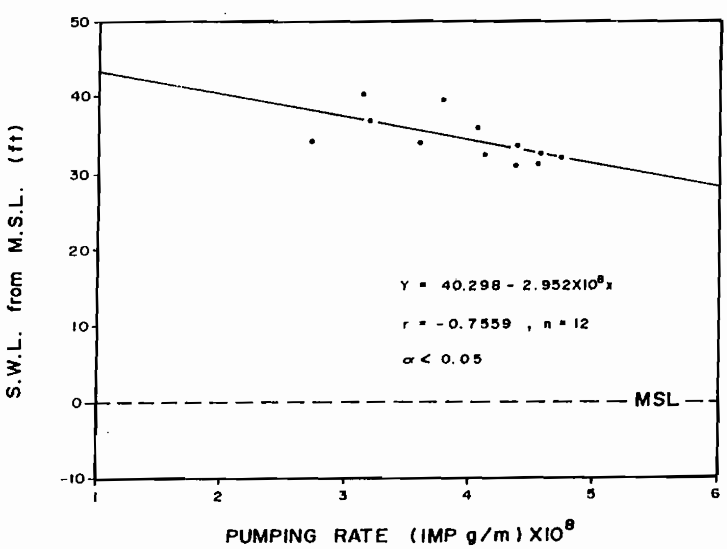

Fig. 5. The least-squares regression relation between the static water level (SWL) and the pumping rate (Imp.g/m × 10^8) for well SU-OW-5 in 1990.

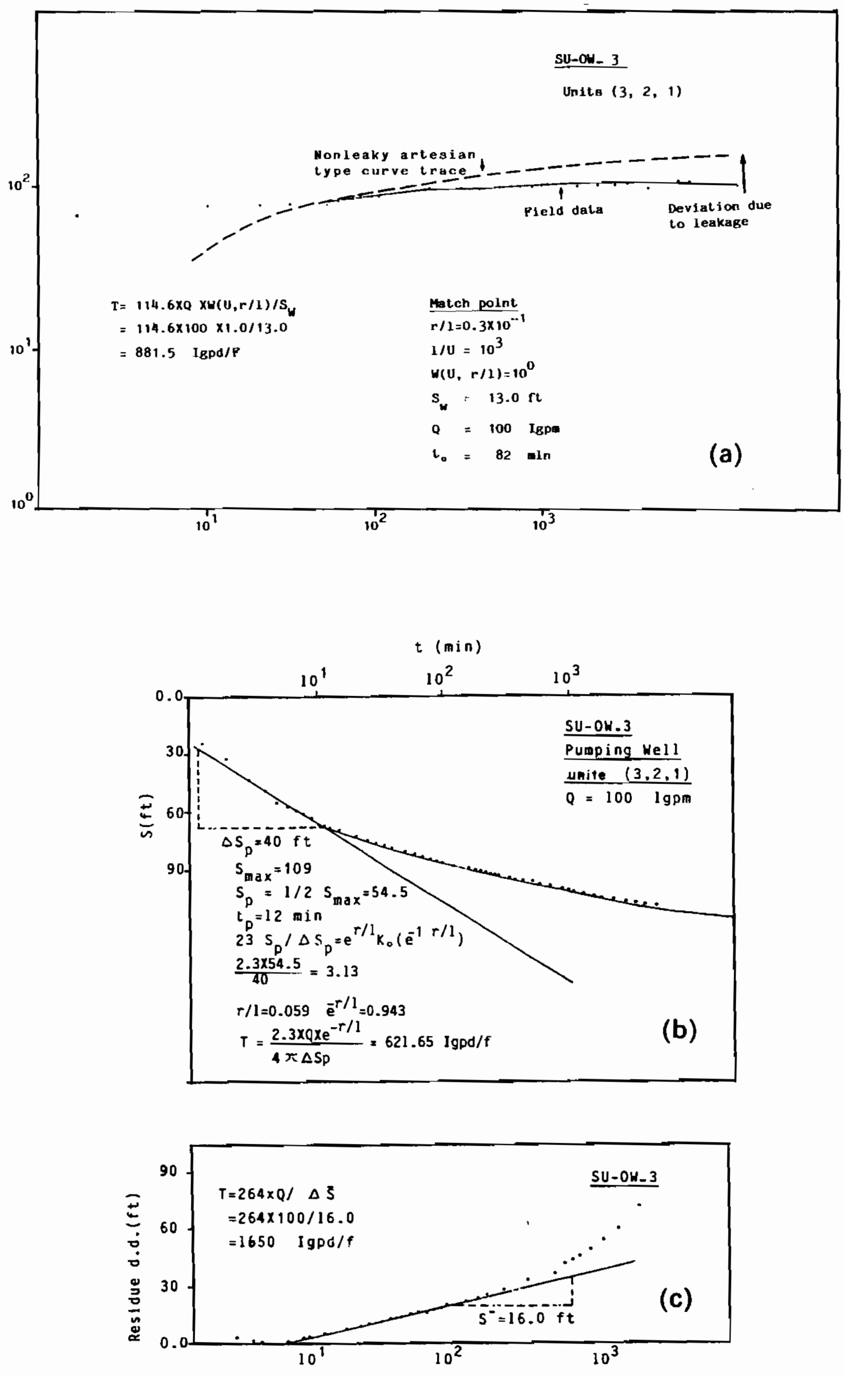

Fig. 6. (a) Log–log plot of time-drawdown of SU-OW-3, (b) semi–log plot of time drawdown of SU-OW-3, (c) semi–log plot of t/t' versus residual drawdown of SU-OW-3.

regression is $h = h_0 + bx$ where h is the (SWL) at any pumping rate; h_0 is the intercept (40.298) ft and represents the initial water level; and b is the slope (-2.952×10^8) indicating the change in water level per pumping rate (h/Q) or the reciprocal of the slope (i.e. the specific capacity of the basin). The correlation coefficient of the former parameters is -0.7559, showing a fairly strong negative correlation and indicating that the water level is heavily influenced by the continuous field development.

HYDROGEOLOGIC PROPERTIES OF THE AQUIFER

A number of short-duration pumping and recovery tests have been conducted in the production wells and have covered most of the area under investigation. The time-drawdown data of 22 wells was compiled, analysed and interpreted. Ninety-nine percent of the pumping tests data analyses reveal that the ground water reservoir is acting as a confined to semi-confined aquifer. The recharge effects are illustrated by plotting the time-drawdown data of well SU-OW-3 on a log–log scale (Figs. 6a & 6b) which show deviations from the non-leaky confined type curve, meanwhile; the recharge effect is confirmed from the plotting of the residual-drawdown (S') versus time ratio t/t' as shown in Fig. 6c. This recharge effect is strongly suggested to be due to the karstified nature of the carbonate aquifer. The plot of the pumping test data of well SU-107 demonstrates clear evidence of the confined response of the aquifer, with a close matching of the field data to the Theis type-curve for a non-leaky confined condition (Fig. 7) or, alternatively, to the straight line method where $u \leqslant 0.1$. The storage coefficient has been determined from the reliable data of observation well SU-OW-4 as shown in Fig. 8 and is equal to 5.12×10^{-4}. The calculated transmissivities have been introduced into a computer program to construct Fig. 9 which shows the areal variation of the transmissivity in the Al-Sulaibiya area. The range of values from 1500 to 5500 Igpd/ft is unequally distributed over the area, reflecting the heterogeneity of the aquifer. The transmissivity values generally increase from NW to SE and then to NE, possibly indicating a relationship between the transmissivity and the general east dip of strata as well as the flow path. This areal variation in

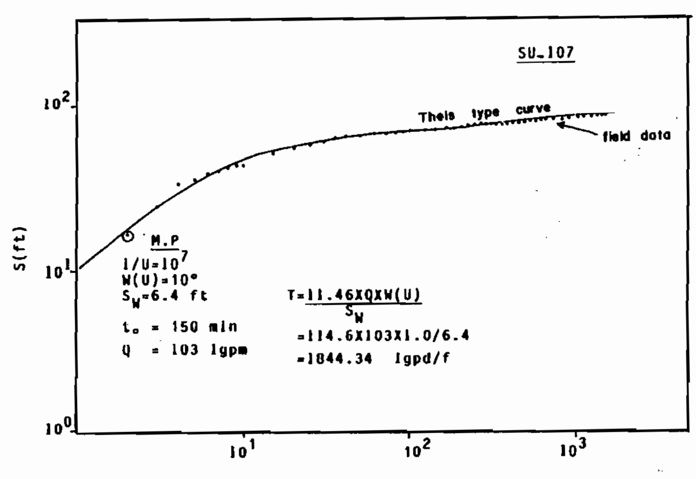

Fig. 7. Log–log plot of time-drawdown of SU-107.

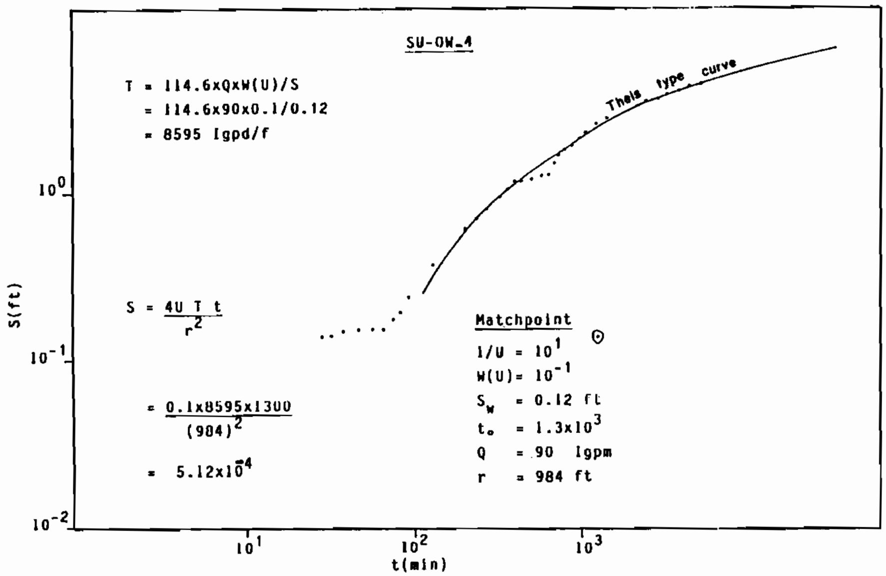

Fig. 8. Log–log plot of time-drawdown of SU-OW-4.

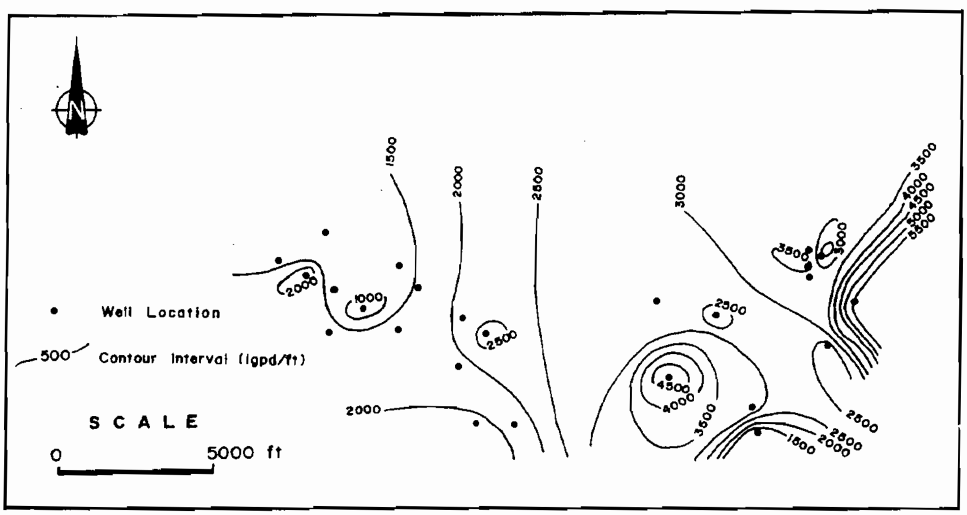

Fig. 9. Areal variation of aquifer transmissivity (in Igpd/ft) in Al-Sulaibiya field.

transmissivity might provide a rough idea about where to exploit and utilise the aquifer in the future.

GROUND WATER MATHEMATICAL MODELING

In the modeling of the Al-Sulaibiya aquifer system, a finite difference method was used based on the basic aquifer simulation program developed by Prickett and Lonnquist of the Illinois State Water Survey (1971). This program was originally written to simulate the aquifer characteristics for both single and multiple aquifers, including confined and semi-confined or leaky flow conditions. This program has been used to predict changes in ground water level within the definite nodal area at any required time intervals. The partial differential equation for the flow condition is:

$$\frac{\delta}{\delta x}\left[T\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta y}\left[T\frac{\delta h}{\delta y}\right]=S\frac{\partial h}{\delta t}+Q$$

where T = aquifer transmissivity, h = head, t = time, S = aquifer storativity, Q = ground water withdrawal per unit area, x, y = rectangular coordinator.

PHYSICAL BOUNDARY CONDITIONS

Accepting the available geologic and hydrogeologic data, there is no impervious boundary preventing lateral flow of ground water from any direction toward the area under study. The Dammam Formation aquifer is characterized by unbroken areal extent beneath all Kuwait; therefore an arbitrary constant head recharge boundary was located at the periphery of the nodal area to define the size of the study area at a distance of 3281 ft. The total nodal area is about 62.88 miles^2. The number of nodes is 255 and the branches are 467. The aquifer characteristics such as static water level and the aquifer transmissivity are assumed to be constant at the boundary nodes. The general aquifer thickness was kept constant at 600 ft for modeling purposes. Transmissivity was kept constant over the time for each node. During implementation of the model for checking the appropriate properties and computing the average change of water level, a time interval (DELTA) of one day was selected; for long term runs, an interval of 10 days was selected.

DATA-INPUT AND RESULTS

Data input in the model included the ground water level H(I) which has been extrapolated for the nodal system from the generalized ground water level contour map of 1975 (Fig. 3). The values of aquifer transmissivity ranged from 1500 to 5500 Igpd/ft. The average daily abstraction rate AQ(I) of the field is about 15 million Imp.g and the storativity equals 2×10^{-4}. Tests of the confined aquifer model may be

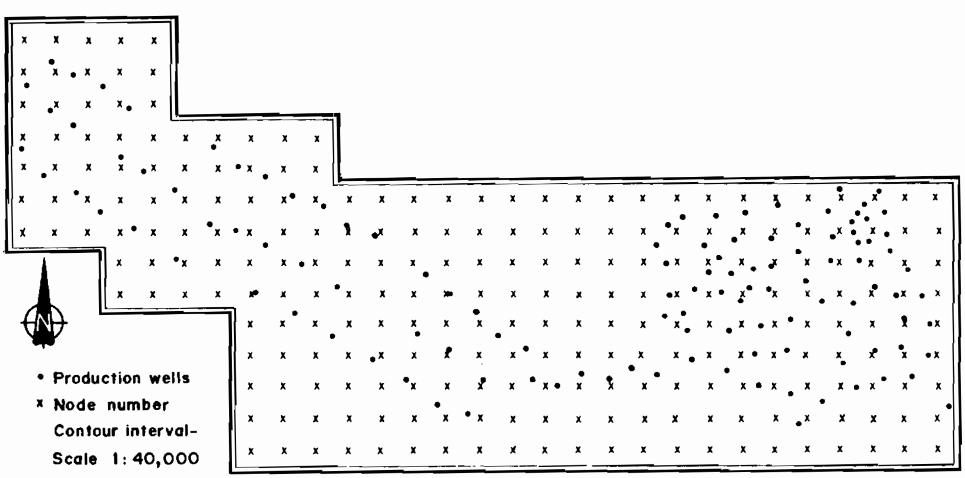

Fig. 10. The nodal system map of the study area.

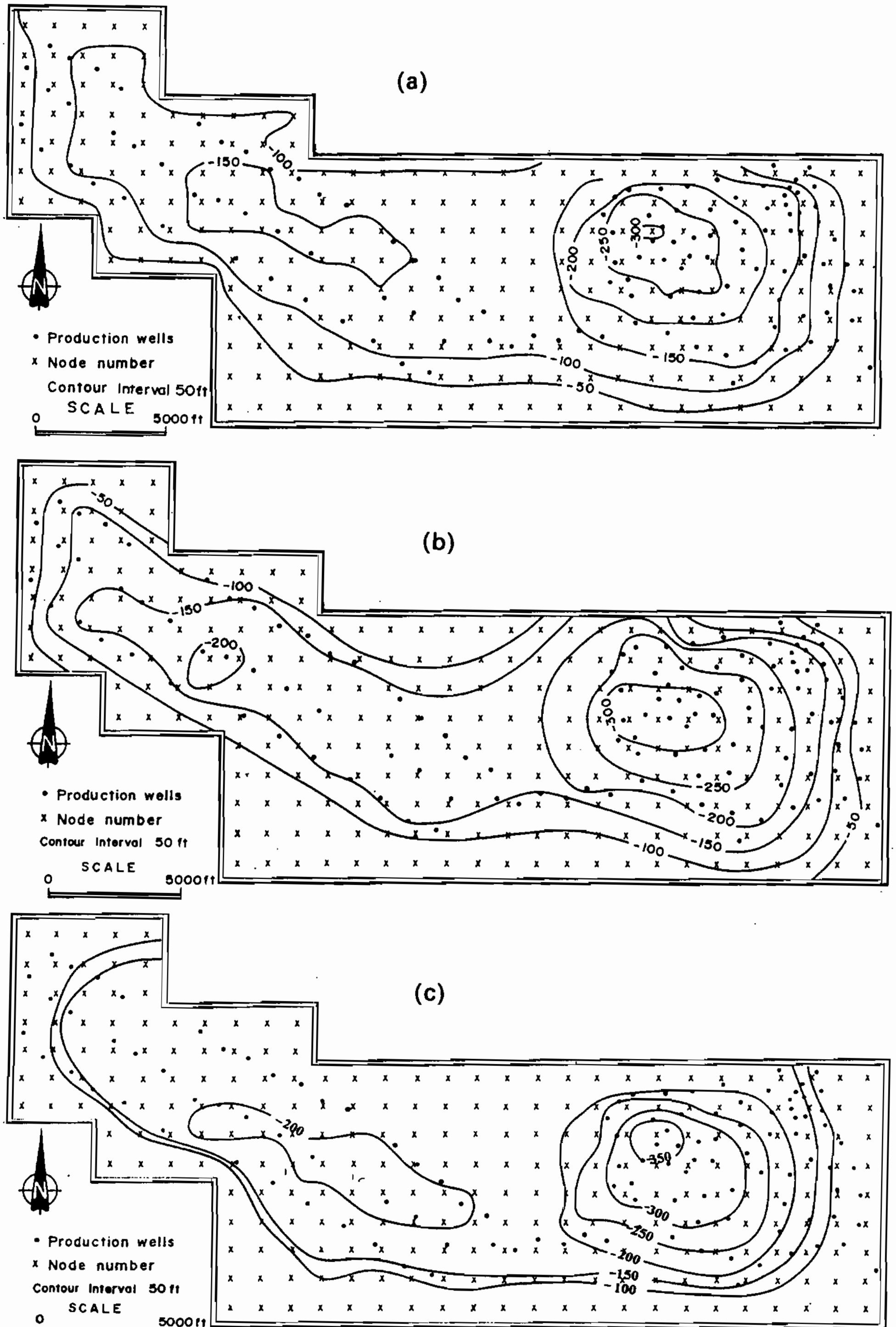

Fig. 11. (a) The predicted piezometric level map in 1985; (b) the predicted piezometric level map of 1990; (c) the predicted piezometric level map of 1995.

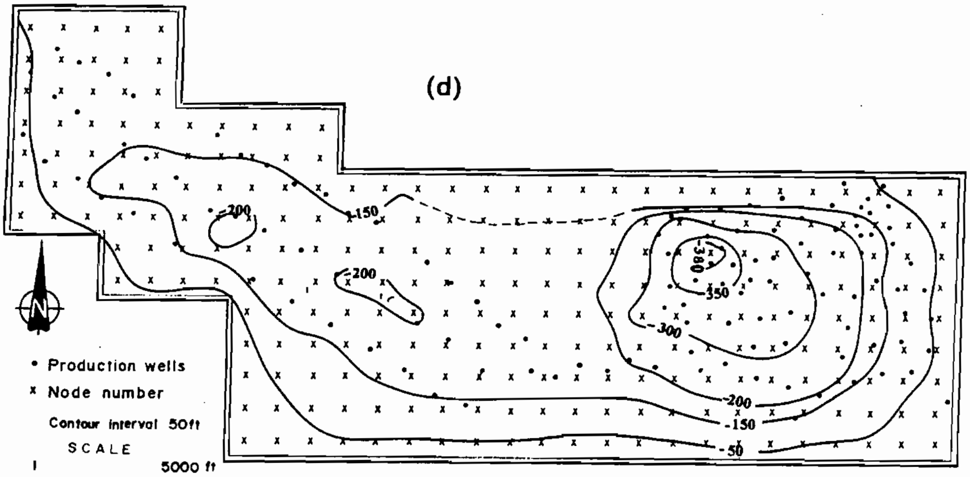

Fig. 11. (d) The predicted piezometric level map of 2000.

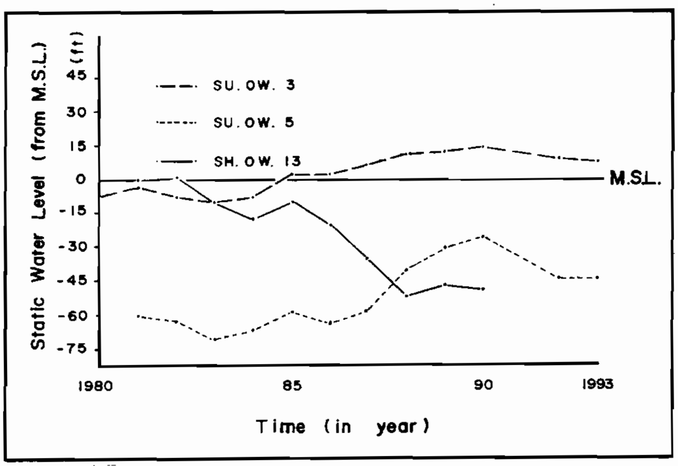

Fig. 12. Field measurements of the water level in the observation wells SU-OW-3, SU-OW-5 and SH-OW-13, in the period 1980–1993.

appropriate for evaluation of short-term pumping tests but may be unsuitable for long-term prediction. The model was used for the prediction of piezometric head changes over the periods 1985–90, 1990–95 and 1995–2000 as shown in Figs. 10 and 11a–d. The predicted water levels are only approximate figures, which might be different than the actual changes, taking into consideration that average values of hydrogeological properties have been used. Furthermore, values of generalised water level distribution (1975) and abstraction (Q) values (1975), which are kept constant through the process of modeling, might not be valid, due to the annual increase in abstraction rate from the field. Nevertheless, the calculated average changes of the predicted water level from the model were found to be 5 ft per annum over the 15 years, a value which is not too dissimilar from the field measurements of annual change. It was found that the piezometric level declined to about −180 ft (MSL) over the period 1975 to 1990. Also, the prediction of the change of water level in the year

2000 shows a continuous decline to reach −380 ft (MSL) in the eastern part of the study area. Thereafter it seems that continued development of the aquifer without a management plan would eventually mine the ground water resources. However, for the period 1980 to 1993, monitoring measurements of the piezometric levels of the Dammam limestone aquifer have been recorded in three observation wells (SH-OW-13, SU-OW-3 and SU-OW-5), which surround the production field as shown in Fig. 12. Generally, there is agreement between the field measurements and the prediction of the water level. Moreover, both SU-OW-3 and SU-OW-5 show a harmonic pattern of water-level fluctuation due to seasonal production. A rise in water level was recorded in the three observation wells in 1990. This is related to the halt of the field production due to the Iraqi invasion which lasted seven months, and inaccessibility of the field for months after the liberation of Kuwait when the fields were surrounded by mines.

CONCLUSION

The water resources in Kuwait are limited to the brackish ground water well fields such as Al-Shagaya, Al-Wafra, Umm-Gudair and Al-Sulaibiya, the last being the subject of this study. The brackish water is used for irrigation, domestic purposes and 3–12% of the brackish water is blended with distilled water. The Dammam Formation aquifer in this area has salinity ranges between 4000 and 6500 mg/l, with some water wells in the eastern part of the field exhibiting a salinity value exceeding 8000 mg/l. The 28-year mean of the precipitation and evaporation is 105 mm and 213 mm/day respectively. The low amount of rainfall and high evaporation rate in an arid country like Kuwait makes the replenishment of the aquifer negligible. The carbonate aquifer of the study area acts as a confined to semi-confined aquifer, with low transmissivity ranging from 1500 to 5500 Igpd/ft and increasing towards the NE, and a storativity value of 2×10^{-4}. The Al-Sulaibiya well field is the oldest but probably the least potential reservoir in the Dammam Formation owing to its very low transmissivity. The ground water flow-lines indicate that the direction of flow is from NW to SE and then toward NE. The field measurements showed a decline of the piezometric level to be about 120 ft in 1975. The ground water modelling of the field predicted a continuous lowering of the piezometric level, especially in the eastern part of the field, to ranges between −300 to −380 ft during the period from 1990 to 2000 as a result of the large number of wells and to the heavy exploitation. The calculated average changes of the predicted water level was found to be 5 ft per annum. However, because the field is under heavy production, natural seepage is less than the discharge.

ACKNOWLEDGEMENTS

I would like to acknowledge Kuwait University for granting me a sabbatical leave for the period from 1990–1991, which enabled me to finish this paper. Thanks are also extended to the Ministry of Electricity and Water, Ground Water Department, for providing the basic research materials. Also, gratitudes are extended to Dr. Akhtar Shaikh, Mr. Hamid Omar and Mr. Haider Khajah for their valuable and fruitful comments and discussion.

REFERENCES

Al-Hajji, Y.Y. 1976. A quantitative hydrogeological study of field 'A', South Kuwait. M.Sc. thesis, Ohio University.

Al-Ruwaih, F.M. 1980. Hydrogeology of Al-Sulaibiya well-Field, southwest Kuwait. Ph.D. dissertation, University College London, United Kingdom. 390 pp.

Davis, John C. 1973. Statistics and Data Analysis in Geology. John Wiley & Sons, Inc., New York, 550 pp.

Hantush, M.S. 1971. Memorandum on the Shagaya ground water project. Ground Water Department, Ministry of Electricity and Water, Kuwait.

Kruseman, G.P. & De-Ridder, N.A. 1970. Analysis and evaluation of pumping test data: International Institute for Land Reclamation and Improvement, The Netherlands, 200 pp.

O'Brine, C.A.E. 1952. A stratigraphical study of the Eocene Upper Limestone in southern Kuwait. Mimeographed report (Unpublished Report).

Owen, R.M.S. & Nasr, S.N. 1958. Stratigraphy of Kuwait-Basra area, in Habit of Oil: American Association of Petroleum Geological Bulletin **42:** 1252–1278.

Prickett, T.A. & Lonnquist, C.G. 1971. Selected digital computer techniques for ground water resources evaluation. Illinois State Water Survey Bulletin. No. 55, 62 pp.

Todd, K.D. 1980. Ground water hydrology. Second edition. John Wiley & Sons, New York, 535 pp.

Yildir, S. 1981. Geohydrology of State of Kuwait. Third Chapter of National Report. Ministry of Electricity and Water. Unpublished report.

(Accepted 25 September 1995)

دراسة هيدرولوجية لخزان الحجر الجيري باستخدام النموذج الرياضي لمنطقة الصليبية بالكويت

فوزية محمد الرويح
قسم الجيولوجيا بجامعة الكويت،
ص. ب: 5969 الصفاة 13060 ، الكويت

خلاصة

يعتبر حقل منطقة الصليبية من أقدم الحقول لإنتاج المياه الجوفية قليلة الملوحة في الكويت حيث تتراوح الملوحة من ٤٠٠٠ إلى ٨٠٠٠ مليجرام/لتر، وتزداد نسبة الملوحة في إتجاه الشمال والشمال الشرقي من الحقل. وقد بدأ الإنتاج في الحقل عام ١٩٥٤ وذلك بحفر ١٣٦ بئرا منتجا في مكمن الحجر الجيري تكوين الدمام. وتدل الدراسات الهيدرولوجية على أن مكمن الحجر الجيري يبدو كخزان مائي محصور إلى شبه محصور. ويتراوح معامل توصيل المياه ما بين ١٥٠٠–٥٥٠٠ جالون إمبراطوري/القدم ويزداد من الجنوب الغربي إلى الشمال والشمال الشرقي في منطقة الدراسة.
ويزداد انتاج المياه الجوفية قليلة الملوحة سنويا بازدياد الحاجة لإستخدامه في الزراعة والاستعمالات المنزلية. ويبلغ معدل الإنتاج في منطقة الدراسة ٥٠٠ مليون جالون إمبراطوري في الشهر. ويسود المنطقة المناخ الصحراوي حيث بلغت كمية الأمطار في متوسط ما يزيد على ربع قرن ١٠٥ مليمتر/السنة، بينما تجاوزت نسبة التبخير إلى ٢١٣ ملم/اليوم مما لا يجعل للأمطار أي دور رئيسي في تغذية الخزانات المائية الجوفية.
من أهداف الدراسة الحالية تقييم الخصائص الهيدرولوجية للخزان المائي مثل معامل توصيل المياه، معامل الخزن، التذبذب في مستوى المياه الجوفية نتيجة لاضطراد مستوى الانتاج وكذلك التنبؤ بمستوى المياه الجوفية خلال السنوات القادمة (حتى عام ٢٠٠٠).
ولقد وجد أن تذبذب سطح المياه الجوفية يتأثر تأثيرا مباشرا بالإنتاج، حيث دل النموذج الرياضي على أن هناك إنخفاض في مستوى المياه الجوفية يصل إلى –٣٠٠ قدم في المنطقة الشرقية من الحقل، ويتوقع أن يصل إلى حوالي –٣٨٠ قدم عام ٢٠٠٠.