Deep Well Dewatering for the Greater Cairo Wastewater Project

Pumping test deep well results can be applied to design modeling, provided the test represents the actual system and is performed at comparable pumping rates.

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An extensive confined aquifer system up to 90 meters in saturated thickness lies beneath the greater Cairo, Egypt, area. This aquifer is recharged mainly by the Nile River.

Construction of the Greater Cairo Wastewater Project (GCWWP) presently underway has required deep excavations, frequently penetrating through the confining layer over the aquifer, which necessitates construction dewatering.

Most construction dewatering has been accomplished using deep well systems. Experience has demonstrated that a number of features of the Nile River aquifer system make the interpretation of pumping tests, as well as design and successful implementation of deep well systems, difficult.

Background

The GCWWP represents a multinational public health effort to rehabilitate and upgrade the wastewater system of Cairo. Project design began in 1979 by a consortium of American and British consultants for the Greater Cairo Wastewater Organization, an agency of the Egyptian government. The United States Agency for International Development is funding a significant portion of the project. The project consists of designing and constructing a comprehensive sewerage system that would handle the projected demands of a rapidly increasing population into the 21st century. Currently, the population of Cairo is over 12 million. It is projected to increase to 16 million by the year 2000.

The urbanized portions of the greater Cairo area are divided by the Nile River, which runs in a northerly direction through an otherwise arid region (see Figure 1). The Nile has appropriately been termed the "lifeblood" of Egypt. Population is heavily concentrated on the fertile, cultivated strip along both banks of the Nile. Independent wastewater systems are being constructed on both sides of the Nile to convey wastewater away from the greater Cairo urban areas and toward the deserts that border the fertile alluvial flood plain.

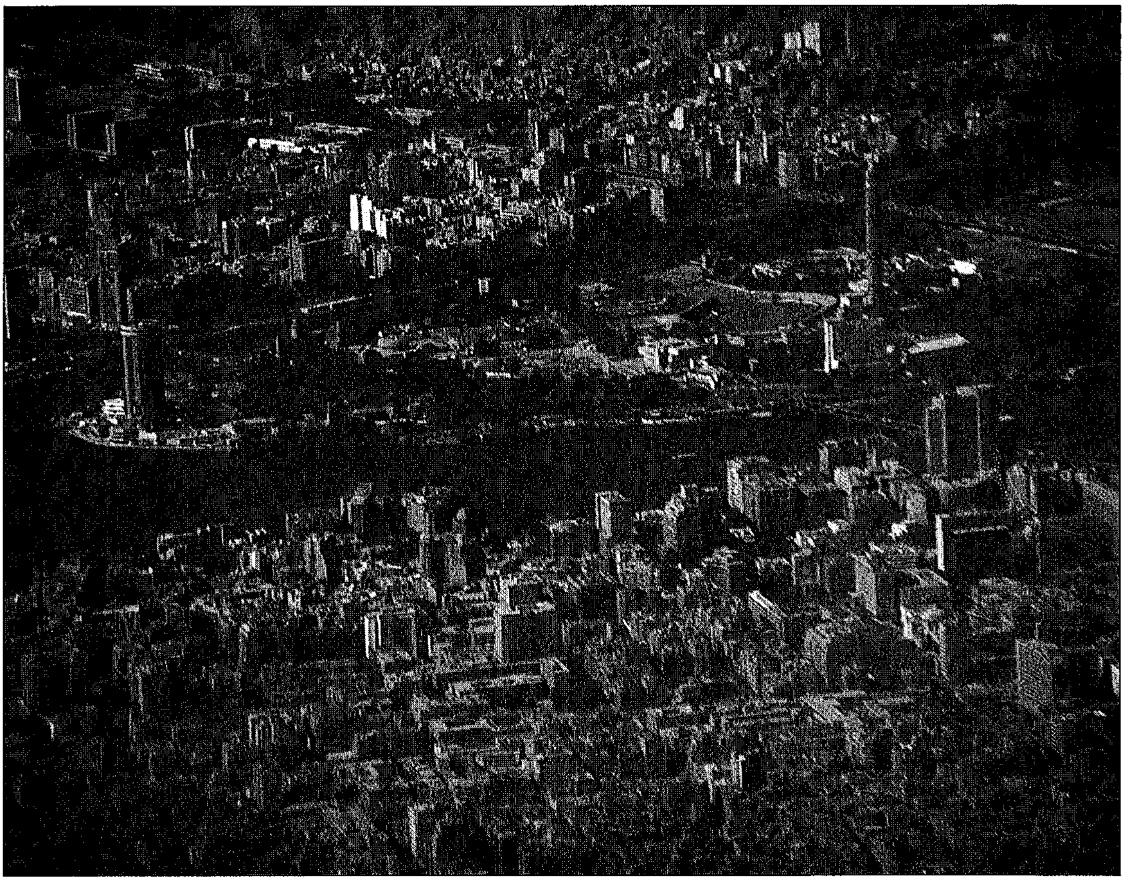

FIGURE 1. Urbanized portion of Cairo along the Nile River.

The GCWWP has required deep, open excavations into alluvial flood plain soils, in some cases up to 12 meters, for the construction of treatment plant facilities, pumping stations, force mains, sewers and collectors. These excavations have extended into the surficial silty clay confining stratum, sometimes requiring penetration into the underlying major sand aquifer.

Since the aquifer is recharged mainly by the Nile, extensive construction dewatering has been necessary. This dewatering is being accomplished most frequently using deep well systems.

During site investigation studies, and as a part of the construction activities, numerous groundwater pumping tests have been conducted on partially penetrating deep wells in order to characterize the hydrogeologic properties of the aquifer and to aid in estimating construction dewatering requirements.

General Aquifer Conditions

Cairo is located on thick alluvial deposits, reported to be up to 500 meters or more in thickness. The alluvial deposits are bounded on the east by limestone cliffs and on the west by the Pyramids Plateau (see Figure 2). The Pyramids Plateau is composed of various sedimentary formations including sandstones, limestones and mudstones, as well as sands and gravels (dune deposits).[1]

A typical soil profile of the project area is shown in Figure 3. The silty clay confining stratum is typically six to ten meters thick, becoming thinner as it moves away from the Nile. This silty clay deposit is fissured and contains occasional layers and seams of sand and silt.

A transition layer, made up of interbedded sand, silt, and clay units and lenses, is generally present between the silty clay stratum and the underlying sand aquifer. The thickness of this

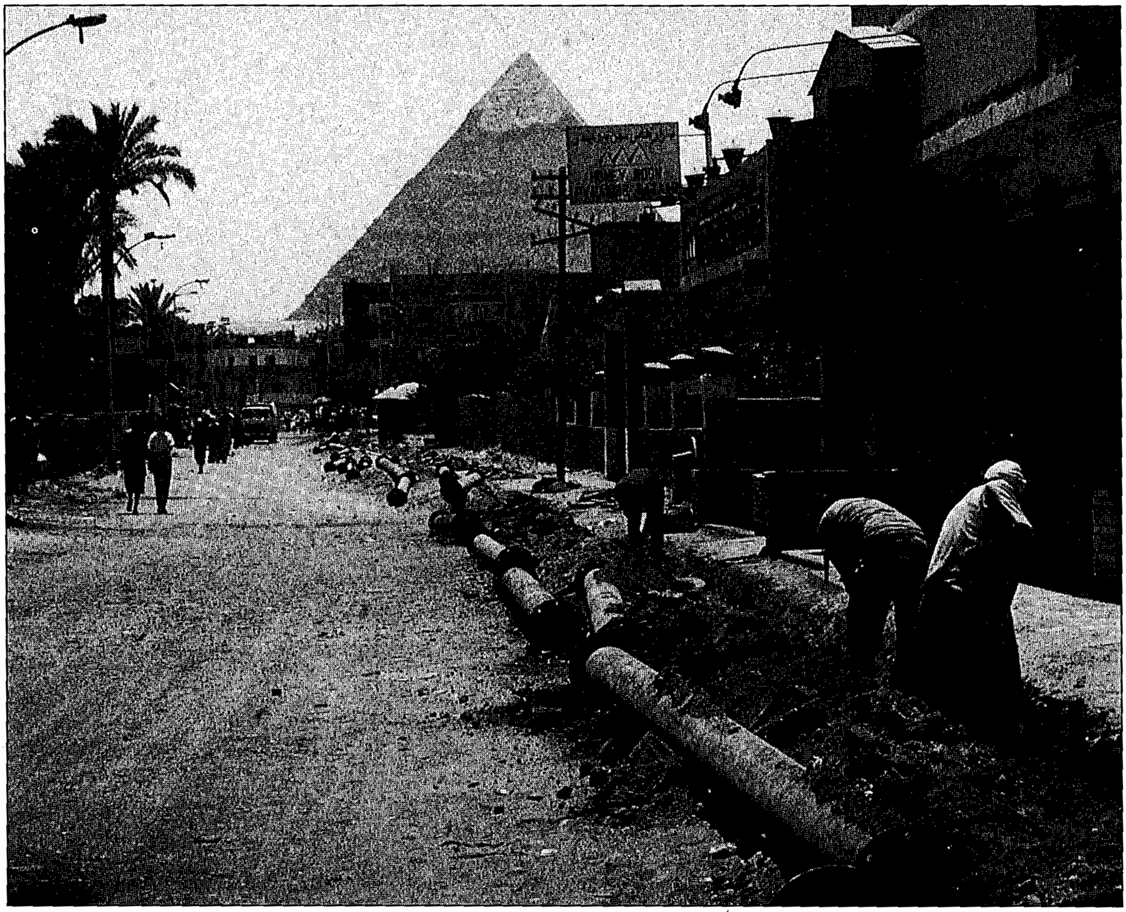

FIGURE 2. The West Bank area of greater Cairo is located in close proximity to the Pyramids Plateau.

transition layer typically varies from zero to about five meters.

The aquifer comprises a medium to fine sand and generally grades coarser with depth to a coarse to medium sand. Gravel, cobbles and discontinuous layers and lenses of silt and clay occasionally occur throughout the aquifer. The aquifer thickness reportedly ranges from 30 to 90 meters in the greater Cairo area and up to 70 meters in the West Bank project area.[1] In a study of Cairo's subsurface geology, Said states that an unconformable continuous layer of plastic clay underlies the sand aquifer.[1] This impermeable lower boundary has been encountered in only a few borings in the West Bank project area, mostly drilled by others before the initiation of the GCWWP. Its presence has also been confirmed in one deep well installation in the village of Nahya for the project, where it was encountered at a depth of approximately 50 meters.

The Cairo aquifer has been described as

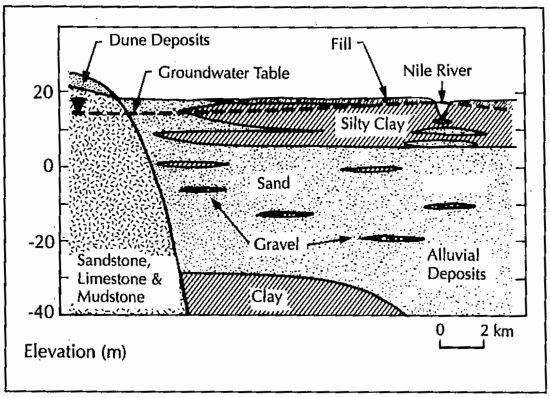

FIGURE 3. Typical soil profile for the West Bank of the Nile River.

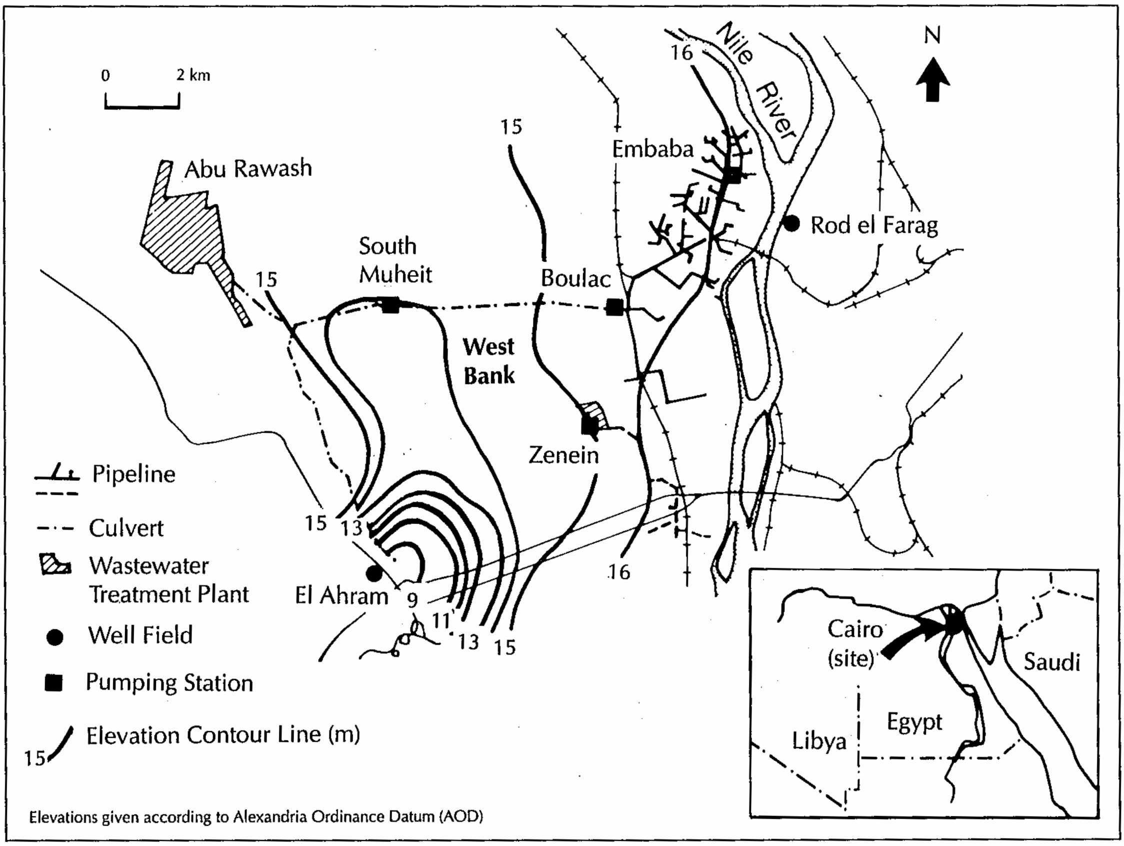

FIGURE 4. Piezometric level contour plan.

"semi-confined" or "leaky."[2] The aquifer piezometric levels are within the confining silty clay stratum, typically to within 2.5 to 3.5 meters of the ground surface. Cracks and fissures within the silty clay, as well as interbedded granular soils, allow some interconnection within the stratum.

A piezometric level contour plan of the area in 1984 (before GCWWP construction) is shown in Figure 4. The piezometric surface is influenced mainly by the Nile and by water supply and irrigation extraction. The piezometric surface slopes away from the Nile, which recharges the aquifer. Nile levels are constant throughout the year except for the month of January, when levels are dropped to permit dredging of the irrigation canal system. Piezometric levels drop during this period.

Also, pumping from various well systems affects the piezometric levels. One major influence on West Bank piezometric levels is the El Ahram well field that pumps continuously, depressing the water table at least seven meters with a radius of influence in excess of four kilometers.

Over 200 soil borings have been drilled in the West Bank project area during the GCWWP. The majority of the borings have been less than 25 meters in depth, and have penetrated only the upper portion of the aquifer. Grain size (D_{10}) analyses performed on soil samples obtained from these borings indicate that the aquifer sand grades coarser with depth (see Figure 5) and the silt content is greater near the top of the aquifer. Deeper borings indicate that gravelly sand is present in isolated lenses, typically in the lower portion of the aquifer, and therefore, the hydraulic conductivity of the aquifer generally increases with depth.

Because of the horizontal bedded nature of the alluvial deposits, the horizontal hydraulic conductivity, K_h, of the aquifer is greater than the vertical hydraulic conductivity K_v. Rahman reported that the average value of isotropy,

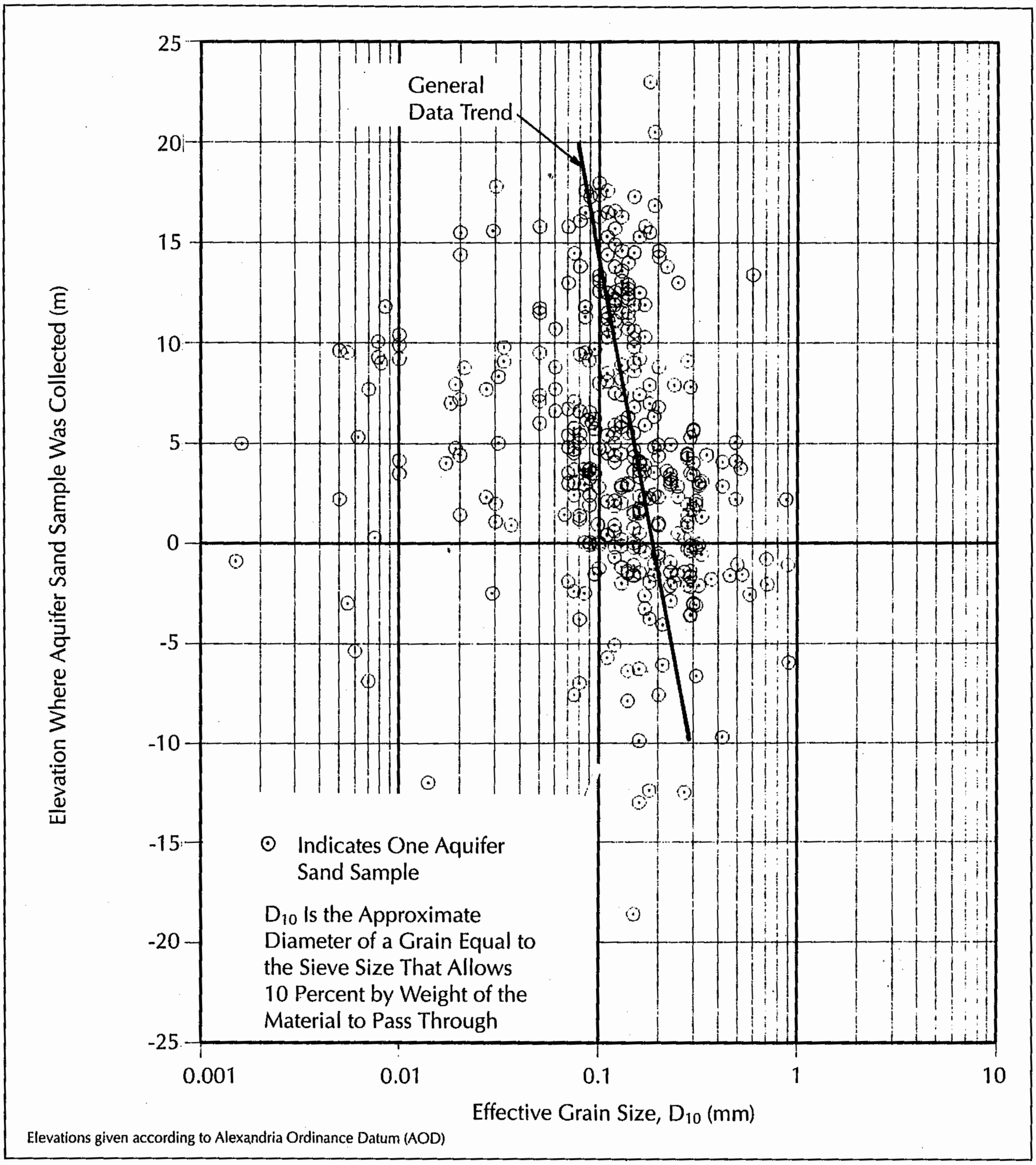

FIGURE 5. Effective grain size, D_{10}, versus elevation.

K_v/K_h, is between 0.1 and 1 for the aquifer in the West Bank area.[3] It is probably considerably larger where interbedding is more prevalent, based on the range of grain sizes that were observed there.

Deep Well Design Considerations

Most excavations required for the GCWWP are within the confining silty clay stratum. Excavation depths up to 12 meters have been required and have extended to nine meters below the preconstruction groundwater table, sometimes penetrating to the top of the sand aquifer. Generally, it has been necessary to lower and maintain groundwater levels at least one meter below the proposed invert prior to excavation, because of the leaky nature of the fissured silty clay confining stratum.

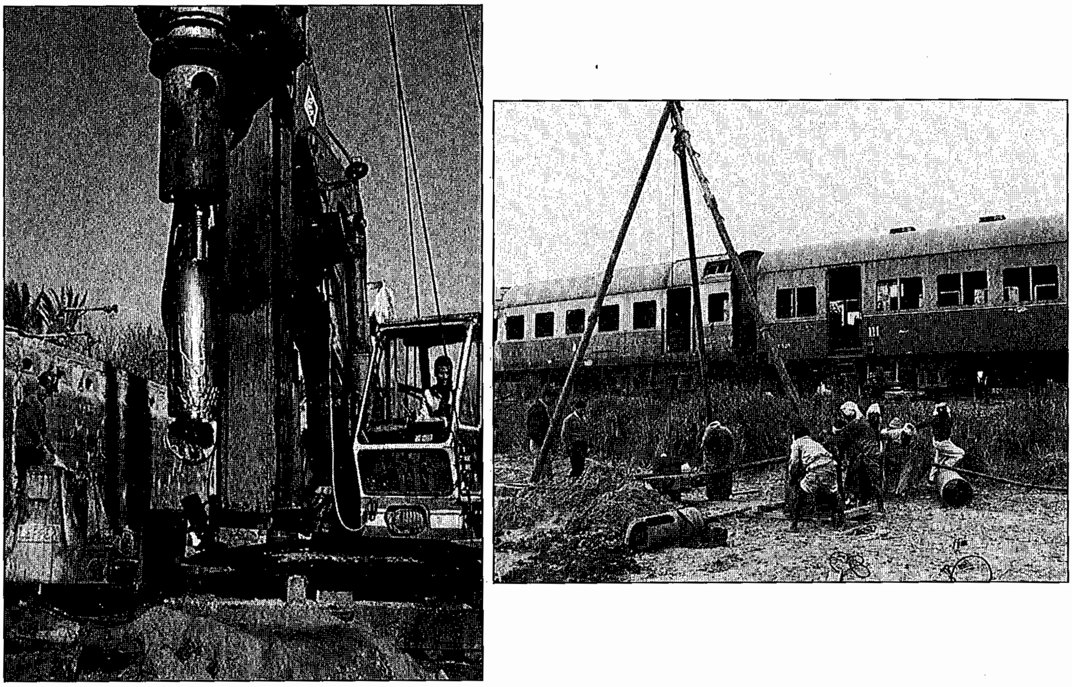

FIGURE 6. Typical well drilling methods used for construction dewatering deep well installation.

Typically, the most effective method of dewatering the Nile aquifer soil has been with deep wells. Fully penetrating wells are generally not economical because they would need to be 50 to 70 meters or more deep, which is beyond the capabilities of most of the locally available drilling equipment (see Figure 6). Partially penetrating deep wells installed with submersible pumps, therefore, have been the main system employed for dewatering the deeper excavations for the project.

Designing a partially penetrating deep well requires experience and substantial information on the hydrogeologic properties of an aquifer. Pumping test data are essential to design adequate dewatering systems. Pumping tests for construction dewatering design should resemble the probable final systems as much as possible in order to provide representative data.

Screen lengths and depths are critical factors in partially penetrating deep well design, especially in the Nile aquifer system where permeability increases with depth. The screens must be installed deep enough to provide sufficient submerged screen length to accommodate the pumping rates required in order to achieve the necessary drawdowns. However, there is a trade-off since installation costs increase substantially with deeper wells, which require more expensive drilling methods and greater material cost. Also, deeper wells produce larger volumes of water because the screens penetrate the higher permeability soils deeper in the aquifer.

Several pumping tests were designed and conducted for the GCWWP using partially penetrating deep wells that were believed to be representative of what would be required for actual construction dewatering for excavations. Results of one pumping test for a partially penetrating deep well are discussed below.

Groundwater Pumping Test Results

One partially penetrating deep well and seven piezometers were installed in 1984 at the Embaba site, as shown in Figure 7. The well, in-

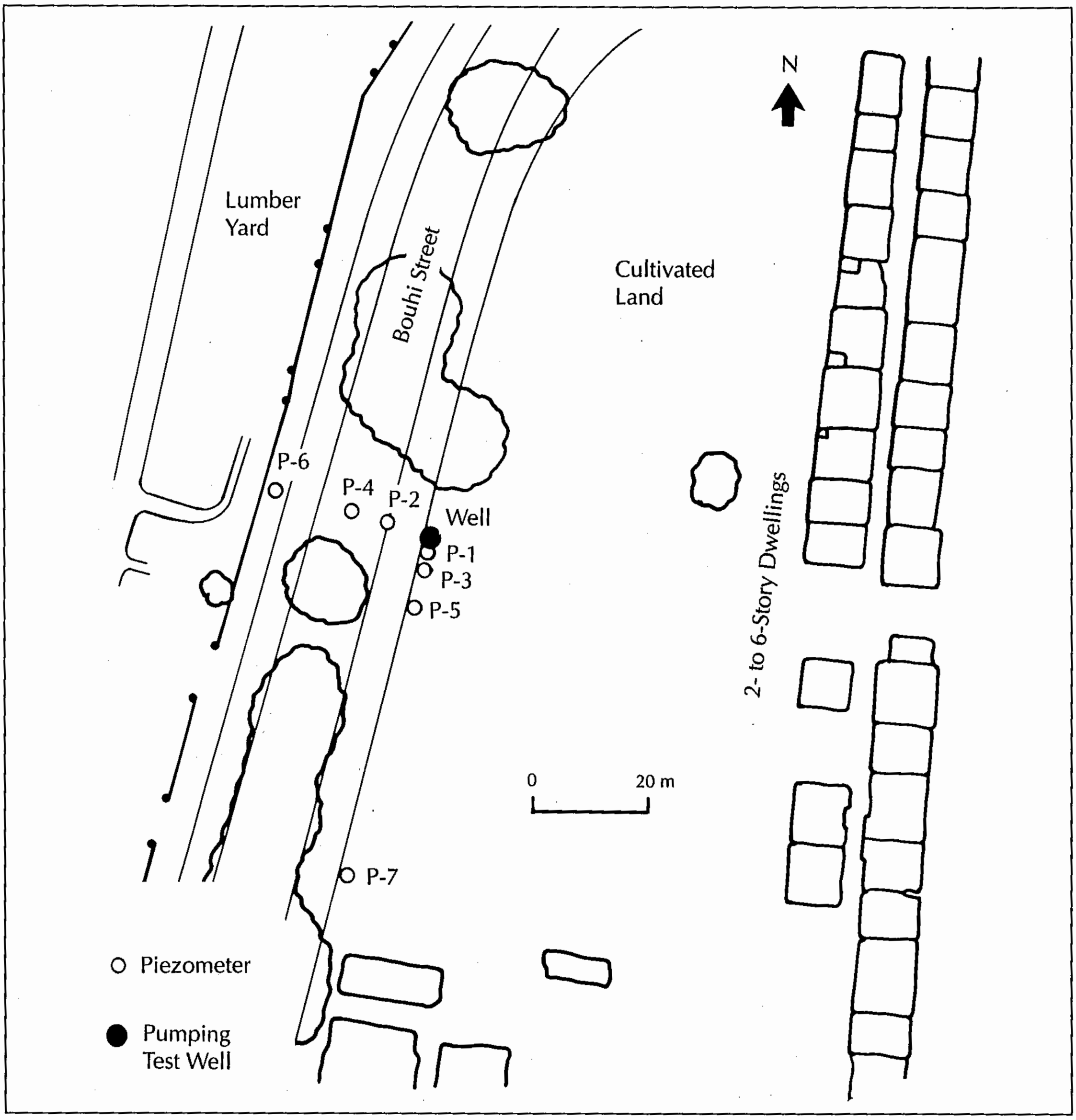

FIGURE 7. Embaba site pumping test set-up.

stalled to a depth of 24 meters, partially penetrated the aquifer, which was estimated to be about 60 meters thick at the site.[1] Installation was accomplished with a rotary drill using a flight auger in clay and a bucket auger in sands while maintaining a positive head of water in the hole. Holes were cased to a depth of about three meters.

The well consisted of a screen 12 meters long and 0.45 meters in diameter, and of a 12-meter blank riser section above the screen.

Six piezometers were installed to depths of about 14.5 meters. Another piezometer was installed to a depth of 17.9 meters. Although not shown in Figure 7, one other piezometer was installed within the 72-millimeter thick annular filter pack of the well, with a tip level just above the top of the well screen. The filter pack of the well was typically a quartz sand, uniformly graded from 0.5 to two millimeters.

A step-drawdown test was conducted at an initial pumping rate of 49 cubic meters per hour (m^3/h) for one hour, followed by recovery for one hour. The sequence was repeated at two

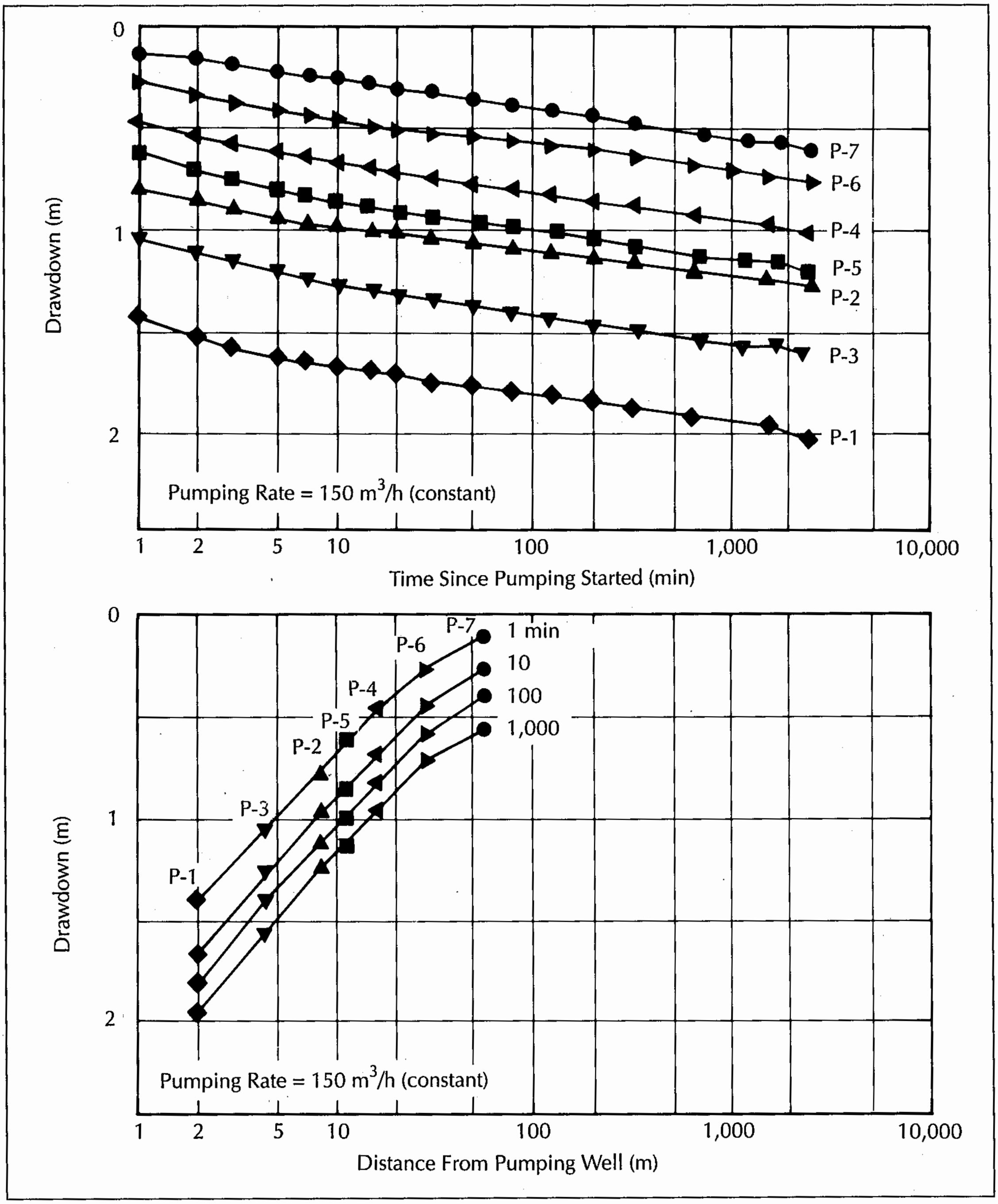

FIGURE 8. Pumping test results from the Embaba site.

additional pumping rates of 113 m^3/h and 145 m^3/h. After completing the step-drawdown test, a long-term test was conducted — the well was pumped at 150 m^3/h for 33 hours, followed by a period of recovery.

During the long-term test, the drawdown in the well ranged from 5.5 to 6.5 meters. The drawdown in the piezometer within the well filter was four to five meters. Drawdown in the piezometers at the end of the pumping period ranged from a minimum of 0.6 meters to a maximum of two meters.

The results of the Embaba pumping test are typical of pumping tests conducted in other areas of the West Bank within the Nile aquifer system. Graphical results of the long-term pumping test are shown in Figure 8.

Simplified Jacob analysis for transient conditions was used to estimate aquifer transmissivity. Such an approach is recommended by Powers[4] and was found to be a reasonable and practical method that was suited for the purpose of assessing construction dewatering requirements. Based on the slope of the drawdown versus log distance plot, a transmissivity on the order of 50 square meters per hour (m^2/h) is suggested. This value is not representative of the aquifer because, for a partially penetrating well, the plot is distorted close to the well due to upward flow. Comparison with actual dewatering system results show this value to be low. The distortion is typically present within a distance equal to about one aquifer thickness away from the well. Since the farthest piezometer was only 55 meters from the pumping well, the curve lies within the area where partial penetration affects drawdown. To interpret such a plot, a correction for partial penetration must be made, or drawdown data must be obtained further from the well. Procedures for correcting the distorted curve based on estimates of isotropy, K_v/K_h, are available as proposed by Jacob[5] and Butler,[6] among others. Results of the drawdown versus log time plot show that the actual transmissivity of the aquifer is about 200 m^2/h. This value agrees well with actual dewatering system results.

Deep Well System Details

From July 1986 through about August 1987, deep well dewatering systems were installed around excavations and operated continuously to permit the construction of four pumping stations on the West Bank portion of the GCWWP.

The general layout for the deep well system used at the Embaba site is shown in Figure 9. Stratigraphic conditions at the site include a silty clay to silt confining stratum that is approximately seven meters thick. Below seven meters, a fine to medium sand aquifer unit was encountered. The aquifer is estimated to be 60 meters thick at the site. The original static groundwater level is about two meters below the ground surface.

The excavation for the pumping station structure was an open cut with sides sloping to almost ten meters below existing groundwater. Fifteen deep wells, each about 27 meters deep, were installed for dewatering this excavation. Eight of these wells were operating during initial dewatering. Piezometers were installed within and around the excavations to monitor the performance of the deep well dewatering system. To estimate flow rate, discharge from the well was routed through a V-notch weir box before emptying into an irrigation drain.

Details on the dewatering systems installed at three other sites in the GCWWP are summarized on Table 1, along with data from the Embaba site. The locations of the sites are shown on Figure 4. Generally, the pumping station excavation geometry was as shown in Figure 9 at all sites except for Zenein, where sheet piles were used around the deepest portion of excavation. A typical dewatered pumping station excavation is shown in Figure 10.

Deep Well System Performance

During 1986 and 1987, the performance of the deep well dewatering systems for the excavations at the four sewage pumping stations (as shown in Figure 4) was monitored. All sites were successfully dewatered, although multiple attempts were required at several sites as a result of the inadequacy of the initially installed systems.

Problems resulted from initial underestimation of flow quantities, not installing well screens deep enough and/or lack of proper well development. Estimated peak flows for the final successful dewatering systems and actual aquifer parameters based on dewatering results are shown in Table 2.

Of particular interest in comparing pumping test results to dewatering system results are the drawdown versus log distance curves obtained for each deep well system. A plot of drawdown versus distance from the centroid of pumping is shown in Figure 11 for each of the four sites. A bend (distortion) in all of the curves is noted at a distance of approximately 50 to 100 meters from the centroid of pumping, corre-

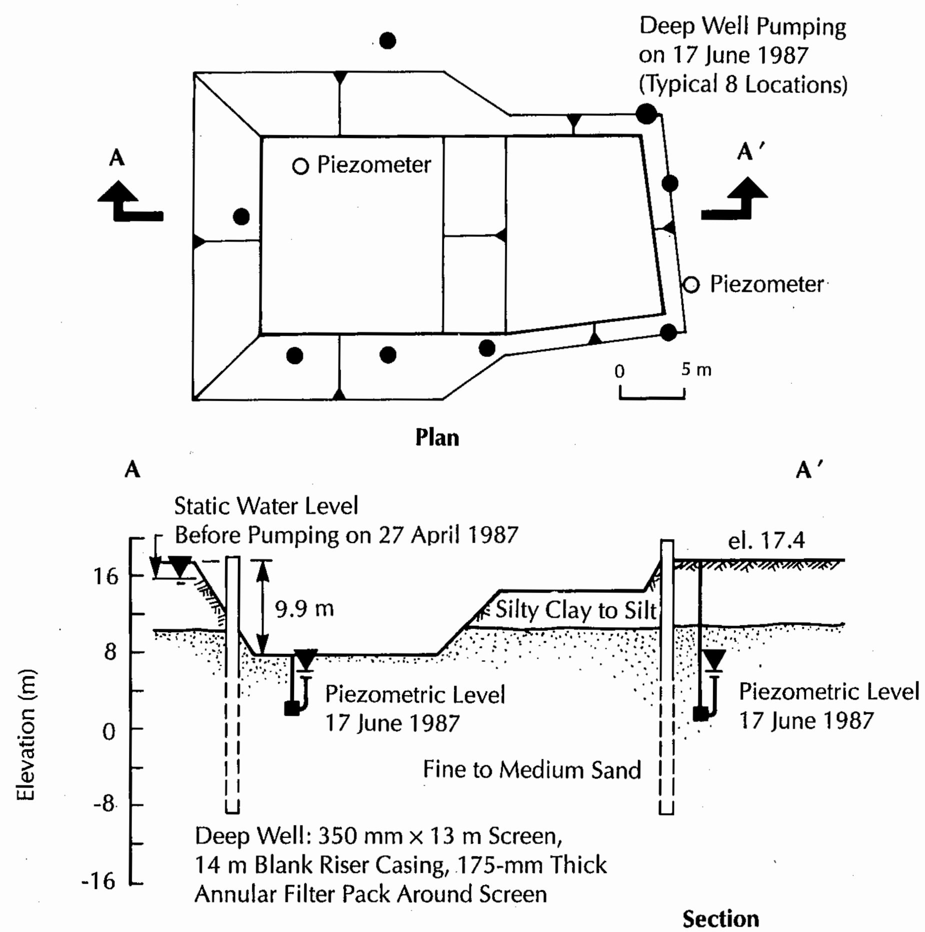

FIGURE 9. The deep well system layout for the Embaba site.

TABLE 1
Deep Well Dewatering System Details

	Boulac	Embaba	South Muheit	Zenein
Ground Surface Elevation, m	17.5	17.4	16.4	18.0
Subgrade Elevation, m	5.7	7.5	4.9	6.3
Excavation Depth, m	11.8	9.9	11.7	11.7
Elevation Top of Aquifer, m	5.7	10.0	6.0	5.0
Estimated Aquifer Thickness, m	40	60	50	70
Initial Groundwater Elevation, m	14.5	15.5	13.0	14.5
Number of Deep Wells Installed	23	15	31	10
Depth of Wells, m	27	27	19-29	25-29
Deep Well Screen Length, m	15	13	7-13	8-11
Deep Well Boring Diameter, m	1.0	0.7	0.7-1.0	0.4
Deep Well Casing Diameter, m	0.35	0.35	0.35	0.3

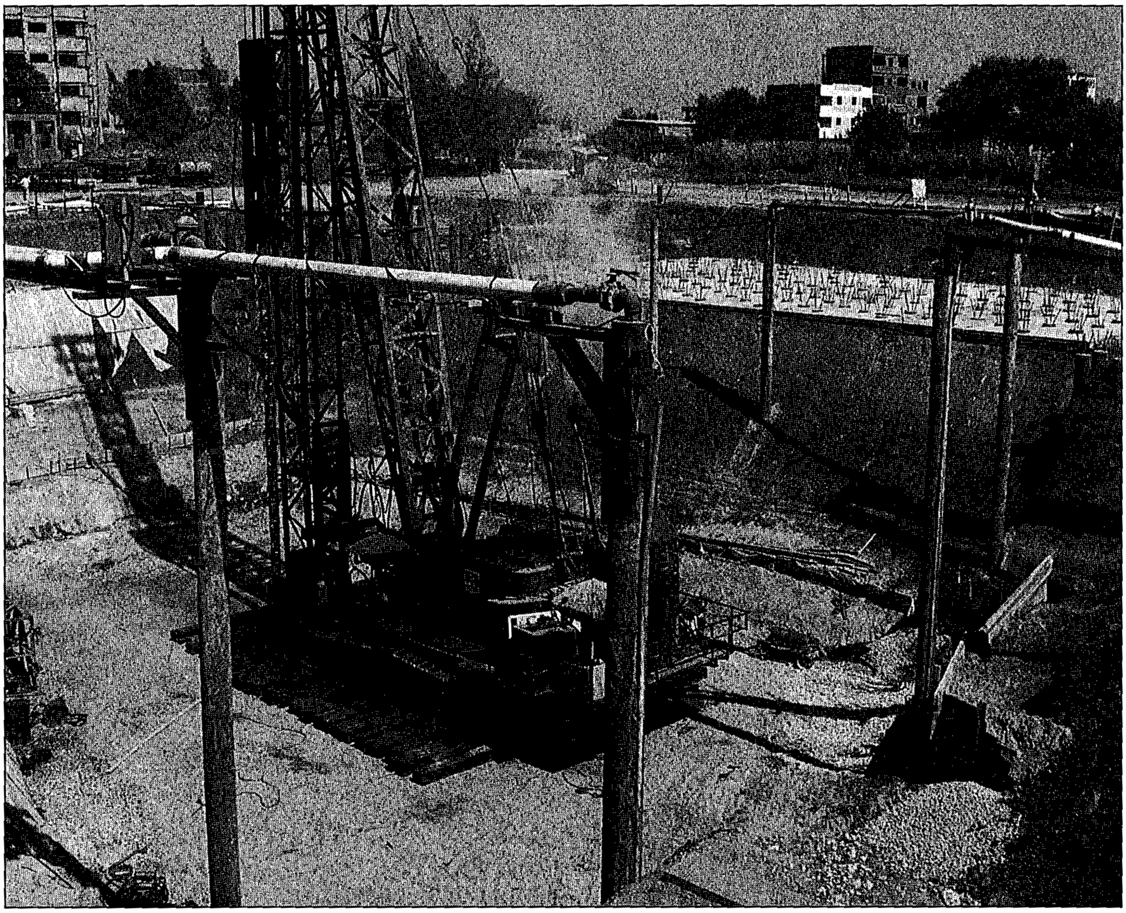

FIGURE 10. Dewatered excavation for a West Bank Pumping Station (the Boulac site).

TABLE 2
Deep Well Dewatering System Results

	Boulac	Embaba	South Muheit	Zenein
Number of Deep Wells Operating at Peak Discharge	13	8	23	10
Estimated Peak Discharge, m^3/h	960	1,150	2,530	1,930*
Estimated Aquifer Thickness, m	40	60	50	70
Approximate Drawdown at Centroid of Pumping System, m	8.9	9.7	10.8	9.3
Estimated Radius of Influence of Dewatering System, m	2,500	1,500	2,500-5,000	3,000
Pumping Duration, days	70	90	130	285
Calculated Aquifer Transmissivity, m^2/h	140	160	390	570
Hydraulic Conductivity, m/sec	1×10^{-3}	7×10^{-4}	2×10^{-3}	2×10^{-3}

* Includes 160 m^3/h from wellpoints.

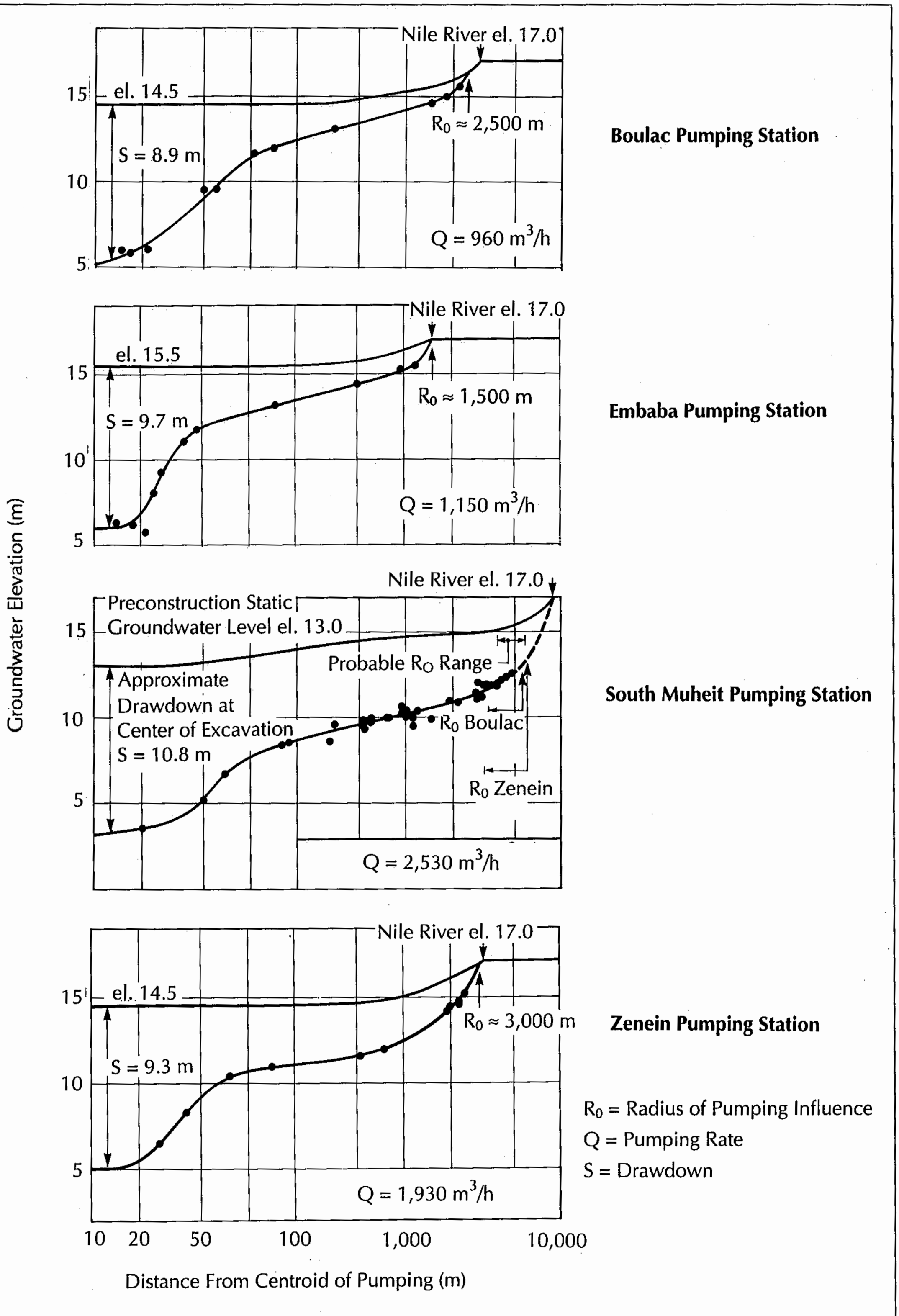

FIGURE 11. Deep well system drawdown versus log distance for each site.

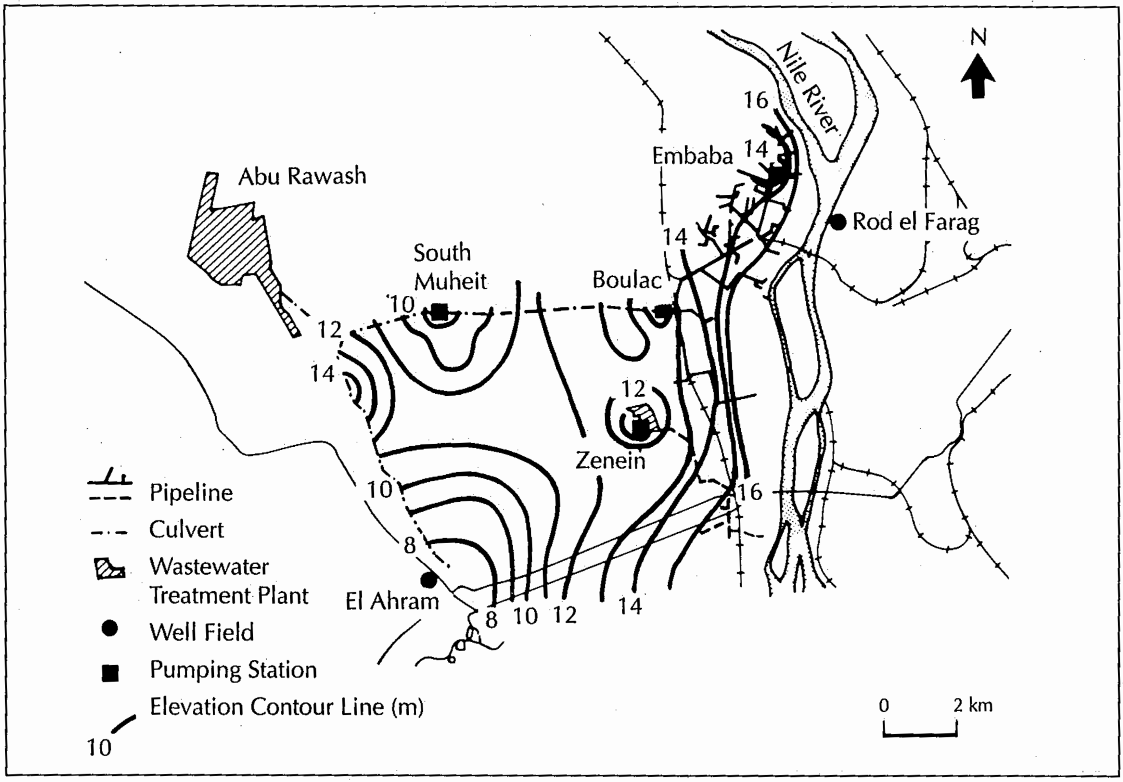

FIGURE 12. Piezometric level contour map during construction dewatering in July 1987.

sponding to a distance of about one to two aquifer thicknesses. Beyond this point, partial penetration effects are negligible since flow is predominantly radial in direction. Simplified Jacob analysis of the drawdown versus log distance data agrees well with the analysis of the drawdown versus log time data.

Another significant feature of the drawdown curves is the large radii of pumping influence, R_0. Estimated R_0 values for the sites range between 1,500 meters and approximately 5,000 meters. Figure 12 shows a piezometric level contour map based on measurements obtained during July 1987, when dewatering was in progress at all sites. When compared to the preconstruction piezometric level contour plan, Figure 4, this figure demonstrates the profound influence that dewatering pumping had on piezometric levels in the entire West Bank area. The cones of depression overlapped. Peak discharge rates were estimated to range from 960 to 2,530 m^3/h. These flow rates are comparable to pumping rates for the public well fields at El Ahram, also shown in Figure 12.

Results

Values of transmissivity have been recalculated for dewatering systems at the four sites, based on modeling the group of wells as a single well with an equivalent radius. The slope of the drawdown versus log distance curve at a distance greater than 100 meters has been used to avoid the influence of partial penetration. Calculated transmissivity values range from about 140 to 570 m^2/h. The value calculated for the Embaba site, 160 m^2/h, closely agrees with the value calculated from the time-drawdown pumping test data at the same location.

More sophisticated groundwater models are available for calculating transmissivity in partially penetrating confined aquifers. Methods have been proposed by Jacob,[7] Sternberg as reported by Bouwer,[8] and Streltsova.[9] These methods require a reasonably close estimate of aquifer thickness and the degree of anisotropy of the aquifer. Application of these models has been performed by Rahman[3] and is beyond the scope of this study.

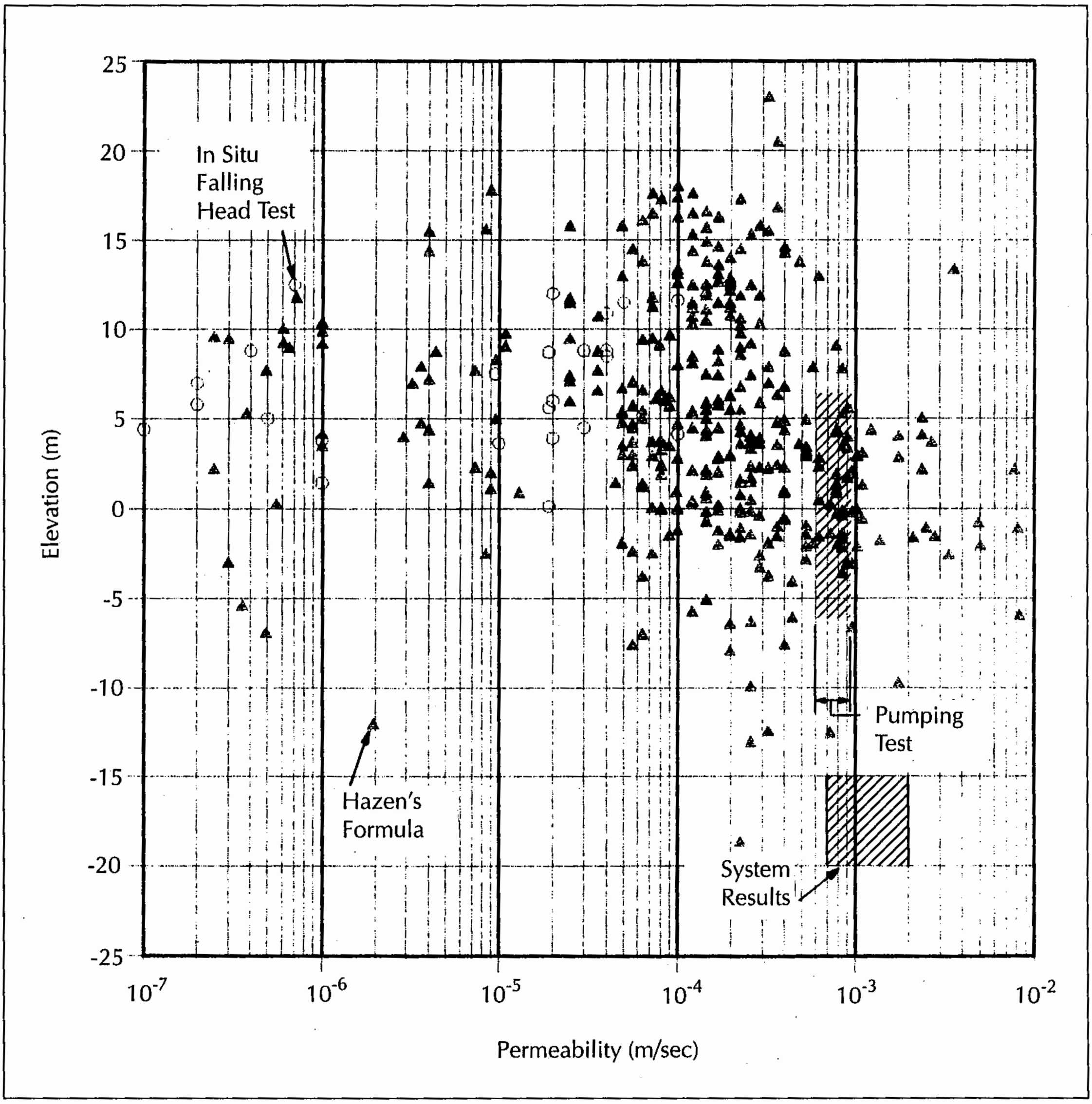

FIGURE 13. Summary of permeability data.

The point at which the drawdown-distance curve bends (distorts) because of partial penetration can also be used in order to estimate the anisotropy in permeability of the aquifer. The study by Rahman indicates values of K_v/K_h on the order of 0.1 to 1.0 for the aquifer.[3] Based on the vast amount of grain size data from the GCWWP reviewed, it is believed that, although the upper portions of the aquifer probably have a higher ratio of anisotropy and are less permeable, the aquifer becomes more permeable and less anisotropic with depth.

Figure 13 presents estimated soil permeability ranges based on various methods of determination. A large scatter in data is apparent with estimates from in situ falling head tests significantly underpredicting permeability compared to actual system results by up to several orders of magnitude. Estimates from grain size correlations can also be misleading, especially due to the lack of data from lower in the aquifer where deep well screens are typically located. Unless there is an understanding of the hydrogeology of the Cairo aquifer, the use of such data can lead to large errors in predicting dewatering system requirements, due to the anisotropy and the increasing permeability with depth. For the Nile aquifer system, a properly performed pump test is the most appropriate method for estimating dewatering requirements.

Conclusions

Design of a partially penetrating deep well dewatering system in the Cairo West Bank area requires an understanding of the unique features of the Nile River aquifer system and the consequences of partial penetration of wells. A properly designed and performed pumping test program is recommended for estimating dewatering requirements.

The pumping test should be representative of the actual dewatering system anticipated at a particular site. It is further recommended that some of the monitoring piezometers be installed at a distance of at least 200 meters (two aquifer thicknesses) away from the pumping well to provide drawdown data at a distance where predominantly radial flow is expected. The data and drawdown data from piezometers can be used to construct the complete distance-drawdown curve, providing a realistic estimate of aquifer transmissivity. If piezometers cannot be installed at this distance, then time versus drawdown data should be used to predict transmissivity.

If the pumping test deep well is representative of an actual system component and is performed at comparable pumping rates, then the pumping test results can be used directly to "calibrate" an analytical model used for design. A complete distance-drawdown curve from a reliable aquifer pumping test can be used to predict the number of deep wells required to dewater a particular site, based on cumulative drawdown. Depending on the experience of the designer, this approach may be more appropriate than attempting to apply one of the available design models for partially penetrating deep well dewatering systems.

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REFERENCES

1. Said, R., "Subsurface Geology of Cairo Area," *Memoires de L'Institute d'Egypte Tome Soixante*, 1975.

2. Research Institute for Groundwater, "Groundwater Studies for Greater Cairo," Ministry of Irrigation, Water Research Center, Final Report, Phase 1, 1982.

3. Rahman, A., "The Hydrologic Analysis of Partially Penetrating Deep Wells in Anisotropic Confined Aquifers," M.S. thesis, Cairo University, 1989.

4. Powers, J.P., *Construction Dewatering: A Guide to Theory and Practice*, J. Wiley & Sons, 1981.

5. Jacob, C.E., *Flow of Ground-water in Engineering Hydraulics*, Wiley, N.Y., 1950.

6. Butler, S.S., *Engineering Hydrology*, Prentice-Hall, Englewood Cliffs, N.J., 1957.

7. Jacob, C.E., "Radial Flow in a Leaky Artesian Aquifer," *Transactions, American Geophysical Union*, 27 (2), 1946, pp.198-205.

8. Bouwer, H., *Ground-water Hydrology*, McGraw-Hill, 1974, pp.79-82.

9. Streltsova, T.D., "Analysis of Aquifer-Aquitard Flow," *Water Resources Research*. Vol. 12, No. 3, 1976, pp. 415-422.