COMBINED PERFORMANCE OF PUMPING AND TRACER TESTS: A CASE STUDY AT THE SEVENTH RING ROAD SITE, KUWAIT

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ABSTRACT

The useable groundwater reserve of Kuwait, both fresh and brackish groundwater is a strategic reserve in the water-starved arid climate of Kuwait. There was a significant decline in the potentiometric heads of the aquifers since 70's in the central and southwestern parts of Kuwait. The proper understanding of the aquifer characteristics, the interaction of the different groundwater aquifers, quality regime, groundwater flow, source and age of the groundwater and the aquitards especially when the aquifers are being exploited will ensure the long-term sustainable exploitation of these aquifers.In the light of the aforementioned, a program of derivation of hydrogeologic parameters and information using tracer experiments covering the main water fields and most of Kuwait was conducted in this study. This paper describes the tests that have been conducted in one of the sites i.e. Seventh Ring Road (Site T-10). Both natural and artificially introduced tracers were used for this purpose. The main aim of the tracer study was to provide information on the groundwater flow and transport conditions in greater details to give clearer picture of water movement paths and flow rates within the aquifer system. The pumping and tracer test indicated that the ground flow in the Kuwait Group is matrix dominated as opposed to the secondary porosity dominated flow of the Dammam Formation, as indicated by high porosity (> 0.10, 10%) values obtained from the analysis of the tracer test data. The upper (20 top 35 m) and lower (40 to 55 m) zones of the Upper Kuwait Group at the study site (Site T-10 7th Ring Road) are hydraulically well connected. It is recommended to establish a country-wide network of monitoring wells in which water level and water quality are sampled on regular basis.

1 INTRODUCTION

Works of Omar et al. (1981), Senay et al. (1987), Hamdan and Mukhopadhyay (1991), Al-Sulaimi and El-Rabaa (1994), Al-Ruwaih (1994; 1995), and Mukhopadhyay et al. (1994) provided general guidelines on the aquifer hydrology and groundwater flow within the aquifer system in Kuwait. Specific knowledge about actual flow paths followed by groundwater in the local scale and the prevailing fluid velocity related to the hydraulic conductivity and the head gradient at that locality is not, however, always forthcoming. The information of this type is important when managing the groundwater resources of an area such as Kuwait.

Due to the effective mining of the very limited usable groundwater resource over the past several decades, it is currently under severe strain. The brackish water consumption (2,500-5,000 mg/l total dissolved solids) has increased over the past at a very rapid rate. The production had jumped from 7760 MIG in 1970 (MEW, 1998) to 31,297 MIG (MEW, 2015) in 2014 in the water fields operated by the Ministry of Electricity and Water (MEW) and Kuwait Oil Company (KOC). Brackish water in Kuwait is mainly used for non-potable use in households and for mixing with desalinated water at ratios of less than 10% of the total volume to make the mixture potable. Moreover it's also used for irrigation and landscaping, livestock rearing and construction work.

With very low precipitation, there is very little natural recharge of the aquifers within the territory of Kuwait, and most of the groundwater inflow in the country is from Saudi Arabia and Iraq to its west. Although this general pattern of inflow of groundwater from across its western border and the discharge along the coastal areas of the Arabian Gulf is known, the detailed pattern of the flow paths of water within the aquifer system, the variation of aquifer characteristics like hydraulic conductivity and storativity,which controls the ease and direction of the groundwater flow, its velocity and the aquifer energy loss during its exploitation are not known to the degree desired for the planning of this exploitation strategy.

In the light of the aforementioned, a program of derivation of hydrogeologic parameters and information using tracer experiments covering the main water fields and most of Kuwait was conducted in this study. This paper describes the tests that have been conducted in one of the sites, i.e., Seventh Ring Road (Site T-10). Both natural and artificially introduced tracers were used for this purpose. The main aim of the tracer study was to provide information on the groundwater flow and transport conditions in greater details to give clearer picture of water movement paths and flow rates within the aquifer system.

The shallow geology of Kuwait consists of the Kuwait Group and the underlying DammamFormation. The Kuwait Group (KG) ranges in thickness from about 30 to 400 m with the greatestthickness occurring in the north of Kuwait, near the Iraqi border. The Kuwait Group consists of alithologically diverse sequence of undifferentiated fluviatile clastics (gravelly sands and sandygravels), calcareous sandstones, calcretes, and less permeable muddy layers. TheDammam Formation has a total thickness of about 60 to 200 m range and consists mainly oflimestone and dolomitic limestone. Both the Kuwait Group and Dammam Formation are locallydivided into an upper and lower aquifer unit, whose hydraulic relationship is a subject of thisinvestigation.

The study involves the drilling, construction, development, and testing of 3 groundwater wells inthe Seventh Ring Road Site,which is located within Sulaibiya groundwater field southern Kuwait City (Fig. 1). This paper documents the results of pumping and tracer tests performed at site T-10.

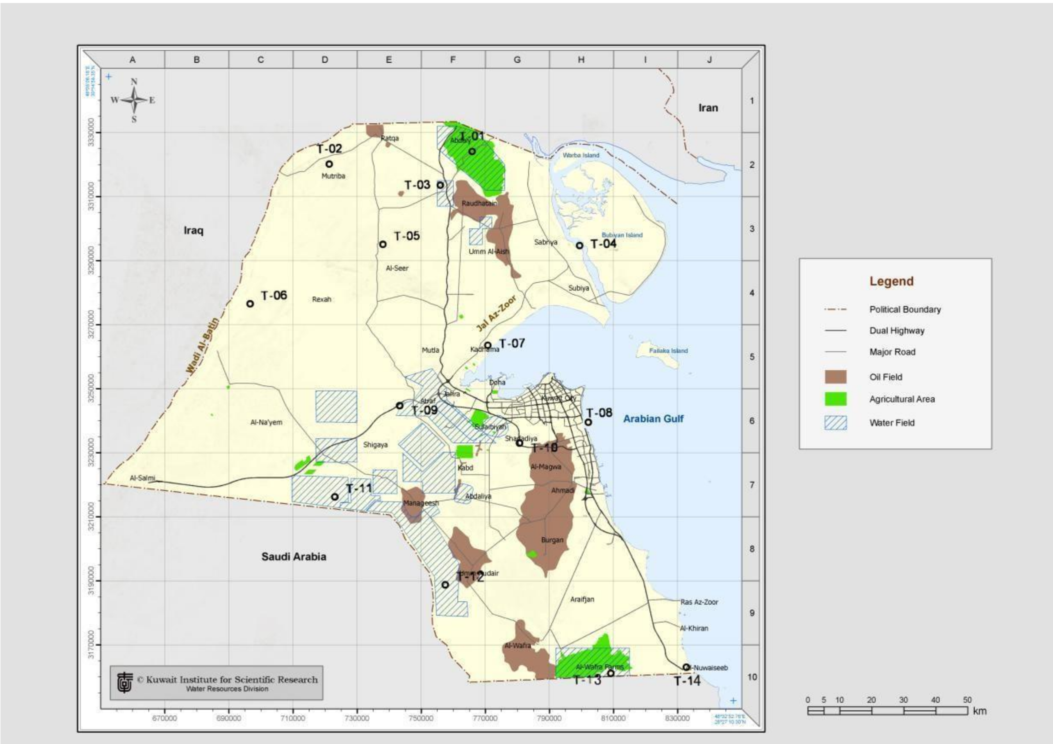

Figure 1. Location map of the study site (T-10).

2 METHODOLOGY

The testing at the study site included the followings:

- A conventional aquifer pumping test for Kuwait Group aquifer involving the pumping of one well at a constant rate and measuring the drawdown versus time in two observation wells completed in the aquifers zones.
- Upper Kuwait Group natural-gradient tracer-dilution test in which the rate of dilution of tracer in the injection well is used to determine the rate of groundwater flow.
- Kuwait Group inter-aquifer zone forced-gradient tracer test in which tracer was released (injected) in one well and monitored in another pumped well completed in the same aquifer. Fig.2 shows the location of the tested wells in the study site.
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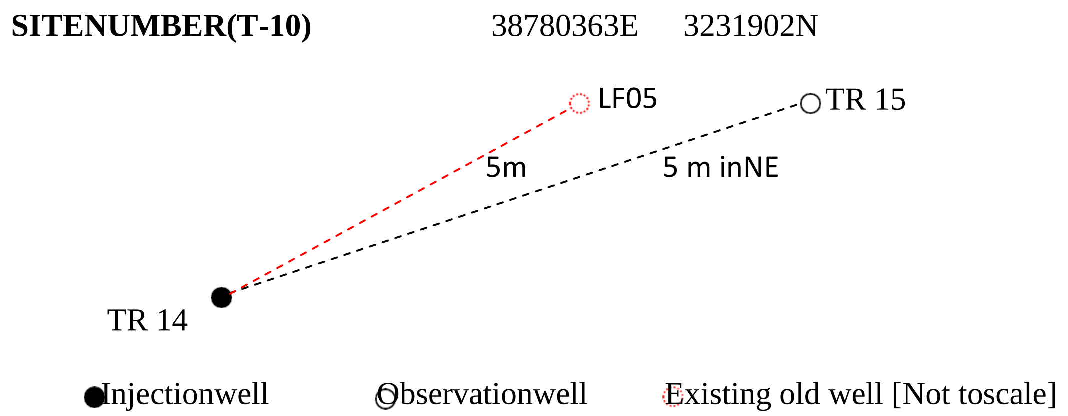

Figure 2. Site T-10 well location diagram.

The interpretation of aquifer pumping test data is ultimately based on the Theis (1935) non-equilibrium equation, which employs a curve-matching solution. The Theis (1935) method is based on the equations

$$u = \frac{r^2 S}{4Tt}$$

$$s = \frac{Q}{4\pi T} W(u)$$

where,

s = drawdown (m)
Q = pumping/discharge rate (m^3/d)
T = transmissivity (m^2/d)
u = empirically derived functions
r = distance from observation well (m)
t = time since pumping/discharge began (m)
S = storage coefficient
$W(u)$ = 'well function' or 'Theis well function'

A set of time drawdown data for an aquifer pumping test are plotted on a square logarithmic grid of the same grid size as a plot of W(u) versus 1/u. The graphs are shifted until the time drawdown data are superimposed on the Theis curve with the axes of the two graphs parallel (Fig. 2). A match point is selected, at which a set of values of s, t, W(u), and u are obtained. To simplify the calculations, a match point of W(u) = 1, and 1/u = 1 is commonly used, and the s and t values are recorded for that match. In practice, interpretation of pumping test data using the Theis method is now performed using software that facilitates the data plotting, curve matching, and calculations.

The following three modifications of the Theis non-equilibrium equation are used in the data analysis.

1. The Hantush-Walton method (Hantush and Jacob 1955; Walton 1960, 1962), provides a solution for leaky confined aquifers with no storage in the confining layers. Transmissivity and storativityare still obtained from the match to the Theis curve. The match of the late data to 'r/B' curves allows for the leakance (hydraulic conductivity divided by thickness) of the confining units to be calculated. The parameter 'B' is the leakage factor.
2. The Cooper and Jacob (1946) modification of the Theis non-equilibrium equation, also known as the 'straight-line' method, involves preparation of a semi-logarithmic plot of drawdown versus time with drawdown on the linear scale. Transmissivity and storativityare estimated from the slope of the line (Δs, change in drawdown over 1 log cycle).
3. The Cooper and Jacob (1946) recovery method is used to estimate transmissivity in a similar manner to the Cooper and Jacob method with the exception that residual drawdown (s') is plotted against equivalent time (t/t'), rather than drawdown versus time (Theis, 1935). Transmissivity is calculated.

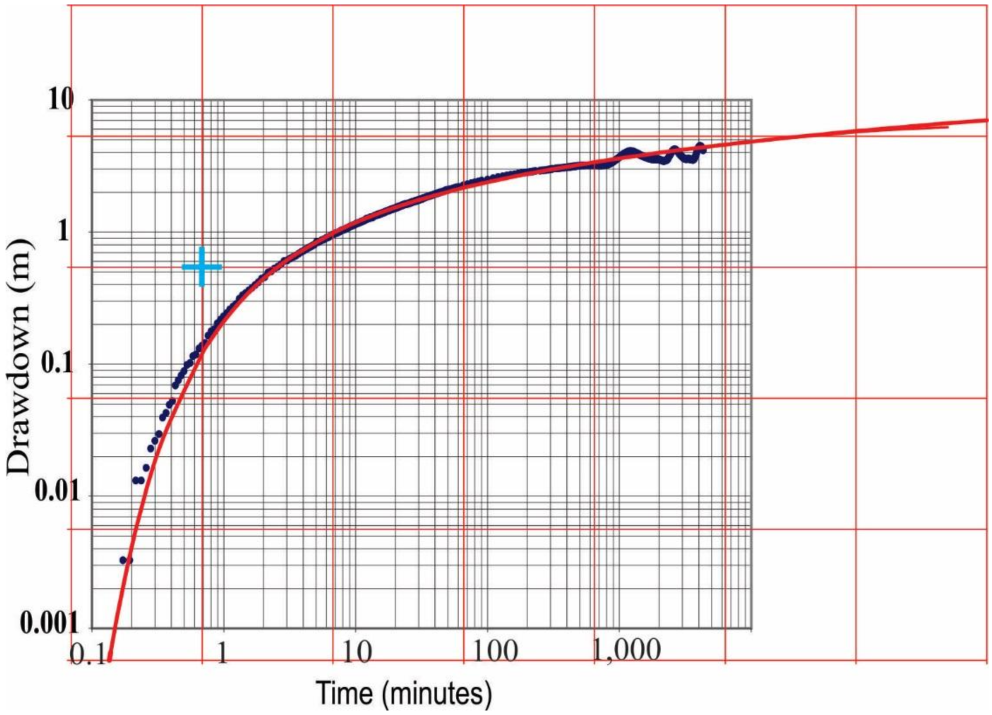

Figure 3. Example of the Theis curve-matching procedure.

3 RESULTS

A two, and, half, day pumping test was performed on the Kuwait Group Aquifer using well TR-15 as the pumping welland wells TR-14 and LF05 as observation wells (Fig. 2). The wells have different completion depthswith well TR-15 screened from 40 to 55 m, well TR-14, from 20 to 35 m, and well LF05witha total depth of 32.5 m. TR-15 was the pumping well and the pumping rate was 60 gpm for 2.55 days duration. The pumping tests' conditions arepresented in Table 1,and the results for the Upper KuwaitGroup pumping test are summarized in Table 2 and the tracer testing performed at the same Site T-10 is summarized in Table 3.

Table 1. Site T-10 Pumping Test Conditions

Well	Aquifer	Depths (m below land surface)	Maximum drawdown (m)
TR-14	Kuwait Group	20 to 35	1.99
TR-15	Kuwait Group	40 to 55	4.15
LF05	Kuwait Group	32.5	1.70

Table 2. Summary of Site T-10 Pumping Test Results

Well	Method	Transmissivity (m^2/d)	Storage coefficient	Leakance
TR-14	Hantush-Walton	57.3	5.4×10^{-3}	9.2×10^{-2}
TR-14	Cooper and Jacob	104	1.5×10^{-3}	-
TR-14	Cooper and Jacob recovery	67.3	-	-
LF-05	Hantush-Walton	78.1	1.04×10^{-2}	1.2×10^{-1}
LF-05	Cooper and Jacob	108.2	6.6×10^{-3}	-
LF-05	Cooper and Jacob recovery	58.7	-	-
TR-15	Hantush-Walton	49.5	-	-
TR-15	Cooper and Jacob	86.7	-	-
TR-15	Cooper and Jacob recovery	46.1	-	-

The average transmissivity value for the tested upper part of the Kuwait Group is 72.9 m^2/d.

Table 3. Site T-10 Tracer Test Summary

Test type	Aquifer	Injection well	Pumped well	Observation well	Tracer(s)	Start	End
Tracer dilution	UKG	TR-14	n/a	n/a	NaBr	18/2/16	27/3/16
Forced gradient	UKG	TR-15	TR-14	n/a	F	14/2/16	16/2/16

Tracers: F: Fluorescein (100 g); NaBr: Sodium bromide (500 g); Tracer injection: Instantaneous (slug)

Tracer-dilution testing was performed on well TR-14 using bromide as a tracer approximately 2 days after the termination of the pumping for the forced-gradient test. A regression line for the early data that encompasses a 2 log reduction in concentration (Fig.4) gives the following values:
Well radius 0.1 m (200 mm diameter)

Slope: $\ln C_t - \ln C_0 = -3.5$ over 50,000 minutes,apparent filtration velocity = 1.1×10^{-5} m/min,apparent filtration velocity = 0.016 m/d,corrected filtration velocity = 0.0079 m/d

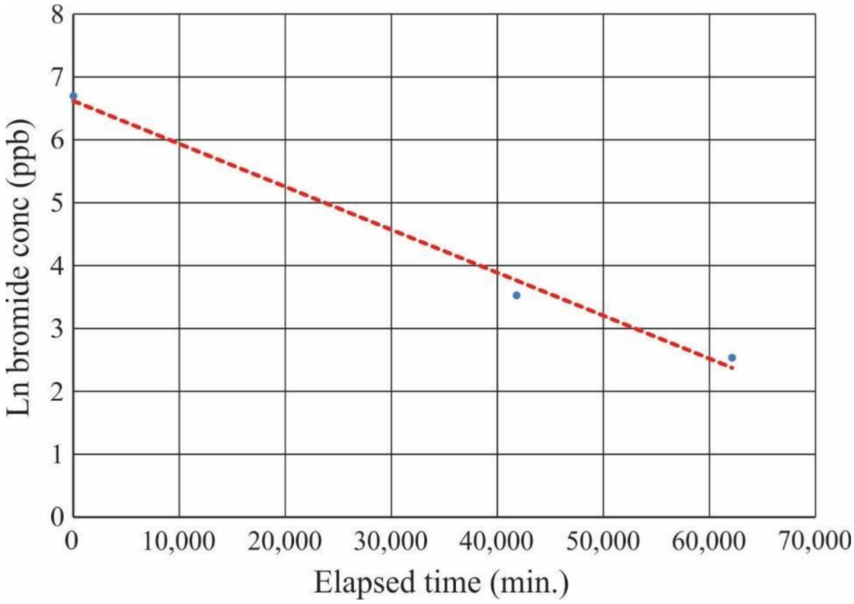

Figure 4. Well TR-14 bromide tracer-dilution plot.

Recent local hydraulic gradient data are not available for the SeventhRing Road site vicinity. Available potentiometric surface maps (compiled by Alsharhan et al. 2001) suggest that the gradient is approximately 0.002 towards the northeast. The estimated hydraulic conductivity using a gradient of 0.0002 is 4.0 m/d, which is close to the average hydraulic conductivity value of 5.1 m/d obtained from the well TR-14 pumping test data and 2.0 m/d obtained by dividing the average transmissivity of 72.9 m^2/d by the total thickness of the tested interval (36.6 m).

Fluorescein dye was injected in well TR-15 while well TR-14 was pumped at a rate of 60 gallons per minute gpm. The breakthrough curve has two peaks (Fig. 5), which indicates two separate flow paths that each transmitting a very roughly equal amount of flow. If one flow path had a much higher transmissivity than the other, then it would have transmitted most of the flow, and the second path would not be detectable as a distinct peak. Interpretation of the data is greatly complicated by the pumped and injection intervals having different depths.

Qualitatively, the forced-gradient test indicates a strong connection between the upper (20 – 35 m) and lower (40 – 55 m) zones of the Kuwait Group at the seventhRing Road site. The tracer travels the 5 m horizontal and 5 m vertical distance between the wells in 0.37 days (first arrival) with a time to the first tracer peak of 0.47 days. The tracer peak pattern could not be duplicated using a 3-layer MODFLOW and MTD3MS model, which gave very broad, slow arriving peaks using hydraulic parameter data indicated by the hydraulic testing.

The monitoring data from well LF-05 shows a slight peak in concentration to 2.75 ppb after 12 hours (approximately coinciding with the first tracer peak in TR-15), which is consistent with lateral dispersion of the tracer being drawn by pumping to well TR-15.

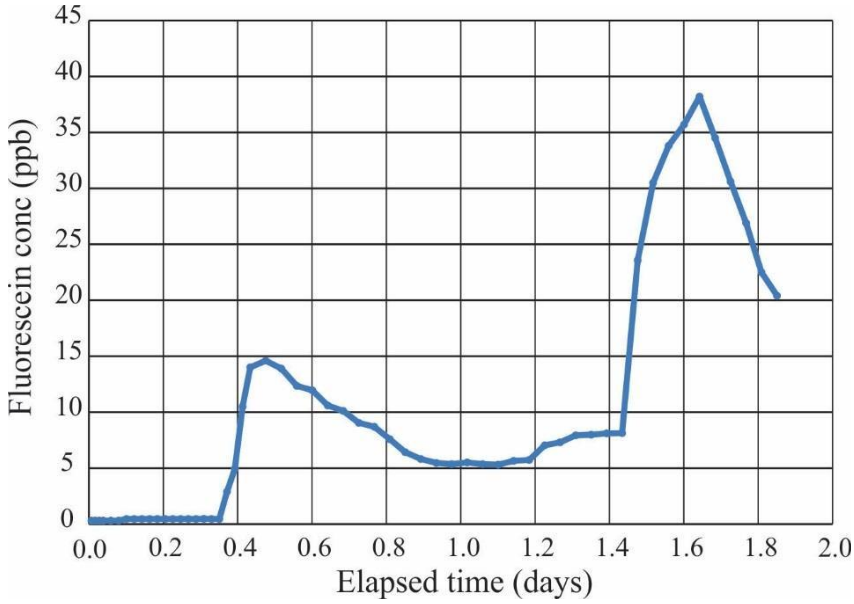

Figure 5. Well TR-15 breakthrough curve.

4 CONCLUSION

The pumping and tracer test indicated that theground flow in the Kuwait Group is matrix dominated as opposed to the secondary porositydominated flow of the Dammam Formation, as indicated by high porosity (> 0.10, 10%) valuesobtained from the analysis of the tracer test data. Theporosity values obtained from the Kuwait Group tests are consistent with the siliciclasticlithology.The tracer peak shape for the Upper Kuwait Group of a relatively abrupt increase in concentration to a sharppeak followed by a longer tail is indicative of a main high-porosity fast flow zone and subsidiary slower flow paths (less permeable intervals).

The upper (20 top 35 m) and lower (40 to 55 m) zones of the Upper Kuwait Group at the study site (Site T-10Seventh Ring Road) are hydraulically well connected.Hydraulic conductivity values estimated from tracer-dilution data tended to be in agreement withvalues estimated from pumping test data, especially considering the uncertainty in some keyparameters (e.g., local hydraulic gradient). It is recommended to establish a country-wide network of monitoring wells in which water level and water quality are sampled on regular basis.

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REFERENCES

Al-Ruwaih, F.M. 1994. Pattern of ground water chemistry, Kuwait Group aquifers. *Journal of Environmental Hydrology* **2**(1):24–35.

Al-Ruwaih, F.M. 1995. Geochemical model of Dammam Limestone Aquifer in Kuwait. Unpublished Report, Kuwait University, Kuwait.

Alsharhan, A.S., Rizk, Z.A., Nairn, A.E.M., Bakhit, D.W., and Alhajari, S.A. 2001H*ydrogeology of an arid region: The Arabian Gulf and adjoining areas*. Elsevier.

Al-Sulaimi, J. S., and S. M. El-Rabaa. 1994. Morphological and morphostructural features of Kuwait. *Geomorphology***11**:151-167.

Cooper, H. H., Jr. and C. E. Jacob. 1946 A generalized graphical method for evaluating formation constants and summarizing well-field history. *Transactions American Geophysical Union***27**: 526–534.

Hamdan, L., and A. Mukhopadhyay. 1991. Numerical simulation of subsurface water rise in Kuwait City. *Ground Water***29**(1):93-104.

Hantush, M. S. and C. E. Jacob. 1955. Non-steady radial flow in an infinite leaky aquifer. *American Geophysical Union Transactions***36**: 95–100.

MEW. 1998. *Statistical Year Book*: Water.Ministry of Electricity and Water, Kuwait.

MEW. 2015. *StatisticalYearBook*: Water. Ministry of Electricity and Water, Kuwait.

Mukhopadhyay, A., Al-Sulaimi, J., &Barrat, J.M. (1994) Numerical modeling of groundwater resource management options in Kuwait. *Ground Water,* **32**(2): 917-928.

Omar, S.A., A. Al-Yacoubi and Y. Senay. 1981. Geology and groundwater hydrology of the State of Kwuait. *Jounrnal of Gulf Arabian Peninsula Studies***1**:5-67.

Senay, Y., L. Hamdan, and A. Yacoubi. 1987. Study of the subsurface water rise in the residential areas of Kuwait, Vol. 3: Hydrogeology. Kuwait Institute for Scientific Research, Report No. KISR2227, Kuwait.

Walton, W. C. 1962. Selected analytical methods for well and aquifer evaluation. *Illinois State Water Survey Bulletin***25**: 81.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: *Transactions American Geophysical Union*, *16*, 519-524.