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Pyramids Plateau Groundwater Lowering Activity

Contract No. EDH-I-00-08-00024-00 Order No.2

Groundwater Modeling and Alternatives Evaluation

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Pyramids Plateau Groundwater Lowering Activity
USAID Contract No. EDH-I-00-08-00024-00-Order No.02

GROUNDWATER MODELING AND ALTERNATIVES EVALUATION

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B AERA Letter

1.0 Introduction

Groundwater levels in the Sphinx area were observed to rise dramatically during 2006 - 2007 to the point where open water became apparent in some low lying areas including the Sphinx and Khafre Wadi temples, east of the Sphinx, and the Workers Area to the south - see Figure 1-1. High groundwater levels can have detrimental effects on archeological resources. Foundations standing in groundwater can sustain damage especially if the groundwater is contaminated by sewerage. Capillary rise of groundwater into the stone of the archeological structures can also cause damage when the water evaporates, leaving behind its salt content. Pressures developed during crystallization and hydration of the salts can be a cause of deterioration of the stone.

Figure 1-1. Appearance of Groundwater at the Valley Temple (left) and Workers Area (right)
Photos - Courtesy of Cairo University

The overall objective of the project is to develop a long term solution to minimize damage to the existing archeological structures and features on the Pyramids Plateau by implementing a means of lowering groundwater to practical and desirable levels in the area of the Sphinx and other affected areas of the Giza Pyramids Plateau. Specific tasks included:

Task 1 – Develop Groundwater Model

- Review existing information
- Develop & Perform Field Investigations
- Develop Groundwater Model
- Identify Causes of Groundwater Rise
- Simulate Alternatives

Task 2 – Engineering Design

- Alternative Development
- Cost Benefit Analysis
- Alternative evaluation
- Detailed design
- Bid document preparation

Other Tasks

- Environmental assessment
- Public hearing

- Bidding Assistance
- Finalize bid package
- Prepare FARA
- Assist during bid period
- Monument Monitoring Program
- CM Services (Optional)

This report covers Task 1 and the first 3 bullets of Task 2.

A general site map is shown in Figure 1-2. The Pyramids Plateau, where the Giza Pyramids, the Sphinx and associated archeological features are located, is in an undeveloped desert area between the Nazlet El Semman section of Cairo, on the east and the Fayoum Road on the west. Another relevant feature is the Mansouriah Canal which flows from south to north, approximately 600 m east of the Pyramids Plateau, conveying irrigation water to farms, north and south of the site area.

An east-west topographic cross section of the Pyramids Plateau is presented in Figure 1-3. The groundwater table is also plotted in this figure based on measurements in the Sphinx area and along Fayoum Road, as well as general hydrogeologic considerations. This groundwater table line provides an indication of groundwater levels in the area prior to activation of Cairo University dewatering wells. The cross-section shows that except for the vicinity of the Sphinx, ground levels are substantially above groundwater levels. The elevations indicated in this plot, as well as the rest of this report, are “asl” which stands for “above sea level”.

A number of studies and activities have taken place in the past that addressed geologic and hydrogeologic conditions in the area of the Sphinx. These studies and activities are reviewed in Section 2 of this report, to place the current project in context and to ensure that previous work is fully taken into account. In particular, a considerable amount of field investigation has taken place and knowledge from this work is valuable for the present effort. The previous information that could be confirmed or that appeared reasonable based on our engineering judgment was used in the current project study. The previous investigations were taken into account in the development of the field investigations program for this project.

The field investigations conducted for this project are briefly described in Section 3, with full reports included in appendices. Establishing groundwater lowering targets is an important element of this project, and this aspect is covered in Section 4. Descriptions of the various alternatives that can be considered to lower groundwater at the Pyramids Plateau are described in Section 5, together with an initial elimination of alternatives that are clearly not applicable or practical for this project.

Groundwater modeling was an important component of this phase of the project to evaluate potential causes of the observed groundwater rise, further evaluate alternatives and size them. The development, calibration and application of a groundwater model are covered in Section 6.

A cost-benefit analysis of the alternatives is presented in Section 7, culminating in a recommendation for a long-term, permanent groundwater lowering solution for the Pyramids Plateau.

Figure 1-2. Aerial Photo of the Pyramids Plateau Area

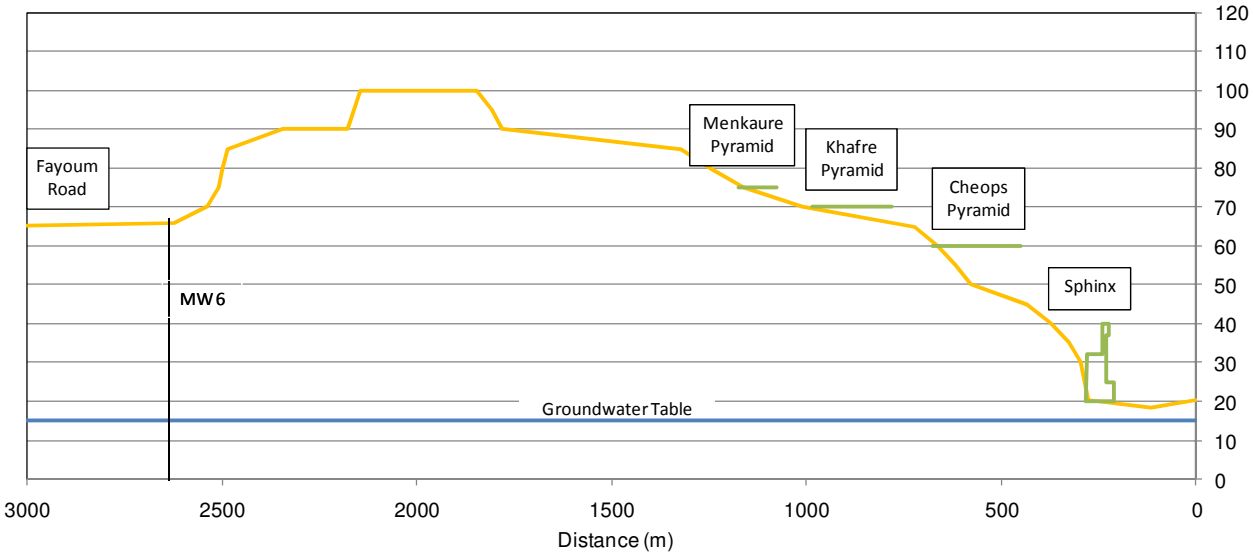


Figure 1-3. East-West Topographic Cross-Section of the Pyramids Plateau

2.0 Review of Previous Information

2.1. Geological Setting

Cairo lies on fluvial deposits at the apex of the Nile delta, bounded on the west by the Pyramids Plateau, Wadi Talun and the Abu Rawash Hills. The upper member of the Nile alluvium generally consists of layers of clay and silt deposited by the Nile during geologically recent periods of flooding, interspersed with layers of desert outwash and Aeolian sands and silt (AMBRIC, 1990). This upper portion can be as thick as 28 m. The lower member of the Nile Alluvium generally consists of coarse to fine sands, becoming coarser with depth. Pockets of gravel as well as lenses of silt and clay occur throughout the sand aquifer. The lower portion can be up to 90 m thick. Between the upper and lower members of the alluvium is a transitional layer of interbedded clays, silty sands and sands.

The Pyramids Plateau is made up of the Mokattam limestone formation from the Middle Eocene age (Aigner, 1983). Bedrock outcrops in many areas of the plateau, but is often covered by fill, aeolean sands and desert outwash sands of up to 4 m in thickness. The bedrock is a soft to medium hard, slightly to moderately weathered, medium to fine grained fossiliferous limestone. The limestone is considerably layered with bedding at a dip of 5 to 10° to the southeast – see Figure 2-1. A secondary joint set is near vertical and is moderately to widely spaced. Also shown in Figure 2-1 is the existence of caverns, thought to be of karstic origin (Wissa, 1988). In general, the bedrock is of poor mass quality, with Rock Quality Designation (RQD) on the order of 30.

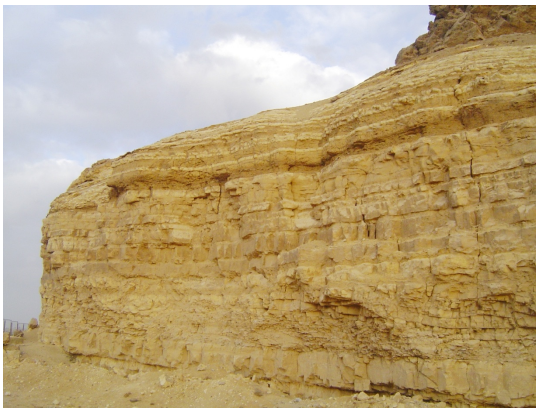


Figure 2-1. Maadi Formation Limestone showing Layering and Caverns

The northern boundary of the Pyramids Plateau is bordered by steep escarpments about 30 m in height, the lowest portion of which extends along the eastern boundary of the plateau (Aigner, 1983). In the Sphinx area, the limestone has been divided into three “members” as shown schematically in Figure 2-2. These members have widely different strengths (Gauri, 1984). Member I, the lowest, is of reefal origin and very hard. Member II is nearly 10 m thick and much softer. It forms the main core body of the Sphinx and has endured considerable erosion. Member III, apparent in the neck and head of the Sphinx, is quite hard.

To the south, the Mokattam Formation is overlain by less resistant sandy marls and marly, weakly cemented limestone of the Upper Eocene Maadi Formation (Aigner, 1983), as shown schematically in Figure 2-2. The top unit of the Maadi Formation includes several meters of massive, partly dolomitized limestone.

The geological contact between the Mokattam and Maadi formations runs approximately 300 m south of the Sphinx, under the contour of wadi bed which discharges from the west in a delta, north of the modern Muslim Cemetery and of the wall of the crow (Bunbury et al., 2007).

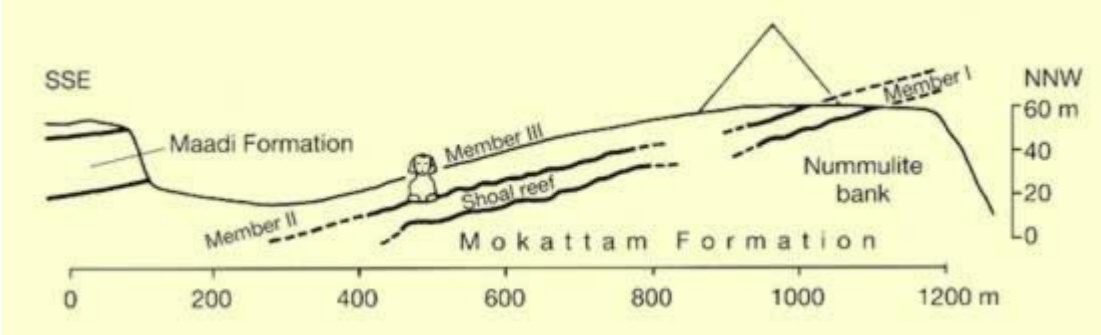


Figure 2-2. Conceptual North-South Cross section of the Pyramids Plateau

2.2. Previous Investigations

The previous studies and activities undertaken in relation with groundwater in the Pyramids Plateau area in Table 2-1, and each is briefly described below.

1. AMBRIC. 1989. Greater Cairo Wastewater Project. West Bank Project. Contract No. 27. Pyramids Area Sewers and Collectors

During the 1980s, as part of the Greater Cairo Wastewater Project, the American British Consultants (AMBRIC) designed and supervised the construction of a wastewater collection system in several sections of Cairo. One area on the west bank of the Nile included the Pyramids Area Project. As part of this work, geotechnical information was collected, which provides valuable data for the present study. The field explorations included test pits, boreholes, and field permeability testing and piezometer installations.

Most of the investigations were in urbanized areas that were to be sewered. The more relevant area is Nazlet El Semman, between the Pyramids Plateau and the Mansouriah Canal. The site investigations included boreholes at the edge of the River Nile alluvium valley and several rock boreholes in the vicinity of the Sphinx.

The investigations showed that between the Mansouriah Canal and the pyramids plateau the aquifer system includes a confined alluvium aquifer, overlain by an impervious clay/silt layer, itself overlain by a surficial aquifer. The clay layer does not appear to extend all the way to the edge of the valley. Some smaller perched aquifers also exist above clay/silt lenses. Piezometers were installed and monitored in both the deep and shallow aquifers.

Table 2-1. Summary of Previous Work

No	Date	Report or Activity	By	Scope
1	Sep 89	Greater Cairo Wastewater Project West Bank Project Contract No.27 – Pyramids Area Sewers and Collectors	American British Consultants (AMBRIC)	● Site investigations including test pits, boreholes field testing and Piezometers, to study the sub surface formation and to monitor deep/shallow aquifers.
2	Jul 90	Greater Cairo Wastewater Project West Bank Project Sphinx Area Groundwater Study	American British Consultants (AMBRIC)	● Installation of monitoring wells in Sphinx area ● Groundwater level measurements ● Groundwater chemical analyses
3	Oct 07	Mena House Oberoi Golf Course and Drainage System	Engineering Consultants Group (ECG)	● Design of underdrain system to minimize groundwater recharge due to irrigation.
4	Feb 08	Lowering of Groundwater at Wadi Temple and Sphinx Area – Final Technical Report (in Arabic)	Faculty of Engineering Cairo University	● Drilling of 15 boreholes ● Groundwater level measurements ● Groundwater chemical analyses
5	Jun 08	Technical Report for the Drilling of Four Boreholes around the Sphinx, Video Logging and Water Level Monitoring (in Arabic)	Faculty of Engineering Cairo University	● Drilling of 4 boreholes, 20m depth ● Groundwater level measurements ● Chemical analyses of water
6	Aug 08	Technical Report for the Drilling and Testing of Three Wells at the Sphinx Area (in Arabic)	Faculty of Engineering Cairo University	● Drilling of 3 wells ● Pumping tests at 3 wells
7	Oct 08	Operation of Production Wells and Piezometer Readings below the Sphinx and Wadi Temple for the Period of 15/7/08 to 15/10/08. (in Arabic)	Faculty of Engineering Cairo University	● Groundwater level readings at 9 piezometers ● Survey of fixed points to check vertical settlement of the Sphinx and Wadi Temple.
8	Mar 09	Lowering of Groundwater below the Sphinx and Wadi Temple – Final Report (in Arabic)	Faculty of Engineering Cairo University	● Drilling of 8 dewatering wells ● Drilling 12 piezometers ● Groundwater level measurements

Groundwater levels in the shallow aquifer were found to vary from 13.6 m to 18.2 m asl, and to be generally above those in the deep aquifer. Groundwater levels in the deep aquifer were found to decrease towards the north, most likely due to pumping from the El Ahram water supply well field to the north.

2. AMBRIC. 1990. Greater Cairo Wastewater Project. West Bank Project. Sphinx Groundwater Study

This study was undertaken to investigate groundwater conditions in the area of the Sphinx in response to the concern that sewage-contaminated groundwater was contributing to the deterioration of the bedrock from which the Sphinx is carved. The study's immediate goal was to document groundwater levels, flow patterns and contamination levels. The study included a review of soil and bedrock geology, field investigations, chemical analyses and data interpretation.

The field investigations included the drilling of a number of borings, installation of monitoring wells, measurements of groundwater levels and chemical analyses of the water. Borings and monitoring wells installed for other stages of the West Bank Project were also used in the analyses. Based on these, geological cross-sections were developed – see Figure 2-3. Groundwater level contour maps were also drawn based on the groundwater level measurements, showing the effect of the El Arham well field – see Figure 2-4.

The groundwater analyses included the following parameters: pH, conductivity, total dissolved solids (TDS), turbidity, chemical oxygen demand (COD), ammonia (NH_3), Nitrate (NO_3), phosphate (PO_4), sulfate (SO_4), Chloride (Cl), total alkalinity, total hardness and iron.

Observations made during the study included the following:

1- Groundwater levels in the area of the Sphinx were between 14.5 m and 14.7 m above sea level, which is about 5 meters below the base of the Sphinx at EL 20.0 m asl.

2- Probable source of recharge to the groundwater system include the Nile, infiltration from canals and drains, leakage from water and sewer pipes, infiltration from irrigation or rainfall.

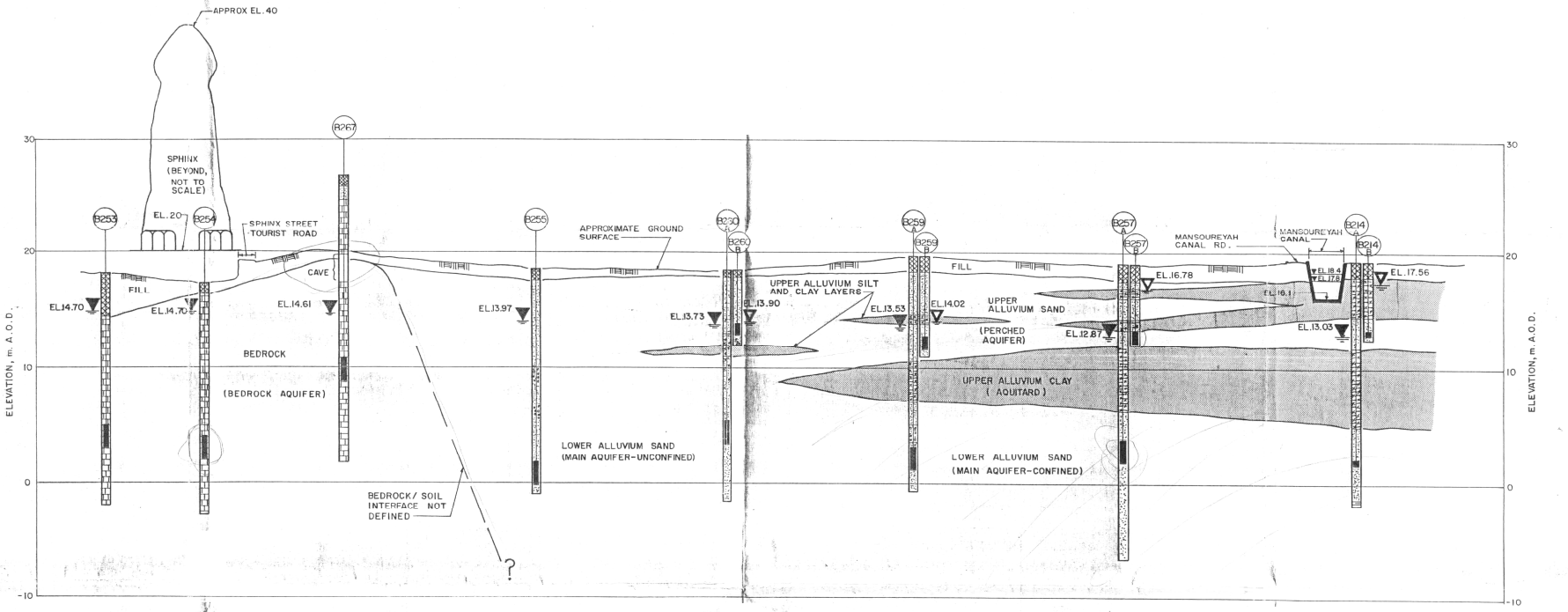
3- Water abstraction from the El Ahram public well fields north of the study area lowers the main aquifer water levels significantly.

4- Groundwater levels in bedrock wells around the Sphinx fluctuate very little compared with the wells installed in the perched and main aquifers of the Nile flood plain.

5- Groundwater levels during most of the year are higher in the bedrock around the Sphinx than in the soil aquifers of the Nile flood plain where the densely populated village areas are located.

6- The highest concentration of chemical substances analyzed in this study was generally found in samples from wells in Nazlet El Semman.

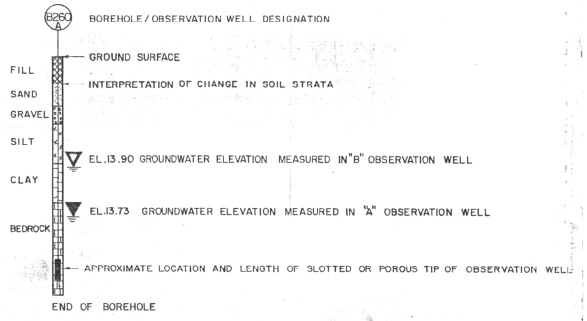
7- Chemical substance concentrations in the groundwater samples from the bedrock wells around the Sphinx were within the international drinking water standards. (World Health Organization WHO standards, 1972 permissible limits)



NOTES:

1. LOCATION AND ORIENTATION OF SUBSURFACE PROFILES INDICATED ON FIGURE 2, STUDY AREA PLAN.
2. CHANGES IN SOIL STRATA ARE INTERPRETED FROM TEST BORING DATA. VARIATIONS FROM THE STRATA INTERFACE LINES SHOWN, ARE LIKELY. REFER TO THE REPORT TEXT AND THE TEST BORING LOGS IN THE PYRAMIDS GEOTECHNICAL REPORT FOR ADDITIONAL IMFORMATION.
3. MANSOUREYAH CANAL IS SHOWN AS AN OPEN CANAL AS IT WAS AT THE TIME OF THE GROUNDWATER LEVEL MEASUREMENTS SHOWN ON THE FIGURES. THE CANAL WAS REPLACED BY A TWIN BOX CULVERT FROM SPHINX STREET TO PYRAMIDS ROAD IN FEBRUARY 1990. THE TYPICAL RANGE IN WATER LEVEL IN THE CANAL IS SHOWN. HOWEVER, THE CANAL IS DRAINED ANNUALLY IN JANUARY AND FEBRUARY FOR CLEANING.
4. GROUNDWATER ELEVATIONS SHOWN WERE MEASURED IN THE OBSERVATION WELLS ON 7 AND 8 JANUARY 1989 DURING THE PERIOD OF SEASONALLY HIGH WATER LEVELS AND PRIOR TO ANY DEWATERING FOR SEWER CONSTRUCTION IN THE AREA. REFER TO THE REPORT TEXT AND OBSERVATION WELL HYDROGRAPHS IN APPENDIX B OF THIS REPORT FOR DISCUSSION AND DATA ON GROUNDWATER LEVEL FLUCTUATIONS.
5. ELEVATION, m A.O.D. MEANS ELEVATION IN METERS ABOVE ORDINANCE DATUM WHICH IS MEAN SEA LEVEL AT ALEXANDRIA.

LEGEND:



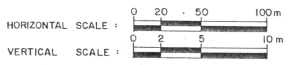


Figure 2-3. Aquifer Cross-Section with Groundwater Levels from the AMBRIC Project (AMBRIC,

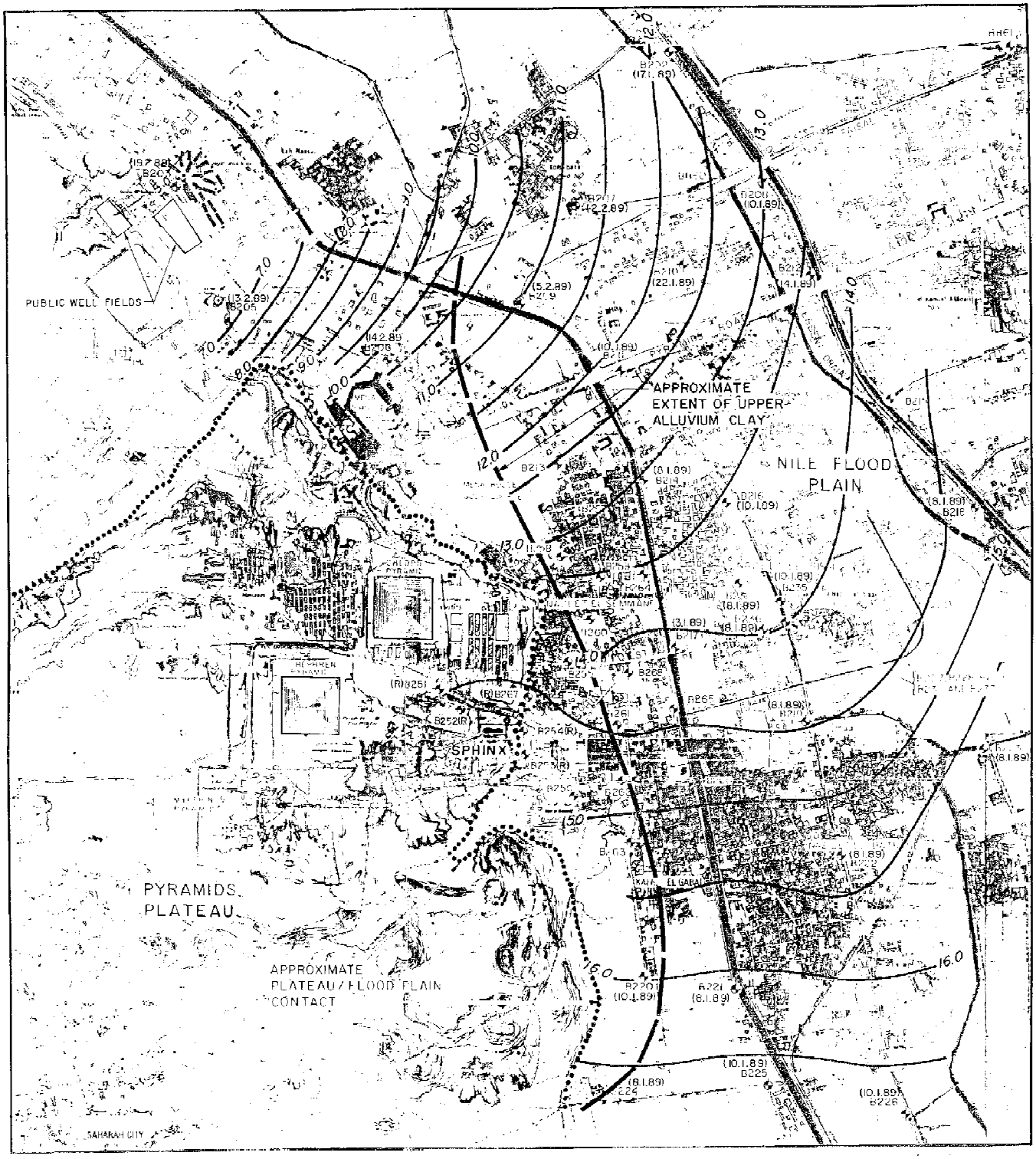


Figure 2-4. El Ahram Well Field and Groundwater Contours (From AMBRIC Project 1990)

Conclusions drawn from the study included:

1- Based on groundwater gradient, flow pattern and differences in fluctuation pattern between bedrock and soil wells, it is not likely that groundwater moves readily between the soil and the bedrock in the study area.

2- It is not likely that groundwater contamination migrates from the Nile flood plain into the bedrock below the Sphinx.

3. ECG. 2007. Mena House Oberoi Golf Course and Drainage System

An under drain system was designed in 2007-2008 by the Engineering Consultants Group (ECG) for the Mena House golf course, with the goal of reducing groundwater recharge from irrigation. The underdrain system includes a network of perforated pipes that would discharge an estimated flow of 300 m^3/day to the municipal wastewater collection system. The golf course would also be isolated by a polyethylene sheet to maximize the flow to the collection system.

In addition to the underdrain system, the current irrigation system would be replaced by a modern irrigation system designed to provide additional control and minimize the applied water. Current groundwater recharge was estimated at 420 m^3/day, accounting for excessive irrigation in the existing system.

Design of the proposed system is complete, and as of this writing construction of the upgrade has just been initiated.

4. Cairo University. Feb 2008. Lowering of Groundwater at Wadi Temple and Sphinx Area – Final Technical Report.

This report sought to identify potential causes for the rise in groundwater levels that has been observed in front of the low lying temples below the Sphinx. A second objective was to prepare designs and technical specifications for works required to lower groundwater levels in this area, to be tendered to specialized companies in this field and to be constructed quickly to save the archeological temples from damage.

As part of the study a survey of the Sphinx area and nearby temples was conducted. An east-west cross-section was prepared showing that the base of Sphinx is at an elevation of about EL 20 m asl, while the level of the base of Wadi temple and Sphinx temple is at about EL 17 m and the level of low-lying areas in front of the temples is between EL 14 m and EL 15 m.

Ground level in the residential area between the Sphinx area and Pyramids Street is at about EL 25 m.
To monitor the groundwater level, 15 boreholes were drilled and converted to piezometers. Their locations are shown in Figure 2-5. Soil classification for the boreholes showed the following:

- PZ-1, 2, 3, 4, 5, 6, 8 and 9: fill deposits underlain by layers of sedimentary materials of sand and gravel with traces of clay, where these deposits constitute the underground reservoir in this region.

- PZ-11, 12, 14, 15 and 16: cracked limestone rock, which is the main component of Pyramids Plateau.

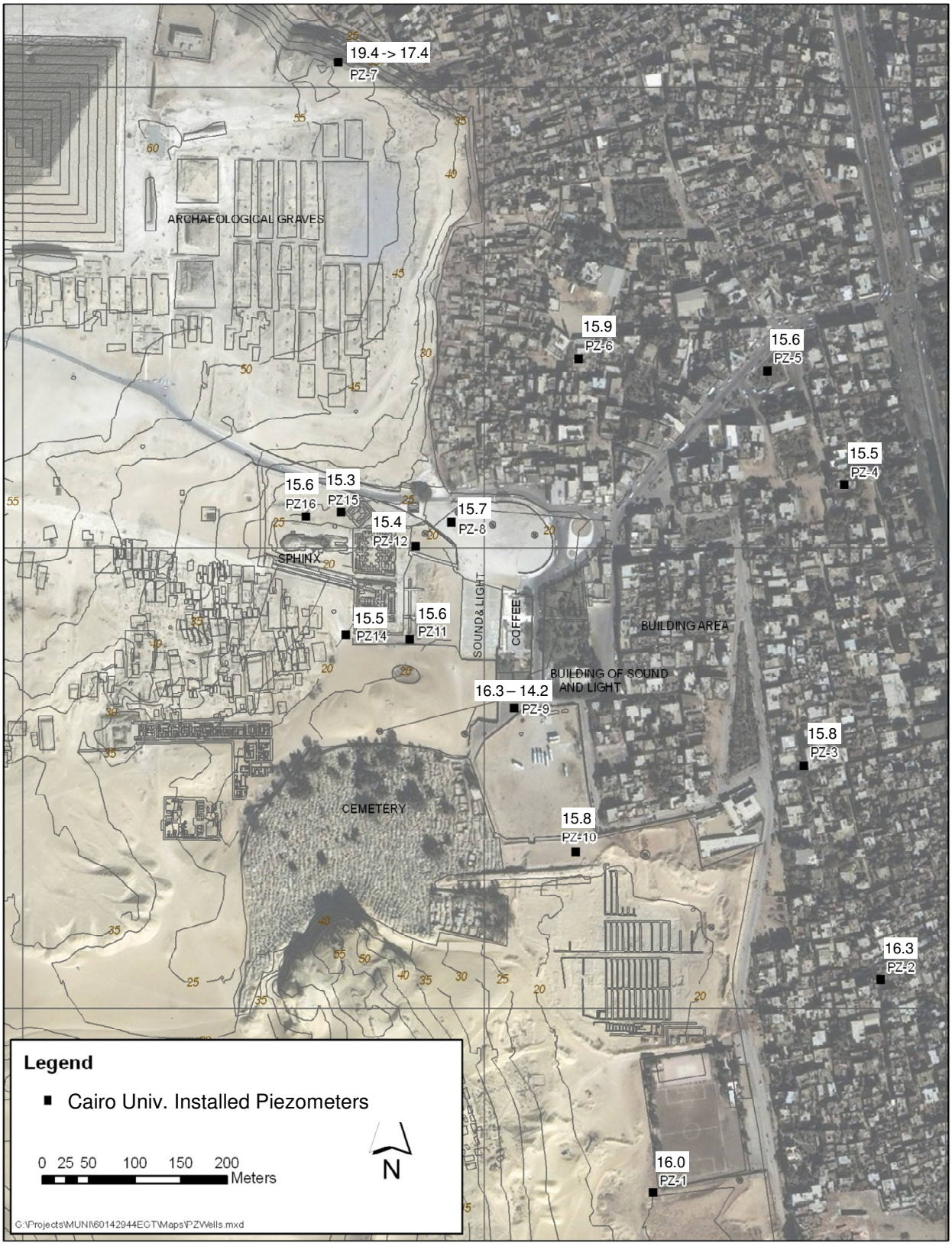


Figure 2-5. Location of 15 Initial Piezometers and Groundwater Level Readings prior to Activation of the Dewatering System

- PZ-7: fill layers underlain by sedimentary rocks from sand and gravel with some of these layers of clay followed by limestone.

During the study and later from November 20, 2007 to January 24, 2008 groundwater levels were monitored periodically in all piezometers. A very slight rising trend was observed at most of the piezometers during this period, averaging about 0.1 m. This rise may be due to rainfall recharge during the winter months. Average groundwater elevations during the monitoring period are summarized in Table 2-2.

Table 2-2. Average Groundwater Elevations at Piezometers (Nov 20, 2007 – Jan 24, 2008)

Piezometer No.	Closest Feature	Groundwater Elevation (m)	TDS (mg/l)	Bacteria (#/100 ml)
PZ-1	Sphinx Club	16.0	1,282	14,000
PZ-2	Nazlet el Semman	16.3		
PZ-3	Nazlet el Semman	15.8		
PZ-4	Nazlet el Semman	15.5		
PZ-5	Nazlet el Semman	15.6	507	50,000
PZ-6	Mena House	15.9		
PZ-7	Mena House	19.4 to 17.4*	369	40,000
PZ-8	Sphinx Temple	15.7		
PZ-9	Sound and Light	16.3 to 14.2*	776	7,500
PZ-10	Sound and Light	15.8	298	3,900
PZ-11	Valley Temple	14.4	6,500	72,000
PZ-12	Sphinx	15.4	6,200	120,000
PZ-14	Valley Temple	14.1	7,900	280,000
PZ-15	Sphinx	15.3	4,400	1,100,000
PZ-16	Sphinx	15.6	7,900	2,100,000
Mansouriah Canal		19.1 to 18.5**		

* Abrupt change on December 24
** Abrupt change on December 9

Groundwater levels prior to initiation of the dewatering are shown in Figure 2-5. Groundwater levels in the Sphinx area were on the order of 15.4 to 15.7 m without significant gradient. These same levels were found in Nazlet El Semman, while slightly higher values were found both north and south of the Sphinx area. However, there is only one measurement point north of the area, near the Mena House golf course, and this point exhibited unclear features, as described below.

Two instances of uncertainty need to be mentioned. First, groundwater levels at piezometers PZ-11 and PZ-14 were reported at 14.4 and 14.1 m (with minor variations) in Nov 07 – Jan 08, and 15.6 and 15.5 m in July 2008, at the initiation of the dewatering. The well reference points were resurveyed but the new elevations were not significantly different than the original ones. The earlier numbers (14.4 and 14.1 m) are suspicious, since water was above ground in the area below the Khafre Valley Temple, at elevation 15.5 m only a few meters away from PZ-11. Also, the 14.4 and 14.1 m numbers cannot be explained from a hydrogeologic point of view (a groundwater sink would need to exist, but no groundwater withdrawal was occurring at the time). Therefore, the July 2008 values were used in Figure 2-5.

Another unexplained feature in the Nov 07 – Jan 08 water level data is the 2 m drop which is reported to have occurred between Dec 17 and 24, 2007 at PZ-7 near the Mena House golf course and at PZ-9 near the Sound and Light Show. These drops have been attributed to reductions in irrigation at these two sites. Irrigation at the Mena House used to be achieved by flooding, and this practice was changed to spray irrigation when SCA requested the change. This may explain the drop, although the 2 m groundwater level drop is thought to be rather large.

Thus, the groundwater levels shown in Figure 2-5 are an interpretation of conditions prior to implementation of the dewatering system based on available data, subjected to as much verification and analysis as is possible given that these conditions cannot be returned to. The groundwater levels do not point to a clear source of groundwater recharge, but rather to a regionally stable groundwater system with little groundwater flow.

Chemical analyses. Groundwater samples from 10 of the piezometers were collected and analyzed for pH, total dissolved solids (TDS), chloride, sulphate, iron and manganese. Measured TDS concentrations are summarized in Table 2-2. These results show a marked difference between to groups of piezometers.

- At PZ-1, 5, 7, 9, and 10, which are generally removed from the Sphinx and lower temples, relatively low values were obtained. The two lowest values were measured at PZ-10 and PZ-7, respectively located near the Sound and Light garden, and the Mena House golf course. These low values may be due to irrigation with drinking water. The highest TDS in this group of piezometers was obtained at PZ-1, which is located beside the Sphinx Club.

- At PZ-11, 12, 14, 15 and 16, which are in close proximity to the Sphinx and lower temples, considerably higher concentrations were obtained, ranging from 4,400 to 7,900 mg/l. The highest concentrations were observed at PZ-16 and PZ-14, respectively north and south of the Sphinx. These high values were attributed to the dissolution of chlorides from the Pyramids Plateau.

Bacteriological analyses (total coliform, although this is not entirely clear) were conducted for samples from the same 10 piezometers for which chemical analyses were conducted. The same grouping as for the TDS levels was noted, with much higher bacterial counts at the piezometers closer to the Sphinx and lower temples. The highest bacterial count of 2,100,000 / 100 ml is quite high, approximating raw wastewater.

Potential causes of the groundwater rise were identified as:

- Increased leakage from the water supply and sewerage systems serving newly developed areas around the Pyramids Plateau
- Nearby cemetery, which contains many trees and a mosque
- Irrigation of Mena House gardens and golf course.

- Seepage from the Mansouriah Canal due to rising water level caused by partial blockage by garbage and floating material.

Proposed works to lower groundwater levels in the Sphinx area included the following:

- Drain line to capture groundwater flow from Nazlet el Semman
- Dewatering wells to lower groundwater until after installation and operation of the drain line.

Recommendations from the study were as follows:

- Maintenance and rehabilitation of the sewer system in Nazlet el Semman
- Requiring Mena House to cease irrigating their golf course until the construction of an integrated drainage system
- Requiring the Sound & Lights Company to stop irrigating their garden and to stop using all kitchens and toilets until after the performance of a complete inspection of their water and sewer system.
- Periodic maintenance of the Mansouriah Canal, and installation of piezometers on the west side of the Pyramids to monitor groundwater flow from this direction
- Undertake studies to construct a permanent cut-off wall surrounding the area

5. Cairo University. June 2008. Technical Report for the Drilling of Four Boreholes around the Sphinx, Video Logging and Water Level Monitoring

This project involved the following:

- Drilling of 4 boreholes to a depth of about 20 m
- Video logging of the boreholes
- Conversion of the boreholes to monitoring wells provide with automatic groundwater level monitoring devices
- Chemical analyses of water samples from the boreholes.

The locations of the boreholes are shown in Figure 2-6.

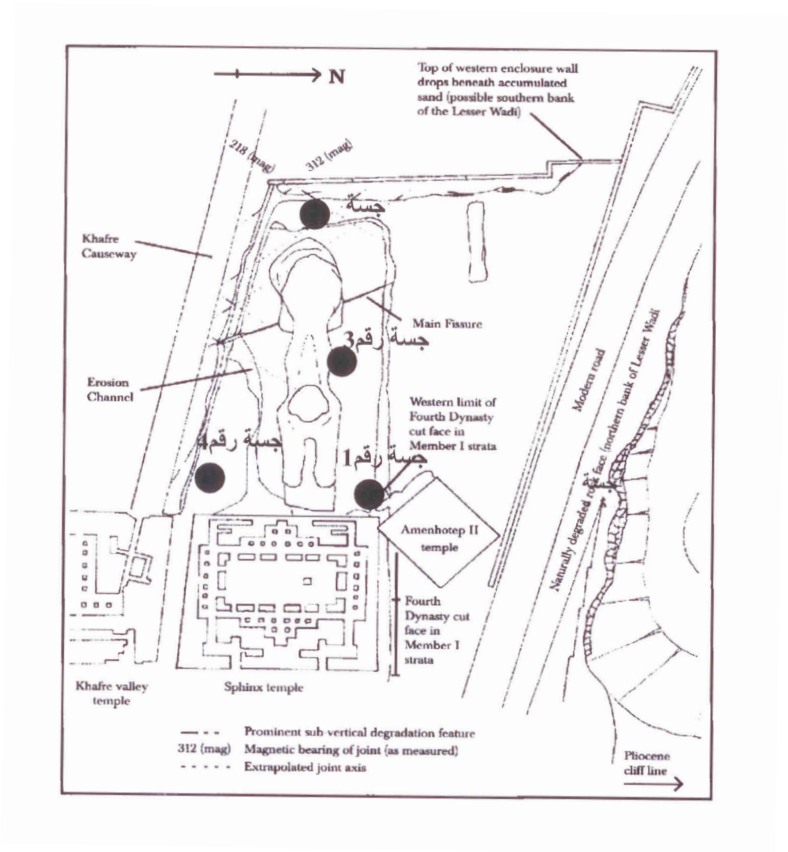


Figure 2-6. Locations of Boreholes around Sphinx
(Source: Cairo University)

Geotechnical Analyses. Evaluation of core samples from the borehole indicated the presence of the following types of rock:

- Sandy Biomicrite - Organic limestone consisting mainly of calcite with archeological fill and some amount of crystal quartz, and traces of sand
- Marly biomicrite – Organic limestone consisting mainly of fine calcite crystals with archeological fill and 5 to 10% clay material.

The study showed that the compression and tension resistance of most of the samples was low compared to similar Egyptian limestones. The samples also contained a percentage of pores. The compression strength of the samples varied from 82 kg/cm^2 to 260 kg/cm^2, with an average density of 2.1 tons/m^3. The pressure exerted by the weight of the Sphinx was estimated and found to be about 20 times less than the lowest underlying limestone compression strength. Therefore, the stone under the Sphinx was determined to safely be able to withstand the weight of the Sphinx.

Groundwater Levels. Values measured between June 8 and 21, 2008 are presented in the report. Average values are summarized in Table 2-3. These values are comparable to those measured at the beginning of the year in the previous study.

Table 2-3. Groundwater Levels and Chemical Analyses of Groundwater Samples

Piezometer No.	Groundwater Elevation (m)	TDS (mg/l)	pH	Nitrate (mg/l)
PZ-S1	15.6	805	7.2	33
PZ-S2	15.7	632	7.5	8
PZ-S3	15.7	1,376	7.2	32
PZ-S4	15.6	1,451	7.2	235

Chemical Analyses. The results of the analyses are listed in Table 2-3. Surprisingly, the TDS concentrations are much lower than those measured at the beginning of 2008 as part of the previous study. Somewhat elevated values of nitrate suggest contamination by sewage. The highest nitrate concentration was observed at PZ-S4, which is closer to the Nazlet El Semman cemetery.

6. Cairo University. Aug. 2008. Technical Report for the Drilling and Testing of Three Wells at the Sphinx Area

This report documents drilling of 3 production wells, 9 piezometers, development/testing of the wells, and analyzing the obtained data; in addition to monitoring of the vertical movement of the Sphinx and the two temples.

The first well was drilled inside the Sound and Light garden, the second in front of Nazlet El Semman cemetery, and the third in front of the populated area of Nazlet El Semman. Step and constant flow pumping tests were conducted at the 3 wells and the results are given in Table 2-4.

Table 2-4. Pumping Test Results

Well Number	1	2	3	
Material	Alluvium	Limestone	Alluvium	
Flow rate	84	60	110	m^3/hr
Monitoring well distance	35.9	14.7	17.7	m
Duration	57	72	72	hrs
Maximum monitoring well drawdown	0.46	0.19	0.55	m
Calculated transmissivity	4,625	6,477	4,820	m^2/day
Storage coefficient	0.00013	0.008	0.00069	

Following the tests, the wells were left operating until the time of issuing of this report. This resulted in a considerable decrease in the water level in the surrounding area. No vertical movement was recorded for the Sphinx or the Wadi Temple.

Based on this it was recommended to construct another 4 wells to further lower the water level to try to reach targeted values.

7. Cairo University, Oct. 2008. Operation of Production Wells and Piezometer readings below the Sphinx and Wadi Temple for the period from 15/7/2008 to 15/10/2008.

This report documents water level measurements below the Sphinx and in front of the Wadi Temple, after the operation of the three production wells, for the period from 15/7/2008 to 15/10/2008, plus a survey for the vertical movements of fixed points along the body of the Sphinx and within the Wadi Temple.

The three production wells were first operated in July 2008. The first well was drilled inside the Sound and Light's garden, the second in front of Nazlet El Semman cemetery, and the third in front of the populated area of Nazlet El Semman complex. Water was discharged via the public sewage network.

From the beginning of operation of the wells until the date of this report, groundwater levels dropped about 50 cm and no vertical movement was recorded for the Sphinx or the Wadi Temple.

8. Cairo University, March 2009. Lowering of Ground Water below the Sphinx and Wadi Temple - Final Report.

This report summarizes all the previous studies that were conducted for the purpose of lowering the groundwater table below the Sphinx and in front of the Wadi Temple. These studies included:

- Survey for the vertical movements of fixed points along the body of the Sphinx and within the Wadi Temple.
- Geological and geophysical studies.
- Drilling of boreholes in which piezometers were installed.

- Video logging of 4 boreholes and transferring them into piezometers with automatic water level measurement devices.

- Water level measurements below the Sphinx and in front of the Wadi Temple.

- Chemical and bacteriological analysis for water samples.

The previous studies led to a suspicion that the rise in groundwater is due to the water seeping from the neighboring populated area of Nazlet El Semman, the gardens of Mena House Oberoi Hotel, the green area around the Sound and Light building, and the rise of the water level of Al-Mansouria Canal due to the repeated partial blockage of the screens at the entrance of the new box culvert.

Based on this, 8 dewatering wells and a group of piezometers were drilled at locations shown in Figure 2-7. The dewatering system was started in July 2008 with 3 wells, which were supplemented by 4 wells in November 2008 and an 8th well in January 2009 (Cairo University, Oct 2008). The well locations are shown in Figure 2-7 and estimates of the well flows are listed in Table 2-5.

Table 2-5. Dewatering Well Flows

Well No	Pumping Start Workers Area	Flowrate (m^3/hr)
1	22-Jul-08	90
2	1-Jul-08	65
3	12-Jul-08	105
4	Nov-08	40
5	Nov-08	105
6	Nov-08	90
7	Nov-08	105
8	Jan-09	24
Total		624

Groundwater levels following initiation of the dewatering system are shown in Figure 2-8. The piezometers where the measurements were made are shown in Figure 2-7. There appear to be two groups of piezometers.

- PZ 11, PZ 14, PZ 15, PZ 2-1 and PZ 2-2 start from about 15.3 to 15.6 m and gradually drop to 14.7 m where they stabilize. The stepped decline can be attributed to the increase in the number of dewatering wells from July 2008 to January 2009. Data for January and February 2010 were also obtained and show the same levels. The common feature of these piezometers is that they are in limestone.

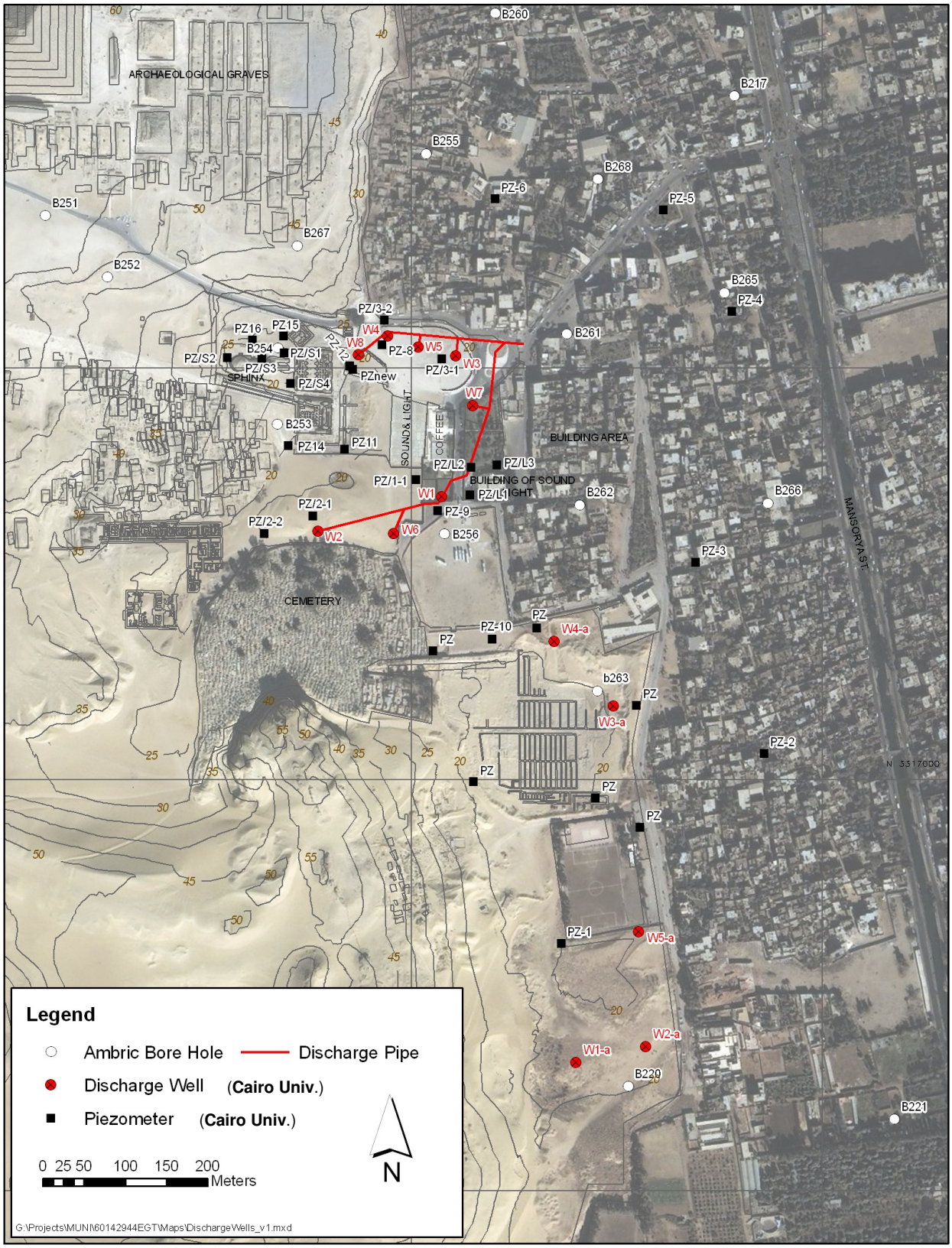
- Another group of piezometers, such as PZ 1-1, PZ 3-1, etc. start below the first set and reach much lower values. These piezometers are in the alluvium.

- PZ-12 is between the two sets described above. It is located close to Well W8 which was started in January 2009 and exhibits a large drawdown soon thereafter.

The above shows significantly different responses between the wells in limestone and those in alluvium. This observation is consistent with the conclusion reached in the AMBRIC studies that the limestone and the alluvium aquifers are not connected. The cause for this separation is not immediately obvious. A possible reason is that a layer of finer material may have been deposited at

the edge of the Nile valley during flood periods, and because velocities at the edge of the flood plain are the lowest, finer particles would have deposited there. Evidence of a clay or clayey sand layer is apparent in the boreholes associated with three of the dewatering wells (Wells 1, 3 and 5) near the limestone/alluvium interface……

Based on the above, the dewatering which has been implemented in the Sphinx area has been effective in lowering groundwater levels. In the limestone, the resulting groundwater level reached is on the order of 14.6 m, while in the alluvium it is down to 11.7 to 12.5 m.


ARCHAEOLOGICAL GRAVES
B260
B217
B255
B268
PZ-6
PZ-5
B251
B267
B252
B265
PZ-4
PZ/3-2
PZ16
PZ15
W4
W8
PZ-8
W5
W3
B261
PZ/S2
B254
PZ/S1
PZ/3-1
PZ/S3
SPHINX
PZnew
PZ/S4
W7
B253
PZ14
PZ11
SOUND& LIGHT
COFFEE
BUILDING AREA
PZ/L2
PZ/L3
PZ/1-1
BUILDING OF SOUND
PZ/L1
LIGHT
W1
B262
B266
PZ/2-1
PZ-9
PZ/2-2
W2
W6
B256
MANSORYA ST.
PZ-3
CEMETERY
PZ
PZ-10
W4-a
PZ
b263
PZ
W3-a
PZ-2
N 3317000
PZ
PZ
PZ
PZ-1
W5-a
W2-a
W1-a
B229
B221
Legend
Ambric Bore Hole
Discharge Pipe
Discharge Well (Cairo Univ.)
Piezometer (Cairo Univ.)
0 25 50 100 150 200
Meters
N
G:\Projects\MUNI\60142944EGT\Maps\DischargeWells_v1.mxd

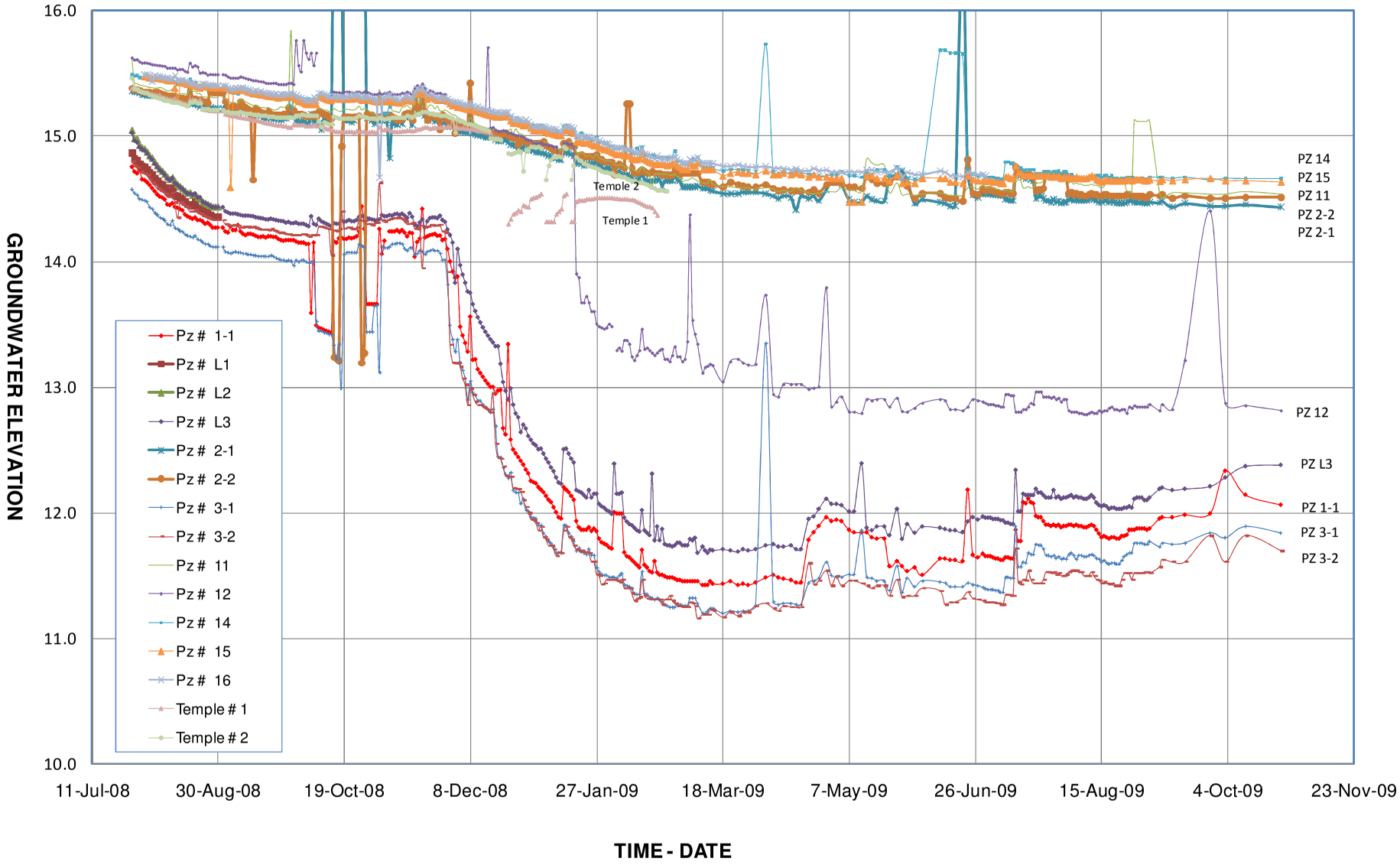


Figure 2-8. Groundwater Levels since implementation of Dewatering
Source – Cairo University

2.3. Summary of Previous Information

Salient items derived from previous studies and other activities are summarized below:

- In the Nile flood plain there is an aquifer in the lower alluvium sands and another aquifer in the upper alluvium, the two aquifers being separated by a clay and silt aquitard, but the integrity of the aquitard diminish towards the Pyramids Plateau.

- Groundwater in the bedrock aquifer under the Pyramids Plateau has a low hydraulic gradient, indicating very low movement. Based on the fact that groundwater levels fluctuate in the alluvium, but remain relatively steady in the bedrock, the AMBRIC study concluded that the two aquifers were distinct, with little groundwater exchange.

- The groundwater level at the Sphinx was on the order of 14.7 m in 1990. Levels prior to that date are not known.

- The groundwater level at the Sphinx was about 15.6 in December 2007, a rise of about 0.9 m compared to 1990. At this time, groundwater became visible in low laying areas south and east of the Sphinx.

- Chemical analyses of groundwater in the Sphinx area indicated a worsening of the water quality from drinking water quality in 1990 to reduced quality in 2007, with elevated levels of TDS, nitrate and bacterial indicators. Surprisingly, the worse groundwater quality was found in close proximity to the Sphinx, and it is possible that some of these data were affected by contamination associated with drilling operations.

- Potential sources of the groundwater rise are:

    - Water supply or wastewater system leakage in Nazlet el Semman
    - Irrigation at Mena House golf course and at Sound and Light gardens
    - Higher water level in Mansouriah Canal
    - New building complexes along Cairo-Fayoum road
    - Stoppage of El Ahram well field

- Dewatering was initiated using 3 wells in July 2008, 4 other wells in November 2008, and a last well in January 2009, resulting in groundwater lowering down to about elevation 14.6 m in the limestone and 11.7 to 12.5 m in the alluvium.

- Five groundwater extraction wells have also installed in the Workers Area, but pumping at these wells has not been initiated.

3.0 Field Investigations

To supplement the existing information that could be confirmed or that appeared reasonable based on our engineering judgment, a field investigations program was developed and implemented including the following elements, whose locations are shown in Figure 3-1:

- Drilling of two test wells near Mena House (Site 1) and in Nazlet El Semman (Site 2).
- Installation of 4 piezometers near the new test wells.
- Conduct of 3 pumping tests, in the two new test wells and at Well 3-a in Workers Area (Site 3).
- Recovery test at the 8 dewatering wells currently in operation in the Temples area (Site 4).
- Installation of 2 piezometers along Fayoum Road (Sites 5 and 6).
- Surveying of new and (still existing) previous piezometers and wells.
- Groundwater level measurements at all new and (still existing) previous piezometers.
- Geophysics (ground penetrating radar and seismic refraction) at 4 locations (Sites 3, 4, 7, and 8).
- Collection and chemical analysis of groundwater samples at 6 locations.
- Movement monitoring of Monuments and structures at pumping test locations.
- Topographic survey of study area around the Sphinx and at the Workers Quarters area.

Detailed reports on the field investigations are provided in Appendix A and salient results are summarized here.

3.1 Groundwater Levels

Important groundwater levels are discussed below.

Fayoum Road – Site 5. A groundwater level of 26.6 m asl was found. This groundwater level is considerably higher than all the other values measured in and around the Pyramids Plateau and it is thought that it may be representative of a perched layer, since clay was found in the lower 12 m of the borehole, down to elevation 1.1 m.

Fayoum Road – Site 6. The boring revealed a 1 m layer of fill above a 4 m layer of mudstone and 65 m of limestone. The measured groundwater level was 15.1 m asl. This level is consistent with the levels measured on the east side of the plateau, indicating very little hydraulic gradient and, hence, very little groundwater movement across the plateau.

Nazlet El Semman. Groundwater elevation was measured at the location of the Nazlet El Semman pumping test (Site 2), and a level of 13.6 m asl was found. This relatively low level confirms the significant effect of the 8 dewatering wells in the alluvium, as compared to the limestone where levels on the order of 14.5 m are measured.

Mena House. A groundwater level of 15.3 m was measured prior to the initiation of the pumping test (Site 1). The test well and 2 piezometers were in the alluvium. This value is consistent with the levels found in the Sphinx area prior to activation of the dewatering wells.

Workers Area. The groundwater level in the Workers Area prior to the pumping test there was 13.8 m asl. This level is with the dewatering system in operation and confirms the large area of influence of the dewatering system in the alluvium.

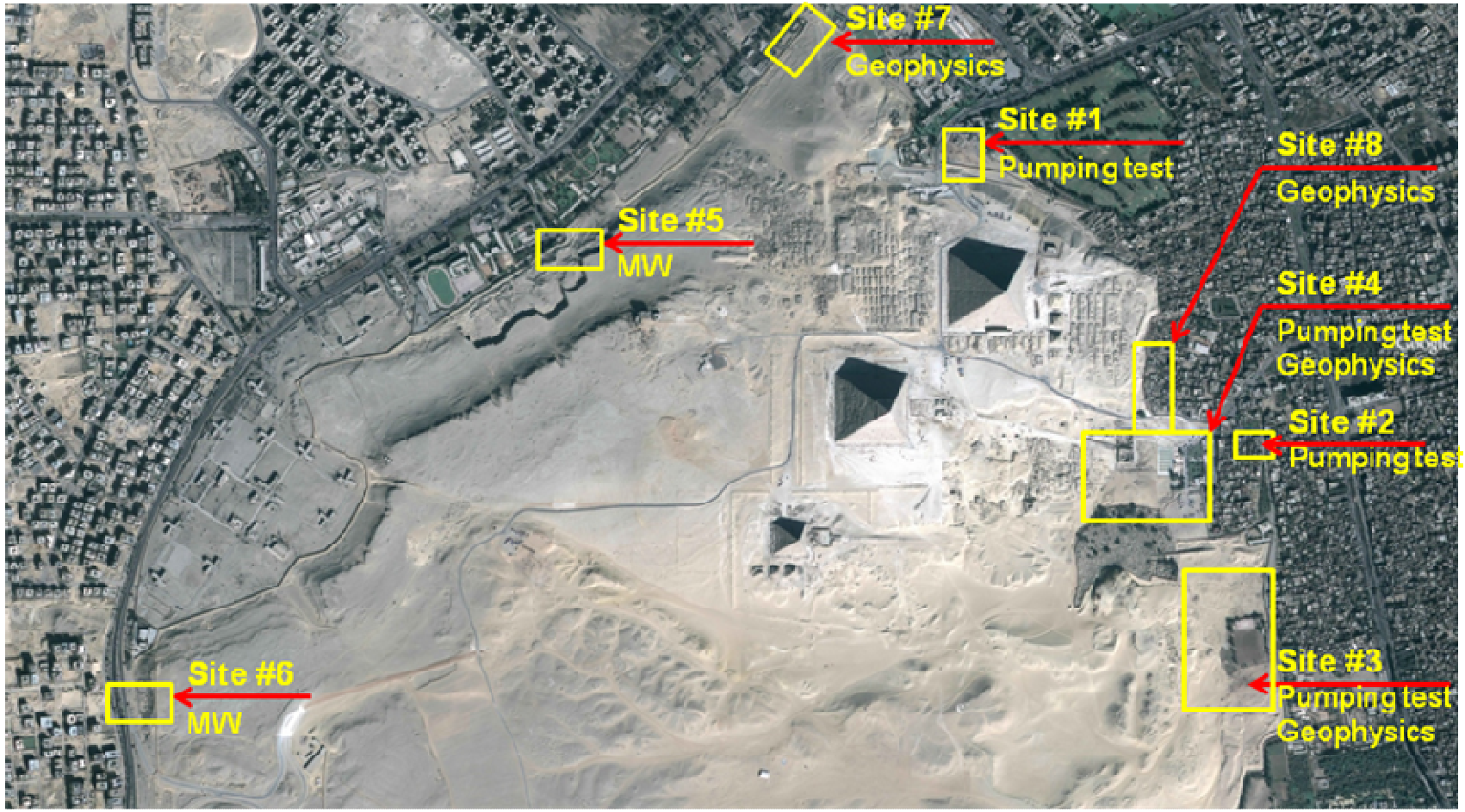


Figure 3-1. Locations of Field Investigations

El Arham Well Field. A groundwater level of 15.3 m asl was measured in January 2010, with the well field inoperative. This level is slightly (0.2 m) less than the levels measured in the Sphinx area prior to activation of the dewatering system. The difference may reflect the south to north gradient that can be expected in reflection of the Nile River gradient.

3.2 Pumping Tests

The results of the pumping tests were initially analyzed using the Cooper Jacob formulation, and those values are reported in Appendix A. However, the measured drawdowns exhibit the delayed yield phenomenon which is common in water table aquifers (Kruzeman and de Ritter, 1970). The initial drawdown is due to the elasticity of the aquifer, followed by a period of drainage from storage during which the rate of increase of drawdown is reduced. In a third period, drawdown increases again. Results of the re-analysis are summarized in Table 3-1. The new values are somewhat lower than the initial estimates.

In general, the transmissivity values resulting from the tests are quite high. A decrease of transmissivity towards the north is apparent, but this may be coincidental.

Table 3-1. Pumping Test Resutls

No.	Location	Material	Neuman Delayed Yield	
			Transmissivity (m^2/day)	Specific Yield
PT-1	Mena House	Alluvium	894	0.5
PT-2	Nazlet El Semman	Alluvium	1,625	0.25
PT-3	Workers Cemetery	Alluvium	2,886	0.025

3.3 Geophysical Testing

In general, the geophysical testing confirmed our understanding of the soil stratigraphy.

In the wadi area, just north of the modern cemetery, the seismic tests indicate two different types of limestone, reflective of the Mokkatam formation (north) with wave propagation velocities on the order of 3,200 to 3,600 m/s, and the Maadi formation (south) with velocities of 2,400 to 2,600 m/s. The lower velocity in the Maadi formation indicates the presence of marly limestone.

The ground penetrating radar and seismic refraction tests conducted at the northern end of the Pyramids Plateau indicate groundwater levels on the order of 20 m, which is considerably higher than the other levels measured around the Plateau. The seismic tests indicate the presence of a marly limestone at depth, which may have a lower hydraulic conductivity and cause a perched water table, as suspected in the piezometers located at Site 5 along Fayoum Road.

3.4 Chemical Testing

Water samples were collected from the wells used for the pumping tests, as well as two of the eight currently operating dewatering wells. In total, six samples were collected and analyzed for the range of regulated parameters for discharges to canals (see Table 3-2). In general, all parameters were below the limits, except for four instances of total dissolved solids, which exceeded the limit by small amounts. In total, the mixed groundwater extraction is not expected to exceed the standard.

Other items worth noting are as follows:

- The sample from near Mena House had an elevated level of nitrate, which may be due to fertilizers applied to the golf course.
- All samples had detectable levels of biochemical oxygen demand, which is unusual for groundwater. These may also be reflective of seepage from the Mansouriah canal, which may contain some amount of wastewater.
- Total suspended solids were detected in all the wells at concentrations varying from 5 to 10 mg/l. These values may indicate the entrainment of fine particles from the alluvium into the pumped flows.
- Cadmium, lead and nickel were always below detection limit.
- Levels of iron and manganese were generally low, indicating a low risk of precipitation when exposed to oxygen.

Table 3-2. Water Quality Measurements

Parameter	Unit	PT1	PT3 Before Pumping	PT3 After Pumping	PT2 Before Pumping	Well 2	Well 4	Permissible Limit*
Biological Oxygen Demand	mg/l	10.8	5.6	5.8	5.0	7.9	6.2	20
Chemical Oxygen Demand	mg/l	19	16	15	11	17	13	30
Total Suspended Solids	mg/l	6	10	8	5	5	3	30
pH	mg/l	7.9	7.2	8.2	8.2	7.1	7.1	6 – 9
Cadmium	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Lead	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05
Nickel	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.1
Iron	mg/l	0.8	ND	0.71	0.52	0.75	0.61	1
Manganese	mg/l	<0.01	0.1	0.2	0.1	<0.01	0.2	0.5
Chloride	mg/l	188	125	120	152	220	220	
Sulphate	mg/l	210	190	200	170	230	228	
Total Coliform	mg/l	ND	ND	23	23	ND	ND	2,500
Total Dissolved Solids	mg/l	1,000	890	650	600	850	1,000	800
Sulphites	mg/l	ND	ND	ND	ND	ND	ND	1
Oil and Grease	mg/l	ND	ND	ND	ND	ND	ND	5
Phosphorus	mg/l	ND	0.2	ND	ND	ND	ND	1
Nitrate-N	mg/l	18	4.5	0.025	0.018	0.74	1.9	30
Dissolved Oxygen	mg/l	5.5				8.0	7.5	
Phenol	mg/l	ND	ND	ND	ND	ND	ND	0.001

ND = Not Detected

* Permissible limits for discharge into a canal

Underlined parameters exceed the permissible limit for discharge to canals

4.0 Groundwater Lowering Targets

Deterioration of archeological monuments in Egypt due to groundwater has been documented (Johansson and Larnellus, 2005) and has resulted in groundwater lowering projects in Luxor and in Old Cairo. Deterioration in the Giza area has also been observed (Fitzner et al, 2003, Gnaedinger, 2006). One of the potential causes of deterioration associated with groundwater is its capillary rise into the stone and associated flux of salts when the groundwater is saline. As the groundwater evaporates it leaves the salts behind, and pressure developed during crystallization and hydration is a cause of deterioration (Ismail et al, 2003).

Therefore, groundwater interaction with archeological structures is controlled by i) the elevation of the archeological features and ii) capillary rise. These two factors are examined below.

4.1 Elevations of Archeological Features

Elevations of the relevant archeological features on the Pyramids Plateau are summarized in Table 4-1, based on input from Dr. Mark Lehner of the Ancient Egypt Research Associates (AERA) – see Appendix B. These elevations correspond to archeological features that warrant protection, based on their historical importance, size, location and potential for display. For example, an ancient wall just east of Zaghloul Street, portions of the Khufu Valley Temple pavement and ancient settlement materials were discovered during the AMBRIC project. These archeological features, however, because of their location detached from the Pyramids Plateau in the busy modern urban area farther east, are not considered as targets for groundwater lowering.

Table 4-1. Relevant Elevations

Feature	Elevation (m-ASL)
Fourth Dynasty Floodplain Level – Giza	12.5
Old Kingdom Average Settlement Level	14.7
Pyramids	
Cheops	60.0
Khafre	70.0
Menkaure	75.0
Sphinx Area	
Sphinx Floor	20.0
Sphinx Temple Terrace	16.8 – 16.9
Khafre Valley temple Tunnel	14.5
Khafre Valley Temple ramp – lowest point excavated	14.0
Workers Area	
Wall of the Crow – Bottom of Foundation	15.4

As shown in Figure 1-3 ground levels in the Pyramids Plateau range from around 14 m on the east side to 60 – 75 m at the Pyramids, and up to 100m in the center of the Plateau.

4.2 Capillary Rise

Capillary rise is the upward movement of water in small conduits, such as the pores in soil or porous rock, due to surface tension. In general, the capillary rise is inversely proportional to radius of the

conduit. For a conduit of constant radius, r (m), the capillary rise of water is given by: h (m) = 1.4 x 10^{-5} / r. In soils and rocks, the capillary conduits have variable radii so that the foregoing formula is not easily applicable. It remains that capillary rise is larger in fine grained soils, such as clay, and can reach values greater than 10 m. Median pore radius in Giza limestone is on the order of 1.2 to 12 µm (Fitzner et al, 2003), which would give a capillary rise of 1.2 to 12 m by simple application of the above equation. Capillary rise is also affected by evaporation and mortar. Evaporation reduces capillary rise, while mortar, depending on its composition can substantially increase capillary rise. Underground, evaporation decreases with depth so that capillary rise increases with depth to groundwater.

Based on the above, a theoretical prediction of capillary rise is tenuous. Therefore, test pits were dug at three locations in the Sphinx area to provide better estimates of capillary rise and a fourth test pit is being dug by SCA as part of the archeological excavation at the east end of the Khafre Valley Temple causeway. The locations of the test pits are shown in Figure 4-1 and the observations are described below.

Figure 4-1. Test Pit Locations

Test Pit No.1 – Wall of the Crow

This test pit was dug in sandy soil along and below the foundation of the Wall of the Crow down to the groundwater level. Photos of the test pit are shown in Figure 4-2. A distinct demarcation line between wet and dry soil was observed 1.2 m above the groundwater. This height is the capillary rise at this location. A capillary rise of 1.2 m was observed.

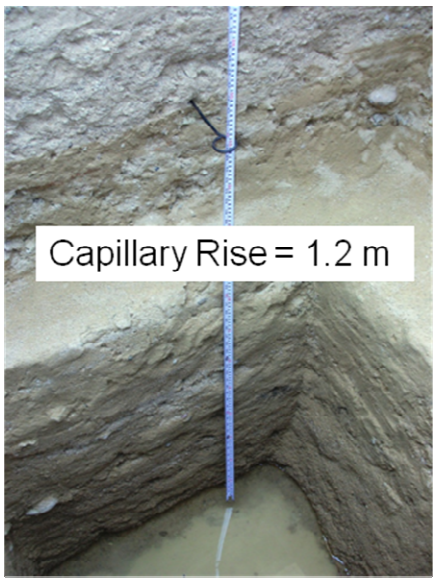


Figure 4-2. Test Pit No.1 along the Wall of the Crow

Test Pit No.2 – South of Khafre Temple

This test pit was excavated in sandy soil. Photos of the test pit are shown in Figure 4-3. A capillary rise of 1.7 m was observed. This relatively high value is somewhat surprising as capillary rise is lower in larger grain size material. However, this sandy soil contains considerable fractions of fines, which would explain the observed rise.

Capillary Rise = 1.7 m

Figure 4-3. Test Pit No.2

Test Pit No.3 – Khafre Valley Temple – East end of the causeway

This archeological excavation is being conducted by SCA to expose the limestone causeway founded on sandy material. When the excavation is completed, capillary rise will be documented.

Test Pit No.4 – Khafre Valley Temple Vestibule

This test pit, shown in Figure 4-4, was located in a previous limestone pit inside the Khafre Valley Temple that had been filled with sand and was re-excavated for this purpose. The pit did not extend down to the groundwater table, however the capillary rise of 1.4 m was computed based on the surveyed elevation of the wet limestone and groundwater levels in nearby piezometers.

Figure 4-4. Test Pit No. 4 – Inside Khafre Valley Temple

4.3 Groundwater Lowering Target Level

The antiquity features most vulnerable to the destructive effects of rising groundwater are situated at lower levels along the eastern edge of the Pyramids Plateau near the Sphinx. The antiquities situated at levels higher than 20 m above the mean sea level are considered safe from groundwater impacts.

The goal of this project is to minimize damage to the existing archeological structures on the Pyramids Plateau by lowering groundwater to practical and desirable levels. This implies keeping the top of the capillary fringe below the structures' foundations. Groundwater lowering target levels can be readily determined for structures founded on sandy materials and soil by observing capillary rise in test pits conducted at the foundations.

Most of the archeological structures and features on the Plateau and around the Sphinx are directly founded on or carved out from the bedrock such as the Great Sphinx. Groundwater lowering target levels for these antiquities are proposed based on recommendations from SCA and AERA. AERA recommendations are included in Appendix B.

Based on the above groundwater target levels of 12.5 to 13.0 m asl are proposed for the Sphinx area and 13.0 to 14.0 m for the Workers Quarters area. These target levels will bring the groundwater levels and thereby the capillary rise lower than what they were in 1990 by 1.5 to 2.0 meters.

5.0 Groundwater Lowering Alternatives

Alternative approaches to lowering groundwater levels in the Pyramids Plateau area are described below and reviewed relative to their ability to meet the project goals and their implementability at the site. The review is based on the characteristics of available dewatering methods as well as the results of previous investigations and dewatering efforts at the site. The objective of this review is to develop a short list of alternatives that have the potential for being successfully applicable at the site. The short-listed alternatives will then be further refined in Section 6 of this report based on the groundwater flow model. The alternative dewatering approaches that are considered are:

1. Source curtailment
2. Vertical wells
3. Drains in trenches
4. Drains in micro-tunnels
5. Vertical passive wells with drains
6. Horizontal wells
7. Cutoff wall(s)
8. Restarting the El Ahram well field

These approaches are described and reviewed individually below, but the overall solution may involve several approaches operating in conjunction with each other. Before reviewing these approaches, system requirements common to all the approaches are briefly outlined.

5.1 System Requirements

In addition to meeting the groundwater target level discussed in Section 4, the groundwater lowering system must account for the following requirements:

- Compatibility with the archeological sites, primarily minimum visual impact
- Minimal risk of damage to archeological resources, known and unknown (buried)
- Water disposal. The current dewatering system discharges to the sewer, but discharge to the Mansouriah Canal is believed to be more appropriate
- Passive system as much as possible, with minimum need for maintenance and human supervision
- Flexibility, particularly ability to be adjusted to better meet the target or to meet modified targets.

5.2 Alternative 1 - Source Curtailment

The rational for this alternative is that addressing the cause of a problem (when possible) is often less costly than addressing its consequences. The factors that influence groundwater levels at the site were reviewed in Section 2 and are further investigated using the groundwater model in Section 6. Several factors have an effect, but the recent groundwater level rise was due to the curtailment of pumping at the El Ahram well field, approximately 2.2 km to the north. The well field was lowering groundwater levels over a large area that extended to the site, and thus masked other effects. These other effects and means of minimizing them are listed below.

- Recharge from Mansouriah Canal. Significant portions of the canal are in clay so that leakage is not expected to be very large. Further, the canal has been culvertized over much of its length in the area of the Sphinx so that reconditioning it to increase its imperviousness may be difficult. The groundwater model was used to assess the leakage from the canal and determine whether further leak-proofing is warranted.

- Leakage from water supply pipes and sewers in Nazlet el Semman. The larger of the two factors is likely leakage from the water supply system, and measures can be undertaken to detect and repair the leaks. Such measures should be implemented as part of normal system maintenance, but complete removal cannot be expected.

- Irrigation at Mena House golf course and Sound and Light Show garden. An underdrain system has been designed for the Mena House golf course and is being implemented, and the Sound and Light garden is too small to have a significant impact.

- Irrigation in agricultural areas south of the site. Reducing this groundwater recharge would likely be difficult.

For each case, the groundwater model was used with reasonable assumptions of the flows involved to examine the effectiveness of the potential measure and their advantages, disadvantages and cost/benefit analysis is examined in Section 7.

5.3 Alternative 2 - Vertical wells

Vertical wells are one of the most common approaches to dewatering, particularly for temporary dewatering such as in construction projects. Vertical wells are distributed in the area where groundwater needs to be lowered, often at its periphery, especially when the area needs to have its groundwater lowered for another activity, such as construction, or here to avoid the archeological resources.

A system of vertical wells is already in place and operating in the Khafre Valley and Sphinx temples area, and is in place but not operating in the Workers Area. As described above, the system is effective in lowering groundwater, but additional lowering is required that would require other wells to be installed.

The current system has above ground well heads, and an entirely underground system would be possible, as shown in Figure 5-1. This system would require submersible pump in each well, with power and controls located below the ground surface inside a vault at each well and underground discharge piping systems to the appropriate discharge facilities.

Because a dewatering system involving vertical wells is already operational, this alternative is retained. The number of additional wells required will be determined using the groundwater model in Section 6 of this report.

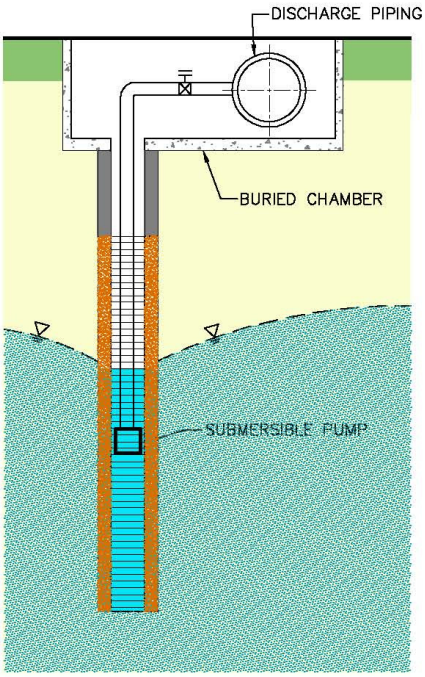


Figure 5-1. Vertical Wells

5.4 Alternative 3 – Linear Drains in Trenches

Linear drains are another common approach to dewatering, and the more frequent construction method is to place the drains in trenches excavated from the surface. The trench is typically lined with a porous geotextile and filled with uniformly graded coarse material, such as gravel, around a perforated pipe, as shown in Figure 5-2. The perforated pipe is sloped towards one or more sumps where groundwater is extracted using pumps.

Depending upon the depth of the trench, its construction may require temporary excavation support and dewatering systems; the use of polymer slurry trench construction methods; or specialized automated trenching, pipe laying and back fill material placement mechanized construction equipment, as shown in Figure 5-3. The pump station will require power and control systems.

For the Pyramids Plateau, a possible system configuration is shown in Figure 5-4. The drain is laid primarily along the fence, since this is where the ground level is lower. Two branches extending towards the west are included to lower the groundwater in the limestone area at Khafre Valley and Sphinx Temples. A single pumping station would be sufficient to service both the temples leg and the Workers Area leg. This configuration is refined using the groundwater model – see Section 6.

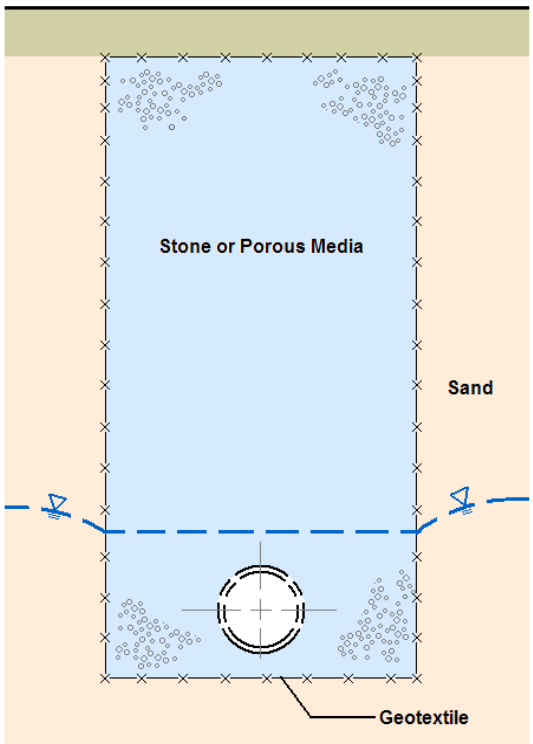


Figure 5-2. Linear Drains in Trenches

Figure 5-3. Automatic Trencher, Pipelaying and Backfill Equipment

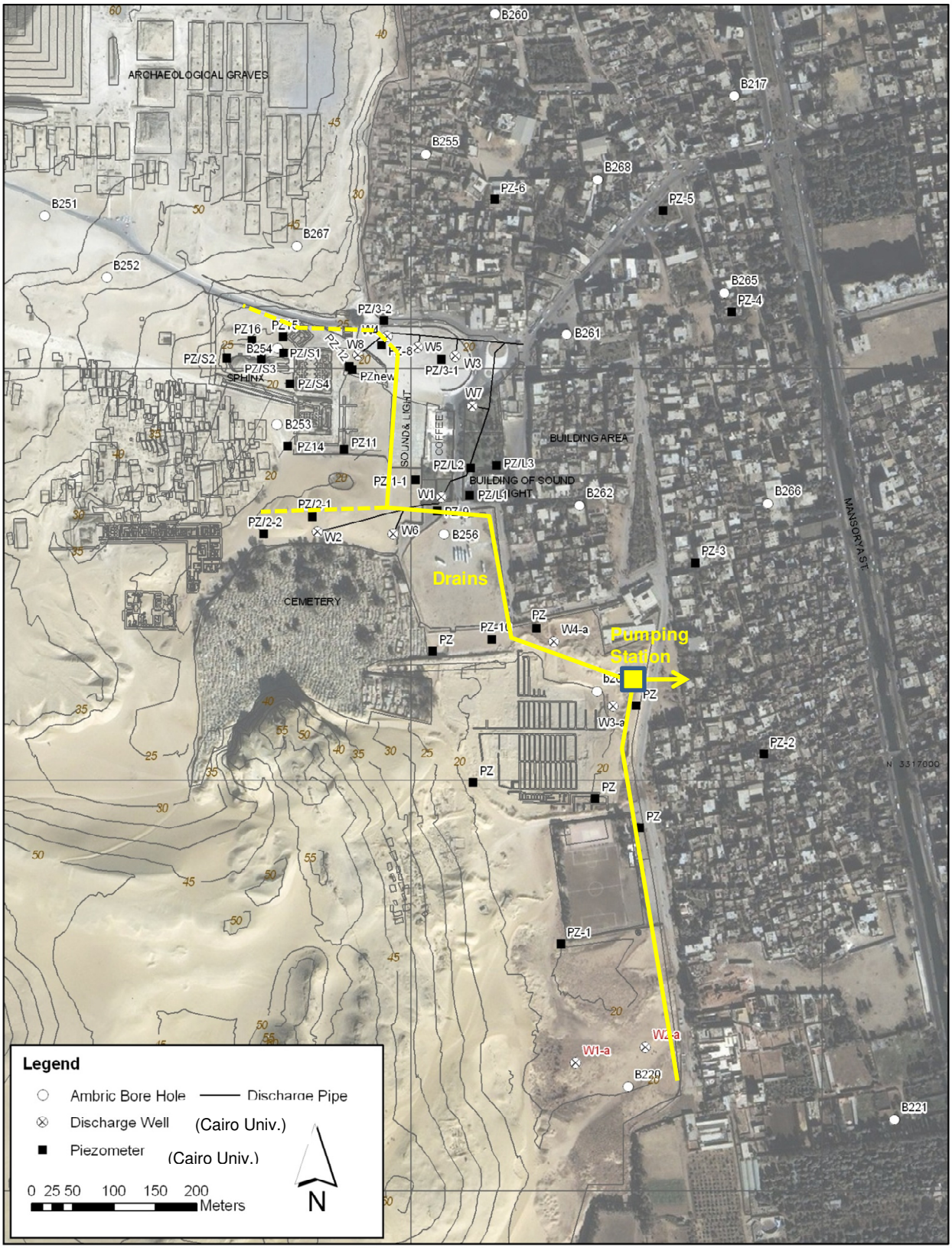


Figure 5-4 Preliminary Drain Layout

5.5 Alternative 4 – Linear Drain in Micro-Tunnel

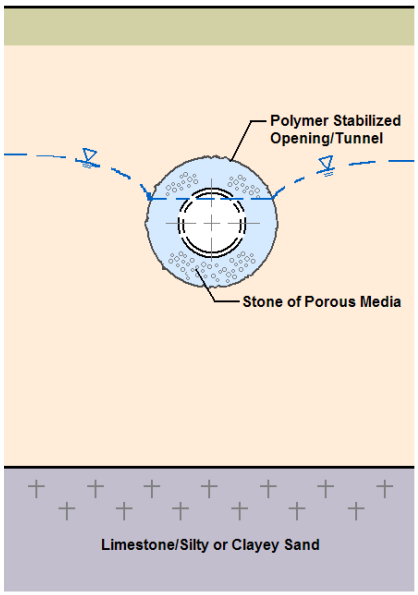


Figure 5-5. Linear Drain in Micro-Tunnel

In areas where the trench would be too deep to be constructed economically, micro-tunneling or horizontal directional drilling (HDD) can be used. A circular tunnel is excavated and filled with perforated pipe. Stone or other porous material can be placed around the perforated pipe, as shown in Figure 5-5, but this may not be necessary.

Micro tunneling or directional drilling (see Figure 5-6) or a combination of both can be utilized based upon subsurface conditions along the system route and in-country availability of equipment and knowledgeable installation specialty contractors.

For smaller diameters, HDD can be implemented as a blind hole. For this application, a 300 mm hole about 300 m long could be drilled from one location near the trench, to which it would later be connected. Biodegradable drilling mud would be used for the drilling so as not to plug up and compromise the rock porosity around the hole. After completion of the hole, a 200 mm slotted pipe would be pushed into it. There is a risk that the hole would collapse after the drill is removed and before the slotted pipe is inserted, but in that case the drill would be run one more time. Equipment would likely need to be brought in from abroad. An area 30 x 50 m would be needed for setup and the drilling of one hole would take 7 to 10 days. Additional holes (for redundancy) would take somewhat less time.

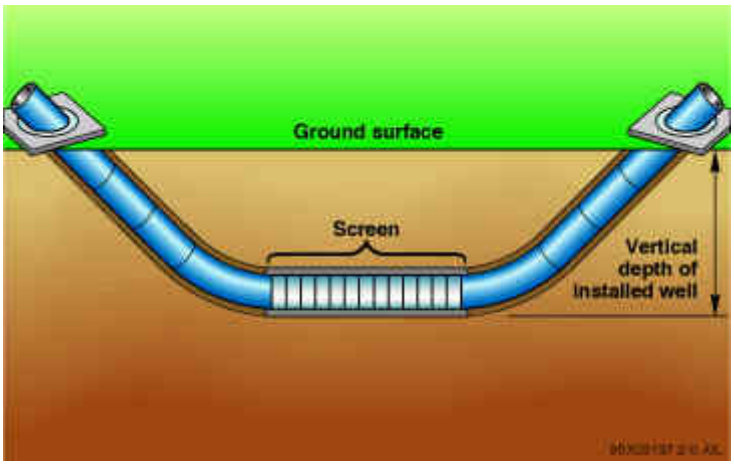


Figure 5-6. Directional Drilling

5.6 Alternative 5 - Vertical Passive Wells with Drains

Vertical wells can be combined with linear drains to increase their capacity. The vertical wells are passive in that they do not have pumps, but they access deeper strata and can bring significant flows to the drains, especially when the hydraulic conductivity of the formation in which the drain is located is low and higher conductivity material exists at greater depths – see Figure 5-7. However, the drains still have to be below the desired groundwater level to provide a low head line towards which groundwater will flow. This same lowered head in the drain drives the flow from the lower strata up the wells and into the drain.

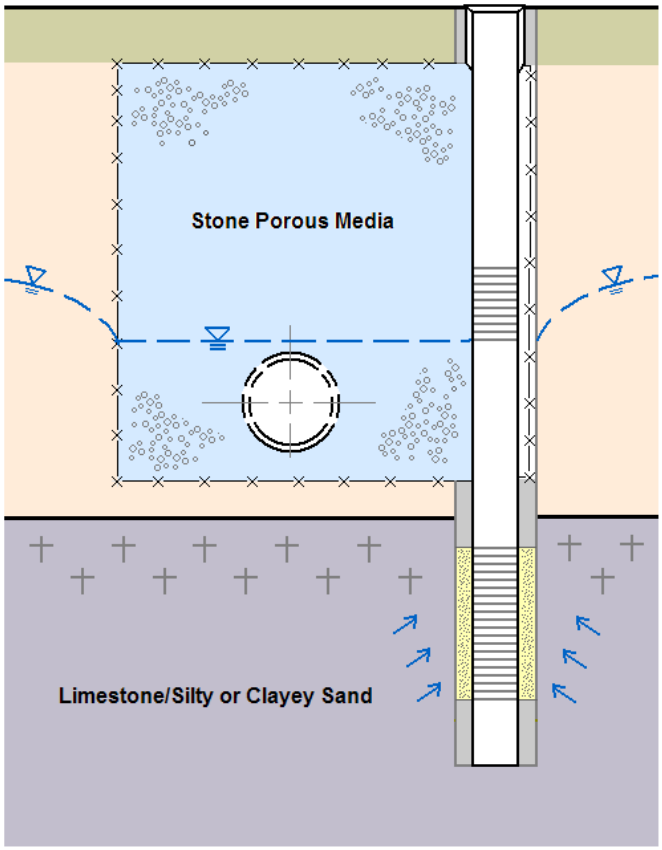


Figure 5-7. Groundwater Collection Trench with Passive Deep Wells

The main advantages of vertical passive wells combined with drains is the increased extraction flow without the need for pumps in each well. This could be used in the limestone to maximize the number of fractures and lineaments intersected by the dewatering system. This system is therefore retained as a means of enhancing the effectiveness of a linear drain system in the limestone.

5.7 Alternative 6 - Horizontal Wells

Horizontal wells, wells, include shafts, and tunnels excavated by horizontal drilling in which perforated or screened pipes are installed – see Figure 5-8. Horizontal wells have the benefit of allowing large flows (as will likely be needed here) with a limited excavation for the shafts. Horizontal wells can be seen as intermediates between vertical wells and linear drains.

Figure 5-8. Horizontal Well Installation

5.8 Alternative 7 - Cutoff Walls

Cutoff walls can be used to minimize the quantity of groundwater to be extracted. Cutoff walls can be built using sheet piling or narrow, clay-filled trenches. Cutoff walls are more effective when they can be anchored into a layer of low hydraulic conductivity at depth. They can maintain a difference of head between the two sides of the wall, as shown in Figure 5-9.

A limitation with cutoff walls is the depth they can reach. To the west of the Sphinx, ground level rises significantly and a cutoff wall would be impractical. Therefore a complete enclosure of the area where groundwater is to be lowered is not possible. However, a cutoff wall could be installed just east of the linear drain shown in Figure 5-4, along the archeological area fence. This wall would limit groundwater flow from Nazlet El Semman, and could decrease the flow of water to be pumped. On the other hand, there is no indication of low permeability material at depth, so the effectiveness of a cutoff wall would be questionable. Therefore, a cutoff wall is not thought to be a viable solution. However, if a trench is selected, a mini cutoff wall could be installed in the trench by lining its east side with an impermeable material (rather than a porous geotextile). The effectiveness of this cutoff wall would likely be small, but the cost would be minimal so that it can be considered.

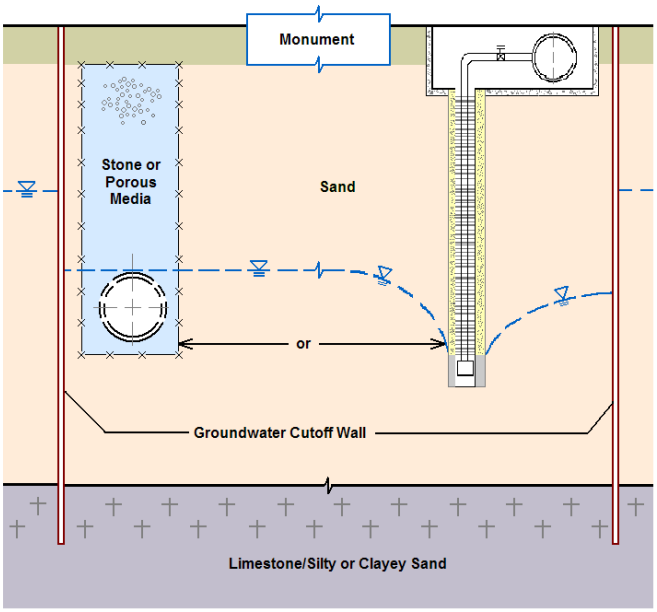


Figure 5-9. Cutoff Walls with Vertical Wells or Linear Drains

5.9 Alternative 8 - Restart of El Ahram Well Field

Analyses conducted to date show that the El Ahram well field produced a drawdown on the order of 1 m in the area of the Sphinx. This drawdown disappeared when the well field was shut down. Although the drawdown generated by the well field was not sufficient to meet the desired level of groundwater lowering, it would contribute a significant amount. We understand that the possibility of restarting the well field for the purposes of providing irrigation water is being investigated by others. However, the viability and whether or not this measure would move forward is not under the control of SCA and well field shutdown at some point in the future could not be discounted.

5.10 Next Steps

The alternatives that have been short listed here are refined using the groundwater model in Section 6.5. For example, for the vertical wells alternative, the model was used to determine how many wells would be required, assuming comparable flows with the existing extraction wells. Based on the input from the groundwater model, preliminary designs were prepared and cost estimation developed, as the basis of the cost benefit analysis presented in Section 7.

6.0 Groundwater Modeling

6.1 Groundwater Flow Conceptual Model

A conceptual model is the description of the groundwater flow regime in the area of interest and the factors that influence it, including the site geomorphology, boundary conditions and aquifer stresses, such as groundwater recharge and extractions. Development of a groundwater flow conceptual model is important before embarking in a numerical modeling exercise to ensure that the numerical model will correctly simulate the groundwater system and be suitable for its purposes (Anderson and Woessner, 1992).

Overall Groundwater Regime

In accordance with the geomorphologic structure of the area, the groundwater regime can be divided into two distinct aquifers: the alluvium and the limestone aquifers. The groundwater regime in these two aquifers is reviewed below based on previous and recent investigations. It should be noted that the understanding of the groundwater regime in the area was refined through the process of model calibration.

The Alluvium Aquifer

The alluvium aquifer in the Nile plain is divided into a lower and an upper aquifer separated by a clay and silt aquitard. Available information from the AMBRIC study suggests that the thickness and integrity of the aquitard diminish towards the Pyramids Plateau, as shown previously in Figure 2-3.

The Mansouriah Canal appears to be located in an area where the aquitard is consistent, based on the fact that the piezometric heads measured during the AMBRIC study in the upper aquifer were up to about 4 m higher than in the lower aquifer (see Figure 2-4). The head in the upper aquifer at the location of the Mansouriah canal was on the same order as the canal water surface elevation. This would indicate good hydraulic connection between the canal and the aquifer. Since the time of the AMBRIC study, much of the canal has been covered and lined, so that the degree of hydraulic contact has likely been reduced.

The area between the Mansouriah Canal and the Pyramids Plateau is occupied by Nazlet El Semman, which is densely populated. As in all developed areas, leakage of the water supply and wastewater collection system is likely. The corresponding recharge to the groundwater system would contribute, in addition to leakage from the Mansouriah Canal, to the higher groundwater levels observed in the upper aquifer.

Based on the above, and the groundwater levels measured during the AMBRIC study - shown in Figure 2-3 – a groundwater regime can be hypothesized in which recharge occurs from the Mansouriah Canal and leakage in Nazlet El Semman, generating a groundwater flow towards the west in the upper aquifer, to the point where the upper and lower aquifers join. There, the groundwater flow turns vertically downward and back towards the Nile in the lower aquifer. Indeed, the hydraulic gradient in the lower aquifer was towards the Nile.

The Limestone Aquifer

Groundwater in the limestone aquifer was found to be of drinking water quality during the AMBRIC studies, in the late 1980s, with a very low hydraulic gradient, indicating very low movement. Based on the fact that groundwater levels fluctuate in the alluvium, but remain relatively steady in the bedrock, the AMBRIC study concluded that the two aquifers were distinct, with little groundwater exchange. As

will be shown in the model calibration section, this conclusion is confirmed by the model, although the cause of the apparent aquifer separation is not readily apparent. Further, the rise of the groundwater level in the limestone that was recently observed was likely due to a rise of groundwater level in the alluvium. Therefore, the two aquifers are not completely isolated from each other.

The low hydraulic gradient observed during the AMBRIC study is consistent with the fact that recharge from precipitation is very small. The AMBRIC measurements, however, did not extend far into the limestone aquifer. New piezometers installed for this study along the Fayoum Road have confirmed a low hydraulic gradient in the area.

6.2 Groundwater Numerical Model Development

Modeling Software

The modeling software utilized for this application is MODFLOW, developed by the USGS and used throughout the world (Harbaugh et al., 2000). MODFLOW is a public-domain, three-dimensional finite-difference ground-water flow model that was first put forth in 1984 and has been continuously upgraded since. It has a modular structure that allows it to be easily modified for a particular application. Many new capabilities have been added to the original model.

MODFLOW simulates steady and unsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of the two. External stresses, such as wells, areal recharge, evapotranspiration, drains, and rivers, can be simulated. Hydraulic conductivities or transmissivities for any layer may vary spatially and be anisotropic (different in different directions), and the storage coefficient may be heterogeneous. Boundary conditions, which need to be specified at the periphery of the model domain can be i) specified head, ii) specified flux and iii) head dependent flux. In the latter, the flow across the model boundary is proportional to the head difference between a "source" of water outside the modeled area and the boundary block. In addition to simulating ground-water flow, the scope of MODFLOW has been expanded to incorporate related capabilities such as solute transport and parameter estimation.

MODFLOW solves the ground-water flow equation using the finite-difference approximation. The flow region is subdivided into cells in which the medium properties are assumed to be uniform. In plan view, the cells are made from a grid of perpendicular lines that may be variably spaced. Model layers can have varying thickness. The groundwater flow equation is solved for each cell, resulting in the piezometric head at the center of that cell and the groundwater flow direction and magnitude. Several solvers are provided for solving the resulting matrix problem; the user can choose the best solver for the particular problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

For this application, MODFLOW was implemented using the GMS (Groundwater Modeling System) graphical user interface initially developed at the Brigham Young University and put forth by Aquaveo, a private company. This user interface facilitates model development and calibration, as well as analysis of the results. In particular, GMS allows results to be plotted in a number of different ways.

Model Setup

The model coverage is shown in Figure 6-1, including portions of both the alluvial and limestone aquifers. The grid extends sufficiently far from the immediate area of the Sphinx to minimize boundary effects on the predictions. The grid includes the major elements that may affect

groundwater conditions at the site including the Mansouriah Canal, the Mena House golf course, developments along Fayoum Road and the El Arham well field. The latter is at the edge of the model grid, which limits simulation of its entire zone of influence. The approach implemented in this model was to assume that half of the well field flow comes from outside of the model grid, and, thus, only half of the well field flow was input to the model. Reasons for this approach were a desire to limit the model extent and the fact that hydrogeological conditions north of the well field are not known.

The model extent is 4,000 m x 4,000 m, with a cell spacing of 10 m x 10 m. Based on planned uses for the model and set boundary conditions, cells in the first two layers to the east of the Mansouriah Canal were inactivated. The resulting number of active cells in the model is 434,380.

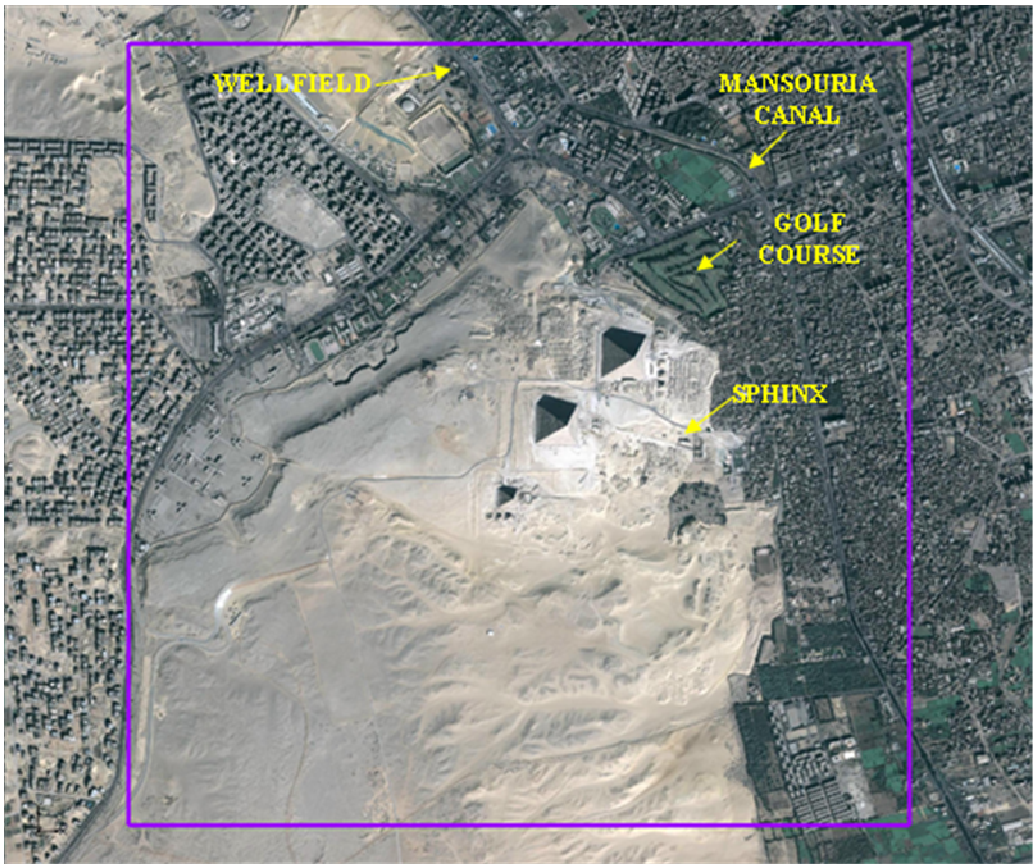


Figure 6-1. Model Extent

Surface elevations for most of the model grid were generated from a 1990 Egyptian Survey Authority map. Surface elevations beyond the available data were estimated based on boring ground elevations and extrapolation of data. The bottom of the model was set at a constant elevation of -32 m asl. This elevation was established based on the deepest boring data available. The actual aquifer depth is properly accounted for through the specification of the equivalent hydraulic conductivity.

Model Stratigraphy

Available soil data (both historical and recent borings) were utilized to generate stratigraphy across the model domain. Estimates of the stratigraphy at the edge of the model grid and in areas with limited borings were developed based on knowledge of the area's geology. Figures 6-2 and 6-3 present the available boring locations associated with the area of interest. In total, over 70 borings were available. Utilizing this information, a conceptual stratigraphic model was developed (see Figures 6-4 through 6-7) for use in developing the numerical model layers. The stratigraphic model

was modified to avoid features that would cause model instabilities, while keeping the same overall configuration.

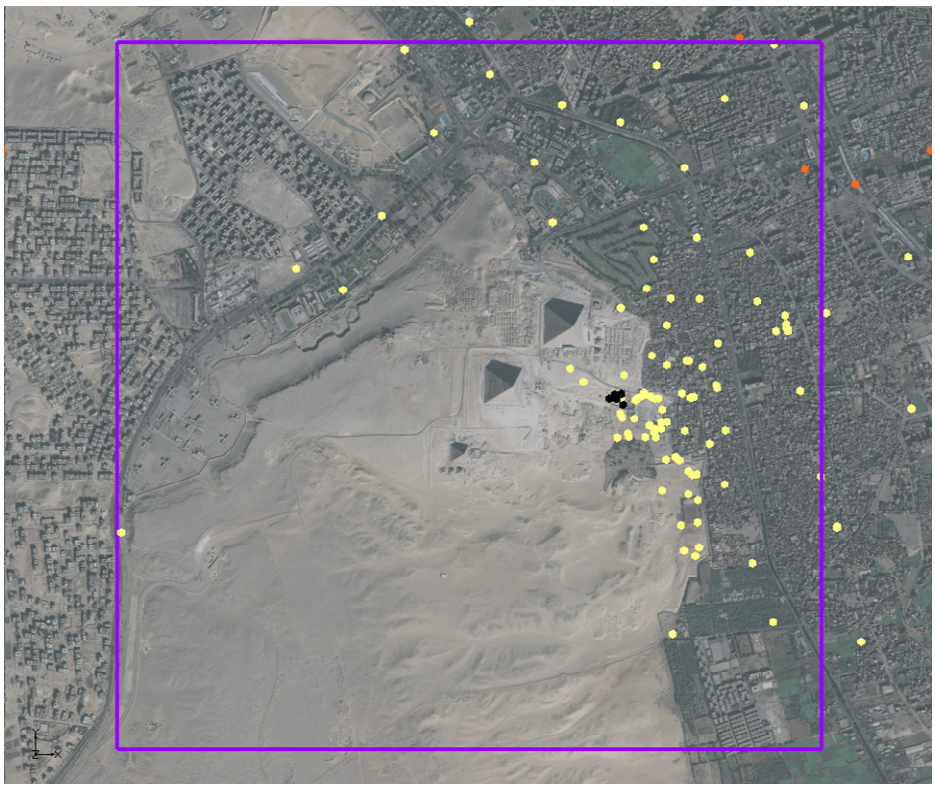


Figure 6-2. Borings in the Model Grid Vicinity

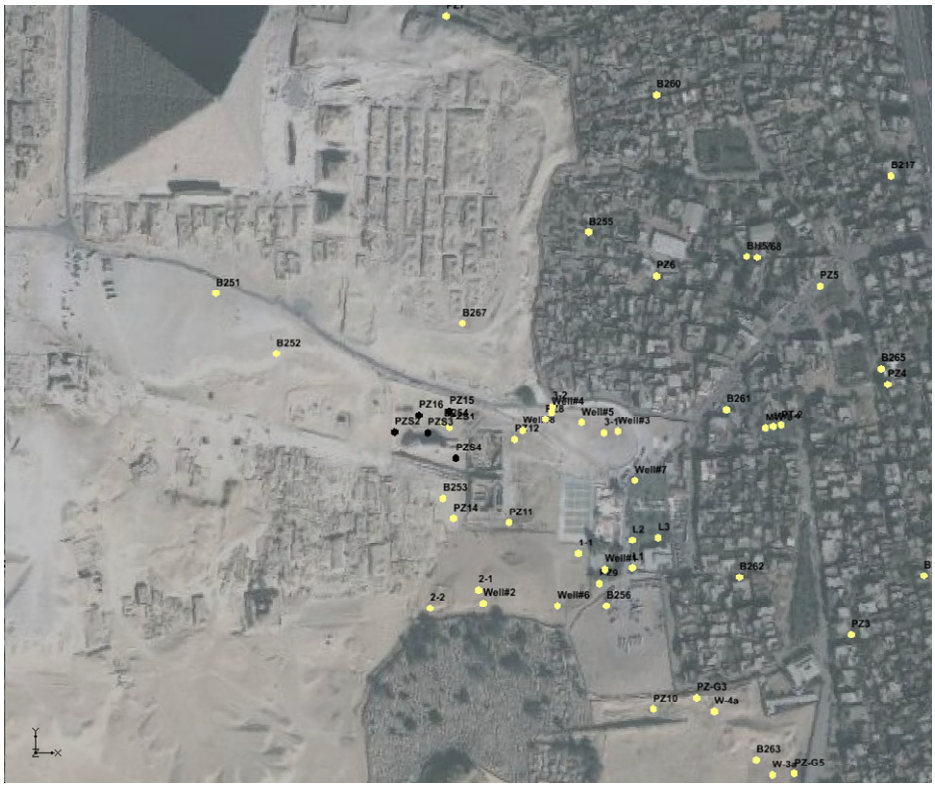


Figure 6-3. Borings in the Sphinx Area

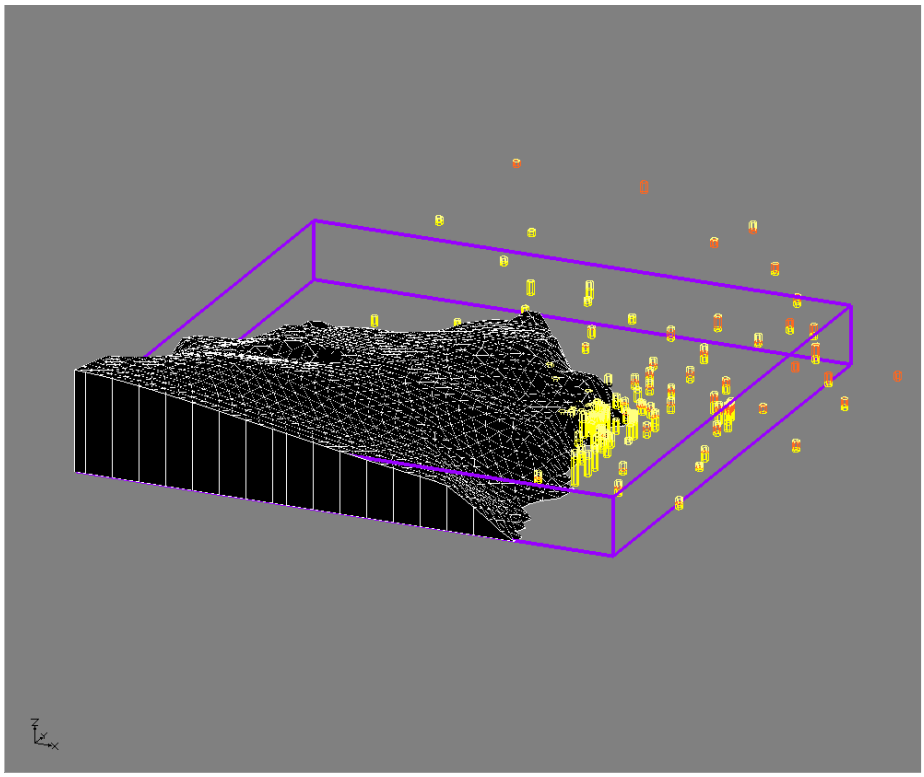


Figure 6-4. Stratigraphic Conceptual Model – Limestone Layer

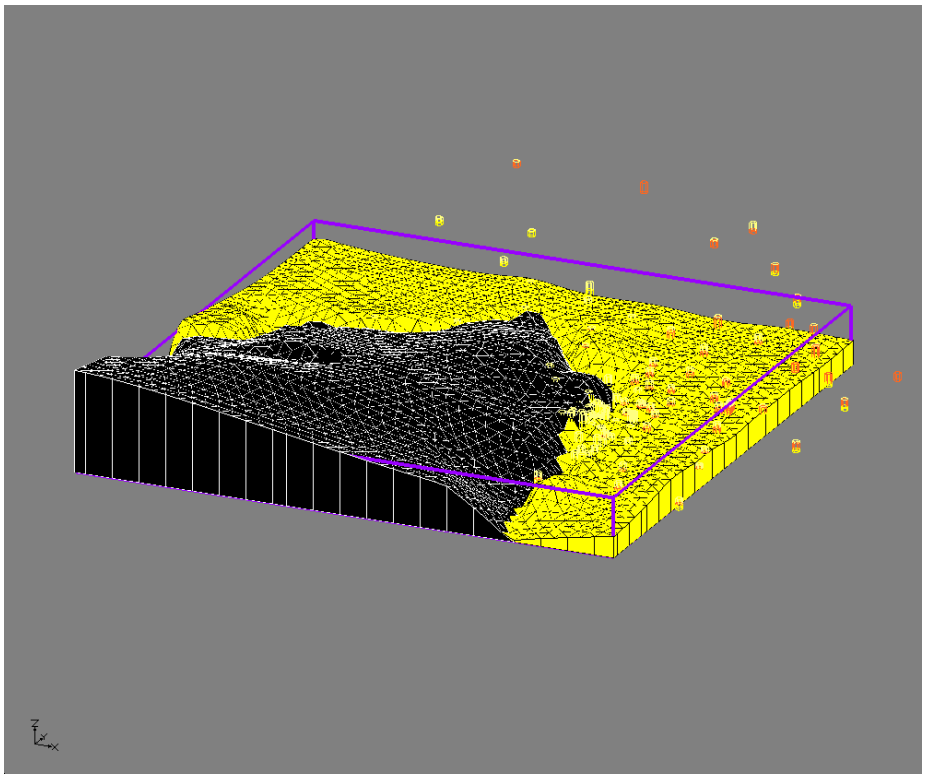


Figure 6-5. Stratigraphic Conceptual Model – Lower Sand and Gravel Layer

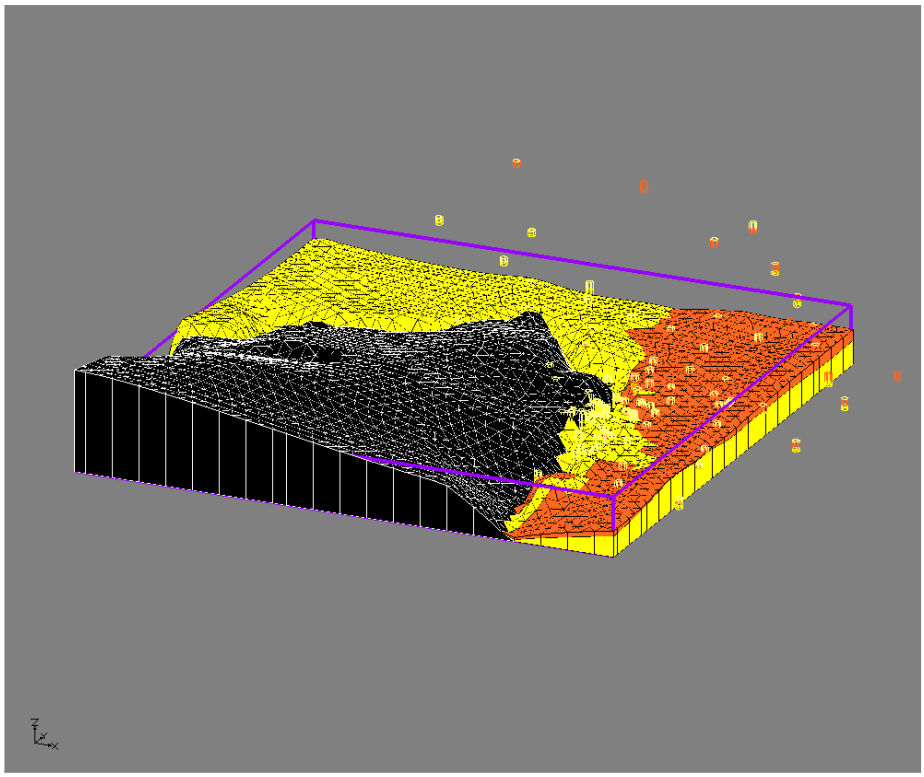


Figure 6-6. Stratigraphic Conceptual Model – Clay Layer

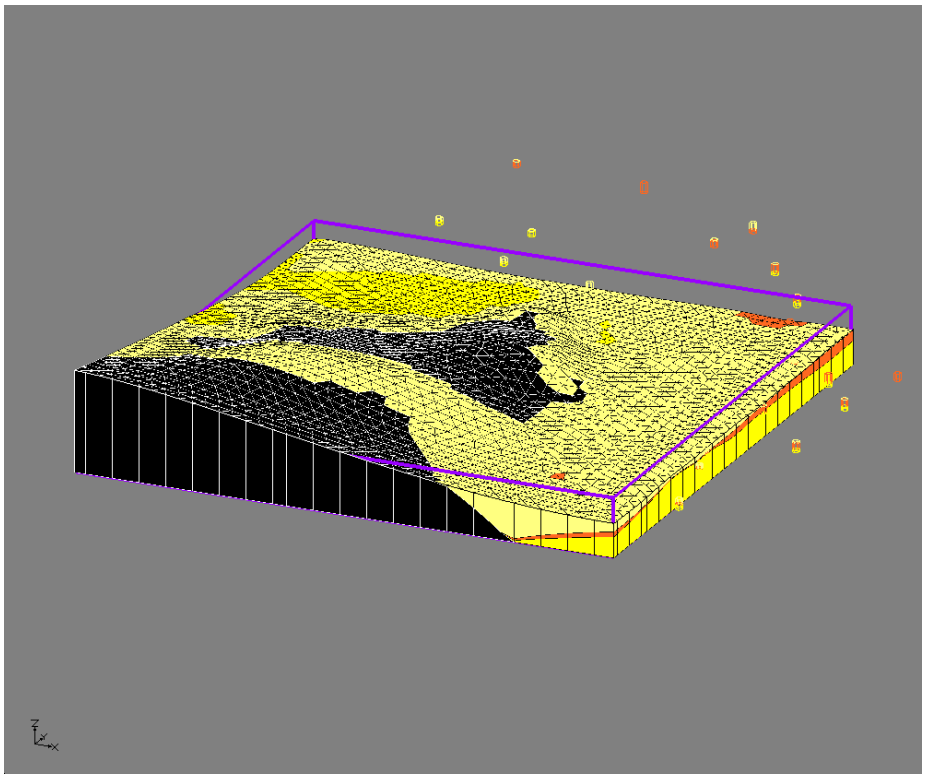


Figure 6-7. Stratigraphic Conceptual Model – Upper Sand and Fill Layer

In order to account for the stratigraphic features of importance to the groundwater flow regime in the area, the model was designed to have three layers. In the alluvial area, the three layers represent, from the top down, 1) the perched zone, with partial hydraulic connection with the Mansouriah Canal and input from water supply and wastewater leakage from Nazlet El Semman, 2) the confining clay layer, and 3) the lower member of the alluvium, which is connected with the Nile River. In the limestone aquifer area, the three layers simulate the bedrock aquifer. Top and bottom elevations for the clay layer were developed through the use of available soil boring data.

Aquifer parameters for the different formations were initially specified based on previously developed information, as well as data collected in the field testing as part of this study. The main aquifer parameter to be specified in the model is its hydraulic conductivity, K, which can be determined from pumping tests. Those provide the aquifer transmissivity, T, which is related to the conductivity by T = K H, where H is the aquifer thickness. Also important, but to a lesser degree, is the specific yield or storage coefficient, which controls the speed at which stresses propagate in the aquifer. Available data are summarized in Table 6-1 and presented graphically in Figure 6-8.

Table 6-1. Aquifer Parameter Data

Location	Source	Formation	Transmissivity (m^2/day)	Specific Yield
Cheops Pumping Station, Nazlet El Semman	AMBRIC	Alluvium	1,750	
Sphinx Well No.1	Cairo University*	Alluvium	944	0.35
Sphinx Well No.2	Cairo University*	Maadi Limestone	5,400	0.024
Sphinx Well No.3	Cairo University*	Alluvium Wadi area	3,070	0.024
Near Mena House	AECOM	Alluvium	894	0.5
Workers Area	AECOM	Alluvium	2,886	0.025
Nazlet El Semman	AECOM	Alluvium	1,625	0.25

* Reanalyzed by AECOM

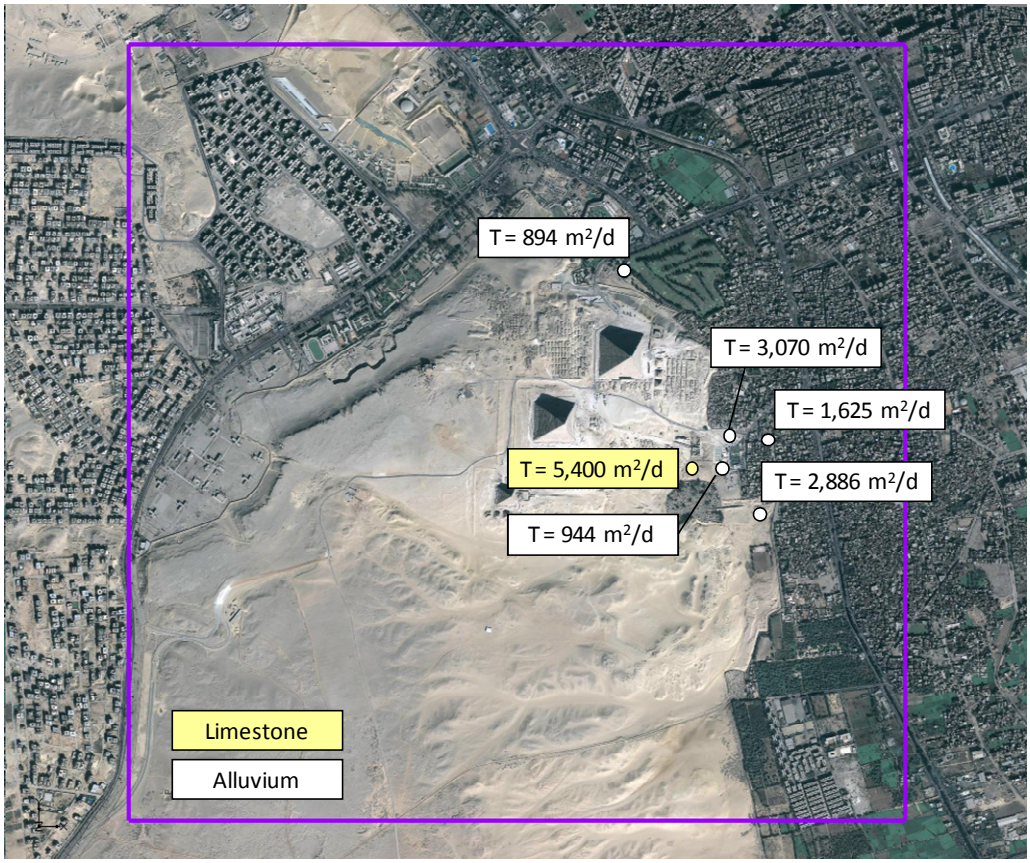


Figure 6-8. Measured Transmissivities

This information was used to initialize aquifer parameters prior to model calibration (see Section 6.3) and adjustments were made in an attempt to match these field measurements as closely as possible. Figures 6-9, 6-10 and 6-11 present the post-calibration material hydraulic conductivities in each layer. As the aquifer thickness in most of the model is approximately 47 m, this may be used to convert the conductivities to transmissivity.

Following calibration, the resulting conductivity for limestone in layers 1, 2, and 3 was 115 m/day (T = 5,405 m^2/day). This compares well with that shown in Table 1. While it is not expected that this magnitude of transmissivity exists throughout the limestone, use of this value provided favorable calibration results. Evidence that the limestone is, as expected, heterogeneous was determined during calibration when it was necessary to include tighter material (0.01 m/day) along the interface of the limestone and alluvium. This magnitude is not unusual for rock; however, it is unusual for horizontal flow to be as limited in limestone as field measurements showed that it was along that interface.

The hydraulic conductivity of the lower alluvium in layers 2 and 3 was primarily 50 m/day (T = 2,350 m^2/day), which is in the middle of available pump test results. The northeast zone in layer 3 was 25 m/day (T = 1,175 m^2/day), which is slightly above the result from the pump test near Mena House. There is little data on the northwest corner of the model. However, based on boring information, it appears that there may be significant amounts of clay in that area. During calibration, lowering the conductivity of that area significantly, as if it were clay, provided improved results. This area is assumed to be clay-like with a conductivity of 3 m/day.

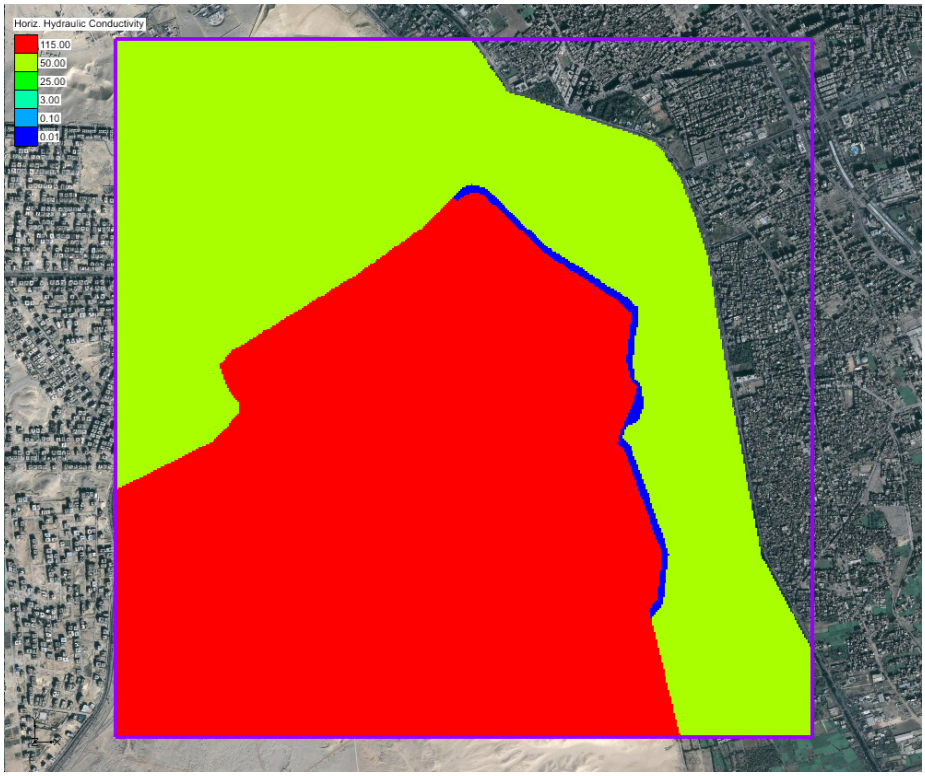


Figure 6-9. Hydraulic Conductivity (m/day) – Layer 1

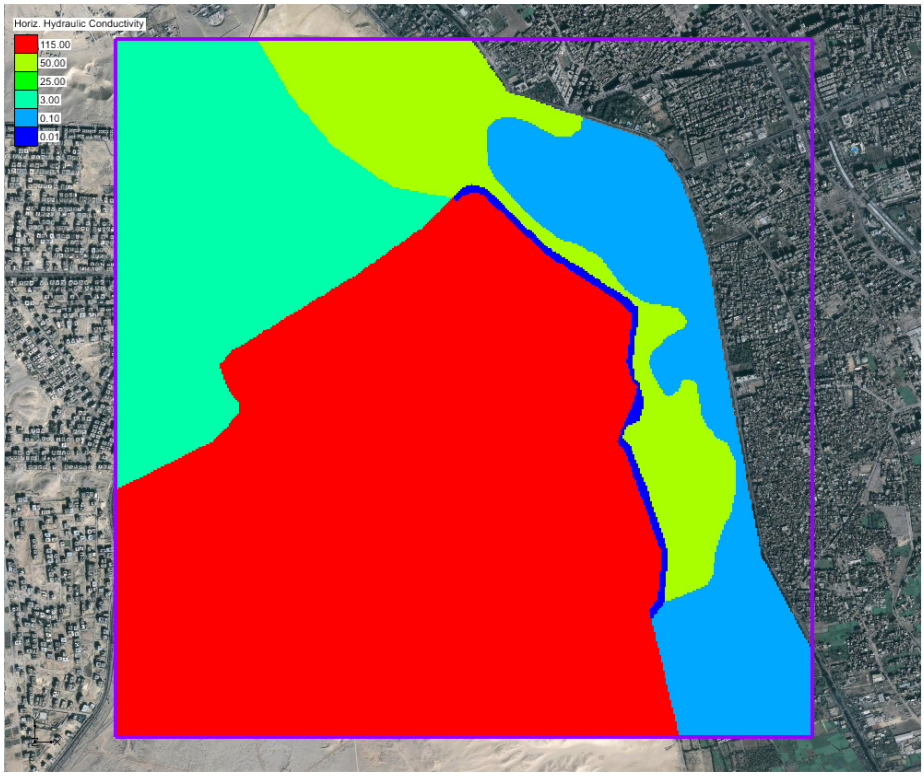


Figure 6-10. Hydraulic Conductivity (m/day) – Layer 2

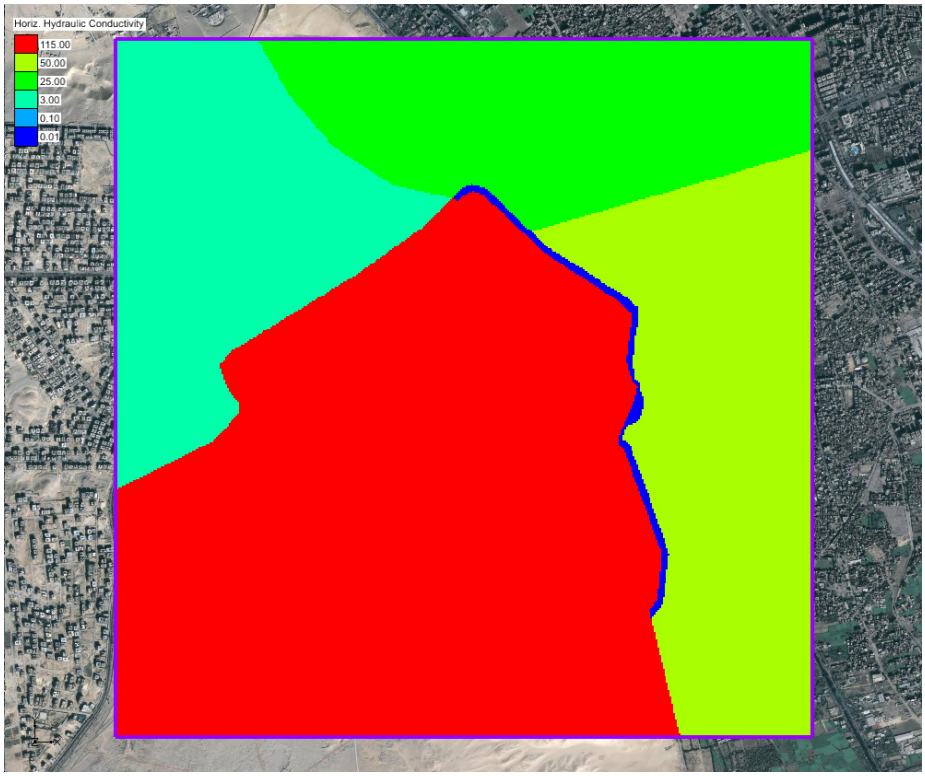


Figure 6-11. Hydraulic Conductivity (m/day) – Layer 3

The hydraulic conductivity of the confining clay in layer 2 was assumed to be 0.1 m/day, while the upper alluvium sand and fill was assumed to be 50 m/day. Additionally, vertical hydraulic conductivity was assumed to be 1/10 of horizontal conductivity except for limestone (1/1).

Boundary Conditions

Boundary conditions were assumed as follows (values presented are post-calibration):

- West boundary: specified head (linear north to south 15 to 15.2 m asl) based on groundwater measurement at a monitoring well (MW-6) installed as part of the project.

- North boundary: No flow, meaning that groundwater flow in the area was assumed to be parallel to the boundary. This is obviously an approximation; however, this boundary is far enough from the Sphinx to ensure minimal effects in the area of interest.

- South boundary: No flow, with the same comments as for the north boundary.

- East boundary:

    - Lower layer: head-dependant flow boundary based on water level in the Nile River and data from the AMBRIC study (linear north to south 15 to 16 m asl; conductance for ¾ of the boundary equal to 50 m^2/day, while the remaining ¼ of the boundary in the northwest was 0.1 m^2/day, based on significant clay in the area).

    - Middle layer: No flow, since any (limited) groundwater flow in this layer will be vertical, between the two layers, rather than horizontal, because the horizontal gradient is much smaller than the vertical gradient.

- Top layer: Partial hydraulic connection with the Mansouriah canal, simulated in MODFLOW as head-dependant flow, with a conductance determined during model calibration (generally linear north to south 18.5 to 19 m asl based on recorded measurements; conductance ranging from 0.1 m^2/day to 5 m^2/day).

Recharge

There are several potential sources of groundwater recharge in the area, and those are discussed below, with initial estimates developed. Figure 6-12 presents the applied recharge following calibration.

- Precipitation recharge. Average annual rainfall in Cairo is 29 mm, essentially between November and May. This rainfall amount is very small and the corresponding aquifer recharge is likely minimal. In the developed area of Nazlet El Semman, a significant fraction of the rainfall runs off on impervious pavement and into the drainage system. On the Pyramids Plateau, groundwater is deep in most areas, so that percolating rainfall will likely evaporate before reaching the water table.

- Recharge from leakage in Nazelt El Semman. The 2010 population of Nazlet El Semman is 48,300, with a water consumption of 19,000 m^3/day. The unaccounted for water is on the order of 30%, but a portion of that is un-metered water and leakage can be assumed to be on the order of 15 to 20%. Assuming 17% (3,230 m^3/day) applied over an area of 820,911 m^2, results in an average of 0.0039 m/day.

  Leakage from the sewers is likely small since pressures are limited, in contrast with the water supply system. In fact, groundwater discharge from the sewers is likely in spots. Measured bacteria TDS and nitrate levels in the groundwater can be used to develop estimated sewer system leakage. Relatively high concentrations were observed in some of the groundwater analyses that were performed by Cairo University (Cairo University, Feb 2008), but the high values were at wells close to the Sphinx, while wells closer to or in Nazlet El Semman had low values.

- Mena House Golf Course Irrigation. A recharge rate of 420 m^3/day was estimated by ECG. This rate applied over an area of 158,168 m^2, results in an average of 0.0027 m/day.

- Fayoum Road Development and Other Surrounding Developments. Based on review of an aerial photo, recharge was applied to areas outside of the golf course and Nazelt El Semman which appear to require irrigation to sustain plant life. Similar to Nazelt El Semman, not enough information was available to establish a set recharge rate, and initial assumptions of recharge rates were applied, followed by adjustment during calibration. North of Mena House Golf Course, a rate of 0.0001 m/d was applied over an area of 811,877 m^2. A recharge rate of 0.0026 m/day was applied to an agricultural area (843,184 m^2) in the southeast corner of the grid and 0.0005 m/d was applied in the northwest corner (assumed clay area; 1,859,801 m^2).

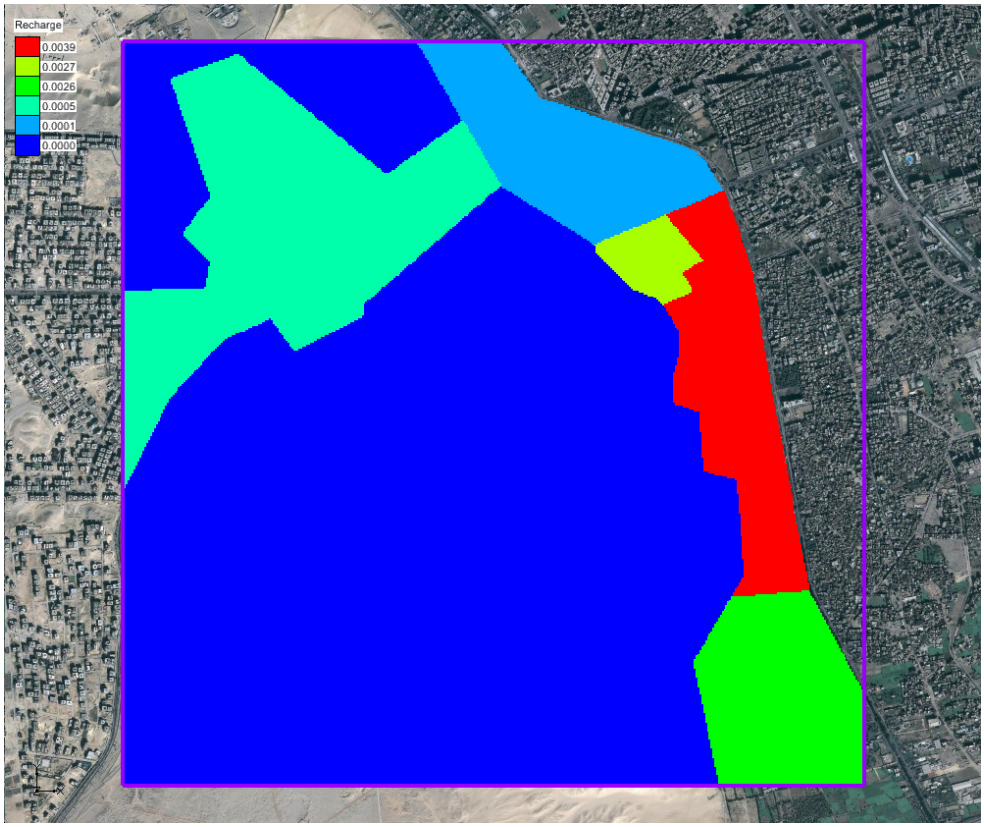


Figure 6-12. Applied Recharge (m/day)

6.3 Numerical Model Calibration

Flow model calibration was performed for multiple scenarios, based on the available groundwater measurements collected during various investigations. While there was some uncertainty associated with stresses on the aquifer at the time measurements were collected for some scenarios (e.g., recharge, well field and surrounding irrigation well extraction rates, canal and river elevations), assumptions were utilized to simulate average conditions for each scenario.

Four calibration scenarios were evaluated:

- Pumping – El Ahram well field in operation (1970 to September 2005)
- No Pumping – El Ahram well field shut down (September 2005 to July 2008)
- Dewatering – Dewatering wells operating near the Sphinx (July 2008 to 2010)
- Dewatering Well Recovery – 5-day test with dewatering pumps turned off (February 2010)

Each of these scenarios is discussed further below. Adjustments were made to various hydraulic characteristics of the aquifer and boundary conditions to balance the results for all four scenarios. Resulting values for each parameter were presented in Section 6.2.

As calibration adjustments are performed, the GMS software calculates calibration error to help the user determine overall differences between observed and calculated heads. The values of interest include mean error and mean absolute error. When the mean error is 0, differences between points that are calculated high (positives) are offset by those calculated low (negatives). The mean absolute error takes the absolute value of all negative differences and then calculates a total average. This value shows the average difference between the calculated values and the observed values.

Calibration Scenario 1 – El Ahram Well Field in Operation (Pumping Scenario)

Flow rates extracted from the El Ahram well field averaged approximately 25,000 m^3/day. Half the flow is assumed to come from beyond the northern no-flow boundary, so a well was placed in the lower layer of the model (lower alluvium) drawing a flow rate of 12,500 m^3/day. Calculated results were compared to observed elevations used in the AMBRIC 1990 report (January and February 1989) to generate groundwater contours (see Figure 2-4).

In this scenario, the mean error shows that, overall, the calculated values are 0.31 m high. The mean absolute error shows that the average difference between calculated and observed values is 0.89 m. Visual review (see Figure 6-13) shows most piezometer groundwater elevations match well in the Sphinx area limestone, but are slightly high in the alluvium.

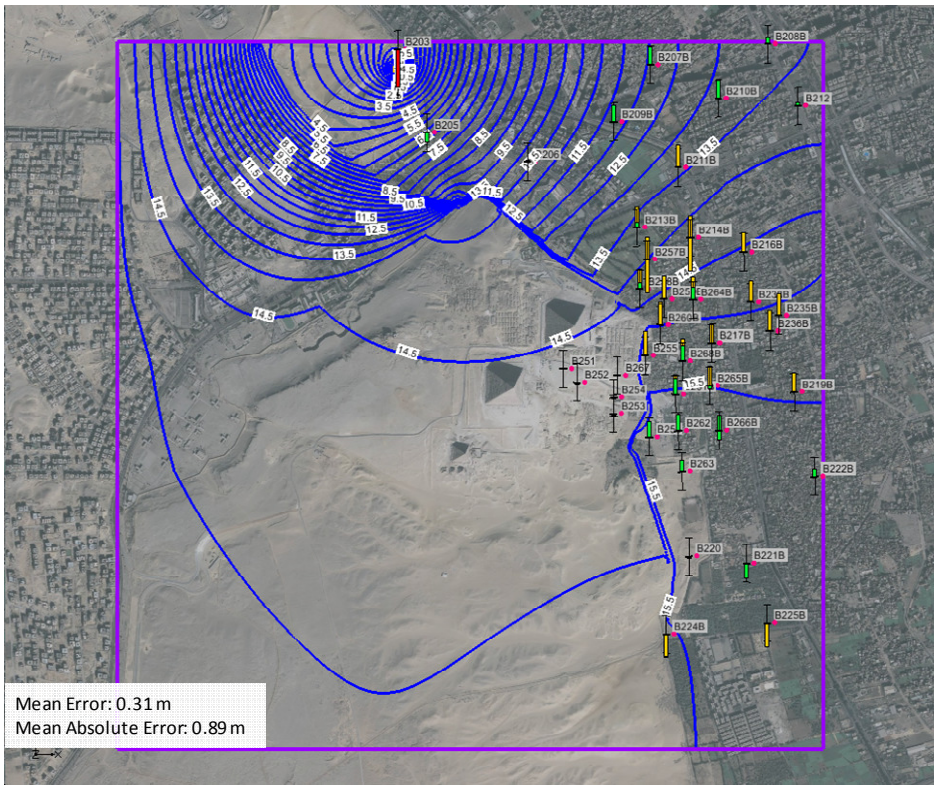


Figure 6-13. Pumping Scenario Calibration Results

Calibration Scenario 2 – El Ahram Well Field Shut Down (No Pumping Scenario)

Partial shutdown of the El Ahram well field began in September 2005, with full shutdown in March 2006. Calculated results were compared to average observed piezometer readings around the Sphinx between 11/20/07 and 01/24/08. Initially, a steady-state run was performed with total well field shutdown. Afterwards, a transient run was performed based on partial shut-down of the well field. Results were only marginally different.

In this scenario, the mean error shows that, overall, the calculated values are 0.45 m high. The mean absolute error shows that the average difference between calculated and observed values is 0.46 m. Visual review (see Figure 6-14) shows most piezometer groundwater elevations as slightly high, but close to measurements in the Sphinx area limestone.

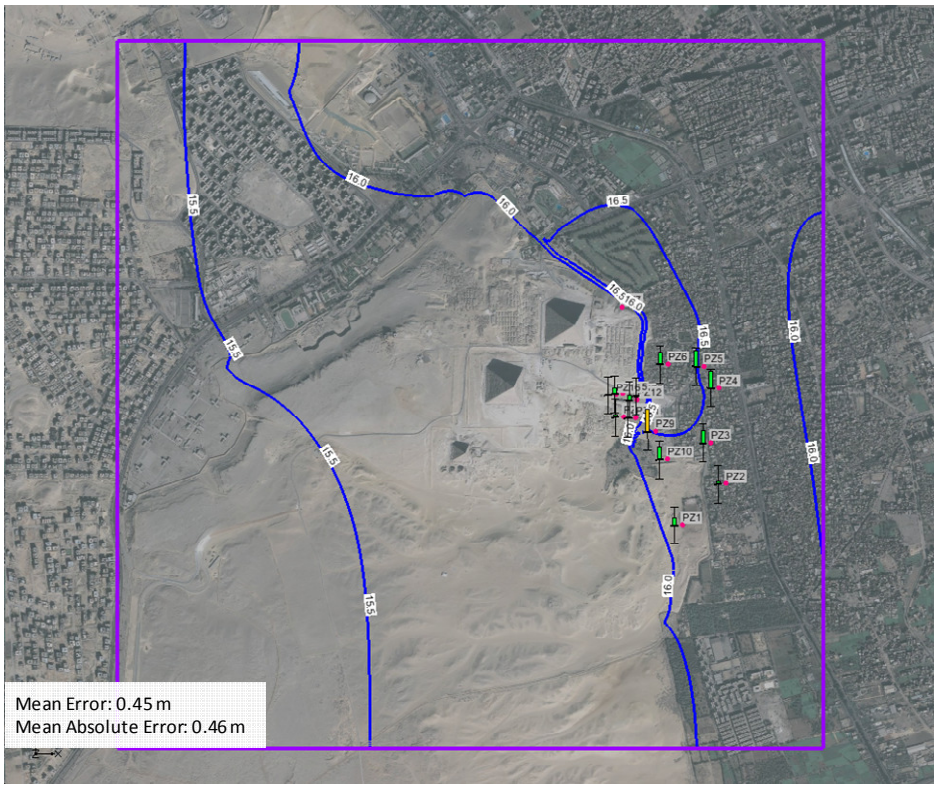


Figure 6-14. No Pumping Scenario Calibration Results

Calibration Scenario 3 – Dewatering System in Operation (Dewatering Scenario)

Under this calibration scenario, a transient run was performed to simulate the eight dewatering wells operating near the Sphinx for a year (July 2008 through June 2009). Calculated results were compared to observed piezometer readings around the Sphinx from 06/30/09 and appeared to be consistent.

Additional calibration information which was utilized in this scenario:

- El Ahram average well field observation from 02/16/10 – 15.33 m
- Mena House pre-pump test (PT-1) elevations – average observation of approximately 15.4 m
- Nazlet El Semman pre-pump test (PT-2) elevations – average observation of 13.2 m
- Workers Area pre-pump test (PT-3) elevations – average observation of approximately 13.8 m

In this particular case, the mean error shows that, overall, the calculated values are 0.01 m high. The mean absolute error shows that the average difference between calculated and observed values is 0.22 m. Visual review (see Figure 6-15) shows a very good match all around. The outer calibration points (Workers Area and PT-2) also match very well.

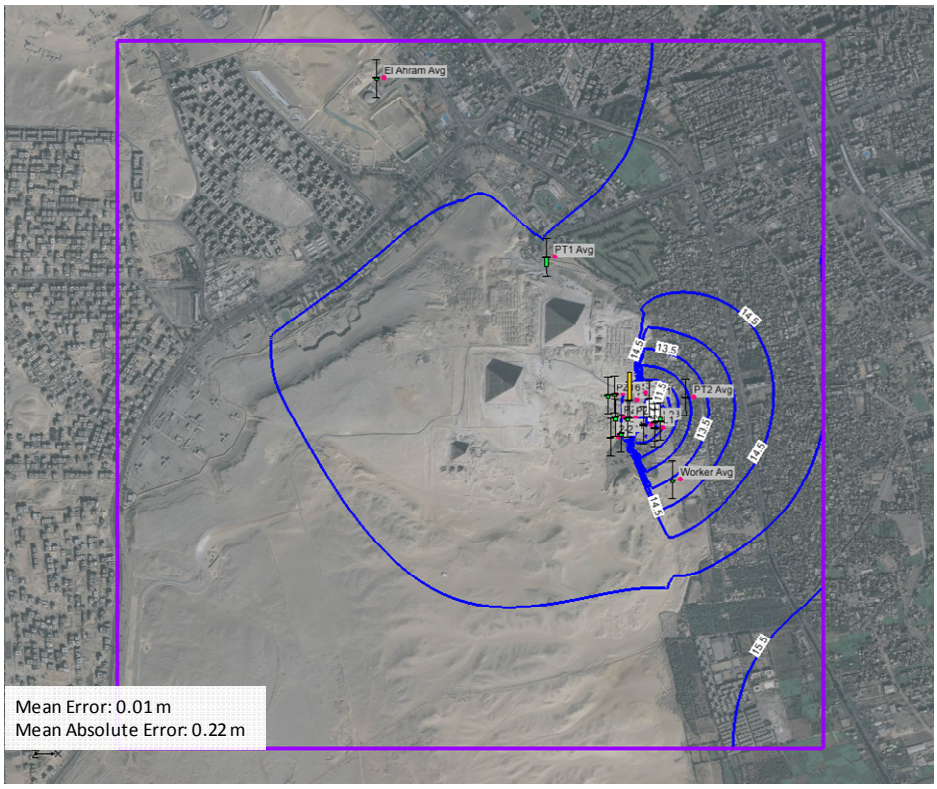


Figure 6-15. Dewatering Scenario Calibration Results

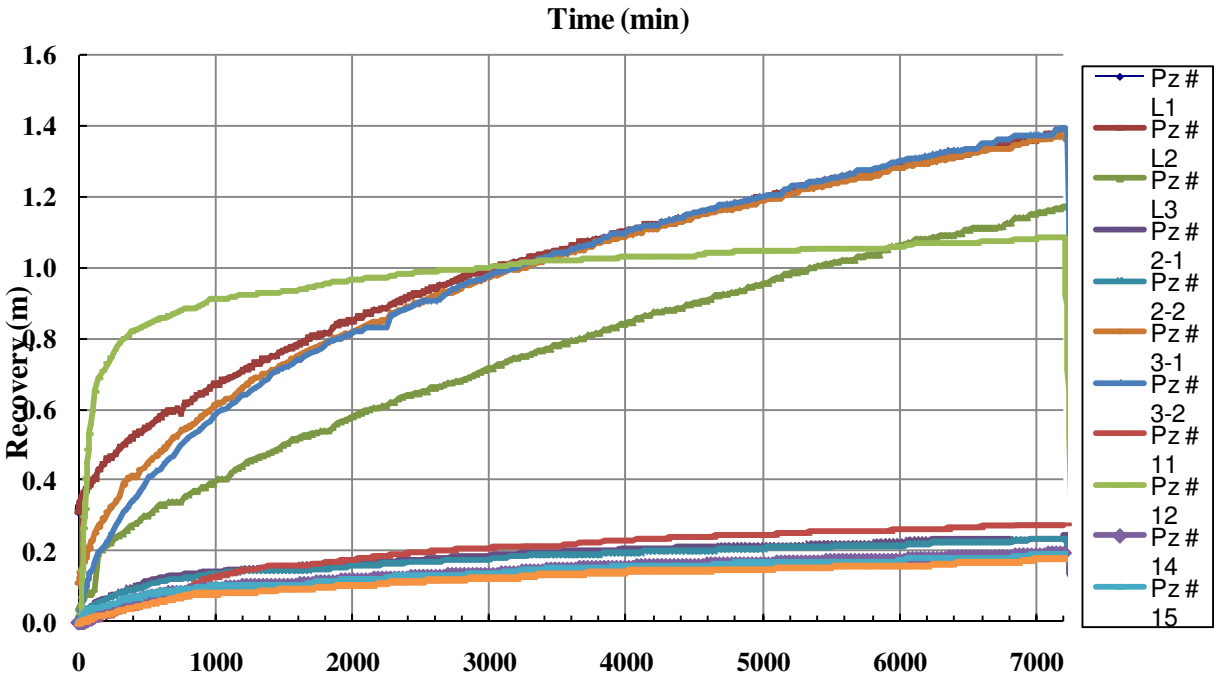
Calibration Scenario 4 – Recovery Following Dewatering System Shut Down (Recovery Scenario)

For this calibration scenario, the dewatering wells were turned off for 5 days. The modeled recovery rates were similar, albeit slightly higher, to those measured during the field tests (see Figure 6-16). Of particular importance is the fact that the model correctly reproduces the difference in response of the limestone and alluvium aquifers.

Calibration Summary

The model was calibrated using four different scenarios with stresses of different nature and location. This level of calibration is considerably more extensive than in most groundwater models, where a comparable number of conditions with accompanying measurements is usually not available. The fact that the model was able to closely reproduce these four sets of conditions provides confidence that it appropriately simulates the Pyramids Plateau aquifer system. In particular, the observed hydraulic discontinuity between the limestone and alluvium aquifer is reproduced in the model.

Groundwater flow modeling, however, always retains an inherent and unavoidable level of uncertainty. This is particularly true for limestone aquifers in which flow occurs in fractures and lineaments that are non-uniform, spatially variable and incompletely known. This level of uncertainty must be taken into account in the interpretation of model results.



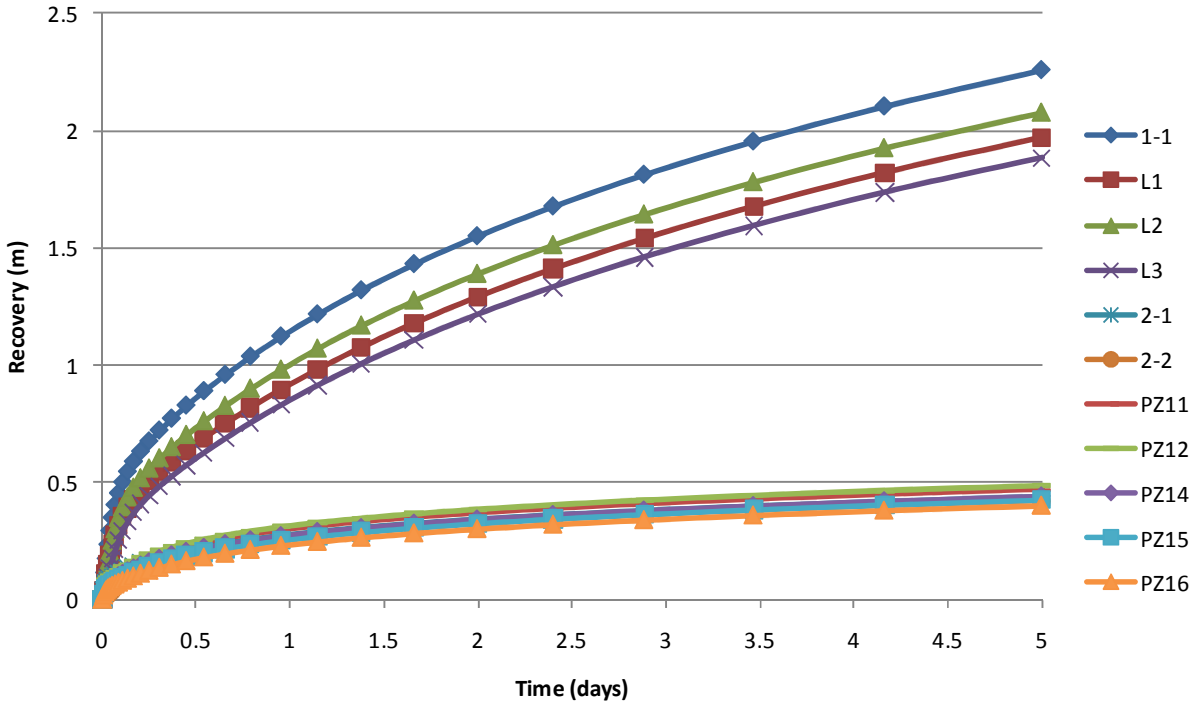


Figure 6-16. Recovery Scenario Calibration Results

6.4 Evaluation of Potential Sources

The model was used to investigate the possible causes of groundwater rise previously postulated – see Section 2.3. This was investigated in the model by removing the potential groundwater source (such as Nazlet El Semman leakage) or changing the corresponding boundary condition (for example, lowering the water level in the Mansouriah Canal).

The results are summarized in Table 6-2 in terms of the groundwater drop or rise associated with the action, in both the alluvium and limestone. These results are for steady state conditions, i.e., after several years. The greater effect is the stoppage of the El Ahram well field, which caused a groundwater rise of 1.0 m at the Sphinx. The observed groundwater rise in 2007 can directly be attributed to this event. According to the model, steady state had not been reached at that time, and the rise predicted by the model for that time was 0.9 m, as was observed.

Completely stopping leaks of the water supply and wastewater systems in Nazlet El Semman (which is essentially impossible) would lower groundwater levels at the Sphinx by 0.09 m; but the effect in the alluvium would be considerably greater, estimated to be 0.55 m. The large difference between the alluvium and limestone aquifers is due to the hydraulic separation between the two which has been discussed previously.

Recharge from the Mena House golf course irrigation is estimated at 0.02 m in the limestone, but two and a half times that much in the alluvium.

The influence of the Nile River is almost 1 for 1 in the alluvium. In the limestone, a smaller effect is predicted, but this is thought to be due to the "specified head" boundary condition applied along the Fayoum Road. If the water level in the Nile were to drop substantially, over time the water level along the Fayoum road would also drop.

Table 6-2. Influence of Different Sources on Groundwater Levels in Sphinx Area

Source	Model Simulation	Change in Groundwater Level (m)	
		Limestone	Alluvium
Nazlet El Semman	Stop recharge from water and wastewater systems leakage	0.09	0.55
Mena House Golf	Stop recharge from irrigation	0.02	0.05
Mansouria Canal	Lower water level by 0.5 m	0.01	0.04
	Reduce leakage by half	0.02	0.07
Nile River	Lower water level by 1 m	0.3	0.78
El Arham well field	Stop pumping	1.0	

Based on the above results, it can be concluded that the high groundwater levels observed at the Sphinx in 2007-2008 were due to the natural groundwater regime in the area, mostly driven by the water level in the Nile River. Leakage in Nazlet El Semman, irrigation recharge from the Mena House, and seepage from the Mansouriah Canal all contribute to raise groundwater levels in the area, but only by relatively small amounts. The fact that groundwater levels were lower prior to 2006 was due to the drawdown from the El Ahram well field, located 2.2 km north of the Sphinx. This drawdown masked the overall groundwater level regime in the area. Thus addressing the groundwater recharge from the different sources outlined above is not expected to lower groundwater levels to the desired target levels.

6.5 Evaluation of Groundwater Lowering Alternatives

The calibrated model was used to evaluate and refine the different groundwater lowering alternative. The alternatives that were considered were:

- Vertical Wells
  - Existing 8 operating dewatering wells + existing 5 wells in Workers Area
  - Existing 8 operating dewatering wells + 7 additional wells in limestone
  - Existing 8 operating dewatering wells + existing 5 wells in Workers Area + 7 additional wells in limestone
- Linear Drains
  - Phase 1 system with drain in Temples area
  - Phase 1 system + Phase 2 System in Workers Area
  - Phase 1 and 2 systems with additional HDD leg

For each alternative, several model simulations were conducted with different configurations and the optimum configurations are presented in the following. Calculated groundwater levels are presented one year after implementation of the alternative, starting from the equilibrium no-dewatering scenario. In practice, it is expected that the current dewatering will not be stopped before the new system is in place, however, this way of presenting results is conservative, in particular as regards drain flows, which will be highest for higher groundwater levels. Groundwater levels are expected to continue dropping after the 1-year time of the results, but this contributes to the overall conservativeness that is warranted for groundwater systems.

Existing Eight Operating Dewatering Wells + Existing Five Wells in Workers Area

Calculated groundwater levels are shown in Figure 6-17 with four wells pumping 55 m^3/hr and one at 75 m^3/hr. With the Workers Area wells activated the groundwater levels drop in this area, but the effect in the limestone is limited. Thus, simply activating the Workers Area wells is not sufficient to meet the target level in the Sphinx Area.

Existing Eight Operating Dewatering Wells + Seven Additional Wells in Limestone

Seven additional wells were added in the limestone, to the west of the operating dewatering system. Each well was assumed to pump 50 m^3/hr, which is the average of the wells currently pumping from the limestone. Calculated groundwater levels with these 7 new wells together with the 8 operating ones are shown in Figure 6-18. Groundwater levels in the limestone are lowered to within the target level in the Sphinx area.

Existing Operating Dewatering Wells + Existing Wells in Workers Area + Additional Wells in Limestone

Calculated groundwater levels with the 5 Workers Area wells and the 7 additional limestone wells are shown in Figure 6-19. With this configuration, target groundwater levels are met in both the Sphinx area and the Workers Area.

Linear Drain

A linear drain system was investigated with the overall configuration shown in Figure 6-20. The drains are partly in the alluvium and partly in the limestone, in particular the two legs that extend from the main trunk in the Sphinx Area. Phased implementation was considered and results for the different phases are shown below. The elevations shown in Figure 6-20 are the elevations of the water level in the drain. Considering approximately 0.5 m water above the pipe invert, plus 0.5 m for the pipe

bedding, the invert of the trench would need to be 1.0 m below the numbers in Figure 6-20. These elevations were optimized to reach the desired groundwater lowering target, but to provide a factor of safety, lowering the actual drain by an additional 0.5 m is recommended.

Thus, the invert of the trench would be 1.5 m below the numbers listed in Figure 6-20.

Phase 1 System with Drain in Temples Area

In Phase 1, only the portion of the system in the Sphinx area would be implemented. Calculated groundwater levels are shown in Figure 6-21. The 12.5 m target level is achieved in the Sphinx area and the flow discharging to the drain is 1,050 m^3/hr. To be conservative, however, it is recommended that this scenario be supplemented by passive wells penetrating deeper in the limestone aquifer than the drains. Also, extending the wadi leg of the drain in a sub-branch behind the Khafre Valley Temple should be considered to maximize the groundwater extraction from the limestone.

Phase 1 and 2 Systems with Additional HDD Leg

Although Phase 1 is shown to meet the 12.5 m target groundwater level in the Sphinx area, some degree of conservatism is warranted given the complicated nature of the interface between the alluvium and limestone aquifers. Therefore, adding another leg to the system within the limestone to the north of the temples and Sphinx should be considered. Because of the large depths involved, and the presence of a temple as well as a road, use of HDD would be required.

Calculated groundwater levels with this additional leg are shown in Figure 6-22. The area where groundwater is below 12.5 m increases and the flow discharging to the drain increases to 1,170 m^3/hr.

Phase 1 System + Phase 2 System in Workers Area

Calculated groundwater contours are shown in Figure 6-23. As compared to the contours for Phase 1 alone, shown in Figure 6-22, adding Phase 2 extends the groundwater lowering to the south, as would be expected, but only to a limited extent. Phase 1 alone almost met the target for the Workers Area and, therefore, adding Phase 2 may not be necessary. Thus, a phased implementation is all the more warranted, with the decision to proceed made after the performance of Phase 1 is documented.

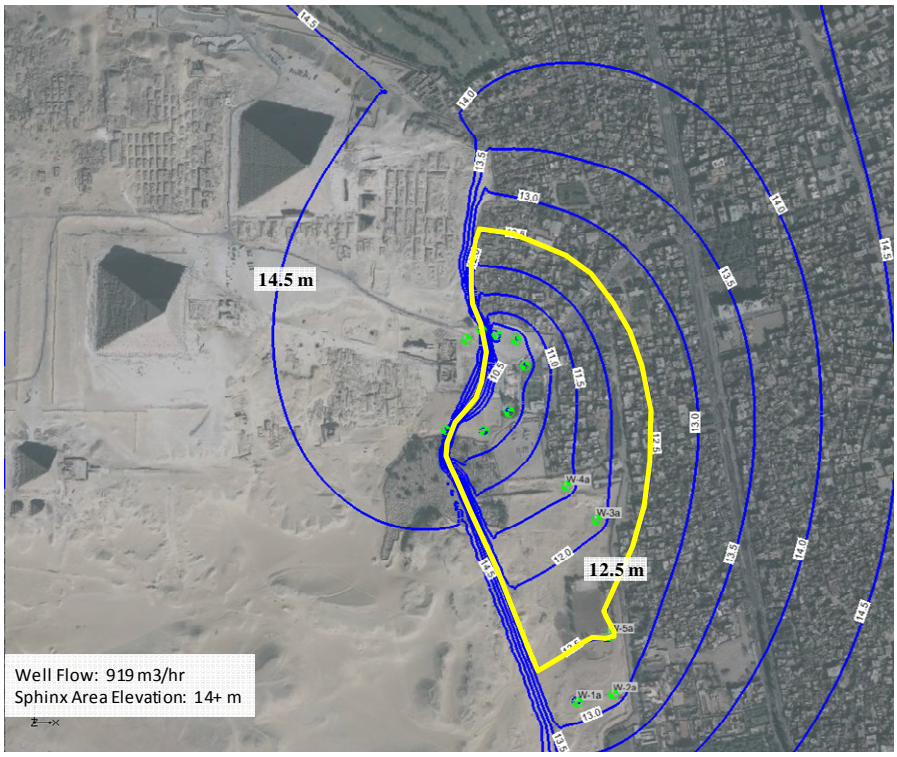


Figure 6-17. Groundwater Levels for Existing Operating Dewatering Wells + Existing Wells in Workers Area

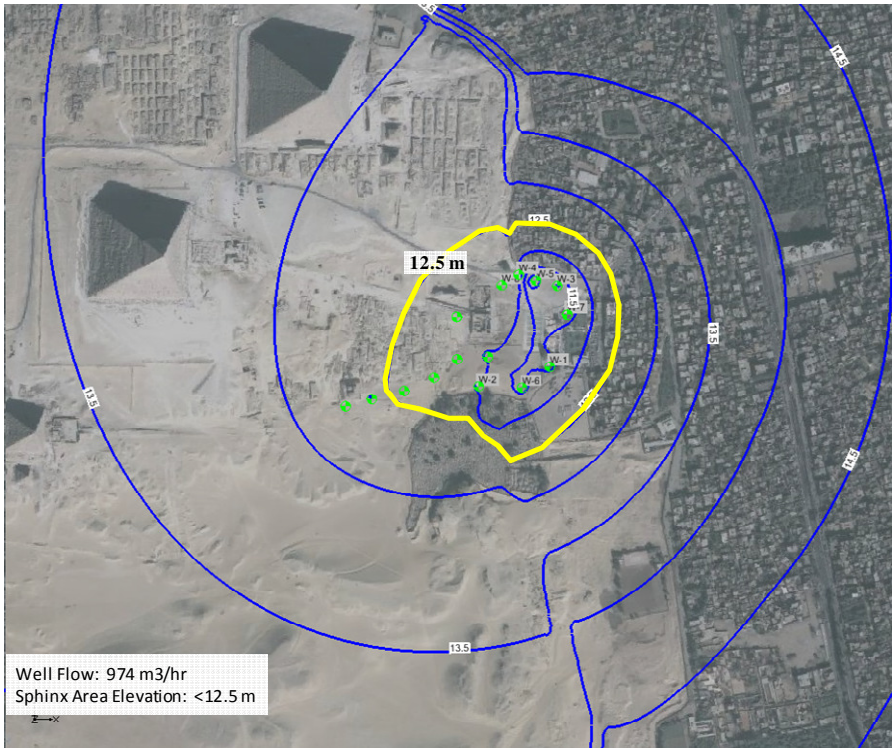


Figure 6-18. Groundwater Levels for Existing Eight Operating Dewatering Wells + Seven Additional Wells in Limestone

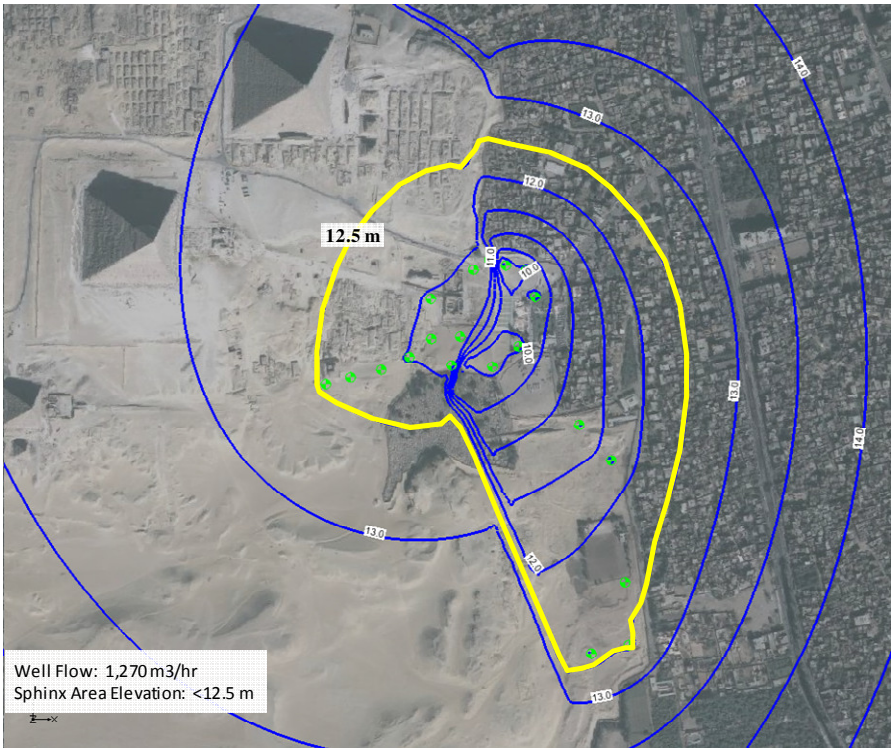


Figure 6-19. Existing Operating Dewatering Wells + Existing Wells in Workers Area + Seven Additional Wells in Limestone

Figure 6-20. Overall Linear Drain Configuration and Elevations

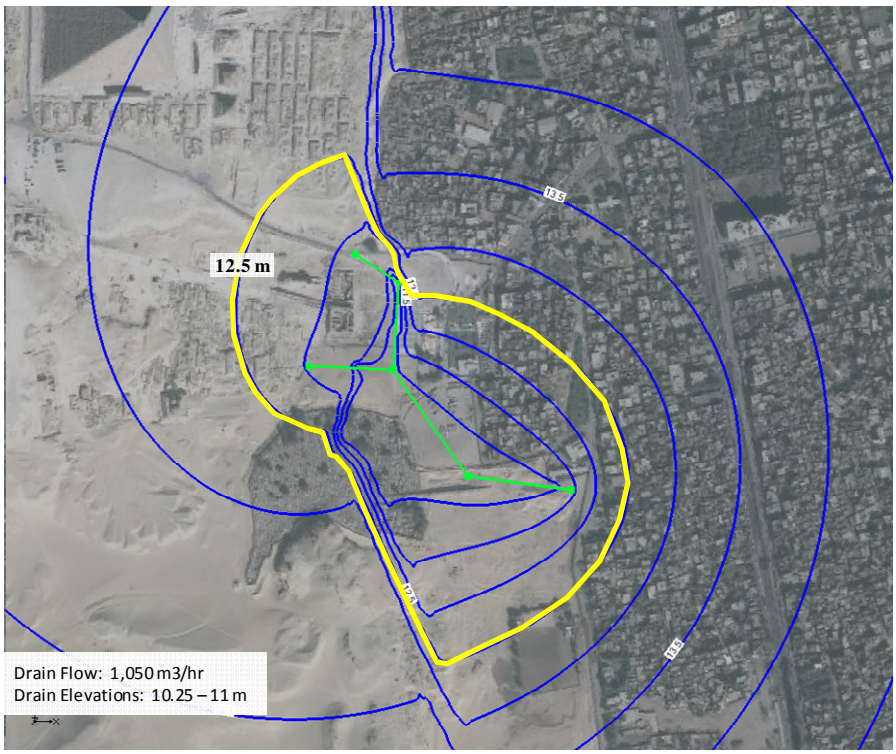


Figure 6-21. Calculated Groundwater Levels for Phase 1 Drain

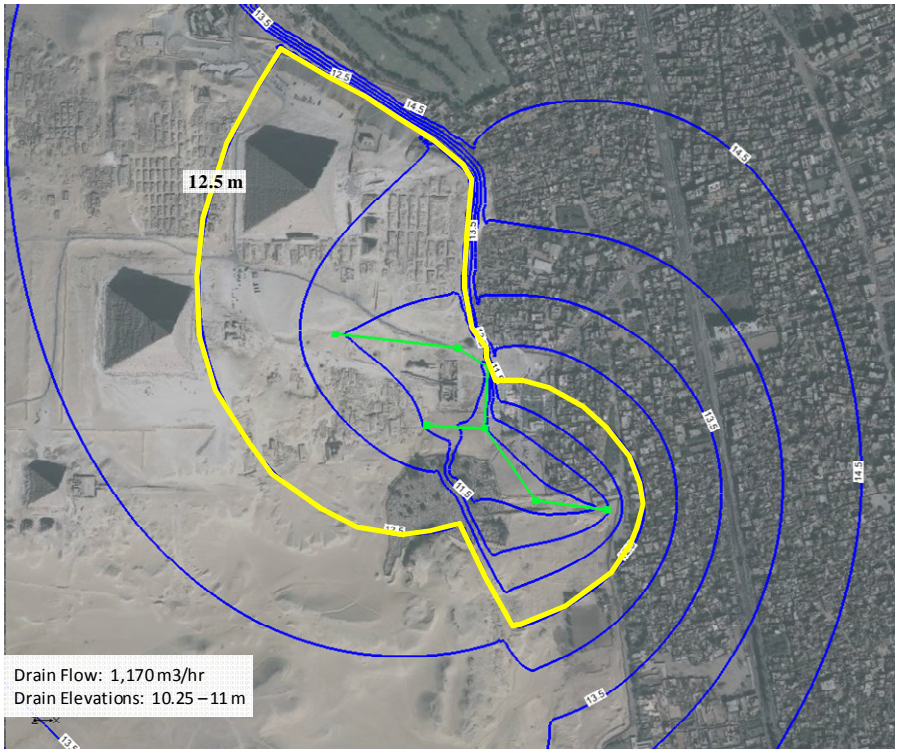


Figure 6-22. Calculated Groundwater Levels with Phase 1 Drain and Additional HDD Leg

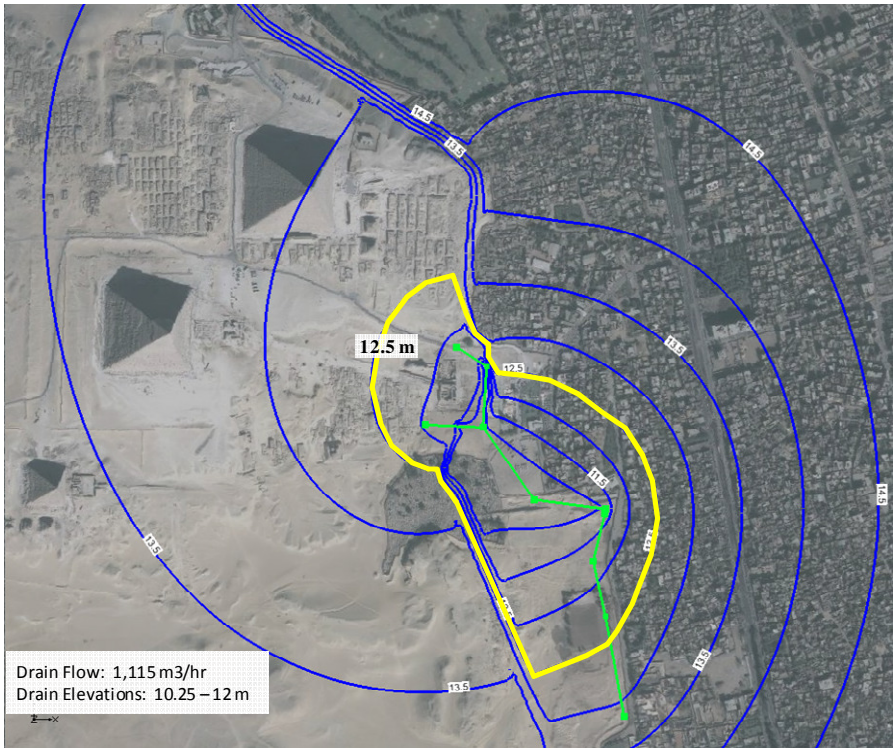


Figure 6-23. Calculated Groundwater Levels with Drain Phases 1 and 2

7.0 Cost Benefit Analysis

4.4 Alternatives Considered

The alternative approaches to lowering groundwater levels in the Pyramids Plateau area that were described in Section 5 of this report are:

9. Source curtailment
10. Vertical wells
11. Drains in trenches
12. Drains in micro-tunnels
13. Vertical passive wells with drains
14. Horizontal wells
15. Cutoff wall(s)
16. Restarting the El Ahram well field

The alternative approaches that were found viable were refined using the groundwater model as discussed in Section 6.5. In some cases, alternatives have been combined to take advantage of benefits under certain site conditions. Where alternatives were determined feasible, cost analysis were also performed. The collective advantages, disadvantages and costs are summarized in the paragraphs that follow.

Source Curtailment (Alternative 1)

As previously discussed, addressing the cause of the problem can be less costly than addressing its consequences. The recently observed (2006-2007) groundwater level rise at the site was primarily due to the curtailment of pumping at the El Ahram well field, approximately 2.2 km north of the site, which masked the actual groundwater levels and other effects. These other effects were discussed in Section 6.4.

- Recharge from Mansouriah Canal.
- Leakage from water supply pipes and sewers in Nazlet el Semman.
- Irrigation at Mena House golf course and Sound and Light Show garden.
- Irrigation in agricultural areas south of the site.

The advantages and disadvantages of this alternative are:

Advantages

- Reduce the required dewatering system capacity
- Better to address to cause than effect

Disadvantages

- Implementation extensive and out of control of SCA and could not be accomplished in a timely manner
- Difficult to implement
- Minimal groundwater lowering impact and does not achieve goals necessary levels to protect antiquities

Given the above advantages and disadvantages, this alternative was not priced and will not be considered further as a component of the permanent groundwater lowering solution. However, several of its elements are worthy and should be considered for implementation. For example, a design for an underdrain at the Mena House golf course has been prepared and is being implemented which will reduce contributions from it. Also, reducing leakage in Nazlet El Semman is a water supply system issue that should be addressed as part of system operation and maintenance.

Vertical wells (Alternative 2)

This option of expanding on and modifying the existing SCA system of vertical wells with individual pumps would build on the successes of University of Cairo efforts in lowering groundwater. The system would include the 8 existing operating wells, the 5 existing non operating wells, and approximately 7 additional wells for a total of 20 wells and should successfully achieve groundwater lowering targets. The advantage and disadvantages of this alternative are:

Advantages

- Modularity (one or more additional wells could easily be added if the original system is found to be insufficient)
- Simple construction
- Existing University of Cairo system would be supplemented
- Lower Capital Cost
- Lesser short term construction impact to touristic site

Disadvantages

- Greatest maintenance and operating costs of the alternatives due to high levels of energy consumption
- Future maintenance in touristic site
- Electromechanical components of approximately 20 wells requiring maintenance within the touristic area
- Numerous vaults or (as now) above ground extensions within the touristic area

Estimated Cost

- Capital Cost LE 6.2 million
- O&M Cost (30 Year) LE 33.3 million
- Total Present Day Cost (30 Yr) LE 39.5 million

This alternative to lower groundwater could be implemented either wholly or to supplement other alternatives as may be deemed feasible.

Linear Drains in Trenches (Alternative 3)

Linear drains placed in trenches excavated from the surface are another common approach to dewatering. This alternative as previously shown in Figure 5.4 provides a passive approach within the touristic area by allowing groundwater to flow by gravity to a pump station located on the boarder of the plateau area. The flow would then be pumped via a force main to the Mansouria Canal. Based on modeling results discussed in Section 6, this alternative should successfully achieve groundwater lowering targets.

Advantages of linear drains in trenches include:

- Largely passive system with only one pumping station required
- Invisible system, with the pumping station located away from the touristic area
- No maintenance required inside touristic area
- May allow discovery of archeological structures or artifacts
- Least total cost (combined capital and O&M)

Disadvantages include:

- Relatively deep trench required resulting in greatest construction impact in touristic area
- High capital cost
- Longer construction period
- Difficult to retrofit if required
- Risk of impact to archeological structures

Estimated Cost

- Capital Cost LE 13.2 million
- 30 Year O&M Cost LE 17.2 million
- Total Present Day Cost LE 30.4 million

The O&M cost of this alternative is less than that of the vertical wells because the pump head is less, and hence the power requirement is less, and the maintenance requirements are also less.

Due to incomplete knowledge of fractures and joints through which groundwater flows in the limestone, this alternative should be supplemented by additional measures described in the paragraphs that follow to help ensure that groundwater level targets are met in the limestone areas.

Linear Drains in Trenches with Vertical Wells and Pumps (Alt. 3 supplemented by Alt. 2)

The linear drain in trenches alternative could be supplemented with vertical wells and pumps in the limestone area. While groundwater model results indicate that the vertical wells would not be necessary to supplement the linear drain in trenches alternative, one or more vertical pumps with wells could be added later, or existing Cairo University wells capped and maintained as a potential backup. Advantages and disadvantages over linear drains in trenches alone are as follows:

Advantages

- Achieves lower groundwater levels in limestone area than linear drains alone
- Modularity (one or more additional wells could easily be added if the original system is found to be insufficient)

Disadvantages

- Reintroduces electromechanical equipment in the touristic areas
- Increases operating and maintenance costs

An estimated cost for this alternative is not included as this supplement would only be introduced should the proposed system incompletely meets the groundwater lowering targets in the limestone.

Linear Drains in Trenches with Vertical Passive Wells (Alt. 3 supplemented by Alt. 5)

As discussed in Section 5.6, vertical passive wells can be utilized to enhance extraction flow from limestone areas without the need for pumps. The vertical passive wells would be located in the linear drains trenches as the drains enter the limestone area to the north and south sides of the Sphinx area. These vertical passive wells would maximize the number of fractures in the limestone that are intercepted by the drainage system. For the purposes of this estimate, we are assuming 3 passive wells would be provided in each linear drain leg adjacent to the Sphinx area for a total of 6 passive wells. Advantages and disadvantages over linear drains in trenches alone are as follows:

Advantages

- Would achieve lower groundwater levels in limestone area than linear drains alone
- Additional capital cost is minimal

Disadvantages

- Difficult to estimate benefit given variables associated with encountering fractures in the limestone.

Estimated Cost

- Capital Cost LE 13.4 million
- 30 Year O&M Cost LE 18.1 million
- Total Present Day Cost LE 31.5 million

Linear Drains in Trenches with Horizontal Direction Drilling (Alt 3 supplemented with Alt. 4)

Horizontal directional drilling (HDD) is an alternative method of implementing linear drains without the construction impact associated with open trench excavation. The dewatering benefits would be equivalent to those of the linear drains in trenches with the added benefit of being able to extend further into the limestone. However, horizontal well construction utilizing micro-tunneling has not been performed in Egypt and could be performed by a limited number of vendors. Further, the local contractors do not have experience in this type of work and the equipment and stainless steel piping materials would need to be imported into Egypt.

Given the above, and the high projected capital costs, the alternative is not considered feasible to implement for all linear drains. However, for the drainage leg north of the Sphinx, this alternative is viable to avoid deep excavation in limestone and provide added assurance that groundwater lowering targets will be met in the limestone area. Advantages and disadvantages over linear drains in trenches alone are as follows:

Advantages

- Should achieve lower groundwater levels in limestone than linear drains alone
- Reduces impact and construction duration in sensitive touristic area

Disadvantages

- Difficult to estimate benefit given variables associated with encountering fractures in the limestone.
- Limited vendors available
- Not attempted in Egypt.

Estimated Cost

- Capital Cost LE 18.7 million
- 30 Year O&M Cost LE 18.1 million
- Total Present Day Cost LE 36.8 million

Horizontal Wells (Alternative 6)

Similar to Alternative 4 discussed above, horizontal wells as presented in Section 5.7 were considered as an alternative to constructing linear drains without the construction impact required utilizing typical open trench excavation. Again, the dewatering benefits would be equivalent to that of the linear drains constructed in trenches.

Advantages

- Little disruption at ground surface with the exception of tunneling shaft locations
- Reduced construction period

Disadvantages

- Requires importation of equipment and materials
- No local experience with horizontal wells
- High cost
- Possible destruction of subsurface antiquities

Estimated Cost

- Capital Cost LE 31.3 million
- 30 Year O&M Cost LE 17.2 million
- Total Present Day Cost LE 48.5 million

Cutoff Walls (Alternative 7)

Cutoff walls as a primary alternative are not considered viable for the reasons discussed in Sub-section 5.8. However, a mini cutoff wall in the form of impermeable material could be installed against the eastern side of the trenches in the direction of Nazlet El Semman. The effectiveness of this cutoff wall would likely be small, but the cost would be minimal so that it can be considered. The option of including a mini cutoff wall with a linear drain with open trench excavation alternative would be further investigated during a detail design effort.

Restart of El Ahram Well Field (Alternative 8)

As previously discussed in Sub-section 5.9, the viability of restarting the Al Ahram Well Field is under investigation by others. However, whether or not this measure would move forward is not under the

control of SCA, future shut down of the well field cannot be discounted, and shutdown of the well field alone would not achieve the desired ground levels. This alternative will therefore not be considered further.

4.5 Cost Comparison

Costs for alternatives considered viable are summarized in Table 7-1 and shown as a bar chart in Figure 7-1.

Table 7-1. Cost Comparison

Alternative	Cost in LE Millions		
	Capital	O&M (30 yrs)	Total Present Day Cost
Vertical Wells w/Pumps	6.2	33.3	39.5
Linear Drains in Trenches	13.2	17.2	30.4
Linear Drains w/Vertical Passive Wells	13.4	18.1	31.5
Horizontal Wells	31.3	17.2	48.5
Linear Drains w/ HDD Leg	18.7	18.1	36.8

As is evident, Linear Drain in Trenches offers the least expensive present day cost of the alternatives. Adding the options of vertical passive wells has little relative impact to the estimate total cost. Adding an HDD section in place of linear drain in trenches along the north side of the Sphinx would provide added dewatering benefit in the limestone while limiting impacts to tourism.

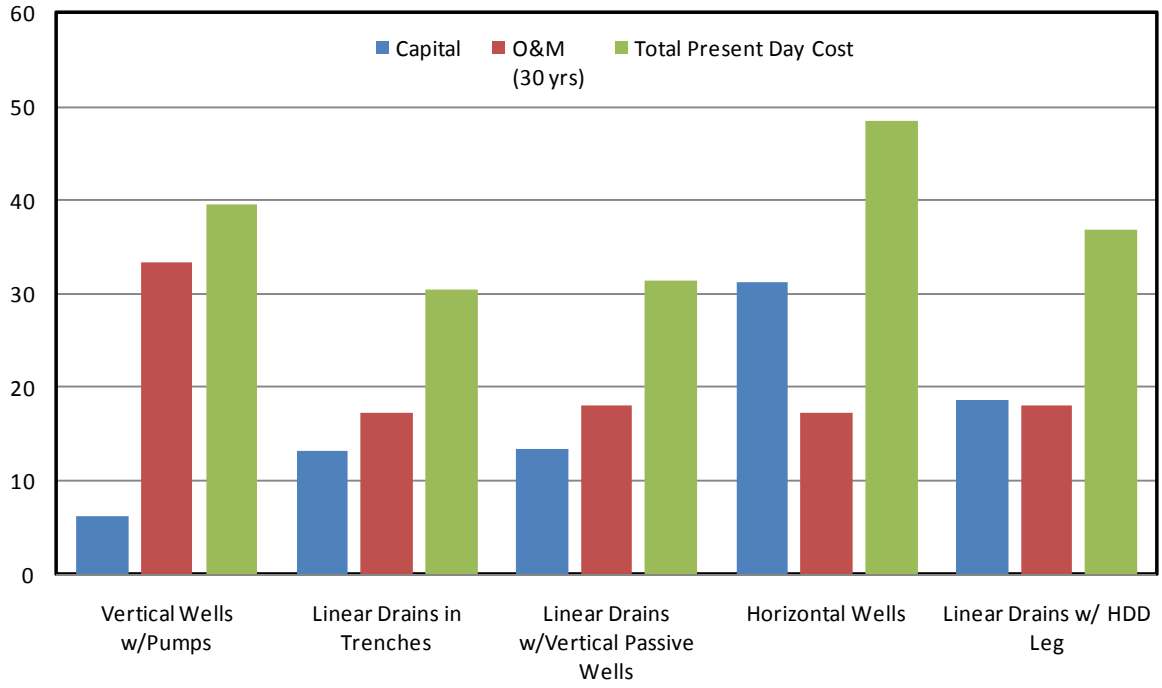


Figure 7-1. Cost Comparison of the Groundwater Lowering Alternatives

8.0 Summary and Conclusions

Groundwater levels were observed to rise significantly in 2006 and 2007 to the point where puddles started to appear in low-lying areas in front of the Sphinx and Khafre Valley Temples and in the Workers Area. In response to this groundwater rise, investigations were conducted by Cairo University and a groundwater extraction system composed of eight lowering wells was installed and operated, which considerably lowered groundwater levels.

The present project was initiated by the Supreme Council on Antiquities (SCA) and USAID to develop a long term groundwater lowering solution for the Pyramids Plateau. The project included studies, field investigations, modeling, engineering design, environmental assessment and other related tasks. This report covers Phase 1 of the project with the following specific components:

- Gather and review existing information
- Develop and conduct field investigations program
- Develop groundwater lowering targets
- Develop, calibrate and apply a groundwater model to determine the cause of groundwater rise and optimize different groundwater lowering alternatives
- Develop groundwater lowering alternatives and conduct cost benefit analysis of the alternatives.

The main elements and results of the above components are summarized below:

Review of Existing Information

The Pyramids Plateau has been the object of a number of geological studies associated with the construction of the Pyramids and Sphinx. These studies provide information on the limestone that forms the plateau.

In the 1980s, the AMBRIC sewering project included the drilling of numerous borings in Nazlet El Semman, east of the Pyramids Plateau, and also several borings in the plateau near the Sphinx. Important information derived from this project includes the following:

- The two major aquifers in the area are the Nile River alluvium and the Pyramids Plateau limestone
- The two aquifers do not appear to be well connected hydraulically
- The El Ahram well field, located 2.2 km north of the Sphinx, has a large area of influence which extends to the Sphinx.

Following the observed groundwater rise in 2007, Cairo University conducted a number of investigations in the Sphinx area that included borings, groundwater sampling and analyses, pumping tests and the installation of eight dewatering wells. Valuable data from this work includes the following:

- Aquifer transmissivity in both the alluvium and limestone is relatively high
- The eight-well dewatering system has been extracting about 624 m^3/h and has achieved drawdowns of 0.9 m in the alluvium and 3.5 m in the alluvium
- Potential sources of the groundwater rise are:
    - Water supply or wastewater system leakage in Nazlet el Semman
    - Irrigation at Mena House golf course and at Sound and Light gardens
    - Higher water level in Mansouria Canal
    - New building complexes along Cairo-Fayoum road

- Five groundwater extraction wells have also been installed in the Workers Area, but pumping at these wells has not been initiated.

Field Investigations

To supplement the existing information a field investigations program was developed and implemented. The program included:

- Drilling of two test wells and four piezometers near Mena House and in Nazlet El Semman.
- Conduct of 3 pumping tests, in the two new test wells and at a well in the Workers Area and one recovery test at the 8 dewatering wells currently in operation in the Temples area.
- Installation of 2 piezometers along Fayoum Road.
- Surveying and groundwater level measurements at the new and (still existing) previously installed piezometers and wells.
- Geophysics (ground penetrating radar and seismic refraction) at 4 locations.
- Collection and chemical analysis of groundwater samples at 6 locations.

Salient results of the program included:

- Measured groundwater levels confirmed the extent of the dewatering system zone of influence
- Groundwater level along Fayoum road is comparable to that in the Sphinx area (except for a measurement that appears to be representative of a perched layer)
- Aquifer transmissivities were consistent with those measured by Cairo University
- The limestone and alluvium aquifers have significantly different responses to the dewatering.
- Except for a few minor exceptions, groundwater in the area is suitable for discharge to irrigation canals.

Groundwater Lowering Targets

Groundwater impacts to archeological structures can arise if groundwater reaches the stone foundations of these structures. Because of capillary rise, groundwater levels must be kept a sufficient distance below the foundations to avoid interaction. Based on a review of the elevations of structures to be protected and capillary rise measurements in four test pits, the following groundwater level targets were developed:

- 12.5 to 13.0 m in the Sphinx, Sphinx Temple and Khafre Valley Temple area
- 13.0 to 14.0 m in the Workers Area

Groundwater Lowering Alternatives

Alternatives that were considered, and the results of initial evaluations were:

- Source curtailment - Should be encouraged, but out of SCA control and will likely not reach the targets
- Vertical wells - Viable solution to be optimized with the groundwater model
- Drains in trenches - Viable solution to be optimized with the groundwater model
- Drains in micro-tunnels – May be appropriate in higher ground or limestone areas
- Vertical passive wells with drains – Should be considered to increase flow to drains in limestone
- Horizontal wells – Viable, but very expensive
- Cutoff wall(s) – Not practical because of large depths involved - rejected

- Restarting the El Ahram well field – Would lower groundwater levels but not to target levels and not a definitive permanent solution as it would not be under the control of SCA

Groundwater Model

A three-dimensional groundwater flow model of the Pyramids Plateau and adjoining alluvium aquifer was developed using the MODFLOW software and calibrated to four sets of conditions:

- Pumping – El Ahram well field in operation (1970 to September 2005)
- No Pumping – El Ahram well field shut down (September 2005 to July 2008)
- Dewatering – Dewatering wells operating near the Sphinx (July 2008 to 2010)
- Dewatering Well Recovery – 5-day test with dewatering pumps turned off (February 2010)

The model was used to investigate the impact of the factors posited as potential causes of groundwater rise at the Sphinx. Results were as follows:

- Water supply or wastewater system leakage in Nazlet el Semman – calculated 0.09 m groundwater rise at the Sphinx
- Irrigation at Mena House golf course and at Sound and Light gardens – calculated 0.02 m groundwater rise at the Sphinx
- Higher water level in Mansouria Canal – calculated 0.02 to 0.05 m groundwater rise at the Sphinx
- Nile River water level – approximately 1 for 1 relationship between Nile River water level and groundwater rise at the site
- New building complexes along Cairo-Fayoum road – no apparent effect
- El Ahram well field – calculated 1.0 m drawdown at the Sphinx

Based on the above it was concluded that the groundwater rise that was observed in 2007 was due to the shut-down of the El Ahram well field which occurred between September 2005 and March 2006. The other factors caused an overall groundwater level rise in the Cairo area, but the well field was masking this effect by its drawdown.

The model was then used to optimize groundwater lowering measures that would meet the targets developed above. Salient results were:

- Reaching the target in the Sphinx area would require an seven additional wells in the limestone
- Phase 1 of a linear drain system, north of a pumping station near the bus parking lot, should meet the target levels, but sub-leg add-ons and deep vertical wells are recommended to provide additional assurance of satisfactory performance.
- Phase 1 and 2 of the linear drain system increase the system's influence in the Workers area, but may not be needed to achieve the target levels.

Cost Benefit Analysis

Of the alternatives discussed, those considered viable in the final analysis are as follows:

- Vertical wells with pumps – High maintenance costs and excessive maintenance in the antiquities area
- Linear Drains in Trenches – most cost effective, and passive system requiring no maintenance in antiquities area
- Linear Drains in Trenches with Vertical Passive Wells – only very slightly more costly than Linear Drain in Trenches alone, with added benefit of further reduction of groundwater in limestone
- Horizontal Wells – Viable but considerably more expensive than other alternatives
- Linear Drains in Trenches with Horizontal Directional Drilling leg in Limestone – additional expense but provides added confidence that groundwater level reductions will be maintained in the limestone areas.

Estimated costs are summarized as follows:

Alternative	Cost in LE Millions		
	Capital	O&M (30 yrs)	Total Present Day Cost
Vertical Wells w/Pumps	6.2	33.3	39.5
Linear Drains in Trenches	13.2	17.2	30.4
Linear Drains w/Vertical Passive Wells	13.4	18.1	31.5
Horizontal Wells	31.3	17.2	48.5
Linear Drains w/ HDD Leg	18.7	18.1	36.8

Recommendations

Based on the above and to avoid maintenance in the antiquities/touristic areas, we recommend implementation of the alterative of Linear Drains in Trenches supplemented with Vertical Passive Wells in limestone areas and a linear drain to the north of the Sphinx constructed by method of Horizontal Directional Drilling (HDD). The added benefits of adding an HDD drain section is to avoid deep trench excavation in this highly visible and touristic area, and added assurance that groundwater lowering targets would be achieved in the limestone area around the Sphinx.

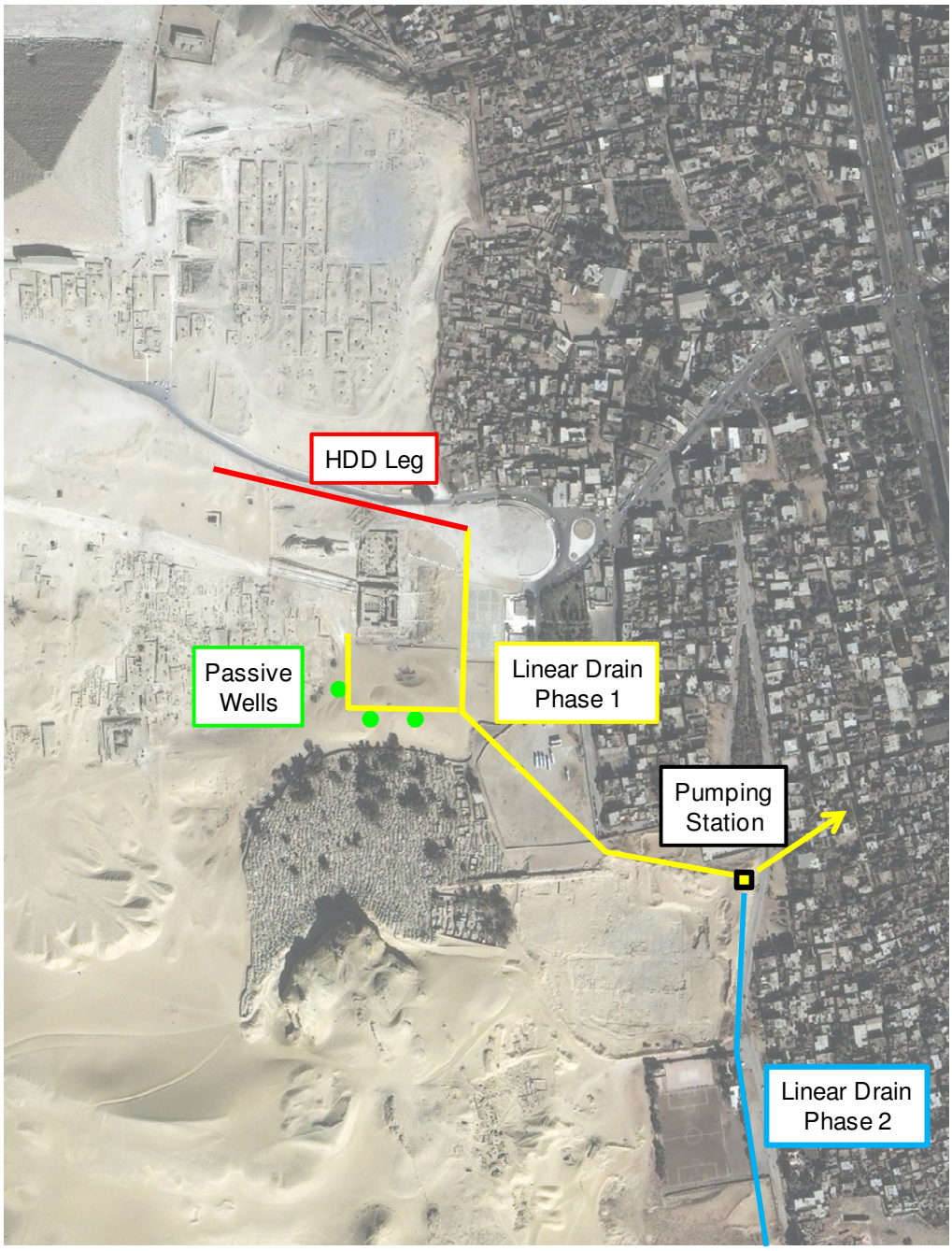


Figure 8-1. Recommended Groundwater Lowering System

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